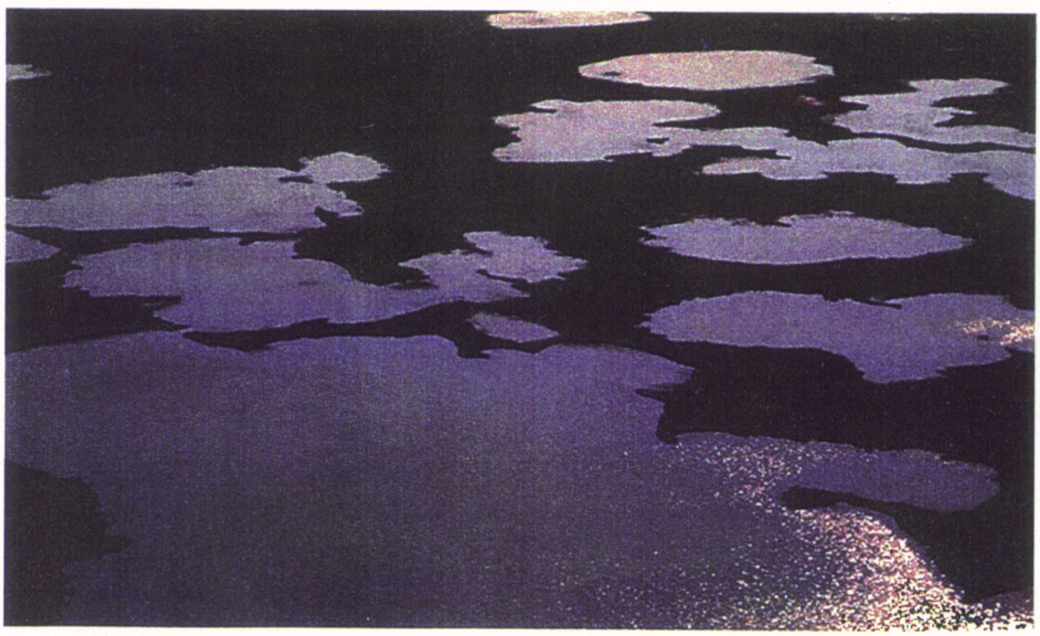
POTENTIAL EFFECTS OF LAKE WATER USE FOR ICE ROADS AND PADS

A Letter Report to BP Exploration (Alaska) Inc. from Jim Aldrich, URS Corporation, with a summary of selected literature related to water budgets of North Slope lakes.



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August 10 2001

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Attn: Bill Streever

RE: POTENTIAL EFFECTS OF LAKE WATER USE FOR ICE ROADS AND PADS

The purpose of this letter is to provide a starting place from which to begin consideration of the potential effects of using lake water for the construction of ice pads and roads in the NPR-A. This letter consists of a summary of a number of articles (provided by BP) that discuss hydrologic conditions in arctic and sub-arctic regions of Alaska and a brief description of the literature. The letter also presents some relevant questions regarding the withdrawal of water for ice roads and pads, and a couple of possible approaches that might be used to further investigate potential effects. As you requested, this discussion focuses on the impact to the physical hydrology of the lakes.

Introduction

Ice roads, airstrips and pads provide access to remote areas and a stable platform for winter exploration without the construction of gravel embankments. The water is withdrawn from approved lakes and spread over the tundra or sea ice. The structures melt in the summer, leaving minimal evidence of their existence. An order-of-magnitude approximation of the quantity of such structures that have been built in the recent past is presented in the following two tables.

Approximate Number of Ice Roads, Pads and Airstrips Constructed in the Kuparuk, Alpine and NPR-A Areas

Winter Season	Miles of Roads		Number of Pads	Number of Air Strips
	On Tundra	On Sea Ice		
88-89	8	0	1	0
89-90	5	0	3	0
90-91	25	0	4	0
91-92	43	8	5	0
92-93	98	0	7	2
93-94	31	0	2	0
94-95	33	0	2	2

Winter Season	Miles of Roads		Number of Pads	Number of Air Strips
	On Tundra	On Sea Ice		
95-96	40	0	6	1
96-97	11	0	3	0
97-98	39	11	5	1
98-99	38	30	3	2
99-00	58	30	7	0
00-01	70-100	50	8	1

Notes:
1. All values are order-of-magnitude estimates based on limited research.
2. Data provided by Lounsbury & Associates
3. Note that more water is used for construction of ice roads, pads and airstrips on tundra than on sea ice.

Approximate Number of Ice Roads, Pads and Airstrips Constructed on the East Side of the North Slope

Winter Season	Miles of Roads		Number of Pads	Number of Air Strips
	On Tundra	On Sea Ice		
93-94	18	0	3	0
94-95	3	0	0	0
95-96	5	22	1	0
96-97	11	27	2	0
97-98	36	0	2	0
98-99	11	38	0	0
99-00	31	52	1	0
00-01	17	18	0	0

Notes:
1. All values are order-of-magnitude estimates based on limited research.
2. Data provided by F. Robert Bell & Associates
3. Note that more water is used for construction of ice roads, pads and airstrips on tundra than on sea ice.

Literature Summary

Approximately 40 articles were provided by BP and reviewed for this project. A brief summary of the relevant parts of the articles is presented in Attachment 1.

Discussion of the Literature

Most of the information concerning hydrologic processes on the North Slope has been collected since the early 1970's. This information has been collected by a variety of groups, including state and federal agencies, the University of Alaska, and private consultants. Often the information was collected for very specific purposes and is not generally available to the public at large. The information reviewed for this discussion was primarily developed by the Water Resources Center at the University of Alaska.

In order to fully address the effects of water withdrawal from lakes on the North Slope, it will probably be necessary to consider, at some level, the annual water balance of the lakes. In other words, how much water enters and leaves the lake each year. A number of studies have been completed that address aspects of the hydrologic cycle and water balance considerations on the North Slope. These studies provide information that might ultimately be useful in addressing the potential effects of lake water use for ice pads and roads.

Precipitation

Several papers discuss the difficulties associated with making accurate precipitation measurements in the arctic environment. Wind and unmeasured trace precipitation may cause the published precipitation record to significantly underestimate the amount of precipitation on the North Slope. Although the Wyoming shield has been thought by many to be a solution to the undercatch of snowfall by the National Weather Service standard precipitation gage, one paper (Yang et al., 2000) reports that even use of the Wyoming shield may lead to an underestimation of snowfall.

Rovansek et al. (1996) discuss the possible magnitude of the unmeasured trace precipitation and condensate water, and its' impact on water balance computations. They reference work by Hobbie and Dingman that suggests that the amount of water in fog and dew on vegetation may equal 23 to 50 percent of the summer precipitation.

Yang et al. (2000) discuss undercatch associated with snowfall measurement and report on a World Meteorological Organization test of the Wyoming shield. Their work suggests that a gage equipped with a Wyoming shield only caught 80 to 90 percent of the snowfall caught by a reference gage.

Data collected over a three-year period near Prudhoe Bay (Robinson, 1995) suggest that very low precipitation and a negative summer water balance characterize North Slope hydrology. The author further suggests that much of the snow that falls during the winter months is destined to replenish the storage lost from ponds and marshes during the previous years growing season.

Surface Runoff

Considerable hydrological and meteorological monitoring has taken place on four North Slope drainages: the Kuparuk River basin (8,140 km^2), the upper Kuparuk River (142 km^2), Imnavait Creek (2.2 km^2), and the Putuligayuk River (471 km^2). Kane et al. (2000) report that the average annual runoff ratios (i.e., the ratio of surface runoff to precipitation) are 0.48 on Imnavait Creek (14 years of data), 0.65 on the Upper Kuparuk River (4 years of data), and 0.58 on the Kuparuk River (4 years of data). These ratios are substantially above the average of more temperate regions and the global average of 0.36.

In general the runoff ratios are higher in years when there is a rapid and sustained (no cold periods) snowmelt. A prolonged period of snowmelt reduces runoff and enhances evaporation and infiltration.

Kane et al. (1999) present runoff ratios for snowmelt and rainfall. Based on their work, the ratio of the snowpack runoff to the snowpack water equivalent at Imnavait Creek varies from 0.50 to 0.80, with an average of 0.67 (n=14 years). This runoff ratio is quite high, but not unreasonable when one considers that the active layer is completely frozen when ablation begins. A five-year average for the upper Kuparuk River is 0.66 (range 0.47 to 0.88) and a four-year average for the entire Kuparuk River is 0.86 (range 0.79 to 0.84). One other factor that contributes to the high ratio is the fact that the water equivalent of snow on the ground is higher near water tracks and along streams, where the wind blown snow accumulates. During snowmelt, runoff dominates as the main exporter of water from the basin.

The rainfall runoff ratios are generally lower. On Imnavait Creek the average ratio of summer runoff (Kane et al., 1999) to summer precipitation is 0.37 (n=13 years) with the range being 0.17 to 0.67. A five-year average (Kane et al., 1999) for the upper Kuparuk River is 0.65 (range 0.56 to 0.78) and a five-year average for the entire Kuparuk is 0.35 (range 0.24 to 0.48). In general, the runoff ratio decreases as the drainage area of the three watersheds increases (Kane, Soden, Hinzman, and Gieck). Steeper slopes in the small headwater catchments generate more runoff than the flatter terrain downstream. Additionally, wet antecedent conditions enhance runoff, and storms with larger cumulative rainfalls result in a greater percentage of runoff due to the limited subsurface storage in the active layer. During summer, evapotranspiration usually dominates as the main exporter of water from the basin (Kane et al., 1999).

During a study of a North Slope wetland, Robinson (1995) found that surface drainage occurred for a short period of time following snowmelt, but after the initial flush had passed through the area, there was no surface movement, and only very minor subsurface flow of water.

Subsurface Flow

Subsurface flow is not usually an important means of water movement in areas beyond the major river channels of the North Slope. The low regional topography results in low hydraulic gradients. This, in combination with low hydraulic conductivity and a shallow active layer, results in typical flow velocities on the order of 1 mm/day through the active layer (Rovansek, 1994). Over the course of a summer season, flow through the active layer was not a significant contributor to the water balance of the ponds studied by Rovansek. Seasonal net inflow/outflow through the active layer amounted to less than 0.5 percent of the seasonal evapotranspiration at a typical pond (Rovansek, 1994).

Evaporation

The most difficult and least accurate of all watershed process measurements are those that include water losses to the atmosphere (Kane et al. 1989). Several studies have attempted to measure evaporation from lakes on the North Slope. Kane and Carlson (1973) reported lake evaporation rates for parts of July and August to be 2.1 mm/day based on a single monitoring season. Water balance computations used to estimate evaporation on the Imnavait watershed are discussed by Kane et al, (1989) and indicate that the evaporation averaged 2.0 mm/day in June, July, and August of 1986. Kane et al, (1989) also suggest that based on other work in northern climates, daily evaporation rates could exceed 4 mm/day. Mendez (1997) reports that during the post-runoff summer period the average evaporation rate for all of the ponds studied for his project was 3.40, 3.60, and 2.33, mm/day in 1994, 1995, and 1996, respectively. Rovansek et al. (1996) reported average daily pond evaporation rates of 2.0 mm/day in 1992 and 2.1 mm/day in 1993.

Evapotranspiration

Evapotranspiration is a very important component of the water balance in arctic coastal wetlands, with a magnitude usually exceeding that of summer precipitation. Based on 4 years of studies in the Imnavait Creek Watershed, Kane, Gieck, and Hinzman (1990) report that evapotranspiration is greater from lakes than from an equivalent terrestrial area, is greatest following snowmelt, and decreases throughout the summer. They also found that the magnitude of evapotranspiration could not be related with certainty to the season length, the amount of precipitation, or the summation of the net radiation. In 1986, 1987, 1988, and 1989 they estimate that evapotranspiration represented 56, 34, 66, and 58 percent of the annual precipitation. During this period, the total amount of evapotranspiration varied between 130 mm and 240 mm (or 1.4 to 2.0 mm/day).

Mendez (1997) used the Bowen ratio energy balance to compute evapotranspiration on an arctic coastal wetland. For 1994, 1995 and 1996 he computed evapotranspiration rates of 1.57, 1.41, and 1.38 mm/day, respectively. He found evapotranspiration rates were higher during wetter, warmer conditions than during drier, cooler conditions. Additionally, evapotranspiration was higher in June and July than in August (Mendez et al. 1998).

<u>Potential Impact of Water Withdrawal</u>

In considering the impact that winter water withdrawal from North Slope lakes might have, the following questions come to mind.

- How much water has been used and from which lakes has it been taken during the last 10 years?
- Are the same lakes used from one year to the next, or are different lakes used each year?
- Are there any obvious signs that water withdrawal has had a physical impact on the lakes from which the water was withdrawn?

- Are there any obvious signs that winter water withdrawal has had an impact on the fish population of the lakes from which the water was withdrawn?
- If the same lakes are used from one year to the next, could different lakes be used in consecutive years?
- How is water withdrawal affecting the water surface elevation and volume of water within the ponds?
- How does the amount of water withdrawn compare to the amount of water evaporated from the lake surface?
- How does the amount of water withdrawn compare to the difference in the amount of water evaporated in a year with a high evaporation rate and a year with an average evaporation rate?
- How does the amount of water withdrawn from a lake compare to the net volume of water available to recharge the lake (net surface inflow – evaporation)?
- Does winter water withdrawal cause the dissolved oxygen concentration in the water to decrease more than it would in a similar lake that did not have water withdrawn during the winter?
- If there is a greater decrease in the dissolved oxygen concentration in a lake from which water is withdrawn during the winter, how does the magnitude of the decrease compare to the change in dissolved oxygen concentration associated with natural variation from one winter to the next?
- If there is a greater decrease in the dissolved oxygen concentration in a lake from which water is withdrawn during the winter, are the fish in the lake significantly impacted?
- Can a method be developed to predict how much water can be withdrawn from a lake without negatively impacting the fish population?
- Does winter water withdrawal cause the turbidity in the lake to increase above that of similar lakes that did not have water withdrawn during the winter?
- If there is an increase in turbidity in a lake from which water is withdrawn during the winter, how does the magnitude of the increase compare to the change in turbidity associated with natural variation from one winter to the next?
- If there is an increase in turbidity in a lake from which water is withdrawn during the winter, are the fish in the lake significantly impacted?
- Can a method be developed to prevent an increase in turbidity as a result of winter water withdrawal?

Possible Approaches To Quantifying Impacts

One approach would be to identify the lakes from which water has been withdrawn over the last ten years and to inspect the lakes. The amount of water removed annually from each lake and the frequency with which each lake has been used would be determined. An inspection would be conducted to determine if there are obvious signs that the lakes have been impacted by winter water withdrawal. The fish population could be sampled to determine if there is any reason to suspect that the fish population has been negatively impacted. To do this, the fish population data collected during the site inspection would be compared to data from similar lakes that have not been stressed by winter water withdrawal.

Another approach that addresses a number of the questions presented above is to conduct a paired study of two or more lakes. Each lake in the pair would be similar, and all of the lakes would contain fish. The lakes would be monitored for at least one year. Water surface elevation, ice thickness, dissolved oxygen, turbidity, conductivity, runoff into and out of the lake, and the fish population would be monitored. Ideally, precipitation and evaporation would also be monitored. One lake in each pair would be pumped. To prevent disruption of the study, the control lakes would not be available for water withdrawal. The lakes to be stressed would be available to construction contractors, but the amount of water withdrawn would be supervised and accurately recorded. Precautions would be taken to ensure that the amount of water designated for withdrawal would be taken, even if it had to be discharged to the tundra. Ideally, the study would be repeated over several years to determine the variability from one season to the next, and the cumulative impact of several years of water withdrawal.

The issue of lake recharge might be addressed by a paired study similar to the one described above, but without the biological component. All of the parameters of the water balance would be measured. As with the study described above, the monitoring effort should extend over several years in order to determine the magnitude of natural variability, and the cumulative impact of several years of water withdrawal.

The lake recharge issue might also be addressed by a water balance assessment conducted with existing hydrologic and meteorologic data. This assessment would involve a relatively small field data collection effort, and rely on computer modeling of the hydrologic processes to assess the impact of water withdrawal. Precipitation data, runoff coefficients, and evaporation coefficients would be obtained from the available data. One method of doing this, which has been used to investigate drinking water supply issues, is to develop a water balance model for the lake within a spreadsheet equipped to run a Monte Carlo analysis. A monthly time increment would probably be used for the computations. The parameters that vary from year to year, such as precipitation and evaporation, would be described statistically based on the available data. The Monte Carlo analysis would then be run for a set number of years and iterations to determine the likely variation in lake water surface elevation and volume over time. The number of years over which the computations are conducted would be set equal to the number of years a lake is likely to be reused for winter water withdrawal. The number of iterations would be set high enough that the results of the model are stable from one run to the next (probably between 1,000 and 10,000 runs). The model would be run with and without water withdrawal, and the results compared in order to estimate the impact of water withdrawal with time.

This review of water on the North Slope is far from exhaustive. Hopefully, it will provide a starting place from which to further discuss the issue of winter water withdrawal on the North Slope. Thank you for the opportunity of working with you on this very interesting project. If you have any questions, please do not hesitate to call.

Sincerely,

URS Corporation

James W. Aldrich, P.E., P.H.
Principal Hydrologist/River Engineer

Attachments: Attachment 1: Summary of Selected Literature

Attachment 1
Summary of Selected Literature

Reference	Summary
Bolton, W.R., L.D. Hinzman, and K. Yoshikawa. 2000. *Stream Flow Studies in a Watershed Underlain by Discontinuous Permafrost.* Pages 31 – 36 in Proceedings of Spring Specialty Conference on Water Resources in Extreme Environments, Anchorage, AK, 2000. American Water Resources Association, Middleburg, VA.	The Caribou-Poker Creeks Research Watershed is located 48 km north of Fairbanks, Alaska. It is underlain by discontinuous permafrost along north facing slopes and valley bottoms. Data from the 1999 field season were used for this analysis. Snow precipitation accounted for approximately 30-40 percent of the total yearly precipitation. Ablation of the snow pack occurred over a 2-3 week period. However, over the final 4-5 days, rapid ablation of the remaining snow pack (over 50 percent of the maximum snow water equivalent) occurred during a period of sustained temperatures above 0 degrees C. Although spring snowmelt is the major hydrologic event of the year, the maximum stream specific discharge occurred during a major precipitation event in June. This event occurred before any significant thawing of the mineral soils within the active layer had taken place. This is a period when the soil storage capacity is near its minimum. Between precipitation events, the high permafrost sub-watershed displayed the lowest specific base flow while the low permafrost sub-watershed consistently displayed the highest specific base flow. As the active layer thaws, the potential storage capacity of the soils increase, resulting in increased subsurface water contributing to stream flow. Using the graphical hydrograph separation techniques described by McNamara et al (1997), the fraction of subsurface water contributing to storm events can be determined. This technique is difficult to use on overlapping storm events, which happened frequently during the 1999 field season. Discharge measurements were averaged over 6 hour periods to aid in this analysis. During the 1999 field season, the amount of old water contributing to the low permafrost sub-watershed remained fairly consistent, while the amount of subsurface water contributing to both the high permafrost and medium permafrost sub-watersheds increased throughout the summer.
Everett, K.R., G.M. Marion, and D.L. Kane. 1989. *Seasonal Geochemistry of an Arctic Tundra Drainage Basin.* Holarctic Ecology. 12: 279-289.	The snowmelt flood at Imnavait Creek takes place sometime between 12 May and 2 June and constitutes the single most important hydrological and geochemical event of the year. Three years of study indicate that this event spans 7 to 10 days and that peak discharge can be expected to be between 0.6 and 0.9 cubic meters per second.
Hinzman, L.D., and D.L. Kane. 1991. Snow Hydrology of a Headwater Arctic Basin 2. Conceptual Analysis and Computer Modeling. Water Resources Research. 27(6): 1111-1121.	The HBV model was used with data collected in the Imnavait watershed over a 5-year period to investigate the hydrologic regime of an Arctic watershed during the spring snowmelt period. Spring snowmelt is a very brief event, usually lasting about 10 days. There is considerable annual variability in the: initial snowpack water content, timing of snowmelt initiation, and snow distribution throughout the watershed. The snow is redistributed by strong winds throughout the winter. Ultimately, the snow is normally deposited in the valley bottom, in small water tracks, and on the lee side of slopes. Snow deposited in the valley bottom retards streamflow for several days after the onset of spring melt, depending upon snowpack depth and density. Peak flow normally occurs within 36 hours of the beginning of streamflow. All downslope water movement occurs within the top 10 cm of the highly organic soil mat or on the surface. Snow damming of snowmelt runoff is an important mechanism that must be considered in the modeling of small watersheds. When the daily measured snowmelt was compared with the average daily air temperature, it was apparent that much of the melt was due to other factors such as radiation and convection, and could not be explained by a simple degree day formulation. The HBV model functioned well in all scenarios. However, the threshold temperature parameter (TT), and a parameter in the transformation function (MAXBAS) need to be adjusted to reflect snowpack properties which vary from year to year.

Attachment 1
Summary of Selected Literature

Hinzman, L.D., and D.L. Kane. 1992a. *Climate Change Impacts on Northern Water Resources in Alaska.* Pages 714 – 733 in Proceedings of 9th International Northern Research Basins Symposium/Workshop, Canada, 1992. NHRI Symposium No 10.	Significant change from the present climate could impact the primary arctic hydrologic processes. Ramifications of climate change may also be manifested in subsidence of roads, buildings and other structures associated with thawing of ice-rich permafrost. Thawing of permafrost along streams and rivers could also substantially increase sediment loads. A change in the active layer thickness will affect soil moisture status, rates of runoff and recessions, and perhaps indirectly, vegetation type.
Hinzman, L.D., and D.L. Kane. 1992b. *Potential Response of an Arctic Watershed During a Period of Global Warming.* Journal of Geophysical Research. 97(D3): 2811-2820.	Climatic warming will impact hydrologic processes, quantitatively increasing some and decreasing others. A deeper active layer will allow for greater variation in the amount of soil water in storage and the amount of water moving downslope. Snow ablation would be earlier, snow deposition less frequent in the summer and later in the fall, cumulative evapotranspiration (ET) would increase, and cumulative runoff would decrease. Superimposing precipitation increases on the warming scenarios would increase soil moisture, cumulative ET, and cumulative runoff. Decreasing precipitation would have the opposite effect.
Hinzman, L.D., and D.L. Kane. 1997. *Measured and Modeled Arctic Hydrologic Processes at the Watershed Scale.* Pages 86-88 in Part I of Proceedings of a Conference on Polar Processes and Global Climate Change, Rosario, Orcas Island, WA, 1997. Intervational ACSYS Project Office, Oslo, Norway.	During the past four years, a large hydrologic field program has been ongoing on the Kuparuk River basin. Meteorological data is collected at seven major stations throughout the basin with a higher density of five additional micro-stations (wind speed, air temperature and rainfall) located in the headwaters. Surveys of the water equivalent of the snowpack just prior to ablation and runoff measurements at four scales, ranging from the hill slope water track to the entire Kuparuk River basin have been made. Presently there is no algorithm to incorporate the effects of snow damming which can retard snowmelt runoff for several days in the headwater basins.
Hinzman, L.D., D.L. Kane, and L. R. Everett. 1993. *Hillslope Hydrology in an Arctic Setting.* Pages 267 – 271 in Proceedings of Sixth International Conference on Permafrost, 1993. South China University Technology Press, Beijing, China.	Many deficiencies exist in our ability to model many of the basic arctic hydrologic processes; premier among these are knowledge of mechanisms and pathways of water movement through the active layer. Physical parameters that control or influence these processes include the thickness of the active layer or depth to permafrost, the soil type and properties, vegetation, slope morphology, and gradient.
Hinzman, L.D., M. Wegner, and M. R. Lilly, 2000. *Hydrologic Investigations of Groundwater and Surface-water Interactions In Sub-arctic Alaska.* Nordic Hydrology. 31 (4/5): 339-356.	Dynamic interactions between rivers and adjacent aquifers can significantly affect near-bank geochemistry and processes associated with natural attenuation of contaminants by mixing water or introducing oxygen or nutrients. During 1997 and 1998 in a study near Fairbanks, Alaska the hydrologic conditions in the Chena River and in the adjacent groundwater were monitored. The river stage, groundwater elevations, and the water chemistry and temperature in both river and groundwater were measured. In the spring of 1997, the groundwater gradient close to the Chena River reversed causing surface water to enter the aquifer. Changes in temperature, specific conductance and alkalinity were used to determine the extent of bank recharge. For approximately one week during the 1997 spring

	snowmelt, surface-water from the Chena River entered the groundwater between approximately the depths of 5.33 m and 9.1 m below ground surface. The effects of bank recharge extended at least 6.1 m, but not to 30.5 m, from the banks of the Chena River into the aquifer. Bank recharge caused 64 to 68 per cent of the groundwater, 6.1 m from the bank at a depth of 6.78 m to be displaced by surface water influx. Peak flows during 1998 were not high enough to cause flow reversals.
Hinzman, L.D., D.L. Kande, R.E. Gieck, and K. R. Everett. 1990. *Hydrologic and Thermal Properties of the Active Layer in the Alaskan Arctic.* Cold Regions Science and Technology. 19 (1991): 95-110.	The active layer is the surficial layer of the soil system that thaws every summer. In the Imnavait watershed, a small headwater watershed north of the Brooks Range, the active layer is an extremely variable multi-layered system consisting of a mat of mosses and sedges on about 10 cm of organic soil over silt. The biological and physical processes that characterize the arctic ecosystem are all affected by the thermal and hydrologic boundary condition of the active layer. The tundra biome is in a dynamic equilibrium to which any disturbance can upset the delicate balance and cause significant change. The thermal and hydrological regimes are so intricately interrelated to each other and to the character and the structure of the active layer that any modification to one parameter will ultimately affect the entire system. The hydrologic and thermal processes and properties of the active layer must be understood to prevent unnecessary damage during economic development. The objective of this paper is to describe the thermal and hydrologic regime of the active layer and provide useful information to the researchers and developers who need to understand the dynamic of the arctic ecosystem.
Hinzman, L. D, M.A. Nolan, D.L. Kane, C.S. Benson, M. Surm, G.E. Liston, J.P. McNamara, A. Carr and D. Yang. 2000. *Estimating Snowpack Distribution Over a Large Arctic Watershed. Water Resources in Extreme Environments.* Pages 13-18 in Proceedings of Spring Specialty Conference on Water Resources in Extreme Environments, Anchorage, AK, 2000. American Water Resources Association, Middleburg, VA.	Extensive snowpack surveys were conducted throughout the 8140 km^2 Kuparuk River basin every spring prior to initiation of melt from 1993 through 1999 for the purpose of quantifying the water equivalent of the snowpack and its spatial distribution. We numerically characterized generalizations of wind, topography, vegetation, and precipitation and incorporated them into a model that generates end-of-winter snow water equivalent distribution maps for the entire Kuparuk watershed for 1994-1997.
Kane, D.L. 1992. *Meteorological and Hydrologic Studies in the Alaskan Arctic in Support of Long-Term Ecological Research.* Pages 13 – 21 in Proceedings of the Ninth Annual Pacific Climate Workshop, 1992. California Department of Water Resources, Interagency Ecological Studies Program. Technical Report 34.	This paper discusses the hydrologic processes that are presently important in the Arctic and how they would be impacted by climate change. It is concluded that climatic warming in the Arctic would result in earlier ablation, greater ET and subsequently less runoff, and later freeze-up in the fall.

Attachment 1
Summary of Selected Literature

Kane, D.L. 1997. *3. The Impact of Hydrologic Perturbations on Arctic Ecosystems Induced by Climate Change.* Global Change and Arctic Terrestrial Ecosystems, pp. 63-81.	Incremental increases in radiative fluxes will provide more energy for both sensible warming of soil and atmosphere and hydrologic processes requiring latent heat. In a warmer environment, evaporation and transpiration during the summer months should increase in the Arctic. Hydrologic changes may be difficult to quantify because of the large annual variations that we see now. Snowmelt events in the wintertime are rare. A warmer environment may produce more of these events.
Kane, D.L., and R.F. Carlson. 1973. *Hydrology of the Central Arctic River Basins of Alaska.* Institute of Water Resources, University of Alaska, Fairbanks. Report No. IWR-41.	This report presents a general summary of the overall hydrology of the area. The primary area of study includes the region of the Putuligayuk, Sagavanirktok and Kuparuk rivers. The accuracy of the presently available precipitation data is questionable because of the continuous high wind intensity and the frequent occurrence of trace precipitation. Values of accumulative pan evaporation and calculated lake evaporation for the month of July and August are 13.6 cm and 10.2 cm, respectively. The ratio of the calculated lake surface evaporation to the pan evaporation is slightly greater than 0.85 for the two months of July and August. For Class "A" weather pans built of galvanized iron, it is generally reported that the actual evaporation from large bodies of water can be determined by multiplying the pan evaporation by a coefficient of 0.70 to 0.75.
Kane, D.L., and L.D. Hinzman. *Permafrost Hydrology of a Small Arctic Watershed.* Institute of Northern Engineering University of Alaska, Fairbanks. pp. 590-594.	A small 2-km2 watershed in an area of continuous permafrost has been monitored for three years (1985 – 1987). Measurements were made of: precipitation, including detailed snow surveys prior to ablation; runoff leaving the basin; and the soil moisture regime in the active layer. They permit the determination of the basin water balance. Considerable variation exists among the 4 runoff plots in regards to percentages of runoff and evaporation losses during snowmelt. Although there are some differences between the plots in terms of slope and active layer soil structure, the most important factor is the distribution of snow on the ground. The plots with the highest snowpack water equivalent also have the highest percentage of runoff. Likewise, those plots with the least snow have the highest percentage of evaporation. Where snow is thin, vegetation extending through the snow and bare ground enhances radiation absorption and surface heating. This provides considerable energy to drive evaporation, whereas the surface albedo remains quite high for the thicker snowpacks. Comparison of the same plots over the three years of study shows that there is much less variation temporally than spatially. In 1986, snowmelt runoff represented 48 percent of the annual runoff, while the snowpack water content represented 40 percent of the annual effective precipitation (snow on ground just prior to ablation plus summer precipitation). Although the water content of the 1987 spring snowpack was nearly equivalent to the 1986 spring snowpack, the snowpack water content was only 28 percent of the annual effective precipitation and snowmelt runoff was also only 28 percent of the annual runoff. Runoff is the dominant process during the snowmelt period, and ET dominated during the dryer summer. Summer runoff events are controlled by the antecedent moisture conditions of the organic soils in the active layer because once thawed, the mineral soils remain near saturation throughout the summer months. Runoff from the plots ceases shortly after snowmelt or rainfall events. During summer periods of little or no precipitation, runoff is virtually zero in the stream. Water from the thawing active layer that could provide runoff during the summer does not appear to be an important process in the Imnavait Creek watershed. The water that is made available by the thawing active layer is evapotranspirated A comparison of the pan evaporation data and the computed evapotranspiration (ET) shows that insufficient water is available for ET to proceed at tits potential rate.
Kane, D.L., R.E. Gieck, and L.D. Hinzman. 1990. *Evapotranspiration from a Small Alaskan Arctic Watershed.* Nordic Hydrology. 21 (1990): 253-272.	Imnavait Creek, a small 2.2 km^2 watershed underlain by continuos permafrost has been studied for 4 years. Evapotranspiration (ET) on a watershed scale has been calculated from water balance studies. These results are compared with point measurements of pan evaporation and daily estimates of evapotranspiration (ET) by the energy balance and Priestley-Taylor methods. The average daily value of ET was determined for the period of record in each case. This average in some cases is for the entire summer period and in other studies only for a few days. Even with the restrictions mentioned several generalizations are evident from the data: (1) ET decreases as the latitude increases, (2) ET losses from lakes are greater than ET losses from an equivalent terrestrial area, and (3) ET is greatest following snowmelt

	and decreases throughout the summer. The total amount of ET as determined from the mass balance technique ranged between 130 and 240 mm (1.4 and 2.0 mm/day). The estimates from the energy balance method ranged between 1.4 and 2.3 mm/day and those of the Priestley-Taylor method ranged between 1.7 and 1.9 mm/day. The Priestley-Taylor, energy balance and pan evaporation methods are developed from point measurements. The results from a water balance are developed on a watershed scale. The amount of ET could not be related with certainty to the season length, the amount of precipitation or the summation of the net radiation. It is undoubtedly related to the complex interaction of many of these features. In the summers of 1987, 1988, and 1989, ET consumed the equivalent of about 39, 46, and 65 percent of the net radiation respectively. From the calculation of the annual water balance in 1986, 1987, 1988, and 1989, ET represented 56, 34, 66, and 58 percent of the annual precipitation respectively. These two theoretically complete calculations of ET were compared with the Priestley-Taylor method and pan evaporation. The techniques investigated all performed adequately to estimate ET. The average ET from the energy balance approach was 1.8 mm/day, the Priestley-Taylor method yielded 1.8 mm/day, and the water balance method had an average of 1.7 mm/day. From these data the average pan coefficient to estimate actual ET is 0.49.
Kane, D. L, R.E. Gieck, and L.D. Hinzman. 1997. *Snowmelt Modeling at Small Alaskan Arctic Watershed.* Journal of Hydrologic Engineering. October: 204-210.	Ablation has been monitored since 1985, in a small headwater drainage of the Kuparuk River. Three different models, an energy balance model, a degree-day model and a combined degree day-radiation model, were used to predict snowmelt. All three of the models worked quite well for predicting ablation at Imnavait Creek. The major advantage of the energy model is that it is physically based and generally works for a wide range of extreme conditions. The advantage of the two index models is that they require minimal data, a condition that is prevalent in the Arctic. The major disadvantage of the surface energy balance model is the large quantity of data that is required as input. There exists numerous models to predict various radiation fluxes, so these field measurements are not required, but there are some difficulties associated with these methods. For this assessment measured values of the radiation fluxes were used.
Kane, D.L., L.D. Hinzman, and E.K. Lilly. 1993. *Use of Spatially Distributed Data to Model Arctic Hydrologic Processes.* Pages 326 – 331 in Proceedings of the Sixth International Conference on Permafrost, 1993. South China University Technical Press, Beijing, China.	This paper describes the formulation of a physically based, spatially distributed hydrologic model for use in the Arctic. Also discussed is how spatially distributed data are utilized in this model.
Kane, D.L., L.D. Hinzman, and J.P. Zarling. 1990. *Thermal Response of the Active Layer to Climatic Warming in a Permafrost Environment.* Cold Regions Science and Technology. 19 (1991): 111-122.	The purpose of this research was an attempt to ascertain what effect warming may have on the near surface thermal regime. This research was not an attempt to predict what the magnitude of global warming will be. In this paper the consequences of global warming on the active layer are examined. Soil temperature data were collected over a four-year period at a field site near Toolik Lake, Alaska. A finite-element, two-dimensional, heat conduction model with phase change was used to predict soil temperatures at the site. After verification that the model could be used with confidence to predict he soil thermal regime, various climatic warming scenarios were used as inputs to estimate the thermal response for the next fifty years. The results of the model suggest that as the active layer thickness increases in response to global warming, available storage in the active layer will increase. If the active layer increases in thickness and the annual precipitation remains fairly constant, then the water table in the active layer will fall.

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Kane, D.L., L.D. Hinzman, C. S. Benson, and K. R. Everett. 1989. *Hydrology of Imnavait Creek, and Arctic Watershed.* Holarctic Ecology. 12 (1989): 262-269.	This paper summarizes what has been learned hydrologically from three years of study at an arctic watershed, Imnavait Creek, on the north slope of Alaska. The most difficult and least accurate of all watershed process measurements are those that include water losses to the atmosphere. Pan evaporation at Imnavait Creek in the summer of 1986 averaged 4.2 mm/day; this compares with 3.4mm/day in 1987. For this basin, from water balance computations, Kane and Hinzman (1988) estimated the evaporation to average 2.0 mm/day for June, July and August in 1986. At Prudhoe Bay on the northern coast of Alaska, Kane and Carlson (1973) measured pan evaporation at 2.8 mm/day and lake evaporation at 2.1 mm/day during parts of June and July. Roulet and Woo (1986) for a wetland in continuous permafrost report average daily losses of 4.3 mm/day from water balance computations. The rate of water loss will depend upon atmospheric conditions suitable for evaporation and transpiration and the availability of water. Under ideal conditions in the Arctic, it appears that daily atmospheric losses could exceed 4 mm/day. The lower limit is near zero, but the actual value will depend upon surface features such as topography, vegetation, soil type, and drainage.
Kane, D.L., L.D. Hinzman, C. S. Benson, and G.E. Liston. 1991. *Snow Hydrology of a Headwater Arctic Basin 1. Physical Measurements and Process Studies.* Water Resources Research. 27 (6): 1099-1109.	In Imnavait watershed, snow begins to accumulate in late September or early October, and maximum snowpack water content is reached just prior to the onset of ablation in mid May. Attempts to accurately measure snowfall precipitation on Alaska's Arctic Slope with National Weather Service precipitation gages have been futile. Use of the Wyoming gage has been examined and shown to be an improvement. No significant midwinter melt occurs in this basin. During the winter, snow cover in this area experiences significant redistribution by the wind, resulting in water equivalent depths ranging from 0 to 1500 mm. Higher than average water contents are consistently found in the valley bottom and water tracks. Hydrologically, this is quite significant because it places the snow very close to the drainage channels. This not only results in higher soil moisture levels in these high deposition areas but produces a higher percentage of runoff during snowmelt than would have resulted if a uniform snowpack had existed. The pattern of ablation was strongly influenced by the direction of the predominant winds. If winds came from the North, air temperatures were much lower and incoming radiation was utilized for sensible heating of the atmosphere. When winds prevailed from the South, coning over the Brooks Range, air temperatures were much warmer and incoming radiation was responsible for ablation. Water moving downslope over very wet snow free areas encounters surfaces with low albedos and high surface temperatures. Evaporation is enhanced in these snow free patches due to the large amount of energy available for evaporation. Runoff in the stream always commenced 1 to 3 days after the initial runoff from plots on the west-facing slope. In fact, there was no flow in any portion of the stream channel, and then in the matter of a few hours, the entire stream channel could be flowing at a relatively high rate. The initial flow originates usually near the headwater of the basin, as a wave of water cuts a channel through the snowpack. But in some years the flow originates at an intermediate point along the stream and subsequent slush flows follow as a channel is carved to the headwaters of the basin. For the watershed snowpack, runoff ranged from 50 to 66 percent, evaporation varied from 20 to 34 percent, and storage increases constitute 10 to 19 percent. Considerable variation existed spatially as evidenced by the results of the runoff plots.
Kane, K. L., L.D. Hinzman, M. K. Woo, and K.R. Everett. 1992. *Arctic Hydrology and Climate Change.* Arctic Ecosystems in a Changing Climate. 35-57.	Climatic warming will affect arctic hydrology through its affect on the active layer. With sufficient climatic warming, an unfrozen layer will develop between the seasonal frost and the permafrost. This unfrozen zone, or talik, will substantially alter surface hydrology by increasing the amount of soil moisture storage; improving subsurface drainage, and consequently, decreasing the amount of soil moisture within the soil profile; and decreasing the total area extent of wetlands in the Arctic.

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Kane, D.L., D. J. Soden, L.D. Hinzman, and R.E. Gieck. *Rainfall Runoff of a Nested Watershed in the Alaskan Arctic.* Pages 539 – 544 in Proceedings of the 7th International Permafrost Conference.	The runoff response to individual rain events is examined at three scales in a nested watershed on the north slope of Alaska. On the Imnavait watershed, the upper Kuparuk catchment and the Kuparuk River basin, the runoff ratio varied from 0.16 to 0.55, 0.21 to 0.42 and 0.08 to 0.39, respectively. In general, the runoff ratio decreases as the drainage area of the three watersheds increases. Steeper slopes in the small head-water catchments generate more runoff than flatter terrain downstream. Wet antecedent conditions enhance runoff. Storms with larger cumulative rainfalls result in a greater percentage of runoff because of the limited subsurface storage in the active layer.
Kane, D.L., L.D. Hinzman, J.P, McNamara, Z. Zhang, and C.S. Benson. 1999. *Nested Watershed Study in the Kuparuk River Basin, Arctic Alaska.* Pages 182-196 in Proceedings of the Northern Research Basins, Twelfth International Symposium and Workshop, Iceland 1999. Engineering Research Institute, University of Iceland.	Presented herein is a comparison of the variability of important runoff processes on several North Slope watersheds. The watersheds studied include the Kuparuk River basin (8,140 km^2) and three smaller drainages: upper Kuparuk River (142 km^2), Imnavait Creek (2.2 km^2) and Putuligayuk River on the coastal plain (471 km^2). Storage of water in the basins is minimal except for within the active layer. The ratio of the snowpack runoff to the snowpack water equivalent varies from 0.50 to 0.80, with an average of 0.67 (n=14 years). This runoff ratio is quite high, but not too surprising, considering the active layer is completely frozen when ablation is initiated. A five-year average for the upper Kuparuk River is 0.66 (range 0.47-0.88) and a four-year average for the entire Kuparuk River is 0.86 (range 0.79-0.84). One other factor that contributes to the high ratio is the fact that the water equivalent of snow on the ground is higher near water tracks and along streams. The average ratio of summer runoff to summer precipitation is 0.37 (n=13 years) with the range being 0.17 to 0.67 for Imnavait Creek. A five year average for the upper Kuparuk River is 0.65 (range 0.56-0.78) and a five-year average for the entire Kuparuk is 0.35 (range 0.24-0.48). During snowmelt, runoff dominates as the main exporter of water from the basin while, except for three years, evapotranspiration dominates during the summer.
Kane, D.L., L.D. Hinzman, J.P. McNamara, Z. Zhang, and C.S. Benson, 2000. *An Overview of a Nested Watershed Study in Arctic Alaska.* Nordic Hydrology, 31 (4/5): 245-266.	The hydrology of a nest of three watersheds has been studied since 1992 on the North Slope of Alaska. The distribution of precipitation, topographic gradients and availability of surface storage are the primary controls of runoff response on the four watersheds reported here. In addition, the lack of subsurface storage due to the presence of continuous permafrost near the ground surface ensures that a larger fraction than normal of precipitation will leave the basin as runoff. The average annual runoff ratios are 0.48 for Imnavait Creek (n=14 years), 0.65 for the Upper Kuparuk River (n=4 years) and 0.58 for the Kuparuk River (n=4years). All of these runoff ratios are substantially above the average of more temperate regions and the global average of 0.36. Two factors can account for high runoff ratios during snowmelt; first, rapid and sustained (no cold periods) snowmelt and second, heavy snowpacks that overload the surface storage system. Prolonged melt periods reduce runoff and enhance evaporation and infiltration, but heavy snowpacks still produce substantial runoff. On the coastal plain the main mechanism of water export from the basin is evapotranspiration (ET) in the summer. About one-third of the summer precipitation leaves the Upper Kuparuk by ET. In the Imnavait catchment, ET and runoff fluctuate between one-third and two-thirds of rainfall, but average about one-half runoff and one-half ET. The percentage of rainfall that becomes runoff is greater when precipitation results from a few large storms. In contrast, the amount of ET is greatest in summers when the precipitation intensities and amounts are low and storms are numerous.

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Knudson, J. A., and L.D. Hinzman. 2000. *Prediction of Steamflow in an Alaskan Watershed Underlain by Permafrost.* Pages 309 – 313 in Proceedings of Spring Specialty Conference on Water Resources in Extreme Environments, Anchorage, AK, 2000. American Water Resources Association, Middleburg, VA.	This study was performed to determine the effectiveness of the Swedish HBV-3 model in predicting streamflow on two watersheds underlain by discontinuous permafrost in the Caribou-Poker Creeks Research Watershed, Fairbanks, Alaska. The HBV model appears to adequately simulate streamflow for the C3 and C4 sub-basins. This success supports continued use of the HBV-3 model as a viable tool for hydrologic modeling within the Caribou-Poker Creeks research watershed, as well as strengthening previous evidence for its potential use throughout the subarctic.
Lynch, A.H., et al. 1998. *Surface Energy Balance on the Arctic Tundra: Measurements and Models.* American Meteorological Society. 12 (August): 2585-2606.	Differences in measured fluxes are due to a large number of factors, including instrument error and sampling issues. However, methodology and site differences contribute a comparable amount to the observed discrepancies. This study confirms that the summer climatology in this area of the Arctic is dominated by net radiation and latent heat fluxes. Sensible heat fluxes are also important during warmer, drier periods. In general, the ground heat flux represents about 10 percent of the net radiation. The spatial variability of fluxes is quite high, especially on the coastal plain where the landscape is nearly 50 percent shallow ponds, and the land areas gradate rapidly between very wet to somewhat dry.
McNamara, J.P., D.L. Kane, and L.D. Hinzman. 1997. *Hydrograph Separations in an Arctic Watershed Using Mixing Model and Graphical Techniques.* Water Resources Research. 33 (7): 1707-1719.	Storm hydrographs in the upper Kuparuk River basin (142 km2) in northern Alaska were separated into source components using a chemical mixing model and by graphical recession analysis. Although streamflow during the snowmelt period in other regions is dominated by old water, streamflow during the snowmelt period in the upper Kuparuk River is almost entirely composed of new water. Summer storm flow in the upper Kuparuk River basin is dominated by old water. Hence there is a dramatic shift in storm flow composition from the snowmelt period to the earliest summer storms. This change can be credited to active layer thickness. Immediately following snowmelt, storage capacity of the soil is restricted to a thin layer in the surface organic soils. The fastest rate of increase in active layer thickness occurs early in the summer.
McNamara, J.P., L.D. Kane, and L.D. Hinzman. 1999. *An Analysis of an Arctic Channel Network Using a Digital Elevation Model.* Geomorphology. 29: 339-353.	Drainage basins possess spatial patterns that can be characterized by fractal dimensions and cumulative area distributions. Features called water tracks often drain hill slopes in basins with permafrost and impose significant control on the hydrologic response of the watersheds. The arrangement of channel networks and water tracks in the Imnavait Creek watershed, in northern Alaska , were analyzed to determine if basins with permafrost possess the same universal characteristics as basins without permafrost. Using digital elevation models (DEMS), the hill slope/channel scaling regimes, the spatial distribution of mass through the cumulative area distribution, and the fractal characteristics of channel networks in the Kuparuk River basin in northern Alaska were explored
Meade, N.G., L.D. Hinzman, and D.L. Kane. 1999. *Spatial Estimation of Soil Moisture Using Synthetic Aperture Radar in Alaska.* Advanced Space Research. 24 (7): 935-940.	It is possible to use SAR derived data in the Arctic to obtain spatially disturbed soil moisture maps for a large watershed that appear to be qualitatively correct. This task is made easier by the complete lack of overstory vegetation and the small stature of grasses, sedges, shrubs, etc.

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Mendez, J. 1997. *Evapotranspiration from a Wetland Complex on the Arctic Coastal Plain of Alaska.* Thesis. University of Alaska, Fairbanks.	Evapotranspiration (ET) is a very important component of the water balance in arctic coastal wetlands, with a magnitude usually exceeding that of summer precipitation. As determined from the Bowen ratio energy balance model (BREB), ET rates for the summer snow free period in this arctic wetland complex were 1.38, 1.41, and 1.57 mm/day for 1996, 1995, and 1994 respectively. The average ET rate over a three year period was 1.45 mm/day. These rates fall within the range of ET rates found by other studies on similar surface types. ET rates were higher during wetter, warmer conditions (August 1994) than during drier, cooler ones (August 1996 and August 1995). In addition ET was higher in June and July than in August. This was attributed to larger net radiation values during June and July than in August. Average evaporation rates from all the ponds in the watershed obtained via the water balance method for the post-runoff summer period were 2.33, 3.60, and 3.40 mm/d for 1996, 1995, and 1994, respectively. Comparison of these evaporation results to ET values obtained for the entire watershed by the BREB for the same time periods indicate that ET from the entire watershed (per unit area) proceeds, on average, at a rate of 0.54 that of the ponds alone.
Mendez, J., L.D. Hinzman, and D.L. Kane. 1998. *Evapotranspiration from a Wetland Complex on the Arctic Coastal Plain of Alaska.* Nordic Hydrology. 29 (4/5): 303-330.	Evapotranspiration (ET) from an arctic coastal wetland near Prudhoe Bay, Alaska was studied during the summers of 1994, 1995 and 1996 to compare different ET models and to gain a better understanding of ET from arctic wetlands. ET is a very important component of the water balance in arctic coastal wetlands, with a magnitude usually exceeding that of summer precipitation. The average ET rate for 1994 - 1996 was 1.45 mm/day. ET rates were higher during wetter, warmer conditions (August 1994) than during drier, cooler ones (August 1995 and 1996). In addition, ET was higher in June and July than in August. Evaporation from all ponds after spring snowmelt averaged 3.11 mm/day. The evaporation rate from ponds was on average twice that of the tundra as a whole.
Prowse, T.D., and C.S.L. Ommanney. 1990. *Regional Snow Ablation in the Alaskan Arctic.* Pages 121 – 139 in Procedngs of the Northern Hydrology Symposium, Saskatoon, Saskatcewan, 1990.	The rates of snowpack ablation were monitored at three sites in northern Alaska for four years in a transect from the Brooks Range to the Arctic Coastal Plain. The initiation of ablation was site specific being largely controlled by the complementary addition of energy from radiation and sensible-heat flux. Although the research sites were only 115 km apart, the rates and mechanisms of snowmelt varied greatly. In the more southerly sites, snowpack ablation progressed much faster when compared to the northerly site. The southerly sites are much more influenced by sensible heat advected from areas south of the Brooks Range. A comparison of the measured energy balances reflected the increasing importance of net radiation in the more northerly site.
Robinson, D.W. 1995. *A Biogeochemical Survey of an Arctic Coastal Wetland.* Thesis. University of Alaska, Fairbanks.	The "Betty Pingo" wetland study site in Prudhoe Bay, Alaska has been extensively studied for three years. Data collected included biogeochemical, meteorological and hydrological. Arctic North Slope hydrology is characterized by very low precipitation and a negative summer water balance. Much of the snow that falls during the winter months is destined to replenish the storage lost from the ponds and marshes of the area during the previous years growing season. Surface drainage of runoff occurs for a short period of time following snowmelt, but after this initial flush has passed through the area, there is no surface movement, and only very minor subsurface flow of water at this site. The magnitude of evapotranspiration (ET) can completely dry up some of the smaller, shallower ponds during the summer, and all of the ponds experienced a stage drop of between 150 and 400 mm of water. August brings increasing rain which recharges the ponds to some degree, but during the course of this study they did not reach their spring bankfull levels by the onset of the winter freeze. Microtopographic relief plays a critical role in defining drainage and storage patterns in these wetlands. They are able to remain wet despite very low levels of overall precipitation by means of limited groundwater infiltration due to ice-rich permafrost and the sponge-like water retentive capacity of the tundra peat active layer. The small scale surficial landscape features make watershed delineation extremely difficult in the low relief wetlands of the Alaskan Coastal Plain. Physical, chemical, and biotic regimes are influenced by the direct and the less obvious impacts of human industry, and it is vital that these impacts are understood within the context of the arctic environment, both its resiliency, and its sensitivity to disturbance.

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Rovansek, R. J. 1994. *The Hydrology and Jurisdictional Status of a Wetland Complex on the Alaskan Arctic Coastal Plain.* Thesis. University of Alaska, Fairbanks.	The hydrology of the tundra at Prudhoe Bay is characterized by a near parity between evapotranspiration (ET) and precipitation. Annual ET from wetter areas, including ponds and wetlands, is greater than annual precipitation. Thus, the maintenance of these wet areas is dependent on runoff from surrounding, higher portions of the tundra. The runoff occurs primarily from snowmelt. Overland flow was not observed on the study site after snowmelt runoff ceased in early to mid-June. The water levels in ponds and wetlands are low prior to snowmelt as a result of water loss during the previous summer. Subsurface flow is not an important means of water movement on the study site. The low regional topography results in low hydraulic gradients. This, in combination with low hydraulic conductivity and a shallow active layer, result in typical flow velocities through the active layer on the order of 1 mm/day. Over the course of a summer season, flow through the active layer is not a significant contributor to the water balance of ponds on the study site. Seasonal net inflow/outflow through the active layer amounts to less than 0.5 percent of the seasonal ET at a typical pond.
Rovansek, R. J., L.D. Hinzman, and D.L. Kane, 1996. *Hydrology of a Tundra Wetland Complex on the Alaskan Arctic Coastal Plain, U.S.A.* Arctic and Alpine Research. 28 (3): 311-317.	This study investigates the water balance and seasonal patterns of water movement on wetlands typical of the Prudhoe Bay area, Alaska. Water levels dropped through June and July, when evapotranspiration (ET) is greatest, and recovered somewhat during August, when precipitation increases and ET decreases. Ponds and wetlands, which experience a net loss of water over the summer, were filled to capacity by snowmelt runoff in spring. Annual ET from ponds and wetlands exceeds annual precipitation and, as a result, snowmelt runoff from surrounding upland areas is necessary to maintain wetlands and ponds. The average daily pond evaporation of 2.0 mm/day (1992) and 2.1 mm/day (1993) obtained in this study closely match measured pan and lake evaporation values of 2.1mm/day for Prudhoe Bay obtained by Kane and Carlson (1973) and 2.05 mm/day at Barrow (Brown et al., 1968). Unmeasured trace precipitation and condensation adds water to the system that is not included in the calculation (Dingman et al., 1980; Hobbie, 1980; Benson 1982). Hobbie (1980) reports comments by Dingman who indicates that condensation of fog and dew on vegetation may equal 23 to 50% of summer precipitation. While no data are available, Dingmans' estimate of trace precipitation could mean up to 3 cm of unmeasured water added to approximately 6 cm observed during this study. Trace precipitation and condensation would both be expected to be concentrated in late summer when measured precipitation is greatest. These unmeasured additions of water could explain the divergence of predicted and measured water levels in late summer. Ponds and wetlands intercept and store runoff water and as a result reduce the size of the snowmelt flood from their drainage's. The available storage prior to snowmelt is determined by the water deficit from the previous summer minus the water equivalent of the snowpack prior to ablation. Loss of storage averaged approximately 16 cm from ponds and 11 cm from wetlands. This is greater than the measured snowpack of 9 cm, indicating that wetlands intercept and store snowmelt runoff from upslope areas in addition to storing meltwater from the snow that covers them.
Rovansek, R.J., D.L. Kane, and L.D. Hinzman. 1993. *Improving Estimates of Snowpack Water Equivalent Using Double Sampling.* Pages 157 – 163 in Proceedings of the 50th Eastern Snow Conference, 61st Western Snow Conference, Quebec City.	Double sampling refers to sampling the snowpack in two ways: measuring the depth at a number of points, and measuring the depth and the water equivalent at a smaller number of points. In 1992 and 1993 double sampling was performed on the North Slope of Alaska. The results of the snow surveys presented herein demonstrate that double sampling can yield improved estimates of average snowpack water equivalent when compared with sampling water equivalent only. This, combined with its adaptability to sampling along a transect and overall simplicity, makes double sampling an attractive alternative for both existing snow courses and new snow surveys. By timing the collection of depth and water equivalent measurements, the optimal ratio of the two measurement types to be utilized in subsequent surveys can be calculated. This paper presents equations developed to estimate average snowpack water equivalent, and to estimate the variance of the estimated water equivalent, and the equations used to predict the ratio of the two types of snowpack measurements that will produce the lowest variance estimate of snowpack water equivalent in a given time.

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Waelbroeck, C., et al., 1997. *The Impact of Permafrost Thawing on the Carbon Dynamics of Tundra.* Geophysical Research Letters. 24 (3): 229-232.	Presented herein are the results obtained with a model of CO_2 exchanges, coupled to a model of the soil thermal and hydrological regime in the tundra. It is shown that as a result of the partial thawing of the permafrost, and the subsequent increase in nutrient availability, the ecosystem's response to warming may be a long-lasting increase in C accumulation, following a temporary increase in CO_2 emissions. This study also provides a consistent picture of CO_2 exchanges in tundra ecosystems, reconciling the short-term experimental response to warming, recent field measurements, and Holocene C accumulation estimates.
Yang, D., D.L. Kane, L.D. Hinzman, B.E. Goodison, J.R. Metcalfe, P.Y. Louie, G.H. Leavesley, D.G. Emerson, and C.L. Hanson. 2000. *An Evaluation of the Wyoming Gauge System for Snowfall Measurement.* Water Resources Research. 36 (9): 2665-2667.	The Wyoming snow fence (shield) has been widely used with precipitation gauges for snowfall measurement at more than 25 locations in Alaska since the late 1970's. This gauge's measurements have been taken as the reference for correcting wind-induced gauge undercatch of snowfall in Alaska. Recently, this fence (shield) was tested in the World Meteorological Organization Solid Precipitation Measurement Intercomparison Project at four locations in the United States of America and Canada for six winter seasons. At the Intercomparison sites an octagonal vertical Double Fence with a Russian Tretyakov gauge or a Universal Belfort recording gauge was installed and used as the Intercomparison Reference (DFIR) to provide true snowfall amounts for this intercomparison experiment. The intercomparison data collected were compiled at the four sites that represent a variety of climate, terrain, and exposure. On the basis of these data sets the performance of the Wyoming gauge system for snowfall observations was carefully evaluated against the DFIR and snow cover data. The results show that (1) the mean snow catch efficiency of the Wyoming gauge compared with the DFIR is about 80 – 90 percent, (2) there exists a close linear relation between the measurements of the two gauge systems and this relation may serve as a transfer function to adjust the Wyoming gauge records to obtain an estimate of the true snowfall amount, (3) catch efficiency of he Wyoming gauge does not change with wind speed and temperature, and (4) Wyoming gauge measurements are generally compatible to the snowpack water equivalent at selected locations in northern Alaska. These results are important to our effort of determining true snowfall amounts in the high latitudes, and they are also useful for regional hydrologic and climatic analyses.
Zhang, Z., D.L. Kane, and L.D. Hinzman. 1999. *Development and Application of a Spatially-Distributed Arctic Hydrological and Thermal Process Model (ARHYTHM).* Hydrological Processes. 14: 1017-1044.	A process-based, spatially distributed hydrological model was developed to quantitatively simulate the energy and mass transfer processes and their interactions within arctic regions (arctic hydrological and thermal model, ARHYTHM). This model is capable of simulating distributed processes such as snowmelt, subsurface flow, overland flow, channel flow, soil thawing and ET. Results from the application of this model to two watersheds, Imnavait Creek and the upper Kuparuk River basin, are presented and discussed.