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An Overview of a Nested Watershed Study in Arctic Alaska

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The hydrology of a nest of three watersheds has been studied since 1992 on the North Slope of Alaska, with some additional data collected at individual sites previously. Hydrologic studies of nested watersheds are rare in the circumpolar arctic. Presented here is a comparison of the variability of important runoff-related processes from the headwater foothills to the low gradient, wetland dominated coastal area. Watersheds studied include Imnavait Creek, Upper Kuparuk River and finally the entire Kuparuk River. Also, runoff data from the low gradient Putuligayuk River, measured earlier (1970-1986), is included. Generally, rainfall constitutes 53 to 67 % of the annual precipitation. Most runoff is generated from the foothills; runoff is normally only generated from the coastal plain during snowmelt. Surface storage is an important process on the coastal plain where vertical processes (precipitation and evapotranspiration) are dominant during the summer. Continuous permafrost produces high soil moisture levels except where there are relatively steep slopes with gravity-induced drainage. Snowmelt results in a nearly saturated active layer with summer moisture levels closely allied with summer precipitation. High runoff ratios prevail during snowmelt and rainfall, except for the summer rainfall-generated runoff of the low gradient Putuligayuk River.

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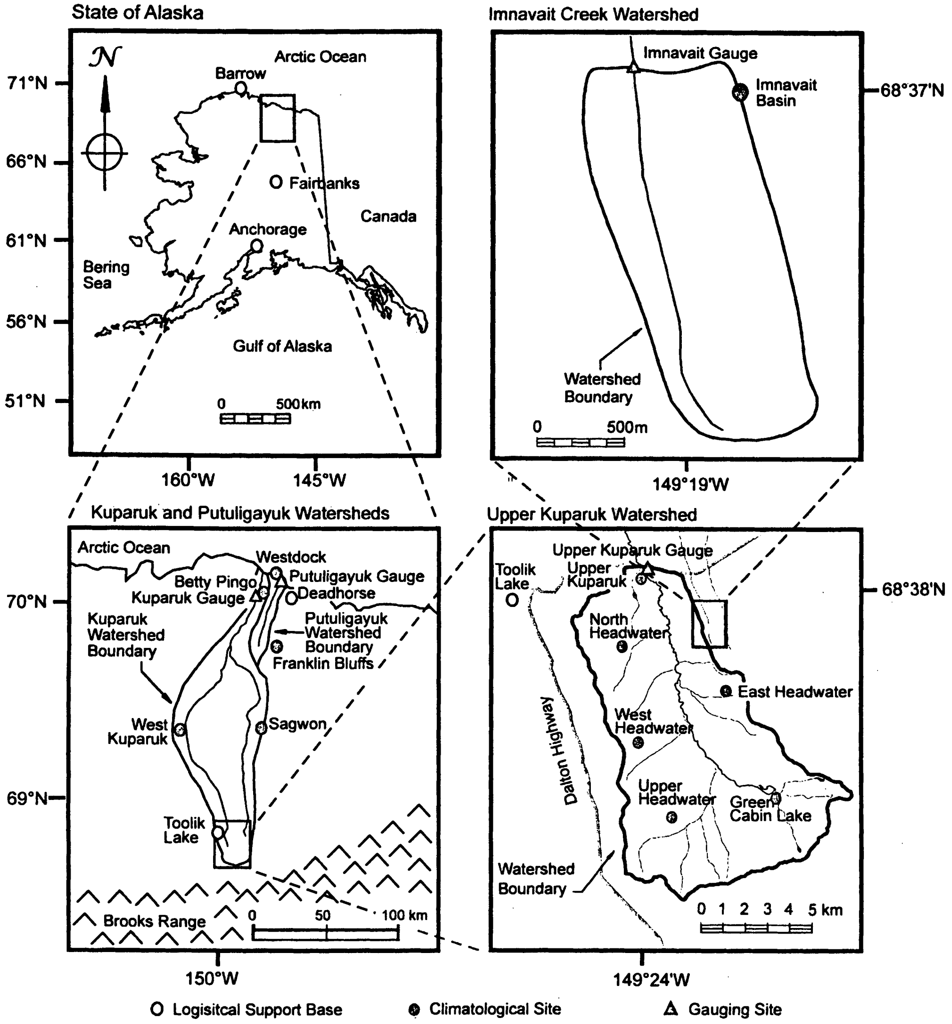


Fig. 1. Location map of nested watersheds of the Kuparuk River basin on the North Slope of Alaska.

Introduction

Driven by the need to improve our understanding of the role that arctic hydrology plays in the regional and global climate, several related hydrologic studies were initiated on the North Slope of Alaska in 1992. These studies included field research and modeling studies of the logistically accessible Kuparuk River basin and selected contributing watersheds, a north draining river system that empties into the Arctic

Ocean. The goals are to collect quality hydrologic data throughout the year, monitor and study as many hydrologic processes as possible, address issues of spatial variability, examine hydrologic responses at various scales, and utilize conventional as well as remote methods of data collection. Reported here are the runoff responses of these assorted catchments to snowmelt and summer precipitation. The area of study (Fig.1) is 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). The Putuligayuk catchment has only been studied in a manner similar to the other basins since 1999, although the U. S. Geological Survey (USGS) collected runoff data for a number of years.

The Kuparuk River basin on the North Slope of Alaska is one of the most intensely studied rivers in the circumpolar Arctic during the past six years. However, the short duration of this study (1992-present) prohibits any meaningful statistical analyses and it pales in comparison to the longevity of basin studies in temperate climates. Streamflows have been measured in some of these drainages since 1970, but there is no other complimentary hydrologic data.

The integrating role that hydrology plays in interfacing between atmospheric-terrestrial-aquatic systems in any climate regime have been established (Entekhabi *et al.* 1996; Delworth and Manabe 1989; National Research Council 1991; Chahine 1992). Trace gas fluxes (CO_2 and CH_4) emanating into or out of the carbon-rich surficial soils of the Arctic (Michaelson *et al.* 1996) are closely tied to both the climate and hydrology (Oechel *et al.* 1993; Burton *et al.* 1996). Mass and energy fluxes that are an integral part of the arctic hydrologic cycle also impact the global climate (Kane 1997). Hydrologic processes associated with phase change (snowmelt, evaporation, soil freezing and thawing, *etc.*) play a more varied role in arctic watersheds than more temperate watersheds. Beyond watershed boundaries, freshwater runoff into the shallow Arctic Ocean is climatically important to maintaining stratification and development of ice cover extent, as well as circulation (Aagaard and Carmack 1989).

Conceptual Model of Arctic Hydrology

Hydrologic processes in the Arctic are not dissimilar to those in more temperate watersheds. However, the structure of the watershed and the magnitude of hydrologic process rates in the Arctic are significantly different than watersheds in warmer environments. Basically, this is due to the continuous permafrost that exists and to the extreme seasonal changes in the surface energy balance. Conceptually, the hydrologic cycle in the Arctic, with watershed structure and both inputs and outputs, is illustrated in Fig. 2.

The main structural components of an arctic watershed are the active layer (including vegetation) above permafrost, water tracks, wetlands, ponds, lakes and

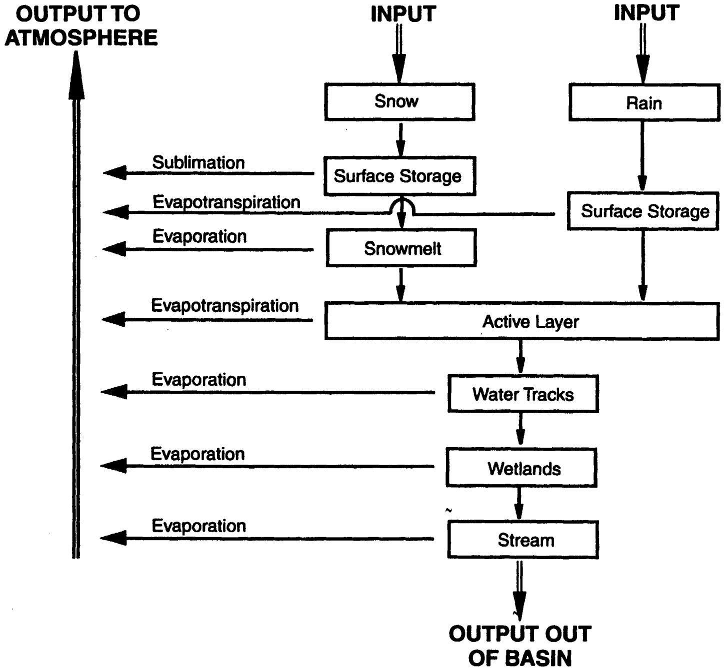


Fig. 2. Conceptual representation of the hydrologic cycle in the Alaskan Arctic.

streams; permafrost serves as the lower boundary and the atmosphere, the upper. Obviously, larger watersheds are an integration of smaller watersheds where streams grow into higher order rivers. Some watersheds have considerable surface storage in the form of wetlands, ponds and lakes; this is more generally the case in the low gradient coastal plain than in the foothills. Eighty three per cent of the coastal plain is characterized as wetlands. Water tracks are an integral component of these arctic catchments as they accelerate the surface runoff response. Spaced at tens of metres, these water tracks efficiently remove water from the hillslope to the base of the hill, but are generally not connected to the stream in the valley bottom.

Snow cover is also an important structural component of the watershed, but it is seasonal (Benson and Sturm 1993). Aufeis on streams and rivers is also a significant storage component that varies greatly in quantity between drainage basins. It persists longer than seasonal snow and in some cases may provide a control on runoff similar to that of glaciers in the headwaters of streams (Li *et al.* 1997; Dean 1984).

Storage, either surface or subsurface, is a major function of all watersheds. As a result of a climate that has produced permafrost in the Arctic, watershed structure and function are altered from that of more temperate watersheds. Specifically, the important subsurface processes are confined to the very shallow active layer, which severely limits the amount of subsurface storage and the magnitude of groundwater flux compared to more temperate watersheds. In fact, in areas of continuous permafrost, the depth of average annual precipitation over a watershed is approximately equal to the amount of water capable of being stored in the active layer at maximum depth of thaw. This implies a relatively short residence time for subsurface water. For example, an active layer 60 cm deep (organic soil-20 cm and mineral soil-40 cm) with the porosities measured at Imnavait watershed could hold, if saturated, nearly 30 cm of water; this can be compared with an average measured annual precipitation of nearly 35 cm. Permafrost is for all practical purposes an impermeable lower boundary of the watershed. The shallow nature of the active layer promotes the occurrence of overland flow. Saturation of the active layer can occur in the summer during major rain events. By late summer the depth of thaw typically averages 50 to 60 cm in this basin and so the potential subsurface storage increases throughout the summer. The only exception to the shallow depth of thaw is the deeper thaw depth beneath surface water bodies such as streams and lakes, due to enhanced transport of heat through the water column (Gold and Lachenbruch 1973).

Hydrologic inputs into the watershed come as snow on any day of the year and as rain, primarily May through September. Even at 70° N latitude in Alaska, only about one-third of the annual precipitation exists as snow on the ground at the end of winter. Actual snowfall precipitation percentages are higher, however sublimation losses over the winter reduce the water equivalent of snow on the ground by winter's end. Redistribution of snow by wind (coupled with sublimation) is a major episode that occurs many times each winter (Benson and Sturm 1993). The snowmelt period is short and intense; typically in a seven to ten day period the ground surface is transformed from a white reflective surface with an albedo of 0.8 to a tundra surface (albedo < 0.2) that absorbs four times more energy. This added energy and meltwater are available for plants at the very beginning of the summer season. Presently, mid-winter melting of the snowpack or rain on snow is rare, although with a changing climate the frequency of occurrence may increase.

The pathways of water back to the atmosphere are evaporation, transpiration and sublimation. The shallow active layer underlain by relatively impermeable permafrost ensures that the water table will be near or above the ground surface, thus enhancing evaporation. In the Arctic, transpiration is ongoing from the end of snowmelt until plants senesce (Kane *et al.* 1990).

Related Work

The hydrologic study of the Kuparuk River reported here is unique in the Arctic in that all the important processes have been studied over all four seasons for initially three nested watersheds (now four with the Putuligayuk catchment) with a concerted effort to quantify spatial variability. There have been numerous hydrologic studies in the Arctic at the plot, hillslope, and small watershed scale. These studies have typically been of short duration, therefore the extremes of record are often not observed. Usually only some of the hydrologic processes are studied so there is no closure on the water balance. Many studies have only been performed during summer months. In this study, the combination of a relatively large watershed (>8,000 km^2), supported with substantial spatially distributed data is unique in the Arctic.

Rather than presenting a complete review here of other studies, the reader is referred to several recent overview papers that list the most relevant arctic hydrologic studies in North America. Woo (1986) summarized improvements in our understanding of physical processes but lamented the lack of long term and spatial data. Kane *et al.* (1992) discussed how the structure and function of Arctic hydrologic systems in the Arctic could potentially be altered by climate change. Kane (1997) also addressed the issue of how hydrologic perturbations cascade through the hydrologic cycle, and the response of the animals and vegetation.

Numerous papers have been published on the earlier work in Imnavait Creek (Hinzman *et al.* 1991, 1993, 1996; Kane *et al.* 1989, 1990, 1991a, 1991b, 1996, 1997; Hinzman and Kane 1991, 1992). More recent publications address the hydrology over the entire Kuparuk watershed with some process specific analyses. McNamara *et al.* (1997) showed that snowmelt runoff was generated directly from water in the snowpack as expected, while summer runoff from rainfall was dominated by old water present in the active layer and not the recent rainfall. Also, McNamara *et al.* (1998) assessed the rôle of permafrost on storm hydrographs. They found fast initial response time to rainfall and attributed this to the large saturated areas immediately adjacent to water tracks. Extended recession curves were explained by delayed drainage from the active layer. For the years 1993 to 1997, Lilly *et al.* (1998) showed the annual water balance for Imnavait Creek, Upper Kuparuk River, and the entire Kuparuk River. Very high runoff ratios are reported for all three watersheds during snowmelt; summer runoff ratios are significantly lower for Imnavait Creek and the entire Kuparuk River, but not the Upper Kuparuk River. Kane *et al.* (1998) examined the hydrologic response of individual storms. They found that the runoff ratio decreased as watershed size increased, and they stressed the importance of limited active layer storage on runoff volume. It is common in all watersheds for the runoff ratio to decrease with watershed size because both rainfall intensity and amount decrease with increasing area. Hinzman *et al.* (1998) developed a spatially distributed thermal model to predict active layer depths throughout the Kuparuk basin. Zhang *et al.* (2000) present a spatially distributed, hydrologic process model (ARHYTHM) that has been successfully applied to both the Upper Kuparuk and Imnavait catchments. Recently these two models have been coupled. For a small wetland complex on the coastal plain, Rovansek *et al.* (1996) reported that surface runoff only occurred during snowmelt and that evapotranspiration was the major mechanism of water loss from the catchment during the summer. For the same wetland, Mendez *et al.* (1998) compared a number of models for simulating the amount of evapotranspiration.

Setting

The Kuparuk River drains northward into the Arctic Ocean and it originates in the northern foothills of the Brooks Range (Fig. 1). No flow from the central mountains of the Brooks Range enters the Kuparuk River; the Atigun River, which runs from west to east through the northern limit of the Brooks Range, captures all this flow and discharges it into the adjacent Sagavanirktok River. The Kuparuk River basin (8,140 km^2) is completely underlain by permafrost (300 m thick in the foothills and 600 m thick near the coast) and is treeless except for some tall shrubs in riparian areas. There are a small number of lakes in the headwaters, but they become much more pronounced in the low gradient coastal plain. Wetlands likewise become more frequent as one proceeds from the foothills to the coastal plain. The Kuparuk River is a clear water tundra stream about 250 km in length that drains northward out of the foothills, across the coastal plain and into the Arctic Ocean. The coastal plain constitutes 44 % of the basin area, with the foothills occupying 56 %. The foothills are composed of till from three glaciations during the Pleistocene (Hamilton 1986). There is no active glaciation in the Kuparuk basin, although neighboring basins with their headwaters in the Brooks Range do contain small glaciers. The coastal plain is un-glaciated with numerous permafrost features such as high and low centered polygons, pingos, wind-oriented lakes, drained-lake basins, strangmoor ridges and hummocky ground. The Kuparuk River is primarily a meandering stream, but in some sections it is braided and anastomosed. One area where the stream is braided is 40 km north of Toolik Lake. This braiding happens to coincide with an aufeis field that forms each winter and covers about 6 to 12 km^2 with a thickness of a few metres. This accumulation of ice is evidence of winter flow in channel and adjacent unfrozen-substrate. The USGS has operated a stream gauging site on the Kuparuk River just inland from the coast (Fig. 1) since 1970. Characteristics of this basin and the other drainages studied are listed in Table 1 along with relative area-elevation curves of each watershed (Fig. 3).

Vegetation is almost continuous over the basin with alpine communities at the higher elevations, tussock tundra over the foothills and sedge tundra on the coastal plain. Dwarf shrubs (~1 m) of willows and birch are common in riparian areas; in the central part of the Kuparuk watershed where the transition from foothills to the coastal plain occurs, shrubs approach 10 m in height in riparian areas. The active layer is typically composed of organic soils covering deeper mineral soils. The depth of the organic layer is least near the ridges and greatest in the valley bottoms. Downslope water movement is greatest in the organic soils; significant movement in the mineral soils is not possible because of the low hydraulic conductivities and short duration of the summer thaw season.

The Upper Kuparuk River watershed (drainage area 142 km^2) drains the highest and steepest terrain in the entire watershed (Table 1). Precipitation is spatially quite variable here because of orographic effects and probably the closeness of the higher

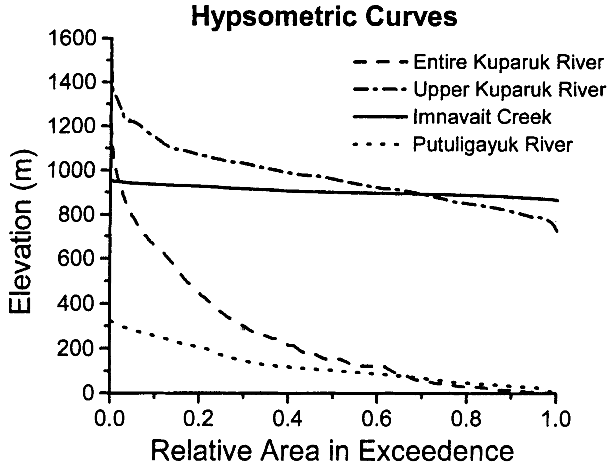


Fig. 3. Hypsometric curves for Imnavait, Upper Kuparuk, Putuligayuk and Kuparuk drainages on the North Slope of Alaska.

mountains just outside the watershed. This drainage is gauged just upstream from where the Dalton Highway crosses the stream near Toolik Lake. It is a north-northwest trending drainage, and on a 1:63,360 USGS topographic map it is a fourth order stream.

Imnavait Creek parallels the Upper Kuparuk basin and enters the Kuparuk River 12 km north of the gauging station (Fig. 2). The small watershed at the headwaters of the Kuparuk River has been monitored since 1985 (Hinzman *et al.* 1993). This stream is a first order stream on the 1:63,360 USGS topographic map; flows persist throughout the summer months, but during the late winter months flow is practically non-existent. The stream is beaded, meaning that the channel connects numerous interspersed small ponds. The ponds formed when massive ground ice melted due to some past thermal disturbance. These ponds are on the order of 2 m deep and a few metres in length and width. Vegetation in the Imnavait watershed is dominated by tussock sedge tundra with dwarf shrubs in the water tracks.

Parallel to the east of the Kuparuk River on the coastal plain is the Putuligayuk River. This catchment (471 km^2) is unique in that the watershed is totally confined to the low gradient coastal plain. It is dominated by wetlands, ponds and wind-oriented lakes. The USGS monitored this stream for 15 years, from 1970 to 1986 (data for 1980 and 1981 missing). There are no corresponding precipitation data to complement the runoff data. We have only recently re-initiated monitoring of this watershed, although we will comment in this paper on the runoff response of this basin from past data.

Table 1– Drainage characteristics of watersheds studied.

Stream	Drainage Area (km2)	Stream Length (km)	Basin Length (km)	Median Elevation (m)	Elevation Range (m)
Kuparuk River	8140	330	250	245	0-1464
Upper Kuparuk River	142	25	16	967	698-1464
Imnavait Creek	2,2	1,37	2,05	904	844-960
Putuligayuk River	471	54	60	39	7-109

Measurement Program

A stream gauging station exists at the mouth of each drainage; Imnavait Creek has a H-flume with water level recorder and pressure transducer to aid in flow measurement estimates, while the others only have water level recording devices with natural controls. Discharge measurements were made for a range of flows and a rating curve was established for each site. During snowmelt-generated runoff, Imnavait Creek and the Upper Kuparuk River are gauged twice daily, in the morning during low flow and in the evening during high flow. These times were chosen because at the end of winter the channels are filled with ice and as this ice erodes the rating curves continually change. Slushflows in the headwater basins are also a problem when snowmelt runoff is first initiated.

There are seven complete meteorological stations in the basin (Fig. 1). Two sets of stations are located very close to each other; one set at Prudhoe Bay (Betty Pingo and West Dock) where there is a strong influence of the Arctic Ocean along the coast. The second set is at Imnavait Creek and the Upper Kuparuk River where elevation differences result in significant temperature and rainfall differences. Variables measured at each site are wind speed, relative humidity and air temperature at two or three elevations (with the maximum at 10 m). Wind direction, rainfall and soil temperatures are also measured. Incoming and outgoing long and short wave radiation are measured from before snowmelt until freeze-up. In the Upper Kuparuk Basin where there is more rugged terrain, five additional stations were installed in 1996 to measure air temperature, wind speed and rainfall precipitation. At two meteorological sites, soil moisture is measured automatically for several profiles at three to four depths with time domain reflectometry (TDR), several times per day.

The water equivalent of the snowpack is measured late each spring at numerous locations over the watershed just before melt begins. The USDA Natural Resource Conservation Service (NRCS) maintains three shielded Wyoming gauges in the basin for measuring precipitation year around. During snowmelt, snow surveys are made daily.

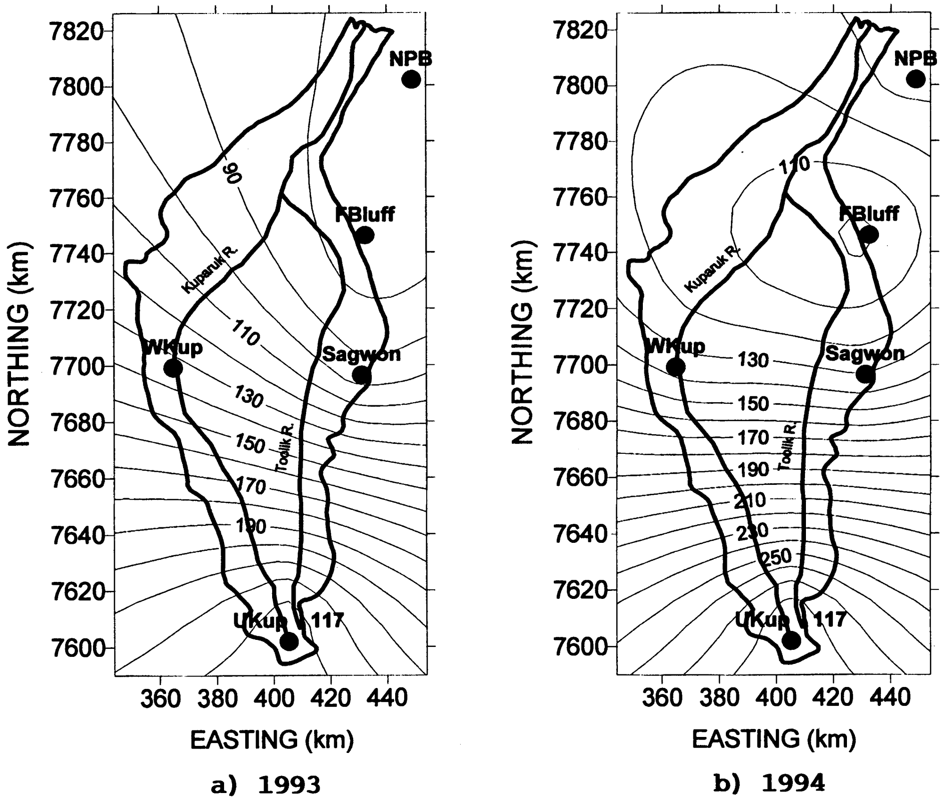


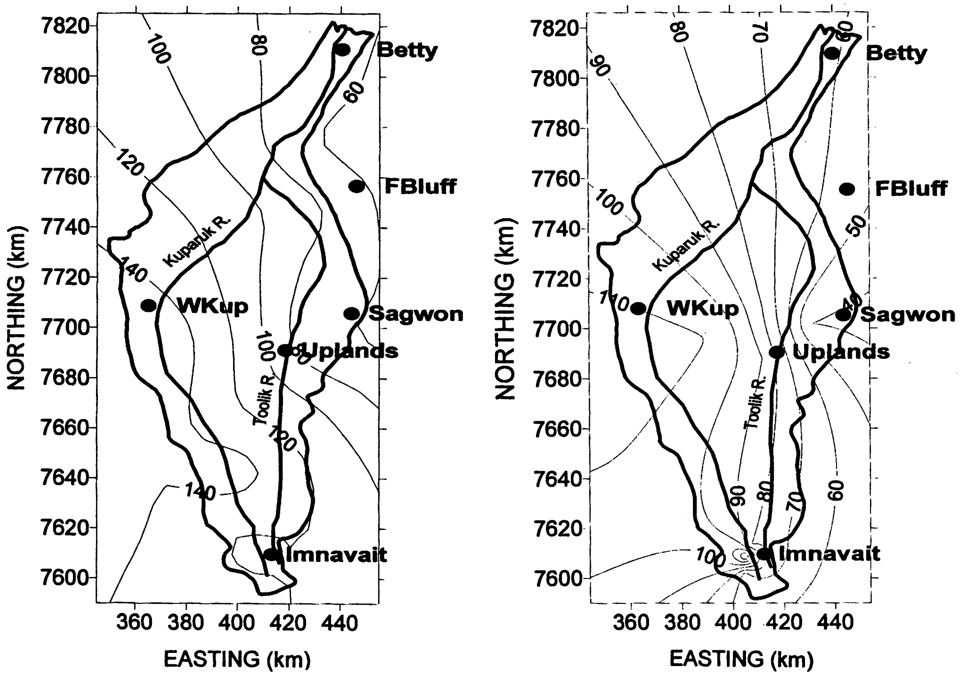
Fig. 4. Spatially distributed total summer precipitation (mm) for the Kuparuk River drainage.

Precipitation Patterns

One of the goals of this project is to obtain good spatial and temporal hydrologic data at various watershed scales. Obviously for closure on water balances and for input into hydrologic models, it is very important to accurately quantify all forms of precipitation input into the basin. This task is made difficult by the remoteness of the sites, windy environment, and occurrence of numerous light precipitation events, particularly along the Arctic Ocean coast.

Spatial Variation

From our meteorological sites, seasonal rainfall patterns can be examined over the entire Kuparuk River basin (Figs. 4a and 4b). Precipitation is less near the mouth of the river and increases in a southerly direction toward the headwaters. The maximum gradient is generally south, but from year to year it can deviate slightly to the east or west. Summer precipitation varies from less than 100 mm on the coast to near



a) 1993 **b) 1994**

Fig. 5. Distribution of maximum end of winter snow water equivalent (mm) for the Kuparuk River drainage during spring.

300 mm in the headwaters. Similarly, the distribution of snow water equivalent (Figs. 5a and 5b) showed that it increased at lower latitudes; however, while the snow depth followed the same trend the snowpack density decreased at the lower latitudes. Overall, snow water equivalent and rainfall increased with elevation and can be as much as two or three times more in the headwaters than at the watershed outlet. This can be seen for snow precipitation in the isolated White Hills that are surrounded by the coastal plain (Fig. 5a). The distribution of snow on the ground is much more complex than rainfall because of redistribution by wind. The number of wind events, wind magnitude and direction, vegetation and topography are all factors that are important to the end of winter snowpack distribution. End-of-winter measurements of depth and water equivalent of the snowpack on the ground do not reflect that portion of the winter precipitation lost to sublimation. Liston and Sturm (1998) estimated with a physically based, spatially distributed model that the annual sublimation losses could represent 9 to 22 % of the winter precipitation at Imnavait Creek. This would be equivalent to 13 to 38 mm of water from the snowpack.

Five additional gauges were installed in the Upper Kuparuk River basin in 1996 to measure the spatial variability of rainfall due to the more rugged headwater topography. Early hydrologic modeling attempts consistently produced low estimates for modeled runoff when compared to measurements for the Upper Kuparuk catchment, while results were much better for Imnavait Creek. It was suspected that the actual precipitation was much greater at higher elevations than the precipitation from the single gauge at the outlet that had been used as model input. For the summer of 1996, the additional gauges showed that there was a significant increase in precipitation with elevation in the Upper Kuparuk River basin and that the isohyets trended southeast to northwest. The gauge at Imnavait Creek recorded a summer total of 156.5 mm, while a gauge on the west headwater tributary stream recorded 220.9 mm, a 41 % increase.

Temporal Variation

Average monthly precipitation patterns show maximum precipitation in July and August and minimum monthly precipitation in November and May (Kane 1997). Average precipitation during all the winter months (October through April) except October is fairly uniform at Imnavait Kuparuk basins. Earlier data from Wyoming gauges operated by NRCS (USDA) showed the maximum in the months of July or August with a decreasing trend through the winter until May at Imnavait Creek, Sagwon and Prudhoe Bay (Kane *et al.* 1989). We have observed similar patterns in our data. May and September are the months of transition where either rain or snow can fall. During any summer month (June through August), precipitation can exceed that in any winter month by 500 to 800 %. Generally, if there are dry periods they occur early in the summer (June) after snowmelt. Summer precipitation can vary by a factor of two from dry to wet years. Also, there are summers that have many low intensity events and summers with a few major storms; obviously the hydrologic response of these patterns is different although the total cumulative precipitation can be nearly the same. Convective storms are more common early in the summer in the uplands when incoming solar radiation is near its maximum, while frontal storms are more common for the remaining part of the year.

Snowmelt

The depth of the snowpack becomes very heterogeneous after seven to nine months of accumulation and redistribution by the wind. Snow accumulates on the lee side of ridges and in depressions, primarily along drainages, at the expense of ridges and exposed windward slopes. High-density layers in the snowpack are common and can be directly traced to wind events. Layers of ice in the snowpack due to rain-on-snow or mid-winter melt events are presently rare, although they do occasionally occur in late winter. The likelihood of these events occurring in a warmer climate is increased.

The importance of snowmelt has already been alluded to in the context of the

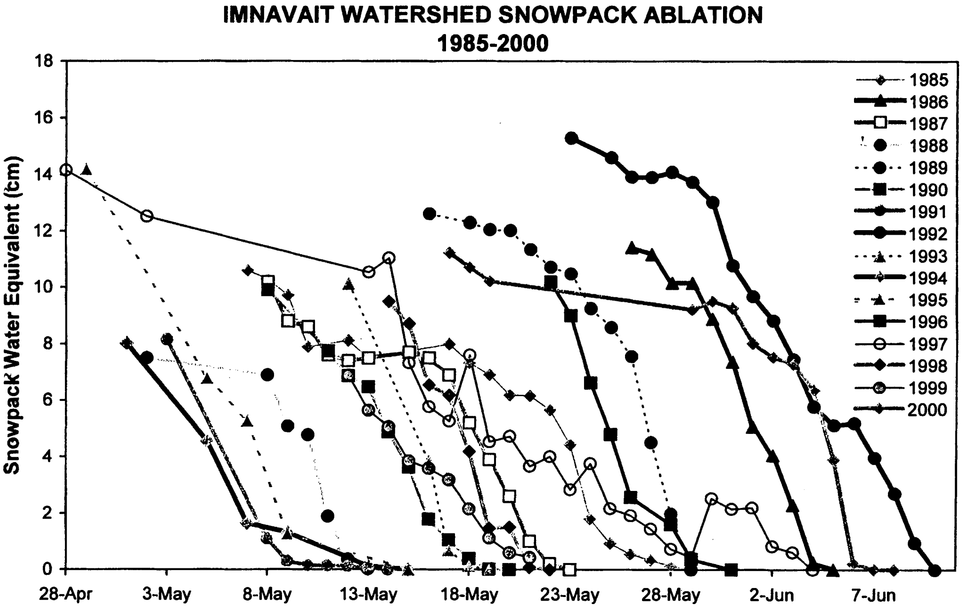


Fig. 6. Pattern of ablation over a 16-year period at Imnavait Creek watershed. Note that ablation can occur over a window in excess of 40 days.

snowmelt runoff discussed above and in numerous publications (Kane *et al.* 1991a; McCann and Cogley 1972; Woo *et al.* 1981; Roulet and Woo 1988; Woo 1986). Obviously there are many other important processes resulting from snowmelt; change in the surface albedo ranks very high among these. In areas of patchy snow, the surface temperature over the snow is 0 °C, while on snow-free ground the surface temperature has been measured at 30 °C or higher. Biologically this is a very important time to both plants and animals. Plants that are shallow-rooted in the surface organic soils respond immediately.

The window of snowmelt in the Kuparuk River is just over one month, with the central portion of the Kuparuk basin generally melting first and progressing both north and south. In the headwaters it can occur from early May to early June (Fig. 6) while near the coast, the onset of snowmelt is usually further delayed one to two weeks (major exception in 1997). Snowmelt period is relatively short for the shallow snowpack, however cold air from over the Arctic Ocean can interrupt the melt (for example 1985 in Fig. 6). In the headwaters, warm air advected from the south over the Brooks Range and solar radiation are the main contributors to melt, whereas near the coast solar radiation is the main energy source for melt.

As a general rule, a deeper snowpack melts later than shallower snowpack (Fig. 6), because the surface albedo stays higher for a longer period of time since vegetation does not protrude through the snowpack. For Imnavait Creek, the only exception to this rule of thumb since 1985 is in 1995 when a deep snowpack ablated in early May. This occurred because record high temperatures persisted for several days, due to a large, warm southerly air mass that impacted the Canadian Arctic and Arctic Ocean as well.

Water Balance

An analysis of the water balance at each catchment enables comparisons of the various hydrologic components for different years within a basin, the hydrologic response between the nested basins each year, and also with basins in other regions. Often it is difficult to do this because one or more important components are missing or it is too difficult to assess changes in the subsurface system. In the Arctic, the subsurface system is limited to the shallow active layer, and the variation in the volume of subsurface water stored is both small and measurable. Water balances on an annual time scale are also made easier in the Kuparuk River basin because similar subsurface moisture conditions occur each year just prior to freeze-up. Where surface storage in ponds and lakes decreases during the summer (Rovansek *et al.* 1996), yearly changes in storage may introduce considerable error. As the density of measuring sites decreases for larger basins, the accuracy of the water balance decreases (Imnavait Creek-1 meteorological station per square km, Upper Kuparuk-1 meteorological station per 20 square km, Kuparuk River-1 meteorological station per 680 square km).

By measuring snowmelt and rainfall inputs and runoff output from a basin, the total seasonal evapotranspiration from a basin can be estimated if one assumes no storage changes in the active layer or depressions, including lakes and ponds. This is a reasonable assumption for the foothills of the Brooks Range, but not for the low gradient coastal plain where lakes and ponds are numerous. For Imnavait Creek, with fourteen years of continuous data, such compilations have been made (Table 2). Storage of water in the basin is minimal except for in 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 = 15 years). The 1993-1996 average for Imnavait Creek (Table 3) is also 0.67, while the four-year averages are 0.62 (range 0.47-0.88) for the Upper Kuparuk and 0.86 (range 0.79-0.98) for the entire Kuparuk River. This runoff ratio is quite high because the active layer is completely frozen when ablation is initiated. One other factor that contributes to the high ratio is the fact that the water equivalent of snow on the ground is higher near drainages such as water tracks and along streams. Wind action tends to produce drifts in these settings. The snow in the drifts is not only deeper but has a higher density than the complex veneer of snow on the tundra (Benson and Sturm 1993). Finally, snowmelt coincides with near maximum solar radiation, so once initiated the event usually proceeds rapidly. Woo *et al.* (1983) reported a value of 0.80 for a high arctic catchment where 75 % of annual precipitation is snow.

Table 2– Imnavait Creek watershed spring, summer and annual water balances.

IMNAVAIT CREEK WATERSHED
SPRING AND ANNUAL WATER BALANCES

YEAR	SNOWPACK WATER EQ. (cm)	SUMMER PRECIP (cm)	TOTAL PRECIP (cm)	SNOWMELT RUNOFF (cm)	SUMMER RUNOFF (cm)	TOTAL RUNOFF (cm)	EVAPO-TRANS (cm)	PAN EVAP (cm)	R_{SNOW} / P_{SNOW}	R_{RAIN} / P_{RAIN}	R_{TOTAL} / P_{TOTAL}	R_{SNOW} / R_{TOTAL}	ET / $P_{AN\,EVAP}$
1985	10,2	25,1	35,3	6,6	*	*	*	*	0,65	*	*	*	*
1986	10,9	16,3	27,2	5,7	6,2	11,9	15,3	31,0	0,52	0,38	0,44	0,48	0,49
1987	10,8	27,2	38,0	7,1	17,9	25,0	13,0	32,0	0,66	0,66	0,66	0,28	0,41
1988	7,8	25,2	33,0	3,9	7,2	11,1	21,9	33,2	0,50	0,29	0,34	0,35	0,66
1989	15,5	25,7	41,2	9,4	7,8	17,2	24,0	42,0	0,61	0,30	0,42	0,55	0,57
1990	10,6	16,3	26,9	6,4	2,8	9,2	17,7	39,4	0,60	0,17	0,34	0,70	0,45
1991	8,2	24,9	33,1	5,6	4,3	9,9	23,2	37,7	0,68	0,17	0,30	0,57	0,62
1992	18,1	24,1	42,2	14,4	6,3	20,7	21,5	32,8	0,80	0,26	0,49	0,70	0,66
1993	12,5	20,8	33,3	10,0	12,5	22,5	10,8	32,1	0,80	0,60	0,68	0,44	0,34
1994	8,0	27,1	35,1	5,2	9,8	15,0	20,1	34,5	0,65	0,36	0,43	0,35	0,58
1995	14,2	20,9	35,1	9,8	13,9	23,7	11,4	29,0	0,69	0,67	0,68	0,41	0,39
1996	13,3	18,8	32,1	10,6	6,0	16,6	15,5	28,0	0,80	0,32	0,52	0,64	0,55
1997	14,2	25,5	36,6	11,4	4,6	16,0	20,6	30,7	0,80	0,18	0,44	0,71	0,67
1998	9,6	23,8	33,4	6,2	11,9	18,1	15,3	28,8	0,65	0,50	0,54	0,34	0,53
1999	6,9	34,2	41,1	4,3	14,3	18,6	22,5	28,6	0,62	0,42	0,45	0,23	0,79
AVG	11,4	23,7	34,9	7,8	9,0	16,8	18,1	32,8	0,67	0,38	0,48	0,48	0,55

* Data not collected

Table 3 – Comparison of average annual (4 years, 1993-1996) ratios of various hydrologic components for three watershed scales (range of values in parentheses).

	R_{snow}/P_{snow}	R_{rain}/P_{rain}	R_{total}/P_{total}	R_{snow}/R_{total}	P_{snow}/P_{total}
Imnavait Creek	0.74	0.51	0.53	0.46	0.33
(2.2 km^2)	(0.65–0.8)	(0.38-0.62)	(0.38-0.62)	(0.35-0.64)	(0.2-0.41)
Upper Kuparuk	(0.2-0.41)	0.67	0.65	0.32	0.34
(142 km^2)	(0.47-0.88)	(0.63-0.78)	(0.58-0.72)	(0.3-0.42)	(0.28-0.37)
Kuparuk	0.86	0.32	0.58	0.69	0.47
(8140 km^2)	(0.79-0.98)	(0.24-0.36)	(0.51-0.67)	(0.52-0.80)	(0.32-0.54)

The average ratio of summer runoff to summer precipitation (Table 2) is 0.38 (n = 14 years) with the range being 0.17 to 0.67 for Imnavait Creek. The 1993-1996 average ratio (Table 3) is slightly higher at 0.51 for the Imnavait catchment, while the four-year averages are 0.67 (range 0.63-0.78) for the Upper Kuparuk River and 0.32 (range 0.24-0.36) for the entire Kuparuk. The high average value for the Upper Kuparuk is due primarily to the steep topography. For years when there are numerous low intensity storms but appreciable precipitation, the runoff ratio is low. The years 1990 and 1991 are good examples for Imnavait Creek. For the years 1987 and 1995, storms were intense and of relatively short duration with ample runoff for this catchment.

An examination of the total runoff to the annual precipitation (Table 2) shows that the ratio of the annual precipitation to runoff for the Imnavait basin (n = 14 years) is 0.48, varying from 0.30 to 0.68. The 1993-1996 average (Table 3) for this basin is slightly higher at 0.53; this can be compared to 0.65 for the Upper Kuparuk (range 0.58-0.72) and 0.58 (range 0.51-0.67) for the entire Kuparuk basin.

By examining the source of the runoff for Imnavait Creek (Table 2), it is clear that one-half of the runoff volume is from snowmelt while the other half initiates from rainfall although two-thirds of annual precipitation is in the form of rain. So, according to collected data during snowmelt, runoff dominates as the main exporter of water from the basin while evapotranspiration dominates during the summer except for three out of 14 years (1987, 1993 and 1995). Also, one-half of the volume of annual runoff leaves the basin in a very short period of time following snowmelt.

Rain produces the largest percentage of total runoff volume (Table 3) for the Upper Kuparuk (68 %), and for the entire Kuparuk it is generated by snowmelt (69 %). Snowfall only accounts for one-third of the annual precipitation (Table 3) for Imnavait and Upper Kuparuk watersheds; for the entire Kuparuk, snowfall accounts for 47 % of the annual precipitation (Lilly *et al.* 1998). The highest fraction of snow-generated runoff occurs for the entire Kuparuk River where 69 % leaves as runoff. This can be contrasted to only 31 % of the rainfall precipitation leaving as runoff, which is the lowest for all the basins. Surface storage during the summer months is responsible for reducing runoff for the entire Kuparuk basin; however, it is not totally clear why this basin has very high runoff ratios during snowmelt unless surface storage is reduced due to antecedent fall precipitation.

There has been limited discussion of measurement errors. Making flow measurements during breakup is never easy because of ice flows and changing conditions as ice and snow erodes out of the channel. Estimates of the spatial distribution of snow cover are difficult because of redistribution by wind. Both snow depths and water equivalents are greater in drainage depressions and lakes because of the winds. Since snow collects in close proximity to drainage channels, the likelihood of leaving the basin as runoff is enhanced. As watershed size increases, the density of the measurement sites decreases dramatically.

Runoff Trends

Good quality runoff data exists for the entire flow season (snowmelt to freeze-up) at four scales: Imnavait Creek (13 years), Upper Kuparuk River (6 Years) and Kuparuk River (26 years, gauged by USGS) and Putuligayuk River (15 years, gauged by USGS). The dimensionless cumulative curves are shown for an average year and the two extreme years (high and low snow) for these four watershed scales (Fig. 7).

The cumulative curves for Imnavait Creek, Putuligayuk River and the Kuparuk River demonstrate the dominance of the snowmelt runoff. In a span of a few days on extreme years, snowmelt runoff has accounted for greater than 90% of the annual runoff volume. For these three drainages, there is a clear transition each year from snowmelt to rainfall-generated runoff; this can be seen in the change in slope although the contributions from snowmelt and rainfall vary each year. This is not true for the Upper Kuparuk River most years, where the steep initial slope is absent and the slope is relatively constant throughout the entire flow period. Following snowmelt, runoff is generally much lower during the early part of summer and increases toward the end of summer as precipitation increases. The Kuparuk River and Putuligayuk River cumulative curves show that snowmelt runoff dominates the annual runoff even more than that of Imnavait Creek. The minimum flow contribution from snowmelt is 70 %, 40 % and 20 % for Putuligayuk River, Kuparuk River, and Imnavait Creek respectively. It is difficult to determine minimum flow contributions from Fig. 7 for the Upper Kuparuk drainage.

Two features of the Upper Kuparuk River drainage are unique when compared to the other streams: the dominance of snowmelt on the annual runoff volume is much less pronounced and the early summer plateau is not apparent. The rugged headwater topography stretches out the snowmelt period (due to adiabatic cooling at higher elevations and deeper snowdrifts) and both convective and frontal storm rainfall is double the snowmelt contribution here, decreasing the dominance of snowmelt.

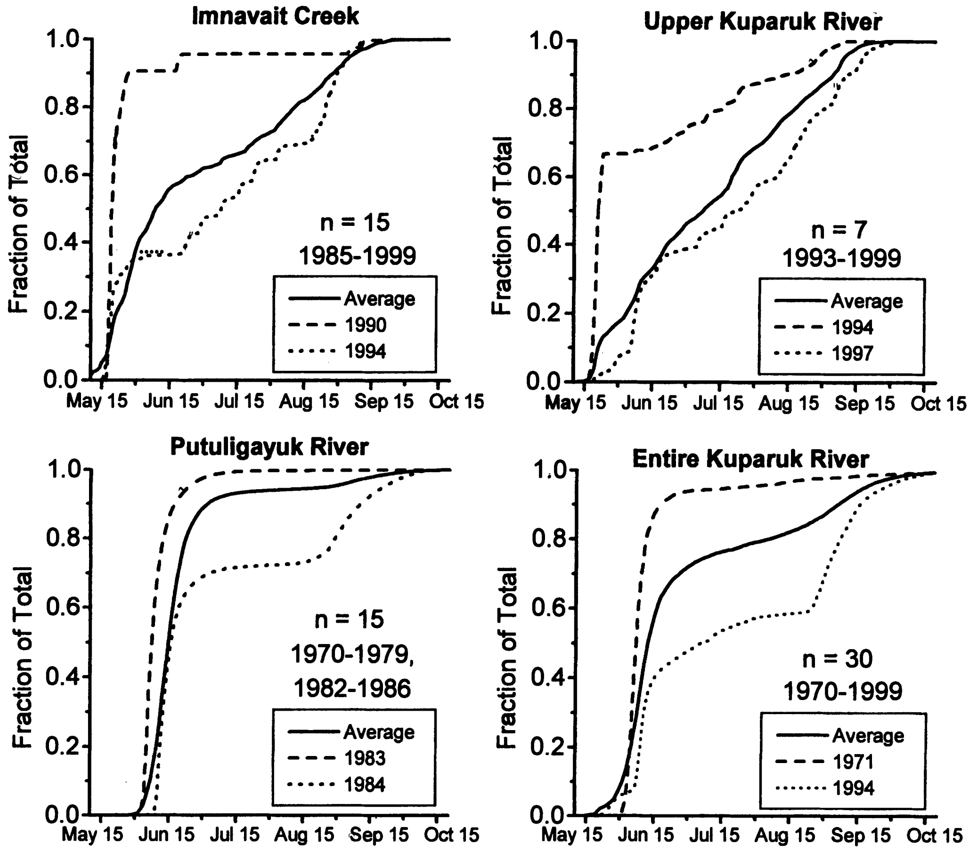


Fig. 7. Cumulative runoff plots for Imnavait Creek, Upper Kuparuk River, Putuligayuk River and the Kuparuk River for an average year, year where snowmelt-generated runoff dominates and a year where rainfall-dominated runoff dominates.

Discharge, using a weir, has also been measured on a small wetland drainage (~ 0.082 km^2) near the Betty Pingo meteorological site on the coastal plain. Because of the low relief, it is difficult to exactly define the drainage basin area. However, each year substantial snowmelt runoff was measured at the weir, but during the four years of study, no runoff generated from rainfall was ever measured (Rovansek *et al.* 1996; Mendez *et al.* 1998). This is consistent with 15 years of measurements by the USGS on the Putuligayuk River (471 km^2) near Prudhoe Bay where the watershed is entirely contained on the coastal plain; snowmelt peaks ranged from 31 to 127 m^3/s, while the maximum rainfall generated peak was 4 m^3/s. For three complete summer periods a steady recession of flow over the summer with no increase in mean daily flow occurred. This implies for the Kuparuk River that little runoff is generated during the summer months from 44 % of the basin area that constitutes the coastal plain.

Summary

The distribution of precipitation, topographic gradients and availability of surface storage are the primary controls on runoff response of 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 the precipitation (snowmelt and rainfall) 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 = 4 years). All of these runoff ratios are substantially above the average of more temperate regions and the global average of 0.36; the only physical characteristic that these three watersheds have in common is the limited subsurface storage capability due to permafrost.

The headwater catchments of Imnavait Creek and Upper Kuparuk River receive greater amounts of precipitation (generally both rain and snow) annually over the basins than the entire Kuparuk (with 44 % of drainage area on coastal plain) and Putuligayuk (with 100 % of drainage area on coastal plain) basins. The rainfall runoff response is greater for these two watersheds, as expected, when compared with the entire Kuparuk basin. However, this is not true for the snowmelt runoff response over a four-year period from 1993 to 1996, for which there are comparable data for the three basins. During this four-year period, an average of 51 % of the rainfall left Imnavait basin as runoff, 67% for Upper Kuparuk basin and only 32 % for Kuparuk basin. For snowmelt, an average of 74 % of the snowpack left Imnavait basin as runoff, 62 % left the Upper Kuparuk basin and 86 % left the Kuparuk basin. Two factors can account for high runoff ratios during snowmelt; first, rapid and sustained (no cold periods) snowmelt and second, heavy snow packs that overload the surface storage system. Prolonged melt periods reduce runoff and enhance evaporation and infiltration, but heavy snowpacks still produce substantial runoff. The surface storage role on the coastal plain needs to be studied before the reasons for the high runoff ratios during snowmelt can be determined for the Kuparuk River basin.

McNamara *et al.* (1998) reported that the Upper Kuparuk basin's contributions of flow to the lower basin are disproportionably high during the summer. The higher response in the foothills is due to the relative lack of surface storage, steeper topographic gradients and greater rainfall amounts. The lack of streamflow contributions during the summer has already been identified for the coastal plain.

On the coastal plain the main mechanism of water export out of the basin is evapotranspiration in the summer (Mendez *et al.* 1998). About one-third of the summer precipitation leaves the Upper Kuparuk by evapotranspiration. In Imnavait catchment, evapotranspiration and runoff fluctuate between one-third and two-thirds of rainfall, but averages about one-half runoff and one-half evapotranspiration. For a given amount of summer precipitation, runoff is greater when the precipitation results from a few large storms. In contrast, the amount of evapotranspiration is greatest in summers when the precipitation intensities and amounts are low and storms numerous.

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