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"Annual Dynamics Within the Active Layer"

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University of Alaska
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MASTER

PROGRESS SUMMARY

We have continued our meteorological and hydrologic data collection in support of our process-oriented research. The six years of data collected to date is unique in its scope and continuity in a North Hemisphere Arctic setting. This valuable data base has allowed us to further our understanding of the interconnections and interactions between the atmosphere/hydrosphere/biosphere/lithosphere. The increased understanding of the heat and mass transfer processes has allowed us to increase our model-oriented research efforts.

Spring snowmelt on the North Slope of Alaska is the dominant hydrologic event of the year. (Kane et al., 1990a). This event provides most of the moisture for use by vegetation in the spring and early summer period. The mechanisms and timing of snowmelt are important factors in predicting runoff, the migrations of birds and large mammals and the diversity of plant communities. It is important globally due to the radical and abrupt change in the surface energy balance over vast areas.

We were able to explore the trends and differences in the snowmelt process along a transect from the Brooks Range to the Arctic Coastal plain. Snowpack ablation was monitored at three sites. These data were analyzed along with meteorologic data at each site. 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 (Figure 1.). Usually, snowmelt begins at the mid-elevations in the foothills and progresses northerly toward the coast and southerly to the mountains. In the more southerly areas snowmelt progressed much faster and was more influenced by sensible heat advected from areas south of the Brooks Range (Table 1.). In contrast, snowmelt in the more northerly areas was slower and the controlled by net radiation. (Hinzman et al., 1990b)

The hydrologic cycle of an arctic watershed is dominated by such physical elements as snow, ice, permafrost, seasonally frozen soils, wide fluctuations in surface energy balance and phase change of snow and ice to water. At Imnavait basin, snow accumulation begins in September or early October and maximum snowpack water equivalent is reached just prior to the onset of ablation in mid May. No significant mid winter melt occurs in this basin. Considerable snowfall redistribution by wind to depressions and valley bottoms is evident (Figure 2). This is hydrologically important as it places the snow close to runoff

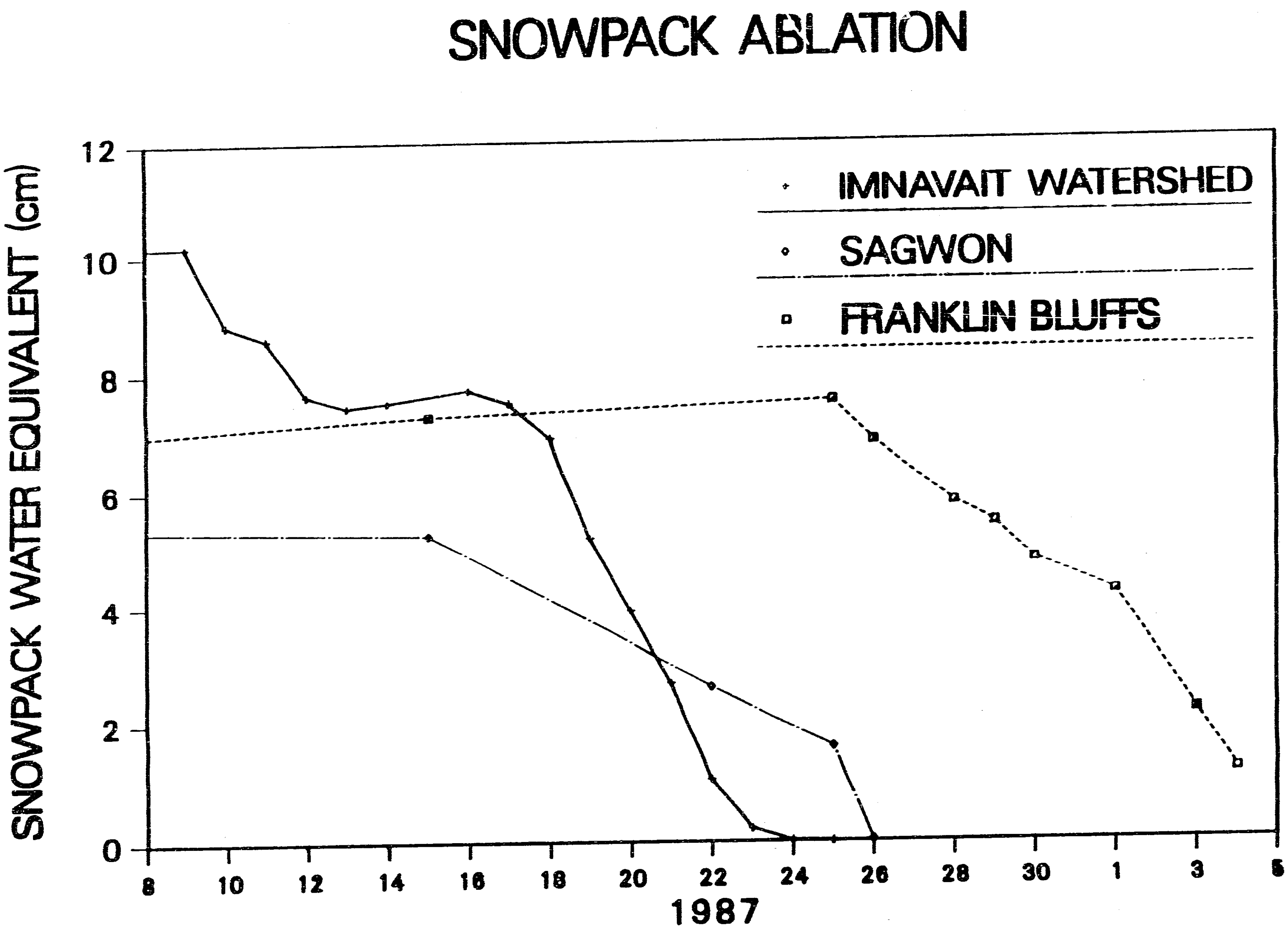

Figure 1. Snowpack ablation at Imnavait Creek, Sagwon and Franklin Bluffs in 1987.

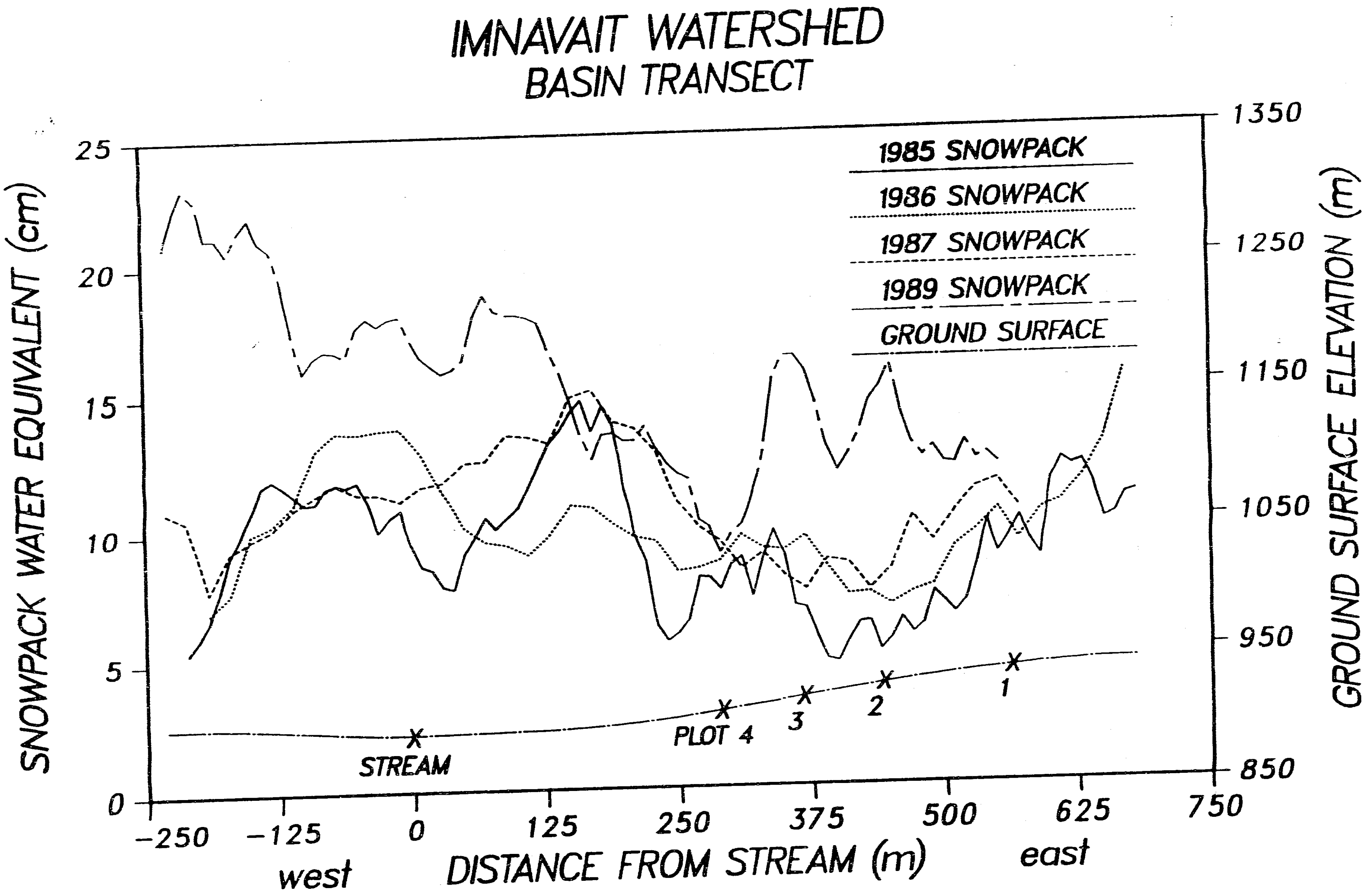

Figure 2. Snow distribution and ground surface elevations on a transect of valley.

Table 1. Comparison of the relative magnitudes (percentage) of components of the surface energy balance at Imnavait Creek, Sagwon and Franklin Bluffs in 1987, 1988, 1989 and 1990.

		Net Radiation (%)		Sensible Heat (%)		Evaporation Condensation (%)		Heat Flux Into Soil (%)		Snow Melt (%)		Snow Melt Period
Location	Year	+	-	+	-	+	-	+	-	+	-	
Imnavait Creek	1987	47.9	6.4	47.5	0.8	0.1	16.1	4.5	41.5	0.0	35.2	May 8-25
Imnavait Creek	1988	65.0	7.9	31.4	9.0	0.1	21.0	3.4	23.7	0.0	38.4	May 10-14
Imnavait Creek	1989	59.1	4.4	39.9	0.0	0.0	14.3	1.0	25.0	0.0	56.4	May 18-30
Imnavait Creek	1990	65.3	3.5	34.4	0.0	0.0	15.4	0.3	44.3	0.0	36.8	May 7-20
Sagwon	1987	63.3	0.0	19.4	25.6	0.2	27.0	17.0	30.2	0.0	17.1	May 9-28
Sagwon	1988	*	*	*	*	*	*	*	*	*	*	May 20-June 7
Sagwon	1989	76.9	0.0	18.5	4.4	2.3	8.9	2.2	30.1	0.0	56.6	May 20-June 1
Sagwon	1990	36.9	0.0	61.3	0.4	0.8	22.9	1.0	15.5	0.0	61.2	May 5-15
Franklin Bluffs	1987	88.8	0.0	9.7	4.6	0.8	10.1	0.8	52.7	0.0	32.6	May 25-June 8
Franklin Bluffs	1988	71.5	0.0	21.3	4.6	1.6	16.4	5.6	43.6	0.0	35.4	May 22-June 3
Franklin Bluffs	1989	76.8	0.0	15.2	0.8	7.7	1.3	0.2	26.0	0.0	71.9	May 27-June 11
Franklin Bluffs	1990	82.9	0.0	14.3	0.2	1.9	5.6	1.0	35.0	0.0	59.2	May 9-14

* - instrument failure prevented analysis

channels, raising soil moisture in these areas and increasing the proportion of runoff. The wind also greatly impacts the properties of the snowpack (Figure 3) by producing high density slabs within the snowpack (Kane et al. 1990a).

Snowmelt ranges from early May to late June. Runoff dominates this portion of the annual hydrologic cycle. The pattern of ablation was strongly influenced by the direction of the predominant winds. Southerly winds generally enhanced ablation and northerly winds retarded ablation. The initial melt infiltrates the snowpack and upper soils and then refreezes warming the the snowpack and upper soils. Around 15 mm of the early melt is stored in the organic soils that are desiccated during the long arctic winter. Little if any melt water enters the relatively impermeable ice rich mineral soils. Evaporation

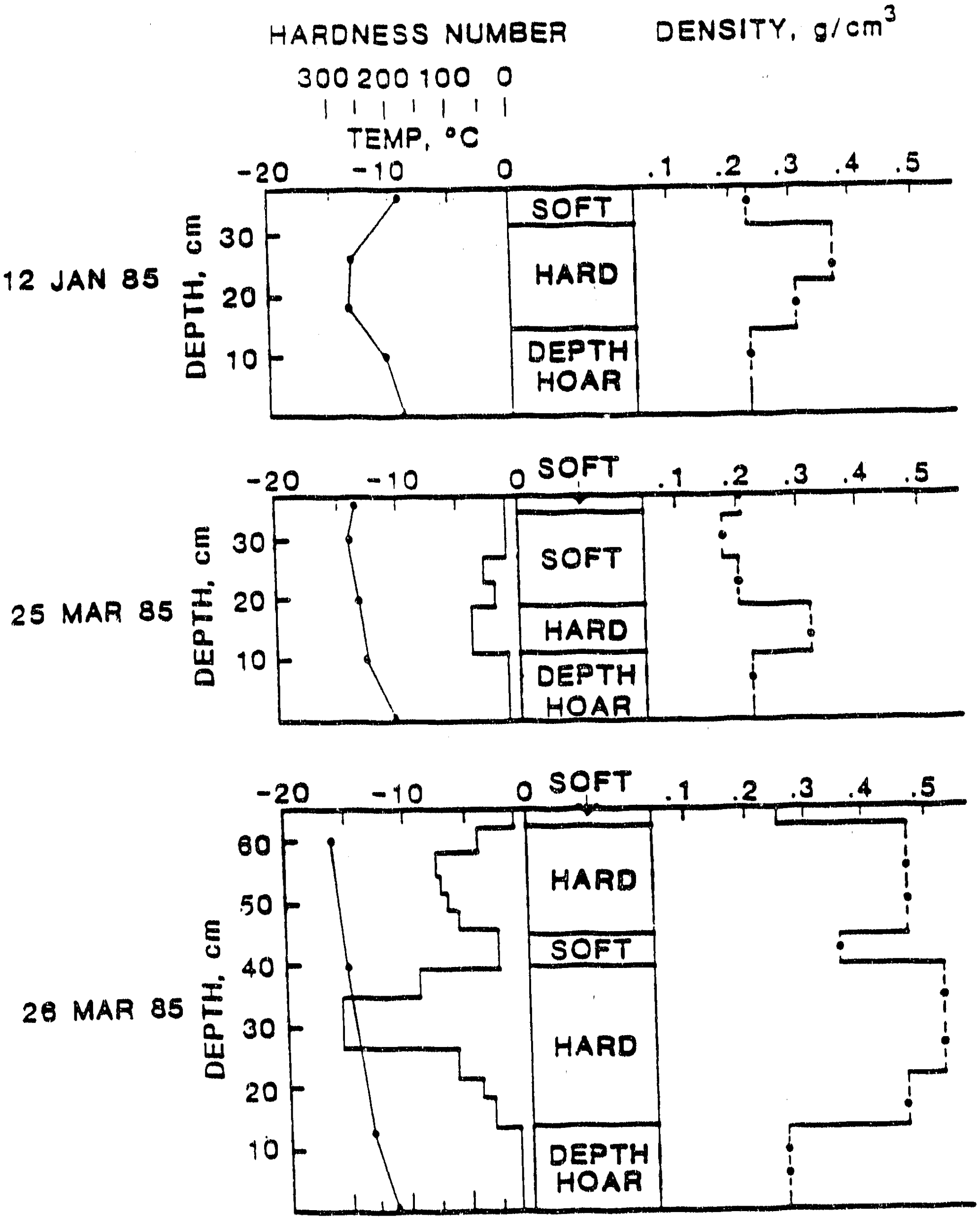

Figure 3. Snowpack properties on three dates during the winter of 1985.

from the melting snowpack is proportionally a significant part of the total snowpack water equivalent. Basin runoff begins 1 to 3 days after melt begins on the west facing slopes. The state and condition of the snowpack greatly affects the pattern of runoff in both timing and rate. A water balance was done for four small plots and the entire basin the partitioning of the snowmelt is summarized in Table 2.

Modeling the snowmelt and runoff processes in the Arctic is limited by both the lack of hydrologic data and the quality of meteorological data available. There are many factors that characterize the snowmelt and runoff that must be considered when modeling these processes in the Alaskan Arctic. Spring snowmelt in the Arctic is a brief event, usually lasting about 10 days. Peak flows normally occur within 36 hours of the beginning of streamflow. All downslope movement of water occurs within the top 10 cm of the highly organic soil material or on the surface. Snow damming of the initial snowmelt runoff is a process that greatly affects the timing and rate of streamflow (Hinzman and Kane, 1990).

Snowmelt was modeled at the three North Slope sites using meteorological and hydrologic data collected at the sites. Energy balance and degree-day modeling methods were both explored. Each method produced reasonably good results. However, the energy balance method requires a very extensive data base and these data are not usually available for other areas in the Arctic. The degree-day method, although simple and not data intensive, does not account for warming and cooling of the snowpack. Because of this flaw, the degree-day method predicts melt beginning too early in each time period, both in the initiation of melt and daily melt when evening temperatures drop below freezing.

The HBV model was used in an investigation of the hydrologic regime of Imnavait Basin during the spring snowmelt period (Hinzman and Kane, 1990). From the analysis of five spring melt events we found that HBV can adequately predict soil moisture, evaporation, snow ablation and accumulation and runoff. It models the volumes of snowmelt runoff well (Table 3), but more data are needed to improve the determination of snowmelt initiation.

The summer hydrology can vary significantly from year to year, depending on the pattern and magnitude of summer precipitation. Annual water balance calculations, including both snowmelt and summer data, are presented in Table 4. The surface organic soils seem to play a much more dominant hydrologic role than the deeper mineral soils. The mineral soils remain near saturation much of the year with phase change being the dominant activity. During dry periods, runoff is minimal or ceases in the headwater stream and water tracks, indicating that subsurface flow contributions from the thawing of the active layer are minimal, if not insignificant (Table 5) (Kane et al., 1989).

Table 2. Partitioning of the melting snowpack.

	Initial Water Content, cm	Runoff %	Evaporation %	Soil Storage %
1985				
Plot 1	13.8	79	10	11
Plot 2	11.7	38	49	13
Plot 3	9.7	22	63	15
Plot 4	10.6	31	55	14
Plot Average	11.4	45	42	13
Basin Average	10.2	65	20	15
1986				
Plot 1	14.7	68	22	10
Plot 2	12.4	50	38	12
Plot 3	8.1	29	53	18
Plot 4	10.2	50	35	15
Plot Average	11.3	52	35	13
Basin Average	10.9	52	34	14
1987				
Plot 1	9.8	69	16	15
Plot 2	10.7	33	53	14
Plot 3	10.2	*	*	*
Plot 4	10.0	20	65	15
Plot Average	10.2	41	44	15
Basin Average	10.8	66	20	14
1988				
Plot 1	7.2	+	+	+
Plot 2	7.3	16	63	21
Plot 3	8.4	43	39	18
Plot 4	6.9	33	45	22
Plot Average	7.4	31	49	20
Basin Average	7.8	50	31	19
1989				
Plot 1	13.5	*	*	*
Plot 2	11.6	34	53	13
Plot 3	11.7	34	53	13
Plot 4	13.7	*	*	*
Plot Average	12.6	34	53	13
Basin Average	15.5	61	30	10

* No measurements made for this plot because of leakage.

\+ No measurements collected

Table 3. Observed and simulated water balances.

	Measured				Modeled Hourly				Modeled Daily			
Year	Snowpack Water (cm)	Snowmelt Runoff (cm)	Soil Storage (cm)	Evapo-trans (cm)	Snowmelt Runoff (cm)	r^2	Soil Storage (cm)	Evapo-trans (cm)	Snowmelt Runoff (cm)	r^2	Soil Storage (cm)	Evapo-trans (cm)
1985	10.2	6.6	1.5	2.1	6.1	0.84	1.8	3.2	6.2	0.87	3.6	3.6
1986	10.9	5.7	1.5	3.7	6.8	0.78	1.3	3.2	7.1	0.90	1.5	4.9
1987	10.8	7.1	1.5	2.2	6.2	0.83	2.7	3.4	8.0	0.87	1.3	4.2
1988	7.8	3.9	1.5	2.4	3.8	0.82	1.4	3.1	3.6	0.77	1.0	4.2
1989	15.5	9.4	1.5	4.6	11.4	0.78	1.0	3.3	12.1	0.69	1.1	4.2

Summer runoff events are controlled by the antecedent moisture conditions of the organic soils in the active layer because the saturated mineral soils are relatively impermeable. Downslope movement of water is initiated when saturated conditions develop following rainfall or summer snowmelt in the near-surface inorganic soils. Water released from the thawing of the mineral soils is probably used by plants or lost through evaporation during dry periods. Summer precipitation events, although never near the volume of snowmelt, can produce peaks in the streamflow hydrograph if the intensity is high (Kane and Hinzman, 1988).

Evapotranspiration (ET) vies with runoff as the primary mechanism for annual water loss from a watershed such as Imnavait Creek that is underlain by permafrost. ET on a watershed scale was calculated from water balance studies and compared to point measurements of pan evaporation and estimates of ET by energy balance and Priestley-Taylor methods (Figure 4.) (Kane et al., 1990b). Since it is difficult to determine the daily change in soil moisture, the energy balance appears to be the best method to determine daily ET. The water balance approach is the best method to determine total ET over the course of the summer because it is possible to delete the soil moisture term due to and insignificant change annually in this watershed. Preistley-Taylor gave adequate estimates of ET with only limited data. ET is greatest in the early summer, immediately following the spring snowmelt, during the period of maximum incoming radiation, but not necessarily maximum air or soil temperatures. The cumulative potential evaporation is greater than the cumulative summer precipitation. The source for ET in early summer is from snowmelt or moisture stored in the active layer (Kane et al., 1990b).

The snow melt flood at Imnavait Creek takes place sometime between 12 May and 2 June and constitutes the single most important hydrologic and geochemical event. Five years of study indicate this event spans 7 to 10 days and that peak discharge can be expected to be between 0.6 and 0.9 cu. m/s Ion concentrations peak during the first 15% of the event while pH is at a minimum. In all cases, ion concentrations in the spring runoff are 4 to 9 times those of the snowpack. Precipitation, including dryfall, contributes significant amounts of Ca, Mg, K, Na, Cl and SO4. Potassium is in surface waters only during melt-

SPRING AND ANNUAL WATER BALANCES

YEAR	SNOWPACK WATER (cm)	SUMMER PRECIP (cm)	TOTAL PRECIP (cm)	SNOWMELT RUNOFF (cm)	SUMMER RUNOFF (cm)	TOTAL RUNOFF (cm)	EVAPO-TRANS (cm)	PAN EVAP (cm)
1985	10.2	25.1	35.3	6.6	*	*	*	*
1986	10.9	16.3	27.2	5.7	6.2	11.9	15.3	31.0
1987	10.8	27.2	38.0	7.1	17.9	25.0	13.0	32.0
1988	7.8	25.2	33.0	3.9	7.2	11.1	18.0	21.9
1989	15.5	25.7	41.2	9.4	7.8	17.2	24.0	42.0
1990	10.6	11.9**	22.5	6.4	2.8	9.2	13.3**	35.0**

* – data unavailable

** – preliminary data

Table 4. Imnavait Watershed spring and annual water balances for the water years 1985 through 1990.

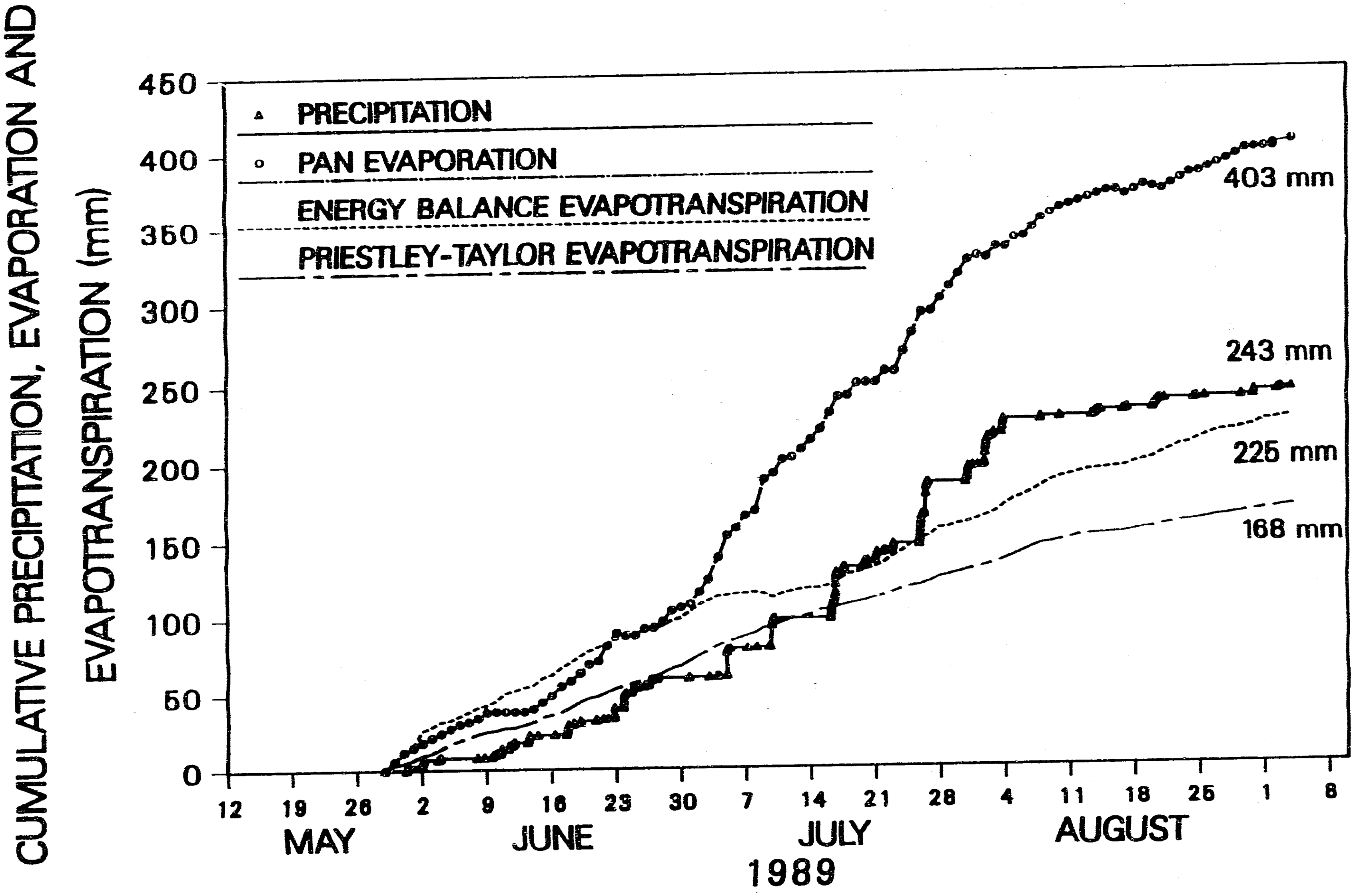

Figure 4. Comparison of precipitation, pan evaporation and calculations of evapotranspiration during the summer of 1989.

TABLE 5. Rainfall events that produced minimal runoff.

Date	Precip (mm)	Runoff (mm)	5 Day Antecedent (mm)	10 Day Antecedent (mm)
1986				
Jun 18-Jun 26	12.75	0.8	0.0	0.24
Jul 9-Jul 11	12.75	0.04	0.0	0.24
Jul 13-Jul 21	15.14	0.3	12.75	12.75
1987				
Jun 26-Jun 27	13.7	~0.0	0.0	2.2
Jul 10-Jul 11	12.6	~0.0	0.0	7.5

off and for a short time after. Calcium, Mg, suspended solids and electrical conductivity all reach broad peaks in mid-summer. Only pH shows a relationship to discharge. On a seasonal basis a substantial charge imbalance favoring cations occurs. It seems probable that the, as yet, unmeasured negative charge is associated with organic anions. No seasonal trends were recorded for Mg, K or Mn in subsurface flow in the surrounding slopes. Calcium, Fe, and Al showed a late season peak, and the concentration of Na and Si decreased as the melt season progressed (Everett et al., 1989).

Almost all biological activity in the far north regions takes place within a shallow zone above the permafrost called the active layer. In Imnavait watershed the active layer is an extremely variable multilayered system consisting of a mat of mosses and sedges on about 10 cm of organic soil over a silt. The layer of organic soil tends to mollify thermal and hydrologic fluctuations below it. We found the temporal pattern of soil moisture and temperatures in the active layer were consistent year to year, but ranged greatly from season to season. The volumetric moisture content of the organic soil varied by up to 60%, but the mineral soil remained near saturation throughout the year. The hydraulic conductivity of the organic soils is 10 to 1000 times greater than the silts below it, and most downslope drainage occurred in the organic soils (Table 6.) (Hinzman et al., 1990).

The thermal conductivity of the soils depend upon the phase and amount of the moisture present. The thermal conductivity of a saturated organic soil decreased by 50% upon thawing. the saturated mineral soil decreased by about 30% after thawing (Figure 5.). Regardless of the temperature of moisture content, the organic soil has a lower thermal conductivity than the mineral soil and will serve as a layer of insulation to the permafrost.

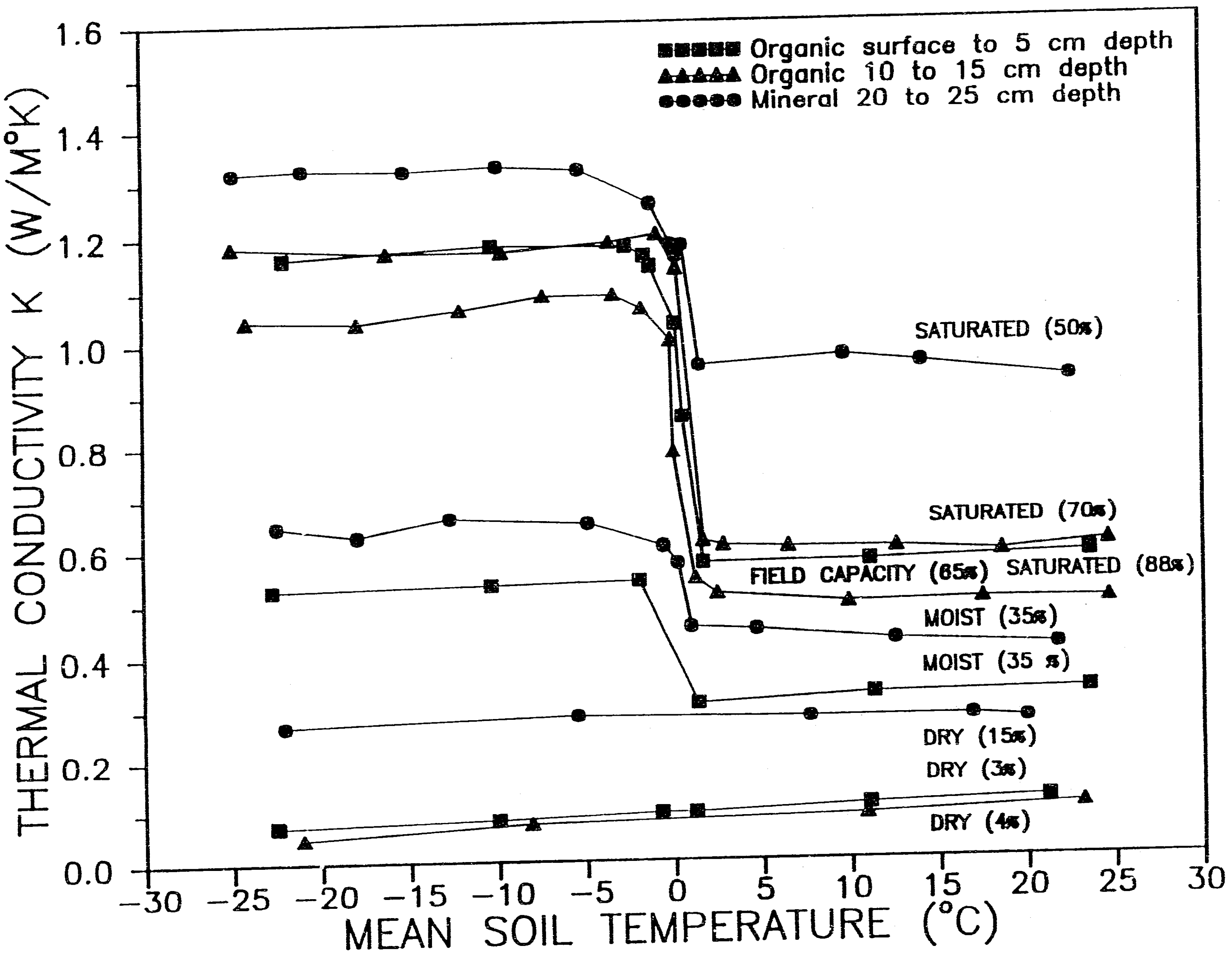

Figure 5. Laboratory measurements of effective thermal conductivity of active layer soils as a function of temperature, soil type and moisture content.

Table 6. Summary of the physical properties of soil samples taken from Imnavait watershed.

Horizon Type	Depth (cm)	Hydraulic Conduct. (cm/s) (10^{-3})	Range (cm/s) (10^{-3})	Bulk Density (g/cm^3)	Range (g/cm^3)	Porosity	No. of Samples
organic	0-5	19.4	16-22	0.15	0.13-0.16	0.90	4
organic	5-10	10.4	1.1-12	0.18	0.16-0.18	0.86	3
org/min	10-15	3.76	0.4-3.4	1.39	1.38-1.40	0.70	3
mineral	15-20	0.87	0.08-2.6	1.53	1.43-1.57	0.55*	6
mineral	20-25	1.42	0.6-3.7	1.33	1.30-1.42	0.54*	3
mineral	25-40	0.94	0.13-3.3	1.40	1.36-1.43	0.46*	3

* Values determined from TDR when soils were saturated.

The topic of global warming is currently being explored by many researchers world wide. We have used our data base and knowledge of the physical systems at Imnavait basin gleaned from our process-oriented research to formulate potential response of an arctic watershed during a period of global climatic change.

Existing climate models predict that the greatest change from present climatic conditions will happen in the polar regions. In the Arctic, continuous permafrost exists and climatic warming could have severe consequences. We examined the consequence of global warming on the active layer using a finite element, two dimensional, heat conduction model with phase change to predict the soil temperatures. After verification that the model could be used to with confidence to predict the soil thermal regime, various climatic warming scenarios were used as input to estimate the thermal response for the next 50 years. Results show that an increase in the average annual soil surface temperature of 2°C increases the active layer thickness at Imnavait Creek by about 20 cm after 50 years. A 4°C change increases the active layer thickness by about 40 cm and increases of 6 and 8°C greatly increase the active layer thickness and eventually produce a talik (Figure 6). These simulations indicate that an increase in surface temperature of approximately 4.5°C will be enough to ultimately thaw the permafrost in this area (Kane et al. 1990c).

The formation of a talik would allow subsurface water flow to persist throughout the winter, which would have substantial impact upon soil moisture levels and streamflows. Hydrologically, in a scenario of climatic warming, snow ablation would be earlier (Figure 7), snow deposition would be less frequent in the summer and later in the fall, evapotranspiration would increase and cumulative runoff would decrease. Superimposing precipitation increases on the warming scenarios would increase soil moisture, cumulative evapotranspiration and cumulative runoff (Figures 8, 9 and 10). Decreasing precipitation would have the opposite effect (Kane and Hinzman 1990).

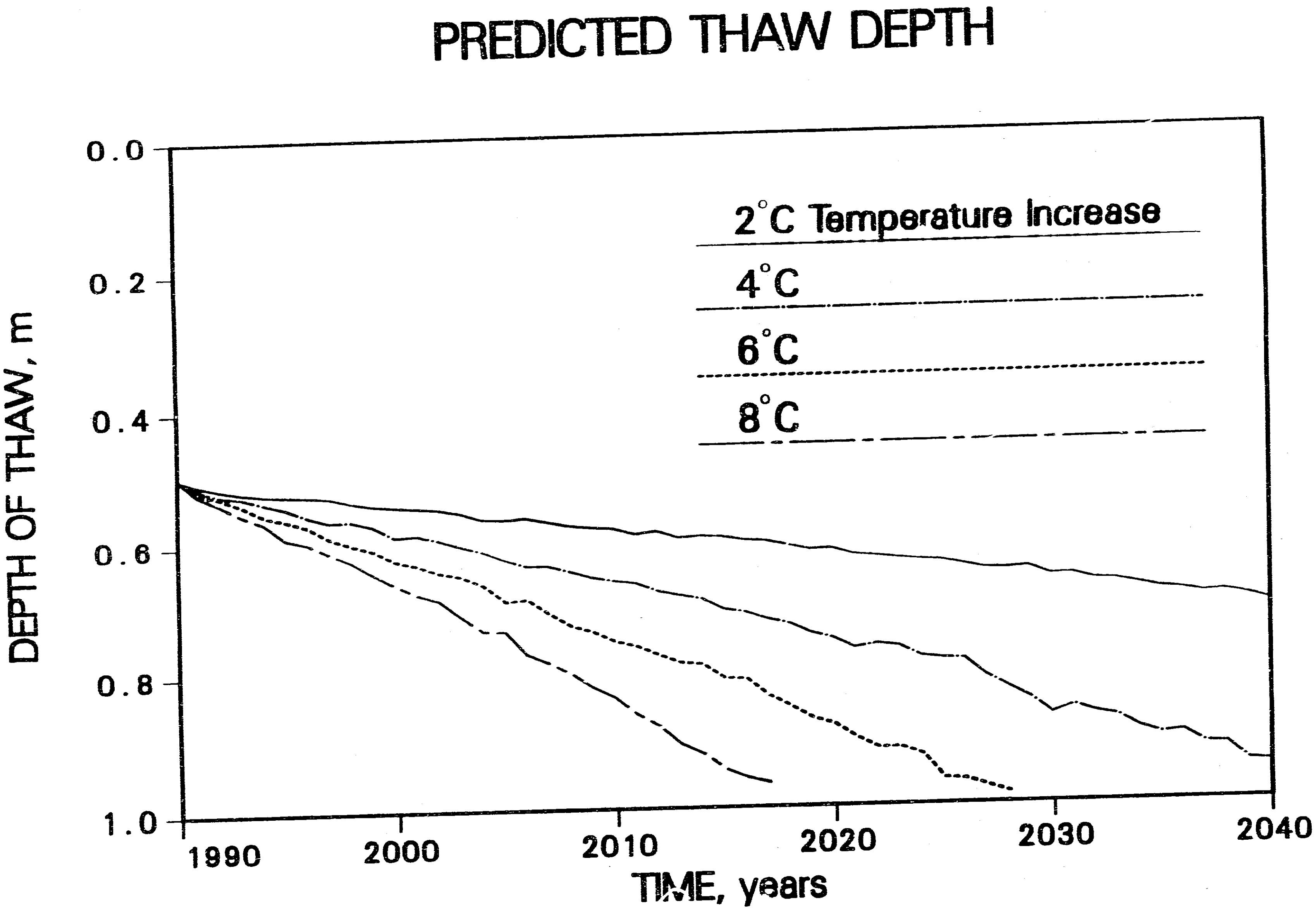

Figure 6. Increased depth of thaw of the active layer in response to each climatic warming scenario over 50 years.

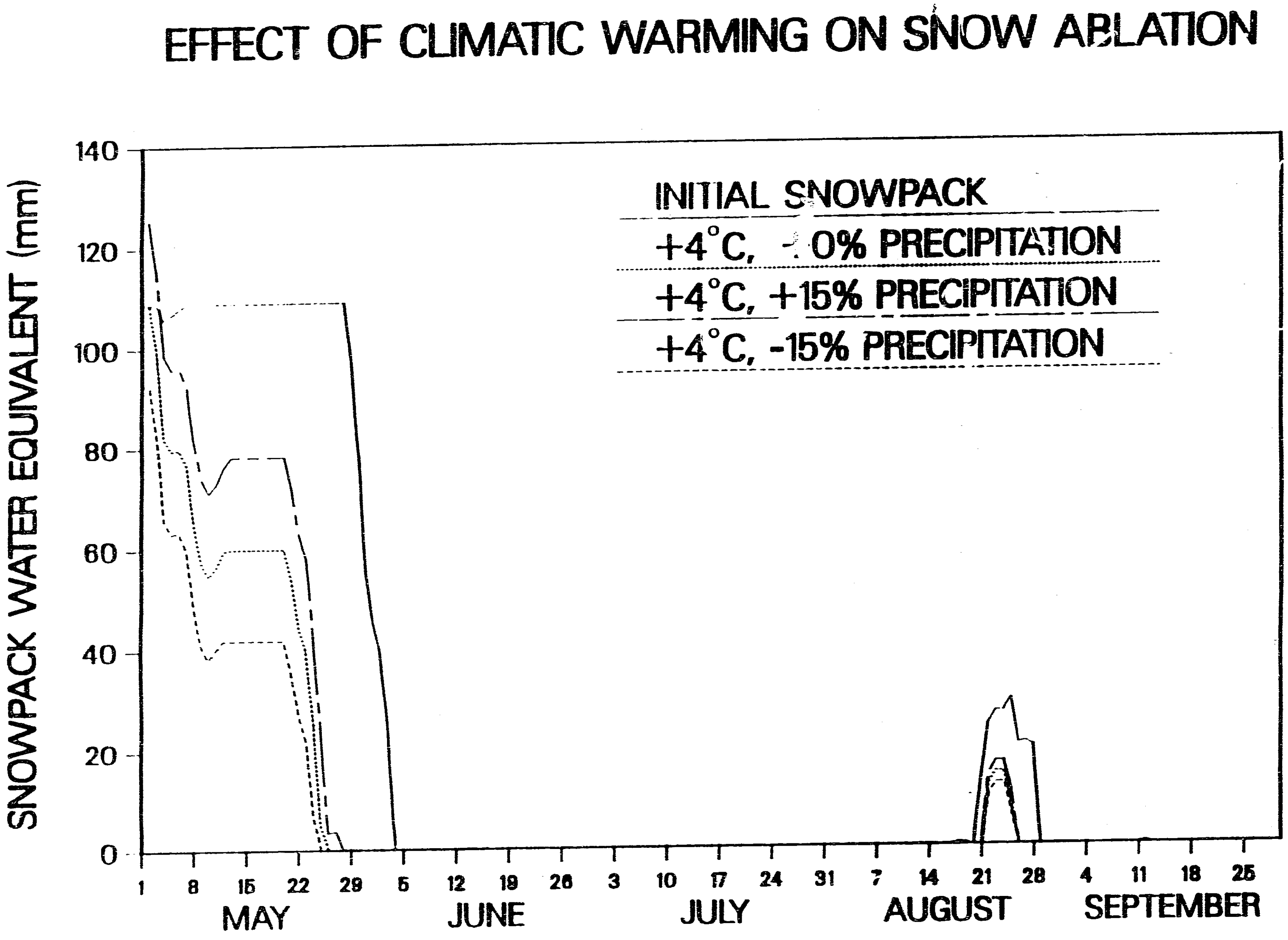

Figure 7. Effect of climatic warming on snow ablation.

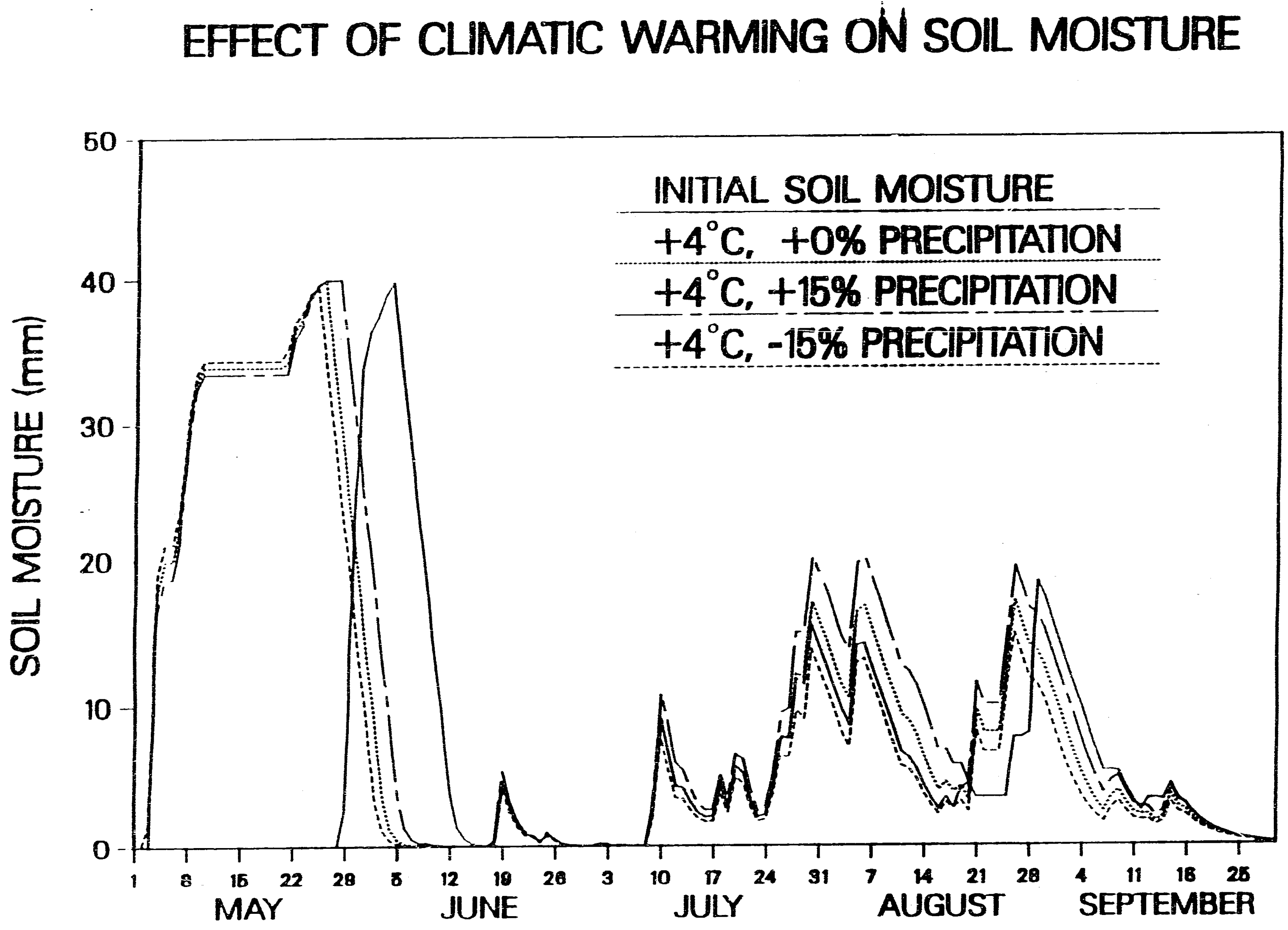

Figure 8. Effect of climatic warming on soil moisture.

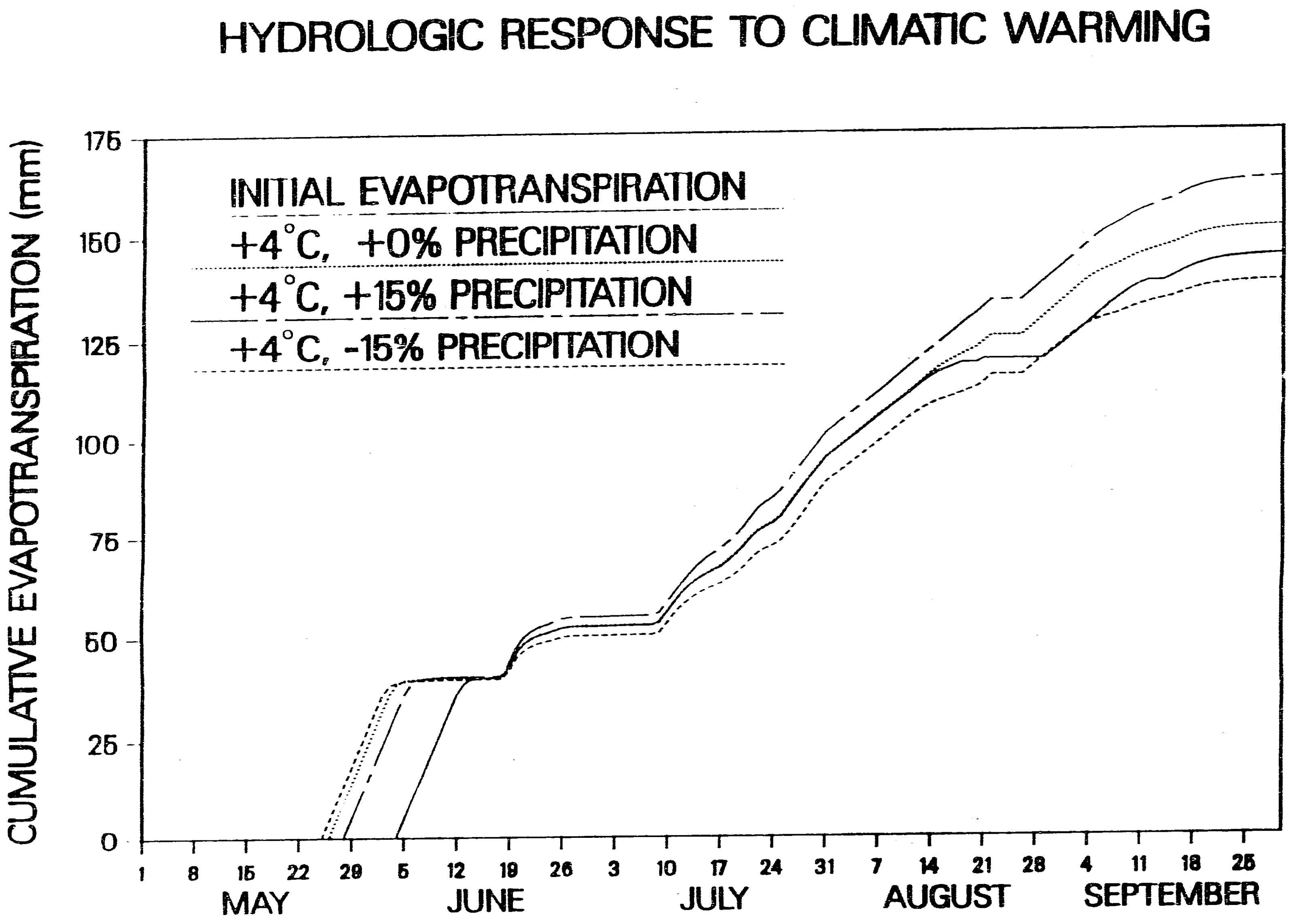

Figure 9. Effect of climatic warming on evapotranspiration.

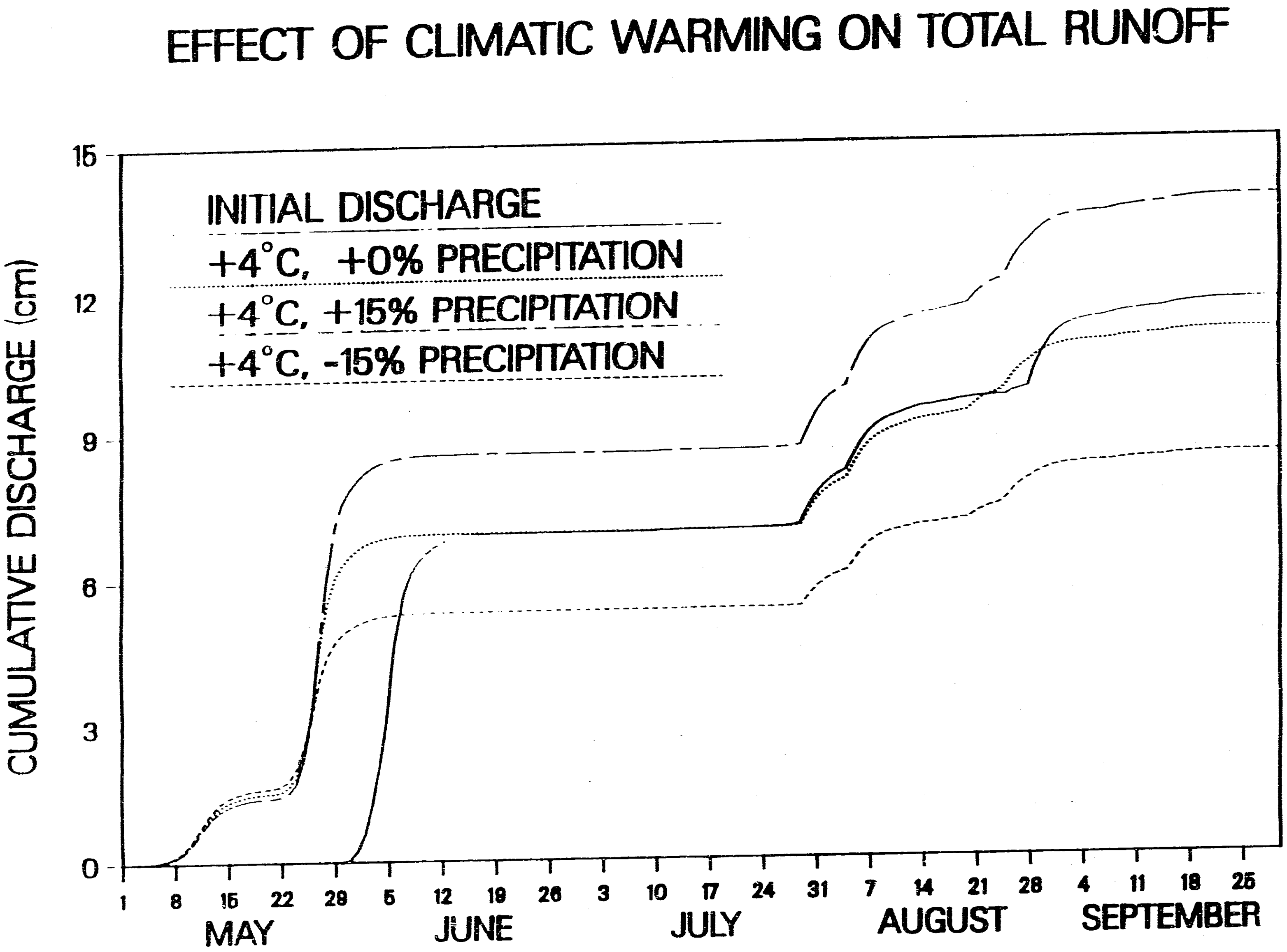

Figure 10. Effect of climatic warming on total runoff.

Two issues that could dramatically alter these results are the response of the vegetation and cloud cover. Although the snow free period will increase, it does not appear that it will be beneficial to the plants. Most of the change will occur in the fall when the plants are responsive to light conditions. Clouds could significantly alter the surface energy balance by reducing shortwave radiation; possibly offsetting atmospheric warming (Kane et al., 1990d). In response to climatic warming, thickening of the active layer will increase the soil-water storage capacity. If massive ice in the soils melt, there would be additional runoff associated with this and there could be additional surface storage in depressions created by the subsiding surface.

A doctoral dissertation was completed by Larry D. Hinzman based primarily on the research at Imnavait Basin. In this work Dr. Hinzman discussed the hydrologic and thermal regimes of Imnavait Creek (Hinzman, 1990).

RESEARCH RELATED PRODUCTS

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