ANNEX X: APPENDIX A

ANNOTATED BIBLIOGRAPHY

Table of Contents

Tables

Abbreviations

Abbreviation	Definition
CV	coefficient of variation
DFIR	Double Fenced Intercomparison Reference
e.g.,	for example
ET	evapotranspiration
E/P	evaporation to precipitation ratio
et al.	more than one additional author
i.e.,	that is
N	north
NWT	Northwest Territories
PT	Priestley-Taylor
R^2	coefficient of determination
RC	runoff coefficient
SD	standard deviation
vs.	versus
W	west
WMO	World Meteorological Organization

Units of Measure

Unit	Definition
%	percent
±	plus or minus
>	greater than
≥	greater than or equal to
°C	degrees Celsius
cm	centimetre
ha	hectare
km	kilometre
km^2	square kilometre
m	metre
m/s	metres per second
m^2	square metre
m/s	metres per second
masl	metres above sea level
mm	millimetre
mm/d	millimetres per day
mm/yr	millimetres per year
n	number of observations
W	wind speed

This appendix presents an update to the annotated bibliographies developed by Golder Associates Ltd. (1997, 2008) for baseline data of climate and hydrology of the Diavik Diamond Mine and prepared for Diavik Diamond Mines Inc., and is divided into three sections that address the following topics:

- snowfall undercatch, sublimation, and wind transport;
- evapotranspiration in northern tundra environments; and,
- runoff coefficients in northern tundra environments.

The update focuses on areas local to the Lac de Gras basin.

A1 SNOWFALL UNDERCATCH, SUBLIMATION, AND WIND TRANSPORT

Marsh P, Quinton B, Pomeroy J. 1995. **Hydrological processes and runoff at the Arctic treeline in northwestern Canada.** In: Proceedings of the 10th International Northern Research Basin Symposium and Workshop, Svalbard, Norway, pp 368-397.

- Arctic treeline site in northwestern Canada, 40 km north-northeast of Inuvik, Northwest Territories (NWT).
- Drainage areas = 63 km^2 and 0.83 km^2.
- Low tundra zone; continuous permafrost region (up to 350 m depth with 0.3 to 1.0 m deep active zone).
- Snowfall accounted for 58% of annual water inputs to the basin.
- Blowing snow accounted for 15% of inputs.
- Sublimation removed 10% of the annual inputs in tundra areas.

Pomeroy JW, Marsh P, Gray DM. 1997. **Application of a distributed blowing snow model to the Arctic.** Hydrol Process 11: 1451-1464.

- Simulation of 1992 to 1993 winter in Trail Valley Creek basin, 50 km north of Inuvik, NWT.
- Snowfall measured "in-glade" (i.e., true snowfall) was 45% higher than the uncorrected winter snowfall recorded at the Inuvik weather station. 1.45 correction factor.
- Simulation results:
  - 28% of annual snowfall sublimated from tundra surfaces, while 18% was transported to sink areas.
  - For the catchment, 19.5% of annual snowfall sublimated from blowing snow, 5.8% was transported into the catchment, and 86.5% accumulated on the ground.
- Winter precipitation alone is insufficient to calculate snow accumulation. Blowing snow processes and landscape patterns govern the spatial distribution and total accumulation of snow water equivalent.
- Benson (1982): Arctic coast of Alaska; 11% of annual snow relocated, 32% sublimated.
- Relocation and sublimation of blowing snow can cause dramatic changes to the water balance.
- Arctic snowfall significantly exceeds snow accumulation.
- Highly dissected terrain with short fetches has less opportunity for sublimation than level plains with long fetches.
- Snow is relocated from areas of low aerodynamic roughness to areas with high roughness without regard for basin boundaries or overland flow divides.

- Spatial distribution of snow water equivalently important for modelling timing, amplitude, and persistence of snowmelt freshet.

Golder Associates Ltd. 1997. **Baseline Data of Climate and Hydrology for the Diavik Diamond Mine EIA.** Prepared for Diavik Diamond Mines Inc., August 1997, 117 p.

- Site climatic characteristics defined based on available local and regional climate data.
- Mean annual precipitation estimated to be 373 mm (229 mm snow and 144 mm rain) after applying a snowfall undercatch factor of 1.75.
- Performed literature review of hydrologic characteristics of Arctic basins.
- Snowfall in Arctic frequently underestimated because of effects of wind and trace events on snowfall gauging.
- The generally flat terrain and lack of vegetation offers little resistance to wind.
- Estimates of snowfall undercatch in Arctic environments range from 20% to 300%.
- Holocek and Vosahlo (1975) report that snow sublimation in spring can account for water losses of up to 40 mm from the snow pack.
- Estimated annual snowfall with no undercatch correction 131 mm.
- A snowfall undercatch correction factor of 1.75 was applied to estimate the actual snowfall on the ground – 229 mm.
- Based on the empirical relationships reported by Metcalfe et al. (1994) and Larson and Peck (1974), the mean snowfall undercatch correction factor for an mean wind speed of 18 km/h without considering trace events is approximately 1.3 (shielded Canadian Nipher gauges).
- The snowfall undercatch correction factor of 1.75 was recommended based on an estimation of basin evapotranspiration (ET) in Coppermine River catchment (drainage area = 19,300 km^2) approximately 200 km downstream of Lac de Gras (drainage area = 3,559 km^2).
- Basin ET was estimated based on assumed correction factors for measured lake evaporation to wetland evaporation, and measured lake evaporation to upland ET.
- Aerial variation of climatic variables may be different from the long-term trend and may vary considerably from year to year.
- Mean snow water equivalent for each terrain type was weighted according to the percentage of the terrain type in each basin, and the total snow water volume in each basin was calculated based on measured catchment areas.

Liston GE, Strum M. 1998. **A snow-transport model for complex terrain.** J Glaciol 44, No. 148: 498-516.

- Model of 6 km^2 domain in the foothill north of the Brooks Range in Arctic Alaska. Includes Imnavait Creek with a drainage area approximately 2.2 km^2.

- Model validated against four years of detailed snow depth maps (1986 to1990).
- Simulation results:
  - 9% to 22% of total winter precipitation sublimated domain wide;
  - majority of winter precipitation falling on wind-ward slopes sublimated (up to 50%); and,
  - transport loss 2% to 7% of total winter precipitation domain wide.
- Sublimation expected to increase with wind speed.

Goodison BE, Metcalfe JR, Louie PYT. 1998. **Country analyses, Annex 5.B Canada.** In The WMO Solid Precipitation Measurement Intercomparison Final Report. Instruments and Observing Methods Report No. 67, WMO, Geneva, Switzerland.

- Compared corrected Double Fenced Intercomparison Reference (DFIR) (World Meterological Organization (WMO) reference gauge) data to measured Nipher data and developed undercatch correction factors.
- Retention or wetting loss (amount of water adhered to gauge when emptied) approximately 0.15 mm ± 0.02 mm. Mean wetting losses greater for larger events and older gauges.
- Nipher with aluminum shields have larger mean catch (0.08 mm to 1.8 mm) than Nipher with fiberglass shields.
- Possible that a gauge can catch some blowing snow. Since wind speeds are generally greater during blowing snow events, a large correction for "undercatch" could be applied to a measured total already augmented by blowing snow. Problem most severe for gauges mounted close to the ground.
- At storm wind speeds up to 2 m/s, no correction for undercatch is required.
- For wind speeds (W) ≥ 2 m/s, catch efficiency decreases.
- Nipher/True (%) = $100 - 0.39\ W^2 - 2.02\ W$ (n = 162, $R^2 = 0.51$).
- Using mean wind speed for the site of 18 km/h = 5 m/s, the undercatch correction is 1.25.

Essery R, Li L, Pomeroy J. 1999. **A distributed model of blowing snow over complex terrain.** Hydrol Process 13: 2423-2438.

- Snow transport and sublimation rates increase rapidly with increasing windspeed.
- Distributed model of blowing snow transport and sublimation – Trail Valley Creek basin; Arctic tundra basin 50 km north of Inuvik, NWT.
- Simulated sublimation for 1996-1997 winter season 25% to 26% of total snowfall for shrub tundra and sparse forest, 40% for lakes, and 47% for open tundra.
- Simulated transport loss for 1996-1997 winter season of 22% on lakes and 18% on open tundra.

Pomeroy J, Hedstrom N, Parviainen J. 1999. **Effects of Snow Sublimation and Redistribution.** In: Wolf Creek Research Basin: Hydrology, Ecology, Environment, Pomeroy, J.W. and R.J. Granger (Eds.). National Water Research Institute, Environment Canada: Saskatoon, SK, Canada. pp 15-30.

- A review of a four-year record of snow studies in Wolf Creek basin, Yukon.
- Site composed of alpine (tundra plateau), shrub tundra (valley shrub-tundra), and boreal forest (lowland forest) environments.
- Discusses sublimation of blowing snow.
- The sublimation rate of a wind-blown snow proceeds several orders of magnitude faster than sublimation from surface snow covers.
- Strong winds and dry air in Arctic regions promote both blowing snow transport and sublimation.
- On mean 50% of snowfall removed from alpine plateau and 25% from low-lying shrub tundra by blowing snow events.
- Pomeroy et al. (1997) – rolling Arctic basin north of Inuvik, NWT: blowing snow sublimation from tundra is 28% of seasonal snowfall, while 18% lost to transport. Over the entire basin area, 19.5% of snowfall sublimated during blowing snow. Snow accumulation in the basin varied from 54% to 419% of seasonal snowfall.
- Recorded snowfall corrected for undercatch. Recorded snowfall at Environment Canada station found to be from 85% to 92% of corrected snowfall. At high-elevation shrub-tundra and tundra stations, measured snowfall ranged from 75% to 97% of corrected; corresponds to undercatch factor of 1.03 to 1.33.
- 38% to 45% (28 to 45 mm) annual snowfall lost to sublimation from spruce canopies at lower elevations. Mid-winter interception 46% to 70% (21 mm to 39 mm) of cumulative snowfall.
- Alpine tundra lost 39% to 79% (62 mm to 147 mm) of annual snowfall due to transport and sublimation; shrub-tundra lost 17% to 46% (26 mm to 68 mm). Inconclusive how much was due to sublimation.
- Deals mainly with snow transport and outlines how it is inappropriate to assume snow accumulation equals snowfall.

AGRA Earth & Environmental Ltd. 2000**. Deep Water Lake Basin Management Plan Hydrology and Water Balance.** Municipal and Community Affairs, GNWT.

- Hydrological analysis of Deep Water Lake 100 km south of Inuvik and 18 km east of Fort McPherson.
- Total catchment area approximately 31.2 km^2, of which 5.9 km^2 is Deep Water Lake and 5.36 km^2 is other tributary lakes. Total land surface 64% of basin.
- Apply an undercatch factor to snowfall data of 1.45 after Marsh et al. (1994) for Trail Valley Creek basin.

- Consider undercatch factor to include effects of accumulation, redistribution, and sublimation.
- 25% retention of annual snowfall assumed for lake surfaces based on snow survey data for lakes in Rankin Inlet.

Soegaard H, Hasholt B, Friborg T, Nordstroem C. 2000. **Surface energy and water balance in a high arctic environment in NE Greenland.** Theor Appl Climatol 70: 35-51.

- Energy balance of a coastal drainage basin in North East Greenland, 514.8 km^2 in size. 1995 to 1998.
- Area classified as ET tundra climate/high arctic.
- Annual Precipitation is 229 to 320 mm/yr; 75% snow.
- Daily evaporation from snow in cases with dry air and strong wind as high as 1.7 mm/d. Measured annual range 17.2 mm (1997/1998) to 38.2 mm (1995/1996).

Dery SJ, Yau MK. 2001. **Simulation of blowing snow in the Canadian Arctic using a Double-Moment Model.** Bound-Lay Meteorol 99: 297-316.

- Referenced Pomeroy et al. (1997) and Essery et al. (1999).
- Seasonal removal of 37 mm to 85 mm snow water equivalent through blowing snow sublimation at a Canadian Arctic tundra site.

Dery SJ, Yau MK. 2001. **Large-scale mass balance effects of blowing snow and surface sublimation.** J Geophys Res 107, No. D23, ACL8: 1-17.

- Values of the divergence of snow mass through wind redistribution when evaluated over large areas is generally two orders of magnitude lower than local scale surface and blowing snow sublimation.
- Mackenzie River basin (drainage area approximately 1.8×10^6 km^2) – surface sublimation removes 29 mm/yr of snow water equivalent, or about 7% of the annual precipitation.

Liston GE. 2002. **Modelled changes in Arctic tundra snow, energy and moisture fluxes due to increased shrubs.** Glob Change Biol 8: 17-32.

- Referenced Benson (1982), Liston and Sturm (1998), Essery et al. (1999), and Pomeroy and Essery (1999).
- 15% to 45% of snow cover in Arctic lost to sublimation.

Rees A, English M, Derksen C, Silis A. 2007. **The Distribution and Properties and Role of Snow Cover in the Open Tundra.** 64th Eastern Snow Conference, St. John's, Newfoundland, Canada, pp 111-117.

- Describes 2003 to 2007 field work in the Daring-Exeter-Yamba river basins (Coppermine River basin, NWT).
- 30,000 snow depth and 5,000 snow core measurements were collected for density and snow water equivalent estimation.
- Field data were compared to satellite measurements to examine tundra snow cover distribution.
- Snow cover was found to be heterogeneous and dependent upon terrain and vegetation.

Rees A M. 2010. **Tundra Snow Cover Properties from In-Situ Observation and Multi-Scale Passive Microwave Remote Sensing.** Thesis submitted in partial fulfillment of the requirements for Doctor of Philospohy in Geography, Wilfrid Laurier University, 268 p.

- Thesis describing field work in the Daring-Exeter-Yamba river basins and concurrent satellite microwave radiometer data.
- "Spatial distribution of snow depth, density, and SWE [snow water equivalent] in the study area is controlled by the interaction of blowing snow with terrain and land cover".
- "Despite the spatial heterogeneity of snow cover, several inter-annual consistencies were identified".
- "The variability in snow water equivalent was least on lakes and flat tundra, while greater on slopes and plateaus. Despite the variability, the inter-annual ratios of snow water equivalent among different terrain types does not change that much".

Mekis E, Brown R. 2010. **Derivation of an adjustment factor map for the estimation of the water equivalent of snowfall from ruler measurements in Canada**. Atmos Ocean 48:4: 284-293.

- Analysis of Nipher gauge versus ruler depth measurements at stations across Canada.
- Derivation of undercatch correction factors to be applied to ruler depth measurements.

Rees A, English M, Derksen C, Toose P, Silis A. 2013. **Observations of late winter Canadian tundra snow cover properties.** Hydrol Process. Doi: 10.1002/hyp.9931.

- Describes a multi-year project, initiated in 2004.
- Objective was to quantify tundra snow cover properties for comparison with satellite data and climate/hydrology models.
- Snow depth and snow water equivalent are "strongly influenced by terrain characteristics".
- Many consistent ratios between snow water equivalent on flat tundra vs. lakes, plateaus, and slopes.

A2 EVAPOTRANSPIRATION IN NORTHERN TUNDRA ENVIRONMENTS

Rouse WR. 1982. **The water balance of upland tundra in the Hudson Bay Lowlands – Measured and modeled.** Le Naturaliste Canadien 109, No. 3: 457-467.

- Two years (1978 and 1979) of water balance measurements at Churchill, Manitoba for upland tundra underlain by continuous permafrost.
- Total ET between final snowmelt and permanent snow cover approximately 200 mm.
- Seepage loss little less than half total ET in normal year, but substantially greater in wet year.
- Largest ET occurs immediately following snowmelt, with a subsequent decrease as the summer progresses (impact on monthly variation of ET).

Stuart L, Oberbauer S, Millar PC. 1982. **Evapotranspiration measurements in Eriphorum vaginatum tussock tundra in Alaska.** Holarctic Ecol 5: 145-149.

- Periodic ET measurements taken from late June to mid August 1978 near Eagle Creek, Alaska.
- Koranda et al. (1978) calculated mean ET rates of approximately 5 mm/d at Barrow Alaska.
- In tussock area, periodic ET rates ranged from 0.37 to 1.24 mm/d (mean 0.8 mm/d) and in intertussock areas from 0.61 to 1.90 mm/d (mean 1.3 mm/d).
- Actual ET 56% of Penman potential evaporation for intertussock (moss and shrubs) areas and 43% for tussocks.

Flugel WA. 1983. **Summer water balance of a high Arctic catchment area with underlying permafrost in Oobloyah Valley, N-Ellesmere Island, N.W.T., Canada.** In: Permafrost, Proceedings of the Fourth International Conference, July 17-22, 1983, Fairbanks, Alaska. National Academy Press, pp 295-300.

- A report on the water balance of the Ooblong Valley, North Ellesmere Island, Northwest Territories.
- Performed during summer months of June, July, and August 1978.
- Actual evapotranspiration only 1% of summer water balance; 51% snow and rain, 48% glaciers.
- Evapotranspiration from soils 0.1 mm/d or 20% of the mean potential evaporation measured.

Nakao K, Ishii I, Urakami K, LaPerriere J. 1985. **Hydrological Regime in Tundra Plain, St. Lawrence Island in Bering Sea.** Journal of the Faculty of Science, Hokkaido University. Vol 8, No 1, pp 1-13.

- St. Lawrence Island, 4,900 km^2 in size located 250 km south of the Bering Strait.

- Composed of 52.2% tundra, 18.6% lakes, and 29.2% mountainous regions.
- Continuous permafrost 14 m to 27 m depth; active layer depth of 0.15 m in summer.
- Ratio of ET over tundra surface to evaporation from lake estimated to be 0.5. ET 50% of lake evaporation.

van Everdingen RO. 1987. **The Importance of permafrost in the hydrological regime.** Chapter 9 in Canadian Aquatic Resources. M.C. Healy and R.R. Wallance (Eds.), Canadian Bulletin of Fisheries and Aquatic Sciences No. 215, pp 243-276.

- A comprehensive overview of surface runoff and groundwater in permafrost areas and water supply issues in the North.

Kane DL, Gleck RE, Hinzman LD. 1990. **Evapotranspiration from a small Alaskan Arctic basin.** Nord Hydrol 21: 253-266.

- Imnavait Creek, Alaska, 2.2 km^2 basin underlain by permafrost to 250 m to 300 m; active layer 0.25 m to 0.60 m.
- Basin ET calculated from water balance studies over a four-year period.
- Compared to point measurements of pan evaporation and daily estimates by energy balance and Priestley-Taylor.
- Water balance approach best method to determine daily and total ET.
- ET greater than cumulative summer precipitation (rain and snow fall after snowmelt).
- Moisture source for ET in early summer is from snowmelt moisture stored in active layer.
- ET decreases as latitude increases.
- Evaporation from lakes greater than ET from equivalent terrestrial areas.
- ET greatest following snowmelt and decreases throughout the summer.
- Based on annual water balance, ET ranged between 34% and 66% (130 mm to 240 mm) of the annual precipitation (mean = 185 mm; median = 186 mm).
- Annual mean ET rates were 1.7 to 1.8 mm/d (range from all methods 1.1 to 2.3 mm/d).
- Annual mean pan coefficient to estimate actual ET is 0.49 (annual range 0.39 to 0.51; median = 0.48). ET approximately 0.7 evaporation assuming a pan coefficient of 0.7 for lake evaporation.
- Patric and Black (1968) report a pan coefficient of 0.59 for actual ET in Fairbanks, Alaska.

Frank DA, Inouye RS. 1994. **Temporal variation in actual evapotranspiration of terrestrial ecosystems: patterns and ecological implications.** J Biogeogr 21, No. 4: 401-411.

- Compared water balance among earth’s major terrestrial ecosystems.

- Monthly and annual potential ET and actual ET derived at 94 sites around the world, representing 11 biomes.
- 10 tundra sites; 5 in Arctic regions of northern Canada and 5 in coastal Alaska.
- Interannual variability was lowest for tundra and taiga.
- Annual values derived by summing over 12 months, January to December.
- Used thornthwaite model.
- Mean annual pot ET inversely associated with latitude.
- Tundra mean annual:
  - potential ET = 278 mm;
  - precipitation = 239 mm; and,
  - actual ET = 202 mm (SD = 34 mm; CV = 19.2).

Gibson JJ, Prowse TD, Edwards TWD. 1996. **Evaporation from a small lake in the continental Arctic using multiple methods.** Nord Hydrol 27: 1-24.

Abstract: Daily evaporation from a small lake in the continental Low Arctic of Canada was examined using three independent experimental methods and a simplified combination model. Mean daily lake evaporation (± variability between methods) was estimated to be 3.2 mm/d and 2.5 mm/d over fifty-day periods during two consecutive summers. Based on these results and additional class-A pan data, total thaw-season evaporation estimates of 220 mm to 320 mm were obtained, equivalent to 70% to 100% of annual precipitation. These values are 15% to 70% higher than predicted by standard evaporation maps of Canada. Our results indicate that the Priestley-Taylor model provides a good approximation of the Bowen ration energy balance model in this settling. As expected, estimates based on mass balance are highly sensitive to uncertainty in measurement of lake inflow and outflow.

Yoshimoto M, Harazono Y, Vourlitis GL, Oechel WC. 1996. **Heat and water budgets in the active layer of the Arctic tundra at Barrow, Alaska.** J Agric Meteor 52, No. 4: 293-300. *In Japanese

- Arctic coastal tundra ecosystem near Barrow, Alaska.
- Deals with the effects of thawing and evapotranspiration to permafrost during the summer of 1993.
- ET much larger than precipitation during summer of 1993. Excess ET supplied by thawing of permafrost.
- ET through June, July, and August 1993 totalled 37 mm.

Wanchang Z, Yinsheng Z, Ogawa K, Yamaguchi Y. 1999. **Observation and estimation of daily actual evapotranspiration and evaporation on a glacierized basin at the headwater of the Urumqi River, Tianshan, China.** Hydrol Process 13, No. 11: 1589-1601.

- 1986; small high altitude (3,403 to 4,479 masl) basin (28.9 km^2 of which 5.74 km^2 glaciated) at headwater of Urumqi River Basin, China.
- 1959 to 1996 mean annual precipitation = 436.4 mm (SD = 51.2 mm). 66% of annual precipitation falls June to August.
- Actual ET ranged between 0.5 mm/d to 5 mm/d on alpine tundra surface (June to August 1986).
- Calculated annual ET on the alpine tundra = 363.8 mm.
- Daily actual ET found to correlate closely with surface soil moisture content in the summer season.

Soegaard H, Hasholt B, Friborg T, Nordstroem C. 2000. **Surface energy and water balance in a high arctic environment in NE Greenland.** Theor Appl Climatol 70: 35-51.

- Energy balance of a coastal drainage basin with glaciers in North East Greenland, 514.8 km^2 in size.
- Area classified as ET tundra climate/high arctic.
- ET rates for fen, heath, and willow snowbed for June to August summer growing season and winter (September to May).
- Annual precipitation is 229 to 320 mm/yr; 75% snow.
- ET values meand from three years (1995/1996 to 1997/1998) with summer being 80.3 mm/yr (range 72.3 to 85.5), winters 25.2 mm/yr (17.2 to 38.2), and a total combined ET being 106 mm/yr (90.5 to 121.2).
- ET estimates for larger basin (weighted with respect to major vegetation types and altitude) ranged between 67.8 mm/year to 90.9 mm/year with a mean of 79.3 mm/year.
- Highest meand ET rates for a 23-day period in 1997 were 1.6, 1.3, and 1.1 mm/d for the fen, willow, and heath areas, respectively.
- Estimation of ET reduction with altitude is 0.1 to 0.2 mm/d per 100 m altitude.
- Comparatively low ET values attributed to shorter growing season.

Gibson JJ, Edwards TWD. 2002. **Regional water balance trends and evaporation-transpiration partitioning from a stable isotope survey of lake in northern Canada.** Global Biogeoch Cy 16, No. 2: 10.1-10.9.

- A 275,000 km^2 area in northern Canada (NWT and Nunavut) composed of more then 60 lakes – landscape-scale; application to small catchments unknown.
- Catchment weighted lake evaporation losses during open-water season (July to September, 1993 and 1994) typically range from 10% to 15% of the total basin ET (evaporation + land ET) in tundra areas.

- Open-water evaporation decreases with increasing altitude and ranges from 5% to 50% of total basin ET.
- Land surface ET greater than 5.7 lake evaporation; land surface ET rates interpolated from the Hydrological Atlas of Canada – NOT MEASURED values.

Ishii Y, Kodama Y, Sato N, Yabuki H. 2004. **Summer water balance in an Arctic tundra basin, eastern Siberia.** Northern Research Basins Water Balance, Proceedings of a workshop held at Victoria, BC, Canada, March 2004. IAHS Publication 290, pp 50-64.

- Arctic tundra basin, eastern Siberia (5.5 km^2; altitude 40 to 300 masl).
- Permafrost to over 500 m depth; active layer 0.2 to 0.7 m.
- Summer water balance for three summer seasons from 1997 to 1999.
- Three surface types: wet moss including sphagnum and sedges; dry moss; and rocky terrain with lichens. Wet and dry moss regions on flat plains and lower parts of slopes; rocky terrain on ridges and upper parts of slopes.
- Sato et al. (2001): actual ET over wet moss tundra 71% of potential ET; actual ET over rocky terrain 18% of actual ET over wet moss tundra, or 13% of potential ET.
- Basin mean ET calculated from aerial mean estimates of ET from three surface types.
- ET from area of rocky terrain with lichen relatively small; 36% of basin area; resulted in relatively small basin-mean ET.
- Seasonal variation in daily ET ranged between 0 to 5 mm/d.
- Cumulative ET 75 mm in 1997; 33 mm in 1998; 54 mm in 1999. Ranges between 15% and 30% of sum of summer rainfall and snowmelt in those years. Permafrost thaw also source of water for ET.

Lilly E K, Kane DL, Hinzman LD, Gieck RE. 1998. **Annual water balance for three nested basins on the north slope of Alaska.** Permafrost 7th international conference, Vol 57, pp 669 – 674.

- Study conducted on three basins: Imnavait Creek (2.2 km^2), Upper Kuparuk (146 km^2), and Kuparuk River (8,140 km^2), all located on the north side of Alaska near Deadhorse.
- Vegetation mostly sedge tussocks, mosses, and low shrubs indicating a tundra type environment. Catchment surrounded by the Brooks range for the most part and transitions to a relatively large area of flat terrain before expelling to the sea.
- Snowmelt period begins between early May and early June, and lasts between 10 and 25 days. The summer rainfall season can vary from 3 to 4 months. ET rates at peak during snowmelt and decline through the summer.
- ET calculated as precipitation – runoff.
- Study conducted over five years (1993 to 1997) means summarized below in Table A-1.

Table A-1 Means Summary

Watercourse	Snowmelt Evaporation (cm)	Summer ET (cm)	Total ET (cm)
Imnavait Creek (2.2km^2)	3.0	14.0	19.1
Upper Kuparuk (146 km^2)	4.4	9.2	13.6
Kuparuk River (8,140 km^2)	1.7	9.2	10.8

cm = centimetre; ET = evapotranspiration; km^2 = square kilometres.

Golder Associates Ltd. 1997. **Baseline Data of Climate and Hydrology for the Diavik Diamond Mine EIA.** Prepared for Diavik Diamond Mines Inc., August 1997, 117 p.

- Site climatic characteristics defined based on available local and regional climate data.
- ET accounted for between 34% and 60% of annual precipitation (Kane et al. 1990) or 70% of annual precipitation (Gibson 1996).
- Flow regulating capacity of wetlands in permafrost areas is very small during snowmelt.
- The summer flow regime is highly affected by evaporation.
- Aerial variation of climatic variables may be different from long-term trend and may vary considerably from year to year.

Wright RK. 1981. **The Water Balance of a Lichen Tundra Underlain by Permafrost**. McGill Subarctic Research Paper No. 33, Climatological Research Series No. 13, Centre for Northern Studies and Research, McGill University, Montreal, PQ, Canada,110 p.

- June to August 1977 and 1978 water balance of a lichen-heath tundra underlain by permafrost near Schefferville, Quebec.
- 0.9 ha hillside (10% slope) and adjacent 100 ha catchment.
- ET estimated by lysimeters and the Priestley-Taylor (PT) method.
- ET for lichen-covered surfaces varied between wet (rainfall greater than 1.26 ET) and dry days.
- Lichen wet day: lysimeter = 1.0 mm/d to 2.7 mm/d; PT = 0.7 mm/d to 2.5 mm/d.
- Lichen dry day: lysimeter = 0.7 mm/d to 2.3 mm/d; PT = 1.4 mm/d to 3.4 mm/d.
- Seasonal PT estimate: lichen areas only = 126.5 mm; entire basin = 141.7 mm.

Spence C, Rouse WR. 2002. **The energy budget of Canadian Shield terrain and its impact on hillslope hydrological process.** J Hydrometeor 3: 208-218.

- Yellowknife River basin.

- An energy balance of a catchment area composed of a valley 700 m long and 1,200 m wide surrounded by bedrock ridges located 100 km north of Yellowknife.
- Lichen dominates the sparse vegetation cover on exposed bedrock. Rest stands of black spruce, mixed stands of spruce and aspen, and peat wetland.
- Permafrost in the region classified as widespread and discontinuous.
- ET ranged from 0.16 mm/d to 3.02 mm/d May through September 1999; and 0.83 mm/d to 1.1 mm/d between May and July 2000.

Spence C, Woo MK. 2002. **Hydrology of subarctic Canadian shield: bedrock upland.** J Hydrol 262: 111-127.

- A study of runoff coefficients on Canadian shield bedrock 4 km north of Yellowknife (62˚ 30’ N, 144˚ 24’ W). Studies occurred from May 1999 to September 2000.
- Mean temperature ranging from –29°C to 16°C with a mean annual precipitation of 280 mm, half of which is generally snow.
- Four areas were tested that had different fissure amounts and soil cover.
- Lichens cover up to 100% of the outcrops.
- Permafrost widespread and discontinuous.
- Surface runoff increases with rainfall and snowmelt intensity.
- Month mean ET ranged from 0.9 mm/d to 2.0 mm/d for the period August to September 1999 and May to September 2000.
- Summer 1999: E/P = 0.29 to 0.36 (soil); E/P = 0.29 to 0.31 (bedrock).
- Summer 2000: E/P = 0.32 to 0.47 (soil); E/P = 0.32 (bedrock).
- Snowmelt 2000: E/P = 0.1 to 0.14 (soil); E/P = 0.24 (bedrock).

Spence C, Woo MK. 2003. **Hydrology of subarctic Canadian Shield: Soil filled valleys.** J Hydrol 279: 151-166.

- A study of runoff coefficients on Canadian shield headwater soil filled valley 10,875 m^2 in size, 4 km north of Yellowknife (62˚ 30’N 144˚ 24’W).
- ET meand 1.8 mm/d between May and July 2000, and 0.8 mm/d in August.

Spence C, Woo MK. 2006. **Hydrology of subarctic Canadian shield: Heterogeneous headwater basins.** J Hydrol 317: 138-154.

- A study of runoff coefficients on 4.9 ha Canadian shield heterogeneous headwater basin 4 km north of Yellowknife (62˚ 30’N 144˚ 24’W).

- 3.8 ha exposed bedrock upland (78% of basin) and 1.1 ha lower soil filled valley (22% of basin).
- Bedrock sparsely covered by lichen with sporadic stands of dwarf birch and jack pine.
- ET estimated using eddy correlation energy budget techniques and instrumentation – accuracy of 20%.
- Basin ET: summer growing season 2000 = 80.5 mm (±16 mm); spring melt 2001 = 25.6 mm (±5 mm).

Summary

- Rates range from 0 mm/d to 5 mm/d with a typical of 1.6 mm/d to 1.8 mm/d.
- ET rates greatest during the snowmelt period.
- ET = 0.39 to 0.59 pan evaporation with a typical value of 0.49.
- ET = 0.5 to 0.8 lake evaporation with a typical value of 0.7.
- Annual ET = 33 mm to 364 mm with a typical of 160 mm; 15% to 85% of annual precipitation with a typical of 48%.
- Summer ET = 37 mm to 200 mm with a typical of 103 mm; 29% to 460% of summer precipitation and melt with a typical of 48%.
- Spring melt ET = 17 mm to 44 mm with a typical of 28 mm; 8% to 34% of winter precipitation and melt with a typical of 20%.

Table A-2 Summary of Evapotranspiration

Reference	Basin Description	Evapotranspiration	Notes
Wright (1981)	• Lichen-heath tundra underlain by permafrost near Schefferville, Quebec; June to August 1977 and 1978 • 0.9 ha hillside (10% slope); 100 ha catchment	• Wet day = 0.7 to 2.7 mm/d • Dry day = 0.7 to 3.4 mm/d • Lichen areas = 126.5 mm • Entire basin = 141.7 mm	
Rouse (1982)	• Upland tundra underlain by permafrost; Churchill, Manitoba; 1978 and 1979	• 200 mm between final snowmelt and permanent snow cover (91% of normal rainfall)	• ET greatest during snowmelt • Seepage loss approximately 50% ET in normal year; greater in wet year
Stuart et al. (1982)	• Eagle Creek, Alaska • Periodic measurements late June to mid August 1978	• 0.37 to 1.24 mm/d (mean 0.8 mm/d) tussock areas • 0.61 to 1.90 mm/d (mean 1.3 mm/d) intertussock areas (mosses and shrubs)	• Koranda et al. (1978) ET approximately 5 mm/d at Barrow, Alaska
Flugel (1983)	• Ooblong Valley, North Ellesmere Island, NWT. High arctic, underlain by permafrost; glaciated; 2 July to 2 August 1978	• 0.1 mm/d from soils	• Glaciated basin
Nakao et al. (1985)	• 4,900 km^2 island 250 km south of Bering Straight • Permafrost 14 m to 27 m; active layer 0.15 m	• Tundra ET = 0.5 lake evaporation	
Kane et al. (1990)	• Imnavait Creek, Alaska; 2.2 km^2; permafrost 250 m – 300 m; active layer 0.25 m to 0.6 m; 1986 to 1989	• 130 mm to 240 mm • 34%-66% of annual precipitation • Mean 1.7 - 1.8 mm/d (range 1.4 to 2.1 mm/d) • ET = 0.49 pan evaporation (range 0.39 to 0.51)	• ET >summer precipitation • ET decreases as latitude increases • Lake evaporation >ET from equiv. terrestrial areas • ET greatest during snowmelt and decreases through summer • Patric and Black (1968) ET = 0.59 pan Fairbanks, Alaska
Frank and Inouye (1994)	• Earth's major terrestrial ecosystems • 94 sites around the world representing 11 biomes • 10 tundra sites (5 arctic Canada and 5 coastal Alaska)	• Potential ET = 278 mm • Mean annual precipitation = 239 mm • Actual ET = 202 mm (standard deviation = 34 mm; CV = 19.2) (85% of mean annual precipitation)	• Mean annual potential ET decreases with latitude • Interannual variability lowest for tundra

Table A-2 Summary of Evapotranspiration

Reference	Basin Description	Evapotranspiration	Notes
Lilly et al. (1998)	• Imnavait (2.2 km^2), Upper Kuparuk (146 km^2) and Kuparuk (8,140 km^2) basins, Alaska; 5 years 1993 to 1997; snowmelt early May to early June (10 to 25 days); summer 3 to 4 months • Tundra type environment	• Imnavait: snowmelt evaporation = 3.0 cm (24% of snowpack); Summer ET = 14.0 cm (55% of summer precip); Total ET = 19.1 cm (51% of total precip) • Upper Kuparuk: snowmelt evaporation = 4.4 cm (34% of snowpack); Summer ET = 9.2 cm (35% of summer precip); Total ET = 13.6 cm (35% of total precip) • Kuparuk River: snowmelt evaporation = 1.7 cm (14% of snowpack); Summer ET = 9.2 cm (64% of summer precip); Total ET = 10.8 cm (42% of total precip)	• ET rates peak during snowmelt and decline through summer
Wanchang et al. (1999)	• Urumqi River Basin, China, 28.9 km^2, 3,403 to 4,479 masl; glaciated • Alpine tundra; June to August 1986	• 0.5 mm/d to 5 mm/d • Calculated annual ET = 363.8 mm (83% of mean annual precipitation)	• Glaciated basin
Soegaard et al. (2000)	• 514.8 km^2 glaciated basin in northeast Greenland; 1995/1996 to 1997/1998; summer June to August; winter September to May • ET tundra climate/high arctic; glaciated	• Mean summer = 80.3 mm/yr (range 72.3 to 85.5 mm); 220% of summer precipitation (range 65% to 460%) • Mean winter = 25.2 mm/yr (range 17.2 to 38.2 mm/yr); 13% of winter precipitation (range 8% to 18%) • Total = 106 mm/yr (range 90.5 to 121.2 mm/yr); 43% of annual precipitation (range 28% to 53%) • Larger basin estimate = 79.3 mm/yr (range 67.8 to 90.9 mm/yr); 21% of precipitation (range 15% to 26%) • 23-day period in 1997 = 1.6 mm/d (fen); 1.3 mm/d (willow); 1.1 mm/d (heath)	• ET reduction with altitude of 0.1 to 0.2 mm/d per 100 m • Comparatively lower ET values attributed to shorter growing season
Gibson and Edwards (2002)	• 275,000 km^2 region of northern Canada (NWT and Nunavut) with more than 60 lakes • Open-water season July to September 1993 and 1994	• Land surface ET >5.7 lake evaporation • Catchment weighted lake evaporation typically 10% to15% of total ET (evaporation + land ET); range 5%-50%	• Land surface ET rates interpolated from the Hydrological Atlas of Canada • Open-water evaporation decreases with increasing altitude • Regional analysis: Landscape scale – applicability to small basins?

Table A-2 Summary of Evapotranspiration

Reference	Basin Description	Evapotranspiration	Notes
Spence and Rouse (2002)	• Yellowknife River basin; 100 km north of Yellowknife • Catchment area 700 m long by 1,200 m wide surrounded by bedrock ridges • Widespread, discontinuous permafrost • Lichen on exposed bedrock; rest stands of black spruce, spruce and aspen, and peat wetland	• 0.16 to 3.02 mm/d (May to September 1999) • 0.83 mm/d to 1.1 mm/d (May to July 2000)	
Spence and Woo (2002)	• Four bedrock plots 4 km north of Yellowknife; May 1999 to September 2000 • Lichen cover • Widespread, discontinuous permafrost	• 0.9 to 2.0 mm/d (August to September 1999 and May to September 2000) • Summer 1999: soil ET = 29% to 36% of rainfall; bedrock ET = 29% to 31% of rainfall • Summer 2000: soil ET = 32% to 47% of rainfall; bedrock ET = 32% of rainfall • snowmelt 2000: soil ET = 10% to 14% of melt; bedrock ET = 24% of melt	• Evaporation from soil cover and rock face of bedrock upland only
Spence and Woo (2003)	• Pocket Lake basin, 4 km north of Yellowknife • Soil-filled valley 10,875 m^2	• 1.8 mm/d (May to July 2000) • 0.8 mm/d (August 2000)	• ET >precipitation May, July, and September • Soil-filled valley only
Ishii (et al. 2004)	• Arctic tundra eastern Siberia; 5.5 km^2; alt. 40 m to 300 masl; permafrost >500 m; active layer 0.2 m to 0.7 m • 23 June to 31 August 1997; 5 June to 26 August 1998; 5 June to 31 August 1999	• 33 to 75 mm • 15% to 30% of precipitation + melt during sampling period • 0 to 4.9 mm/d during sampling period	• Small basin-mean ET attributed to high proportion of rocky terrain
Yoshimoto et al. (2004)	• Arctic coastal tundra ecosystem near Barrow, Alaska; 25 June to 5 August 1993	• 37 mm	• ET >summer precipitation
Spence and Woo (2006)	• Pocket Lake basin, 4 km north of Yellowknife; 4.9 ha with 3.8 ha exposed bedrock upland (78% of basin area) and 1.1 ha a lower soil filled valley • Mean annual precipitation = 280 mm	• Basin ET = 80.5 mm (+/- 16 mm) for 2000 summer growing season (52% of summer precipitation + melt) • Basin ET = 25.6 mm (+/- 5 mm) for 2001 spring melt (18% on spring precipitation and melt)	• Low ET due to high bedrock proportion? • Equivalent basin values

et al. = more than one additional author; ha = hectare;% = percent; NWT = Northwest Territories; km^2 = square kilometre; m = metre; m^2 = square metres; masl = metres above sea level; ET = evapotranspiration; km = kilometre; >= greater than; mm = millimetre; mm/d = millimetres per day; CV = coefficient of variation; m/yr = millimetres per year; +/- = plus or minus.

A3 RUNOFF COEFFICIENTS IN NORTHERN TUNDRA ENVIRONMENTS

Wright RK. 1981. **The Water Balance of a Lichen Tundra Underlain by Permafrost.** McGill Subarctic Research Paper No. 33, Climatological Research Series No. 13, Centre for Northern Studies and Research, McGill University, Montreal, PQ, Canada, 110 p.

- June to August 1977 and 1978 water balance of a lichen-heath tundra underlain by permafrost near Schefferville, Quebec.
- 0.9 ha hillside (10% slope) and adjacent 100 ha catchment.
- Nichols (1966) reported a thaw season runoff coefficient (RC) of 0.60 for a 28 km^2 basin largely covered by lichen tundra.
- Snowmelt runoff does not have a strong interaction with the thaw season water balance because surface does not begin to thaw until most of the snow has melted.
- RC for the thaw season (end June through August 1978) = 0.53.

Kane DL, Gleck RE, Hinzman LD. 1990. **Evapotranspiration from a small Alaskan Arctic basin**. Nord Hydrol 21: 253-266.

- Imnavait Creek, Alaska, 2.2 km^2 basin underlain by permafrost to 250-300 m; active layer 0.25 m to 0.60 m.
- Based on annual water balance.
- Summer runoff ranged between 29% and 66% of summer precipitation (Mean RC = 0.41; median = 0.34).
- Snowmelt runoff ranged between 50% and 66% of snowpack water equivalent (Mean RC = 0.57; median = 0.57).
- Annual runoff ranged between 34% and 66% of total precipitation (Mean RC = 0.47; median = 0.43).

Marsh P, Quinton B, Pomeroy J. 1995. **Hydrological processes and runoff at the Arctic treeline in northwestern Canada.** In: Proceedings of the 10th International Northern Research Basin Symposium and Workshop, Svalbard, Norway, pp 368-397.

- Arctic treeline site in northwestern Canada. 40 km north-northeast of Inuvik.
- Drainage area = 63 km^2 and 0.83 km^2.
- Low tundra zone; continuous permafrost region (up to 350 m depth with 0.3 to 1.0 m deep active zone).
- Majority of annual precipitation released in spring.

- Initiation of meltwater runoff delayed by 13 days by vertical percolation of meltwater into the snow, and frozen soil infiltration.
- Lower limit for frozen soil infiltration approximately 100 mm.
- Basin water storage increased dramatically during the early melt period with over 150 mm of melt occurring before runoff began.
- Over 90% of annual runoff occurred during the melt period.
- Maximum melt rates approximately 60 mm/d.
- Runoff removed 44% of snow in basin at start of melt. Remaining meltwater stored in basin with majority evaporated (62% of water inputs to the basin lost to evaporation).
- Runoff accounts for 30% of the total water inputs to the basin on an annual basis.

Golder Associates Ltd. 1997. **Baseline Data of Climate and Hydrology for the Diavik Diamond Mine EIA.** Prepared for Diavik Diamond Mines Inc., August 1997, 117 p.

- Site climatic characteristics defined based on available local and regional climate data.
- Performed literature review of hydrologic characteristics of Arctic basins.
- Higher runoff yields are observed during snowmelt and rainfall storm events in catchments underlain by permafrost.
- Ford and Bedford (1987): 85% of available water in the Boot Creek basin ran off during the snowmelt period because of the presence of permafrost.
- When active layer is frozen or only thinly thawed, subsurface flow is unimportant and most of the melt water moves downslope as overland flow (Woo et al. 1981).
- Flow regulating capacity of wetlands in permafrost areas is very small during snowmelt.
- The summer flow regime is highly affected by evaporation. Brown et al. (1968) reported that all summer rainfall was lost to evaporation in a small Alaskan basin. Marsh and Woo (1997) reported an RC = 0.005 in summer months.
- Aerial variation of climatic variables may be different from long-term trend and may vary considerably from year to year.
- Mean annual runoff to Lac de Gras assumed to be 171 mm after the Coppermine River basin (of which Lac de Gras is part). Corresponds to a mean annual RC of 0.46. Includes the 1.75 undercatch correction factor.
- In 1996, the mean seasonal (end May to mid Sept) the mean seasonal water yield was 123 mm. Corresponds to a mean seasonal RC of 0.28.
- 1996 estimated mean snow water equivalent in basin from snow surveys = 139 mm.
- 1996 mean measured snowmelt runoff (end May to end June/mid July) = 82 mm to 97 mm.
- 1996 snowmelt RCs = 0.59 to 0.70.

- Mean snow water equivalent for each terrain type was weighted according to the percentage of the terrain type in each basin, and the total snow water volume in each basin was calculated based on measured catchment areas.

Lilly EK, Kane DL, Hinzman LD, Gieck RE. 1998. **Annual water balance for three nested basins on the north slope of Alaska.** Permafrost 7th international conference. Vol 57, pp 669-674.

- Study conducted on three basins: Imnavait Creek (2.2 km^2), Upper Kuparuk (146 km^2), and Kuparuk River (8,140 km^2), all located on the north side of Alaska near Deadhorse.
- Vegetation mostly sedge tussocks, mosses, and low shrubs indicating a tundra type environment.
- Catchment surrounded by the Brooks range for the most part and transitions to a relatively large area of flat terrain before expelling to the sea.
- High runoff coefficients attributed to permafrost conditions.
- Study conducted over five years (1993 to 1997) with means calculated and summarized in Table A-3.

Table A-3 Water Balance Mean Results

Watercourse	Precipitation (cm)			Runoff (cm)			Runoff Coefficient		
	Winter[a]	Summer	Total	Winter	Summer	Total	Winter	Summer	Total
Imnavait creek (2.2 km^2)	12.4	25.4	37.8	9.4	11.4	18.8	0.75	0.45	0.50
Upper Kuparuk (146 km^2)	12.9	26.2	39.1	8.5	17.0	25.5	0.66	0.65	0.65
Kuparuk river (8,140 km^2)	12.1	14.5	25.8	11.4	5.3	16.7	0.86	0.35	0.58

Source: Lilly et al. 1998.
a) A snow water equivalent of measured snowpack data (i.e., includes sublimation, undercatch, and wind drift effects).
cm = centimetre; km^2 = square kilometre.

Stieglitz M, Hobbie J, Giblin A, Kling G. 1999. **Hydrologic modeling of an arctic tundra basin: Toward pan-Arctic predictions.** J Geophys Res 104, No. D22: 22,507-27,518.

- Hinzman et al. (1996; 1991), Kane et al. (1991), and McNamara et al. (1997) reported:
  - Imnavait Creek Basin (northern Alaska); drainage area = 2.2 km^2; continuous/permanent permafrost with 0.25 to 1.0 m thick active layer.
- From 1985 through 1993:
  - 66% of annual precipitation fell in summer;
  - snowmelt represents 47% of annual discharge; and,
  - runoff represents 46% of water budget; evaporation represents 54% of water budget.

AGRA Earth & Environmental Ltd. 2000. **Deep Water Lake Basin Management Plan Hydrology and Water Balance.** Municipal and Community Affairs, GNWT.

- Hydrological analysis of Deep Water Lake 100 km south of Inuvik and 18 km east of Fort McPherson.
- Total catchment area approximately 31.2 km^2, of which 5.9 km^2 is Deep Water Lake and 5.36 km^2 are other tributary lakes. Total land surface 64% of basin.
- Assumed runoff = precipitation less ET with ET = 0.8 lake evaporation.
- Equivalent RC for land surface = 0.58; for the entire basin including lakes = 0.33.

McFadden JP, Liston GE, Sturm M, Pielke Sr RA, Chapin III FS. 2001. **Interactions of shrubs and snow in arctic tundra: measurements and models.** In: Soil-Vegetation-Atmosphere Transfer Schemes and Large-Scale Hydrological Models, Proceedings of a symposium held during the Sixth IAHS Scientific Assembly, Maastricht, The Netherlands, IAHS Publ. No. 270, pp 317-325.

- Kane et al. (1991) and McNamara et al. (1998) indicate 50% to 80% of the Arctic snowpack water content typically goes into runoff.

Spence C, Rouse WR. 2002. **The energy budget of Canadian Shield terrain and its impact on hillslope hydrological process.** J Hydrometeor 3: 208-218.

- Yellowknife River basin.
- An energy balance of a catchment area composed of a valley 700 m long and 1,200 m wide surrounded by bedrock ridges located 100 km north of Yellowknife.
- Lichen dominates the sparse vegetation cover on exposed bedrock. Rest stands of black spruce, mixed stands of spruce and aspen, and peat wetland.
- Permafrost in the region classified as widespread and discontinuous.
- Considerable variability in reported Canadian Shield precipitation runoff ratios ranging from 30% to 69% (Allan and Roulet 1994; Thorne et al. 1994).
- 1999 snowmelt RC = 0.76; 2000 snowmelt RC = 0.58.

Spence C, Woo MK. 2002. **Hydrology of subarctic Canadian shield: bedrock upland.** J Hydrol 262: 111-127.

- A study of RCs on Canadian shield bedrock 4 km north of Yellowknife (62˚ 30’ N 144˚ 24’ W). Studies occurred from May 1999 to September 2000.
- Mean temperature ranging from –29°C to 16°C with and mean annual precipitation of 280 mm, half of which is generally snow.
- Four areas were tested that had different fissure amounts and soil cover.

- Lichens cover up to 100% of the outcrops.
- Permafrost widespread and discontinuous.
- Surface runoff increases with rainfall and snowmelt intensity.
- Mean runoff ratios for specific rainfall events on exposed bedrock plots was 0.48 (range 0.29 to 0.68), and on soil plots 0.04 (range 0 to 0.1).
- Summer 1999: RC = 0.02 to 0.05 (soil); RC = 0.47 to 0.48 (bedrock).
- Summer 2000: RC = 0.05 to 0.20 (soil); RC = 0.60 (bedrock).
- Snowmelt 2000: RC = 0.5 to 0.91 (soil); RC = 0.44 (bedrock).
- Mean over the two years, runoff ratios were 0.52 for the exposed bedrock plots, and 0.08 for the soil plots.

Spence C, Woo MK. 2003. **Hydrology of subarctic Canadian Shield: Soil filled valleys.** J Hydrol 279: 151-166.

- A study of RCs on Canadian shield headwater soil filled valley 10,875 m^2 in size, 4 km north of Yellowknife (62° 30’ N, 144° 24’ W).
- Discusses the importance of lateral inflow from the surrounding bedrock (i.e., infiltration and subsurface flows).
- 2001 spring snowmelt RC = 0.4.

Spence C, Woo MK. 2006. **Hydrology of subarctic Canadian shield: Heterogeneous headwater basins.** J Hydrol 317: 138-154.

- A study of runoff coefficients on 4.9 ha Canadian shield heterogeneous headwater basin 4 km north of Yellowknife (62° 30’ N 144° 24’ W).
- 3.8 ha exposed bedrock upland (78% of basin) and 1.1 ha lower soil-filled valley (22% of basin).
- Bedrock sparsely covered by lichen with sporadic stands of dwarf birch and jack pine.
- Basin runoff not a simple additive function of runoff from each element – landscape topology a major consideration in basin runoff production.
- Basin RC: summer growing season 2000 = 0.03; spring melt 2001 = 0.64.

Runoff Coefficients Summary:

Summer range 0.28 to 0.66 with a typical value of 0.35 to 0.40.

Melt range 0.40 to 0.91 with a typical value of 0.60 to 0.70.

Annual range 0.30 to 0.66 with a typical value of 0.45.

Table A-4 Summary of Runoff Coefficients

Reference	Basin Description	Runoff Coefficients	Notes
Wright (1981)	• Lichen-heath tundra underlain by permafrost near Schefferville, Quebec; thaw season end June (after snowmelt) to Aug 1978 • 0.9 ha hillside (10% slope); 100 ha catchment	• Thaw (summer) season = 0.53	• Nichols (1966) reported a thaw season runoff coefficient of 0.60 for a 28 km^2 basin largely covered by lichen tundra
Kane et al. (1990)	• Imnavait Creek, Alaska; 2.2 km^2; permafrost 250 m to 300 m; active layer 0.25 m to 0.6 m; 1986 to 1989	• Summer = 0.29 to 0.66 (mean = 0.41; median = 0.34) • Snowmelt = 0.5 to 0.66 (mean = 0.57; median = 0.57) • Annual = 0.34 to 0.66 (mean = 0.47; median = 0.43)	
Marsh et al. (1995)	• Arctic treeline site 40 km north-northeast of Inuvik; 63 km^2 and 0.83 km^2; low tundra zone; continuous permafrost 350 m deep; 0.3 m to 1.0 m active zone	• Spring melt = 0.44 • Annual = 0.30	• Majority of annual precipitation released in spring • >90% of total annual runoff in melt
Golder (1997)	• Lac de Gras – STUDY BASIN	• Mean annual = 171 mm or 0.46 • Summer (May to mid-September 1996) = 123 mm or 0.28 • 1996 snowmelt = 82 mm to 97 mm or 0.59 to 0.70	• <u>Higher runoff yields in permafrost catchments</u> • Ford and Bedford (1987) snowmelt = 0.85 • Brown et al. (1968) summer = 0 • Marsh and Woo (1997) summer = 0.005 • Mean annual runoff after Coppermine River Basin of which Lac de Gras is part • Anil Beersing (Golder): annual = 0.3 to 0.4 and snowmelt = 0.6 to 0.7 reasonable given the size of the catchment, the topography, and so on.
Lilly et al. (1998)	• Imnavait (2.2 km^2), Upper Kuparuk (146 km^2) and Kuparuk (8,140 km^2) basins, Alaska; 5 years 1993 to 1997; snowmelt early May to early June (10 to 25 days); summer 3 to 4 months • Tundra type environment	• Imnavait: winter = 0.75; summer = 0.45; total = 0.50 • Upper Kuparuk: winter = 0.66; summer = 0.65; total = 0.65 • Kuparuk River: winter = 0.86; summer = 0.35; total = 0.58	• High runoff coefficients attributed to permafrost conditions
Stieglitz et al. (1999)	• Imnavait Creek, Alaska; 2.2 km^2; continuous, permanent permafrost with 0.25 m to 1 m thick active layer; 0.15 to 0.2 m porous peat underlain by silt and glacial till; 1985 to 1993	• Snowmelt = 47% of annual discharge • Runoff = 46% of water budget	• Numbers based on studies by Hinzman et al. (1996; 1991); Kane et al. (1990) and McNamara et al. (1997)

Table A-4 Summary of Runoff Coefficients

Reference	Basin Description	Runoff Coefficients	Notes
AGRA Earth & Environmental Ltd. (2000)	• Deep Water Lake; 100 km south of Inuvik; 31.2 km^2	• Land surface = 0.58 • Basin incl. lake = 0.33	• Assumed runoff = precip – ET • ET = 0.8 lake evaporation
McFadden et al. (2001)	• Data from Arctic Alaska	• 50% to 80% of Arctic snowpack water content runs off	• Based on studies by Kane et al. (1991) and McNamara et al. (1998)
Spence and Rouse (2002)	• Yellowknife River Basin; 100 km north of Yellowknife • Catchment area 700 m long by 1,200 m wide surrounded by bedrock ridges • Widespread, discontinuous permafrost • Lichen on exposed bedrock; rest stands of black spruce, spruce and aspen, and peat wetland	• 1999 snowmelt = 0.76 • 2000 snowmelt = 0.58	• 0.3 to 0.69 reported in the literature for Canadian Shield basins (Allan and Roulet 1994; Thorne et al. 1994)
Spence and Woo (2002)	• 4 bedrock plots 4 km north of Yellowknife; May 1999 to September 2000 • Lichen cover • Widespread, discontinuous permafrost	• Summer 1999 = 0.02 to 0.05 (soil); 0.47 to 0.48 (bedrock) • Summer 2000 = 0.05 to 0.2 (soil); 0.6 (bedrock) • Snowmelt 2000 = 0.5 to 0.91 (soil); 0.44 (bedrock) • Mean over 2 years = 0.08 (soil); 0.52 (bedrock)	• Bedrock upland only • Runoff increases with rainfall and snowmelt intensity
Spence and Woo (2003)	• Pocket Lake basin, 4 km north of Yellowknife • Soil-filled valley 10,875 m^2	• 2001 spring snowmelt = 0.4	• Soil-filled valley only
Spence and Woo (?)	• Pocket Lake basin, 4 km north of Yellowknife; 4.9 ha with 3.8 ha exposed bedrock upland (78% of basin area) and 1.1 ha a lower soil-filled valley	• Summer growing season 2000 = 0.03 • Spring melt 2001 = 0.64	• Equivalent basin values

et al. = and more than one additional author; ha = hectare;% = percent; km^2 = square kilometre; m = metre; ET = evapotranspiration; km = kilometre; > = greater than; mm = millimetre; m^2 = square metres.