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FINAL REPORT

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and

**ARCTIC HYDROLOGY AND METEOROLOGY
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from

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ABSTRACT

Man's impact on the environment is increasing with time. The response and resilience of an ecosystem to such disturbances can range between subtle and striking. Usually on a macroscale, such as arctic haze and climate change, impacts are subtle and decades are required before significant responses are observed. On the microscale, events such as oil spills and local destruction of surface vegetation, the impact is immediate and readily apparent within one or two years. Mesoscale disturbances can be wide ranging with some impacts immediately apparent, construction of roads and pipelines, while others are not as obvious like dust from roads. The recovery of an arctic ecosystem from microscale disturbances such as the removal of vegetation can take many decades by natural processes.

To be able to evaluate anthropogenic impacts on an ecosystem, it is necessary first to understand all facets of how the ecosystem works: what the main processes (physical, biological, chemical) are, at what rates they proceed, and how they can be manipulated. Arctic ecosystems are dominated by physical processes of energy exchange. Snow, ice and permafrost are dominant characteristics of high latitude ecosystems. Considerable quantities of energy go into latent heat of fusion and vaporization. Snowmelt runoff is the most significant hydrologic event each year. Substantial changes occur in the surface energy balance during snowmelt as the albedo changes from 0.8 to 0.2.

This project has concentrated on a strong program of hydrologic and meteorologic data collection, to better understand dominant physical processes. Field research focused on determining the natural annual and diurnal variability of meteorologic and hydrologic variables, especially those which may indicate trends in climatic change. Comprehensive computer models are being developed to simulate physical processes occurring under the present conditions and to simulate processes under the influence of climatic change.

INTRODUCTION

Industrial development results in anthropogenic impacts on the terrestrial ecology of Arctic Alaska. Examples of these impacts are:

- i) Enhanced surface drainage by newly constructed roads and pipelines
- ii) Deposition of roadway dust on the tundra
- iii) Deposition of atmospheric pollutants that are originally discharged to the atmosphere as a waste product of oil development
- iv) Alteration of soil thermal regime due to changing the surface condition such as the albedo.
- v) The generation of greenhouse gases in the atmosphere may result in warming and degradation of permafrost.

Local disturbances, such as surface albedo alteration or vegetation removal, result in rapid thawing of the permafrost and in certain conditions, considerable erosion by surface runoff. These disturbances are highly visible and persist until the slopes reach a stable stage and revegetation occurs. There are a large number of these disturbances, but the areal extent is much lower. As we look at disturbances on a larger spatial scale, we see that the disturbances to the ecological system are much more subtle. On a microscale (dust from roadways), disturbances need to be studied for many years before significant changes will be observed and on a macroscale, such as the impact of global warming, studies may be needed for many decades. In summary, the larger the area impacted, the more subtle will be the impact and therefore, the longer studies of the ecosystem response will take and the greater the amount of time to develop adequate models for prediction purposes.

While production at the well-known Prudhoe Bay field has peaked, improved oil recovery technology and future development in other highly potential areas, such as the Arctic National Wildlife Refuge, guarantee that ecological disturbances will be ongoing for some time. In order to evaluate ecosystem sensitivity in the Arctic to energy related activities, the Department of Energy initiated an ecosystem study of Arctic Tussock Tundra. This study differed from previous studies in that a strong physical component was integrated into the study that included hydrology and meteorology.

We still lack a complete understanding of the processes associated with the active layer. The active layer is important physically and biologically: It is the source of water and nutrients for plants, conveys water downslope to surface drainages, provides water for evaporation and transpiration, acts as a temporary storage reservoir and dictates the quantity of near-surface runoff during major rainfall and snowmelt events. Hydrologic processes in the Arctic will be altered as the active layer increases in thickness in response to climatic warming. So, climatic change in the Arctic has a two-fold impact; processes such as precipitation, runoff and evapotranspiration will change, but also the structure of the watershed will change in the form of increased active layer thickness and this could cause additional changes to the above mentioned processes.

OBJECTIVES

The main goal specific to this project was to develop a more thorough understanding of the interactions between the physical and biological systems in the Arctic so we can predict long term ecosystem response to anthropogenic impacts of energy development. In order to accomplish this, a sound understanding of heat and mass transfer processes is critical.

There is also a large stochastic component involved in ecosystem processes. The greatest variability occurs in atmospheric

processes, followed by surface and then subsurface processes. Buffering by surface vegetation and soils are primarily responsible for the pattern of variability.

The objectives for this project were to:

- i) Improve our knowledge of the interactions between the physical and biological systems in the Arctic.
- ii) Monitor in the field both meteorologic and hydrologic processes to quantify the absolute values and the year to year variation. This includes runoff on plot and watershed scales, precipitation (both as snow and rain), soil moisture levels, water quality of surface runoff, downslope water movement through the active layer, and numerous meteorological measurements (air, snow and soil temperatures, long-wave and solar radiation incoming and outgoing, windspeed and direction at several heights, and relative humidity at several heights).
- iii) Develop both our watershed hydrologic model and our active layer thermal model to incorporate processes unique to the Arctic. Both models will be expanded into distributed parameter models which can then be utilized over greater areas.
- iv) Apply both our hydrologic and thermal models to evaluate the hydrologic consequences of climatic warming in the Arctic.

PROJECT RESULTS

Nine years (1985-1993) of hydrologic and meteorologic data have been collected at Imnavait Creek near Toolik Lake, Alaska. This is the most complete set of field data of this type collected in the North American arctic. These data have been used in process-oriented research to increase our understanding of atmosphere/hydrosphere/biosphere/lithosphere interactions. Heat and mass transfers between various spheres are monitored to quantify rates. These measurements include rates of mass movement such as hillslope flow and rates of heat transfer for active layer thawing and combined heat and mass processes such as evapotranspiration.

A logical step in this project is model-oriented research. Generally these models, in essence, represent our present understanding and integrate that knowledge with other related processes. For example, we have utilized a conceptual model to predict hydrologic processes. To test the success of this model, we compared our predicted rates of runoff and snowmelt to measured values. A surface energy model was developed to simulate active layer temperatures. The next step in the modeling effort was to predict the impact climatic warming would have on active layer thicknesses and how this will influence the hydrology of our research watershed.

HYDROLOGIC AND METEOROLOGIC DATA COLLECTION

The data collection program included numerous measurements at several temporal and spatial scales. Spatially, measurements were made on plot (10's of m) basin (2 km) and regional (150 km) scales. Measurement times vary from one minute to one day or more in some cases, such as soil moisture.

Since this remote site is not manned all year, some of the field measurements were interrupted during the winter season. Such instruments as radiometers are susceptible to frost and rime ice and cease to function. Many measurements continued throughout the winter because solid state data loggers are capable of functioning at temperatures below -40°C .

The data consist of air temperature, relative humidity and wind speed at 2 or more heights above surface, wind direction, precipitation, barometric pressure (Imnavait only), incident shortwave radiation, reflected shortwave radiation, atmospheric longwave radiation, terrestrial longwave radiation, net radiation, photosynthetically active radiation (Imnavait only), pan evaporation (Imnavait only), snow and soil temperatures at multiple depths, heat flux (Imnavait only), soil moisture (Imnavait only), stream discharge (Imnavait only) and snowpack depth and water content. The sites and data set duration are presented in Table 1.

Table 1. Location and duration of meteorologic data collection.

Site	Location	Period of Record
Imnavait Basin	68° 50'N, 149° 45'W	January, 1985 to present
Sagwon	69° 25'N, 148° 48'W	December, 1987 to present
Franklin Bluffs	69° 50'N, 148° 45'W	December, 1987 to present

In summary, we have an extensive hydrologic and meteorologic data set that is far more complete than any for the arctic region of Canada and the United States. These intensive measurements have allowed us to make a substantial contribution to the understanding of arctic hydrology and are an essential component of research into climatic change in the Arctic.

PROCESS ORIENTED RESEARCH

The initial research objective of this project was to improve our knowledge of system processes. Field data discussed above would be used to support process oriented research. Our initial hypothesis was that in order to understand ecosystem processes and how this system may respond to disturbance, it is critical that we understand physically what is happening in the active layer in terms of heat and mass transfer processes. Once we understand these processes, we can then incorporate disturbance into the system and make predictions about the response.

Snowmelt

Spring snowmelt is the dominant annual hydrologic event on the North Slope of Alaska (Kane et al., 1991a). Runoff and soil water from this event provide the majority of water utilized by vegetation in the spring and early summer period. Many important characteristics of the North Slope of Alaska are determined by the timing and mechanism of snowmelt. These include vegetation type and diversity, avian and large mammal migrations and fish migration and spawning. The radical change in albedo associated with snowmelt has global implications in its effects on surface energy fluxes over vast areas.

We examined the differences and trends in snowpack accumulation and ablation along a transect from the Brooks Range to the Arctic Coastal Plain. Snow accumulation and distribution were monitored periodically throughout the winter months at three sites. Analysis of the ablation and meteorological data gave us important insight into snowmelt processes on a regional basis. Initiation of melt is very site specific, determining factors were mainly snow depth, radiation and sensible heat flux. The rates and mechanisms of the ablation varied greatly along the 115 km transect (Figure 1). Initial snowmelt usually begins at mid-elevations in the southern foothills of the coastal plain, spreading north and south as time progresses. In the southern areas of the foothills the snowmelt progressed more rapidly and the process was dominated by sensible heat flux advected from south of the Brooks Range. In more northern areas of the transect, those on the coastal plain, snowmelt was slower and controlled by net radiation (Hinzman et al., 1991b).

Snowmelt can occur from early May to late June and lasts 10 to 20 days depending on location and climatic conditions (Figure 2). Snowmelt generally begins later and lasts longer on the Arctic Coastal Plain as compared to the Foothills region. The pattern and rates of snowmelt are significantly influenced by the prevailing wind direction. Areas receiving predominantly southerly winds show enhanced melt rates when compared to areas dominated by northeasterly wind and its associated low clouds. The demarcation between these distinct air masses is abrupt and varies in its location from year to year. Topography, slope and aspect, affect both the distribution of the snow and the irradiance received at the snow surface (Figure 3) (Hinzman et al., 1992).

Snow, ice, permafrost and seasonally frozen soils dominate the hydrologic cycle of an arctic watershed. The abrupt change in surface albedo coupled with the energy required for phase change of snow and ice to water produces large variations in the surface energy balance (Figure 4). Snow accumulation begins in September or early October north of the Brooks Range. Maximum snowpack water equivalent occurs between late April and mid May, just prior to the onset of snowmelt. Snowpacks tend to be

SNOWPACK ABLATION

Figure 1. Ablation across a 115 km transect from the northern foothills of the Brooks Range to the arctic coastal plain.

Figure 2. Ablation curves for Imnavait Watershed from 1985-1992.

Figure 3. Topography, slope and aspect affects on snowpack ablation.

SURFACE ENERGY BALANCE IMNAVAIT WATERSHED - 117A - 1992

Figure 4. Surface energy balance from Imnavait Watershed during snowmelt 1992.

heavier in the foothills than those occurring on the coastal plains. Wind plays an important role in redistributing the snow to valley bottoms and depressions. As a result of this redistribution, the snow is placed closer to the stream channel and the proportion of runoff from snowmelt is increased. The wind also changes other properties of the snowpack by producing high density wind slabs within the snowpack as well as incorporating dirt and debris into these layers thereby lowering the albedo (Kane et al., 1991a). These windslabs and/or areas of deeper snow act to dam the stream channel which greatly affects the timing and rates of runoff (Hinzman and Kane, 1993). Peak flows generally occur within 36 hours of the initiation of streamflow. Peak discharge ranges between 0.6 and 1.2 cubic meters per second.

The snowmelt flood is the most important geochemical event of the annual cycle. Ion concentrations peak during the first 15% of the runoff event when pH is at a minimum. In all cases, ion concentrations in the spring snowmelt runoff event are 4 to 9 times those of the snowpack. Precipitation, including dryfall, contributes significant amounts of Ca, Mg, K, Na, Cl and SO₄ to runoff. Potassium is only found in surface waters during the snowmelt freshet and early recession. The concentration of Ca, Mg, electrical conductivity and suspended solids attain broad peaks in mid-summer. Only pH shows a significant relationship to discharge. A substantial charge imbalance occurs seasonally with cations being favored. No seasonal trends were apparent for Mg, K or Mn in subsurface flow on the surrounding slopes. Calcium, Fe, and Al displayed a late season peak, and the concentration of Na and Si declined as the melt event progressed (Everett et al., 1989).

Summer Runoff

Annual variation of the summer hydrologic regime is quite pronounced due to variability in the pattern and volume of summer precipitation. Annual water balances are presented in Table 2 for the entire duration of the snowmelt and summer periods. The organic soils of Imnavait Basin are the predominant control of the hydrologic response to rain and snowmelt inputs. Organic soils vary in water content throughout the summer and are very porous, providing storage and the main flow path for water moving to the stream. The antecedent moisture conditions of the organic soils control the magnitude and timing of the streamflow events. The mineral soils remain at or near saturation throughout much of the year. The most notable activity within the mineral soils is the phase change between liquid and frozen states. The water released by the thawing mineral soil may be an important source of moisture during summer dry spells. During the dry periods streamflow declines to minimal discharge, often ceasing entirely for extended periods (Figure 5) (Kane et al., 1989). Summer precipitation events can produce high volumes of runoff, though usually not as great as snowmelt runoff events (Kane and Hinzman, 1988). Much of the hillslope hydrology of Imnavait Watershed is

Figure 5. Imnavait Creek hydrograph for summer 1990.

Table 2. Annual water balances for Imnavait Watershed.

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	21.9	33.2
1989	15.5	25.7	41.2	9.4	7.8	17.2	24.0	42.0
1990	10.6	16.3	26.9	6.4	2.8	9.2	17.7	39.4
1991	8.2	24.9	33.1	5.6	3.3	8.9	24.2	37.7
1992	18.1	24.1	42.2	14.4	6.3	20.7	21.5	**

* Data unavailable

** Data not yet reduced

either directly or indirectly controlled by the presence of permafrost. Subsurface flow on hillslopes occurs primarily at the interface between the organic and mineral soils. Surface flow mechanisms are dominated by the intertussock and watertrack network. These factors combine to produce runoff from the basin that is flashy in nature with rapid rise to peak flow and brief recessions (Hinzman and Kane, 1993).

Evapotranspiration

Evapotranspiration challenges runoff as the primary mechanism for annual water loss from a permafrost dominated watershed such as Imnavait Creek. Watershed scale evaporation was calculated by water balance method and compared to estimates derived from evaporation pan, energy balance and Priestley-Taylor methods (Figure 6) (Kane et al., 1990). The energy balance method is the best way to estimate daily or hourly evapotranspiration due largely to difficulties in accounting for changes in soil moisture using the water balance method with short time steps. Priestley-Taylor produced reasonable estimates of evapotranspiration using very limited data sets. Actual evapotranspiration is greatest in early summer during peak insolation and when a ready reservoir of water is available in the organic soils. Air and soil temperatures peak later in the season when soils are generally drier limiting actual evapotranspiration to less than the potential rate. Evapotranspiration demand exceeds the available precipitation on a seasonal basis. High rates of evapotranspiration occur in early summer, utilizing snowmelt storage, and following significant precipitation events in mid-summer. Significant precipitation generally occurs in late summer and early fall. Evapotranspiration rates during this period are very low due to reduced insolation, cool temperatures and higher relative humidities (Kane et al. 1990).

Figure 6. Comparison of evapotranspiration models.

MODELING RESULTS

The HBV model was used to simulate the hydrologic regime of the Imnavait Research Watershed during the spring snowmelt period (Hinzman and Kane, 1991). Five spring snowmelt events were analyzed. The HBV model performed well in predicting soil moisture, evaporation, snow accumulation, snow ablation and runoff. The model did well in predicting snowmelt runoff volumes (Table 3), but more work is needed to improve the models prediction of the initiation of snowmelt. It became apparent

Table 3. Comparison of HBV modeled and measured snowmelt runoff.

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

that there was a need for a model that could consider the spatial variability within a basin. To meet this challenge, data collected at Imnavait Basin is being used in concert with a digital terrain model to define flow pathways and describe spatial changes in soil moisture, evapotranspiration, and discharge within the basin. At this time, the model does well in defining flow pathways, further work will attempt to incorporate Synthetic Aperture Radar (SAR) imagery into the model to define the changes in soil moisture, and an energy balance component to estimate evapotranspiration (Kane et al, 1993). The warming of the Arctic, predicted by global climate models, will affect the hydrologic regime. Substantial warming will lengthen the snow free period, increase the active layer thickness, increase evapotranspiration and change the soil moisture storage (Hinzman and Kane, 1992).

S Snowmelt was modeled at three sites using three models: (1) degree day model, (2) combined degree day and radiation model and (3) an energy balance model. These sites represented differing terrain and climatic conditions. These methods yielded reasonably good results. The degree-day method is simple, requiring only air temperature to predict melt, however, it does not account for warming and cooling of the snowpack. Hence, the degree-day method predicts initiation of melt too early in each melt period. The energy balance method can account for the cooling and rewarming of the snowpack but requires an extensive data set not often available in remote arctic areas (Hinzman et al., 1991b). The three snowmelt models were calibrated using data collected between 1985 and 1990 at Imnavait Basin. The resulting calibrated models were then used to simulate snowmelt in 1991 and 1992. The results of the verification of the calibration of these models is presented in Table 4 (Kane et al., 1992b).

Table 4. R^2 Values for calibration and verification simulations for three snowmelt models.

Year	Energy Balance Model	Air Temperature Model *	Temperature-Radiation Model **
Calibration Simulations R^2 Values			
1987	0.995	0.933	0.970
1988	0.938	0.924	0.976
1989	0.994	0.952	0.972
1990	0.990	0.989	0.988
Verification Simulation R^2 Values			
1992	0.973	0.945	0.958

CONCLUSIONS

This research has supplied us with a greater understanding of the numerous physical processes occurring in the Alaskan Arctic, by studying the many heat and mass transfer processes. We have collected one of the most extensive data sets of arctic hydrologic and meteorologic variables in North America. The existence of these data have allowed development and/or calibration of thermal, hydrologic, snowmelt and evapotranspiration models for arctic conditions.

Some important hydrologic and thermal processes still need to be addressed such as: the influence of arctic stratus clouds, redistribution of soil water in active layer during freezing, development of hoar frost at the base of the snowpack and snowpack sublimation during the winter.

RESEARCH RELATED PRODUCTS

The following is a chronological list and status of manuscripts that have been generated from this DOE funded research near Toolik Lake, Alaska. A copy of the published articles follow this listing.

Everett, K.R., D.L. Kane and L.D. Hinzman. In Press. Surface Water Chemistry and Hydrology of a Small Arctic Drainage Basin. J. Reynolds and J. Tenhunen (eds) Landscape Function: Implications for Ecosystem Response to Disturbance. A Case Study in Arctic Tundra. Springer-Verlag, Ecologic Studies Series.

Hinzman, L.D. and D.L. Kane. In Press. Computer Simulations of the Thermal and Hydrologic Processes in Imnavait Watershed. J.F. Reynolds and J.D. Tenhunen (eds.) Landscape Function: Implications for Ecosystem Response to Disturbance. A Case Study in Arctic Tundra, Springer-Verlag, Ecologic Studies Series.

Hinzman, L.D., D.L. Kane, C.S. Benson and K.R. Everett. In Press. Thermal and Hydrologic Processes in Imnavait Watershed. J.F. Reynolds and J.D. Tenhunen (eds.) Landscape Function: Implications for Ecosystem Response to Disturbance. A Case Study in Arctic Tundra, Springer-Verlag, Ecologic Studies Series.

Cooper, L.W., C. Solis, D.L. Kane and L.D. Hinzman. 1993. Application of Oxygen-18 Tracer Techniques to Arctic Hydrologic Processes. Arctic and Alpine Research, In Press.

Hinzman, L.D., D.L. Kane and K.R. Everett. 1993. Hillslope Hydrology in an Arctic Setting. Proceedings of the Sixth International Conference on Permafrost. 5-9 July, 1993, Beijing, China, p. 267-271, South China University of Technology Press.

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Hinzman, L.D. and D.L. Kane. 1992. Potential Response of an Arctic Watershed During a Period of Global Warming. Journal of Geophysical Research - Atmospheres, 97(D3):2811-2820.

Kane, D.L., L.D. Hinzman, M.K. Woo, and K.R. Everett. 1992b. Arctic Hydrology and Climate Change. in S. Chapin, R. Jeffries, G. Shaver, J. Reynolds, and J. Svaboda (eds) Arctic Ecosystems in a Changing Climate. Academic Press, Inc., p. 35-57.

Cooper, L.W., C. Solis, D.L. Kane and L.D. Hinzman. 1991. Combined use of ¹⁸Oxygen and Physical Measurements to Monitor Snowmelt and Streamflow in an Arctic Watershed. Abstract, American Geophysical Union Annual Meeting, December 1991.

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Kane, D.L., L.D. Hinzman, C.S. Benson, and K.R. Everett. 1989. Hydrology of Imnavait Creek, an Arctic Watershed. *Holarctic Ecology*, 12:262-269.

Kane, D.L. and L.D. Hinzman. 1988. Permafrost Hydrology of a Small Arctic Watershed. *Proceedings of the Fifth International Permafrost Conference*. 2-5 August 1988. Trondheim, Norway. p 590-595. Tapir Publishers.

Currently a complete set of the meteorologic and hydrologic data collected for this project are being compiled and will be published on a CD-ROM in the near future by the National Snow and Ice Data Center.

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