ANNUAL REPORT

to

UNITED STATES DEPARTMENT OF ENERGY

ARCTIC HYDROLOGY AND METEOROLOGY

DOE GRANT NO. 60247

1989

from

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PROGRESS SUMMARY

To date, five years 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 Arctic of North America. These data have been used in process-oriented research to increase our understanding of atmosphere/hydrosphere/biosphere/lithosphere interactions. Basically, we are monitoring heat and mass transfers between various spheres to quantify rates. These could be rates of mass movement such as hillslope flow or rates of heat transfer for active layer thawing or combined heat and mass processes such as evapotranspiration.

Although many people feel that sufficient data of the nature described here have been collected in the Arctic, this is definitely not true (Polar Research Board, 1985; Woo, 1986). Usually the time series have large segments of data missing and the quality of the data is questionable. Never has there been a study in the Arctic that has examined all the measurable processes associated with heat and mass transfer.

The logical third step in this research 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 are comparing our predicted rates of runoff and snowmelt to measured values. We have also used a surface energy model to simulate active layer temperatures. The final step in this modeling effort to date was to predict what impact climatic warming would have on active layer thicknesses and how this will influence the hydrology of our research watershed by examining several streambeds. Moss and Lins (1989) and Committee on Earth Sciences (1989) have identified hydrologic response to climatic warming as a high priority area of needed research.

Hydrologic Data Collection

The present data collection program (Table 1) includes numerous measurements at several temporal and spatial scales. Spatially, we are making measurements on plot (10's of m) basin (2km) and regional (150 km) scales. Measurement times vary from one minute to one day or more in some cases.

In windy environments, the quality of any precipitation data is suspect, especially for snowfall. We are using two rain gages, the standard 8-inch diameter orifice gage (used by the National Weather Service) with a wind shield and a special precipitation gage designed for snow, called the Wyoming snow gage. At winter's end, we are also doing detailed snow surveys with Dr. Benson to ascertain the quantity of snow on the ground just prior to ablation. It is known that all precipitation gases under measure (Benson, 1982) but that the Wyoming snow gage is better than most (Clagett, 1988).

Some of the field measurements cease during the winter season because at this remote site, no one is present. Such instruments as radiometers are susceptible to frost and rime ice and cease to function. Many measurements continue throughout the winter and the availability of solid state data loggers has made this possible. These instruments are capable of functioning at temperatures below -40°C.

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.

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

Table 1 Summary of Measurements Program

Type	Timing	Sites	Comments
<u>Hydrologic Measurements</u>			
Rain precipitation	Hourly	5	Quality variable from poor to good
Snow precipitation	Hourly	5	Use - USDA SCS Wyoming snow gage, quality fair
Snow on ground	Intermittent daily during snowmelt	Basin wide	In cooperation with Dr. Benson, quality fair
Plot runoff	Continuous	4	Excellent during snowmelt - selective measurements for rain
Watershed runoff	Continuous	1	In cooperation with Dr. Everett, quality good
Pan evaporation	Daily	1	Quality good
Soil moisture	Intermittent (Every 4-5 days during summer)	4	Quality good
Snow temperatures	Daily or hourly	4	Quality good
Soil temperatures	Daily or hourly	4	Quality excellent
Soil heat flux	Hourly	3	Quality good
<u>Meteorologic Measurements</u>			
Wind speed	Hourly	4	Quality excellent, two elevations
Wind direction	Hourly	4	Quality excellent
Relative humidity	Hourly	4	Quality excellent
Air temperature	Hourly	4	Quality excellent
Incident solar	Continuous - Averaged hourly	4	Quality variable
Reflected solar	Continuous - Averaged hourly	4	Quality variable
Atmospheric longwave	Continuous - Averaged hourly	4	Quality variable
Terrestrial longwave	Continuous - Averaged hourly	4	Quality variable
Net total all wave	Continuous - Averaged hourly	4	Quality variable

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 as to the response. The major processes examined in detail are listed in Table 2. We still have not addressed some processes in detail such as the damming effect of snow, the role of advected energy or ablation, redistribution of soil water in active layer during freezing, development of hoar frost at the base of snowpack and sublimation over the winter from the snowpack.

Table 2 Process Oriented Research

Type	Scale	Comments
Snowmelt runoff	Plot, watertrack, and watershed	With Dr. Everett
Rainfall runoff	Plot, watertrack and watershed	With Dr. Everett
Freezing and thawing of active layer	Point measurements	
Water movement downslope through active layer	Plot	
Active layer moisture regime	Point	
Evapotranspiration	Point, plot and watershed	
Water balance	Plot and watershed	
Snow ablation	Plot and watershed	With Dr. Benson
Surface energy balance	Point	
Snow accumulation and redistribution	Watershed	With Dr. Benson

From our research to date, we have developed the following generalizations:

- i) Precipitation measurements in the Arctic are very poor, and most data is basically useless because it underestimates actual annual precipitation by two to three times.
- ii) Snowmelt is the most dramatic event in the Arctic. Not only does it produce the highest peak runoff events but, once complete, the surface energy balance changes dramatically (Figure 1).
- iii) Early summer (May and June) is a period of low rainfall and this is important because snowmelt infiltration and soil water made available from the thawing active layer are the source of water for plants during this time.
- iv) Water movement downslope is quite complex, depending upon the time of year and the degree of saturation. During snowmelt and periods of high rainfall, near-surface water movement alternates between surface and subsurface flow.
- v) Water tracks running normal to the slope are very efficient at transporting water off the slope to the valley bottom.
- vi) Conduction, except during snowmelt, is the primary mechanism of heat transfer in the active layer (Figure 2).
- vii) Evaporation vies with runoff as the primary mechanism for removing water from a basin (Table 3).
- viii) Vegetative patterns reflect the thermal and moisture regimes of the active layer.
- ix) The temporal distribution of precipitation (rainfall just prior to freezeup) guarantees that soil moistures will be high during freezing and that ice lenses will develop. During the spring snowmelt, this inhibits infiltration and promotes runoff.

SURFACE ENERGY BALANCE IMNAVAIT WATERSHED 1988

Figure 1. Surface energy balance for 1988.

OBSERVED AND SIMULATED SOIL TEMPERATURES 40 cm Depth

Figure 2. Measured and simulated soil temperatures for four years.

Table 3. 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	21.9	33.0
1989	15.5	25.6	41.1	9.4	7.8	17.2	23.9	?

* - data unavailable

? - data available, will be added at a later date

- x) The movement of air masses in conjunction with solar radiation dictates the timing of ablation; warm southerly airflow, coupled with near maximum solar radiation, initiate snowmelt. Reversal of colder air flow from the North retards ablation.

Model Oriented Research

Conceptually, the hydrologic cycle of an arctic watershed can be depicted as shown in Figure 3. The subsurface component of the cycle is simplified because of the presence of the relatively impermeable ice rich permafrost at shallow depths. For Imnavait Creek, the active layer is completely frozen for eight months of the year and streamflow ceases during those periods in small headwater basins. Larger rivers have minimal flows over the winter.

To integrate all the hydrologic processes together, a hydrologic model was utilized for the basin. The model selected was the Swedish HBV watershed model (Bergström, 1976). This model was selected for several reasons; it is used extensively in Nordic countries (Bergström, 1976 and Vehviläinen and Motovilov, 1988), it has a snowmelt routine and minimal data requirements are needed to utilize the model. There are some 41 parameters used in this model that pertain to basin, snow, soil, and transformation functions. Some parameters are very easy to ascertain such as basin area, elevation range, etc. However, some must be determined by calibrating the model with known results. In this case, we compared our predicted runoff rates with measured rates. Other checks such as comparing evapotranspiration with estimates from other methods or comparing predicted snowmelt with field snow surveys were also used. This model does have the advantage that parameter values can be changed at any time. This is quite useful in our case where there is thawing throughout the summer, because the active layer has different properties when frozen and unfrozen.

This model performed quite well for five snowmelt events (Table 4) and was also used to simulate continuous hydrographs throughout the summer

HBV MODEL STRUCTURE

Figure 3. Conceptual flowchart of the HBV runoff model.

Table 4. Performance of model and selected threshold temperature.

Year	r ²	Time Step	Threshold Temperature (°C)	Accumulated Diff. (mm)
1985	0.86	2 hours	0.30	-7.1
1986	0.81	"	-0.70	12.7
1987	0.89	"	-0.40	-2.6
1988	0.82	"	-1.90	-0.4
1989	0.80	"	-0.30	13.2
1985	0.81	1 day	0.25	-7.2
1986	0.77	"	3.30	11.7
1987	0.93	"	0.20	7.7
1988	0.91	"	-1.80	-0.2
1989	0.77	"	-0.35	13.6

(Figure 4). During snowmelt runoff, it is difficult to quantify the effect of snow damming. Usually water is flowing for one to two days in the water tracks and accumulating in the valley floor. However, because of the flat gradient and the high density of the wind-packed snow, water does not immediately drain out of the basin. When it does finally start flowing, the peak can be greater than expected because of all the stored meltwater in the valley bottom. So snow damming not only delays the runoff, but also increases the peak flows.

The role of the active layer in attenuating runoff is more limited when frozen because of the reduced infiltration at that time. During snowmelt, runoff is the dominant (Table 3) hydrologic process, with evapotranspiration and active layer soil water storage accounting for the remainder of the meltwater.

One limitation of the hydrologic model is that the cold content of the snowpack and active layer are not directly accounted. It is quite common for the first meltwater to percolate into the snowpack and refreeze because the snowpack is cold. This releases latent heat that speeds up the warming process of the snowpack. A similar process occurs with the active layer.

It is often common for mixed snow and rain events to occur, particularly in late summer. The model does not perform well at these times; it is not necessarily the fault of the model, but the quality of data that is entered into the model.

Continuous thermal modeling of the active layer with a heat conduction model with phase change was attempted using; 1) measured surface temperature and 2) thermal conductivities of the soils at various depths, temperatures and soil moisture contents (Figure 5). The success of this model, when compared to measured temperatures at the base of the active layer are shown in Figure 6. This figure illustrates that conduction is the major mechanism for heat transfer in the active layer except during snowmelt when warming of the soil is accelerated because

IMNAVAIT CREEK MEASURED AND PREDICTED FLOWS

Figure 4. Measured and HBV simulated discharge for Imnavait Creek, 1986.

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

PREDICTED THAW DEPTH

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

of melt infiltration. It is important to determine the correct moisture content, so that latent heat is accounted for in the freezing process.

With our success at modeling the hydrologic cycle with the HBV model and the thermal regime of the active layer with TDHC heat transfer model we have made some preliminary simulations of the effects that climatic warming may have on arctic hydrology. Not only will we have precipitation changes, vegetation changes, etc., with climatic warming, but the structure of arctic watersheds will change because the active layer thickness will increase. Using the TDHC heat transfer model, we have predicted active layer thicknesses for various warming scenarios (Figure 6). For a scenario of 4°C warming, which appears realistic, over a fifty year period, our active layer thickness for Imnaviat Creek will increase by a factor of 2. With the same precipitation patterns and quantities that we have now, evapotranspiration will increase and runoff will decrease (Figure 7). However, this will change if precipitation patterns change.

Change in active layer soil temperatures for the 4°C warming scenario are shown (Figure 8). It can be seen that considerable warming occurs throughout the year except during the spring melt and fall freeze-up. This is obviously going to enhance vegetation growth if other factors, such as nutrient availability and soil water, are not limited. At this point in time, we need to understand more fully what soil moisture changes will occur in response to climatic warming.

RESEARCH RELATED PRODUCTS

The following is a list and status of manuscripts that have been generated from this DOE funded research near Toolik Lake, Alaska:

Hydrology of Imnavait Creek, an arctic watershed. Douglas L. Kane, Larry D. Hinzman, Carl S. Benson and Kaye R. Everett. Published in *Holarctic Ecology*.

HBV MODELED EVAPORATION POTENTIAL

CUMULATIVE VOLUMETRIC DISCHARGE MODELED BY HBV

Figure 7. HBV modeled cumulative evapotranspiration and discharge with temperature increases of 0, 2 and 4°C.

PREDICTED SOIL TEMPERATURE CHANGE

Temperature Difference Between Year 50 and Year 0

Figure 8. Difference between current ground temperatures and after year 50 warming 4°C.

Permafrost hydrology of a small arctic watershed. Douglas L. Kane and Larry D. Hinzman. Published in Proceedings of the Fifth International Conference on Permafrost. Trondheim, Norway.

Snow hydrology of a headwater arctic basin. Douglas L. Kane, Larry D. Hinzman, Carl S. Benson and Glen E. Liston. Submitted to Water Resources Research.

Modeling the snowmelt hydrology of a headwater arctic basin. Larry D. Hinzman and Douglas L. Kane. Submitted to Water Resources Research.

Hydrologic and thermal properties of the active layer in the Alaskan Arctic. Larry Hinzman, Douglas L. Kane, Robert E. Gieck and Kaye R. Everett. Submitted to Cold Regions Science and Technology.

Thermal response of the active layer in a permafrost environment to climatic warming. Douglas L. Kane, Larry D. Hinzman and John P. Zarling. Accepted for publication in Cold Regions Science and Technology.

Arctic hydrology, now and in the future. Douglas L. Kane, Larry D. Hinzman, Ming-Koo Woo and Kaye R. Everett. Chapter in Ecosystems Book Entitled *Physiological Ecology of Arctic Plants Implications for Climatic Change*. Invited for publication by Academic Press.

Thermal and hydrologic responses in an arctic watershed. Larry D. Hinzman and Douglas L. Kane. Potential chapter in R4D Book.

Interdependence of the hydrologic and thermal processes of an arctic watershed and their response to climatic change. Larry D. Hinzman. Ph.D. Dissertation. University of Alaska Fairbanks.

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