SUPPORTING DOCUMENT NO. 4

HYDROLOGIC BASELINE CONDITIONS - KIGGAVIK PROJECT AREA

District of Keewatin, Northwest Territories

A Report on the Surface Water Hydrology
prepared for:

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1.0 INTRODUCTION

The Kiggavik site is located within the central Keewatin District of the Northwest Territories, in an area drained by Baker Lake, which flows into the Chesterfield Inlet and Hudson Bay. Numerous lakes and adjoining rivers dissect much of the region and wetlands are predominant throughout. The region thus has an extensive, and interrelated, system of surface waters.

In the mid 1970s, Urangesellschaft Canada Limited discovered a uranium deposit within the Kiggavik area. There are plans to develop and put into production a mining operation in this area. Because of the apparently complex system, an assessment of the surface water hydrology is necessary to ensure that environmental effects of the mining operations are limited, and to determine suitable locations for mine tailings disposal. Water budgets and response ratios must be determined for proper estimations of dilutions and dispersions of any liquid discharges, and for predicting impacts in watersheds where natural hydrological regimes are altered for the purpose of site development.

1.1 Surface Water Hydrology

The distribution of water on earth may be described, in general terms, by the hydrologic cycle. Water circulates between the oceans, atmosphere and continents by a number of complex processes. Those of concern here are the processes responsible for moving water from a watershed into a surface water body such as a stream or lake.

Hydrology is the study of water movement and so is an important component of any environmental assessment. Chemicals are commonly transported within and out of watersheds associated with water, and so water pathways can define chemical pathways. Analysis of surface water hydrology in a region can also allow for determination of watershed responses to given precipitation events (rain or snow). The hydrologic character of a region will determine how responsive the system is to changes in regional characteristics (i.e., by mining operations for example).

Precipitation is the major factor controlling the hydrologic cycle of a region. Much of the ecology and geography of a region depends on the functions of the hydrologic cycle, and, therefore, precipitation provides both constraints and opportunities in land and water management.

Precipitation may occur as rain or snow. Rain falling to a surface may first be intercepted by vegetation, resulting in some evaporative loss and possibly some storage. The remainder is free to infiltrate or move across the surface to lakes or streams. The amount of overland flow (Horton, 1933) is determined by the infiltration capacity (IC) of the soil, which is defined as the maximum rate at which a soil can absorb water over a given unit of time. The IC declines exponentially with time after the onset of rainfall, reaching a fairly constant rate after some time. Once the rate of precipitation exceeds that of infiltration, water accumulates and fills small depressions before moving across the soil surface as runoff. When rainfall intensity exceeds the IC, runoff generally rises to a sharp peak, followed by a rapid decline as soon as the rainfall intensity decreases. Horton overland flow (HOF), as described above, generally occurs only over areas where the soil has been disturbed, or where the soil is frozen.

Another potentially important mechanism for water reaching streams is saturation overland flow (SOF). In lowland areas with unfrozen soils, the capillary fringe and/or water table are just beneath the ground surface. Rain events can infiltrate and bring the capillary fringe and/or water table to the surface, creating a seepage face. This can cause outwardly-directed hydraulic gradients, and water can move from within the soil to the ground surface, where it then can move to surface waters as overland flow. Precipitation falling onto saturated areas moves as overland flow to surface waters. These two mechanisms are known collectively as saturation overland flow.

Hydrograph peaks are generally either caused by HOF or SOF mechanisms. The recessions are generally maintained by a subsurface flow mechanism. Water infiltrates and encounters a layer of low permeability (either a compacted horizon or a discrete impeding layer such as clay or ice). A saturated water lense can form above this layer and then water can move through the soil to surface waters (dictated by Darcy's flow law). This mechanism is referred to as subsurface stormflow (SSSF).

At temperatures of about $0^{o}C$ or less, precipitation occurs as snow. The total seasonal water content of snowfall, and the rate at which the snow melts, are of great concern because the resulting meltwater can rapidly fill lakes and saturate the active zone in permafrost areas. Snow will accumulate on a surface until sufficient heat has been transmitted to the pack to raise its temperature to $0^{o}C$. At this point, and when 2 to 8% (by weight) of the pack is melted (Dunne and Leopold, 1978), runoff will be generated. Once runoff has begun, all melting or rainfall releases water from the pack.

The possible pathways that meltwater takes to a stream after leaving the snowpack are as follows:

- o the IC of the soil exceeds the rate of meltwater percolation; all water enters the soil and moves to the stream/lake as subsurface flows (SSSF);
- o the rate of meltwater percolation through the pack exceeds the IC of the soil; because it is frozen, a saturated layer develops in the lower few centimeters of the snow, and water moves downslope as (Horton) overland flow (HOF); and
- o the IC exceeds the meltwater percolation rate and water enters the soil. It drains downward to raise the capillary fringe and water table, which can then intersect the ground surface near the base of the hillslope and generate SOF.

Knowledge of the processes and mechanisms involved in surface water hydrology are critical to understanding system behaviour and response to various inputs. Such information is needed before land use and water management planning can be carried out. The applicability of each of the above mechanisms to the Kiggavik region will be examined in the following analysis.

1.2 The Kiggavik Study Site

1.2.1 Location

The study area is located approximately 80 km west of Baker Lake (64°30'N, 97°47'W), in the central Keewatin District of the Northwest Territories (Figure 1.1).

1.2.2 Climatology

The area receives approximately 235 mm as precipitation annually (30-year normal), of which about 60% occurs as rain. The snow-free period is limited to July and August. The onset of spring, defined as the date the daily mean air temperature (Tam) rises above 0°C, occurs during the first two weeks of June, while fall, defined by the date the Tam falls below 0°C, begins during the last two weeks in September. The mean annual air temperature is -12°C (30-year normal), and there is a 44°C temperature range annually.

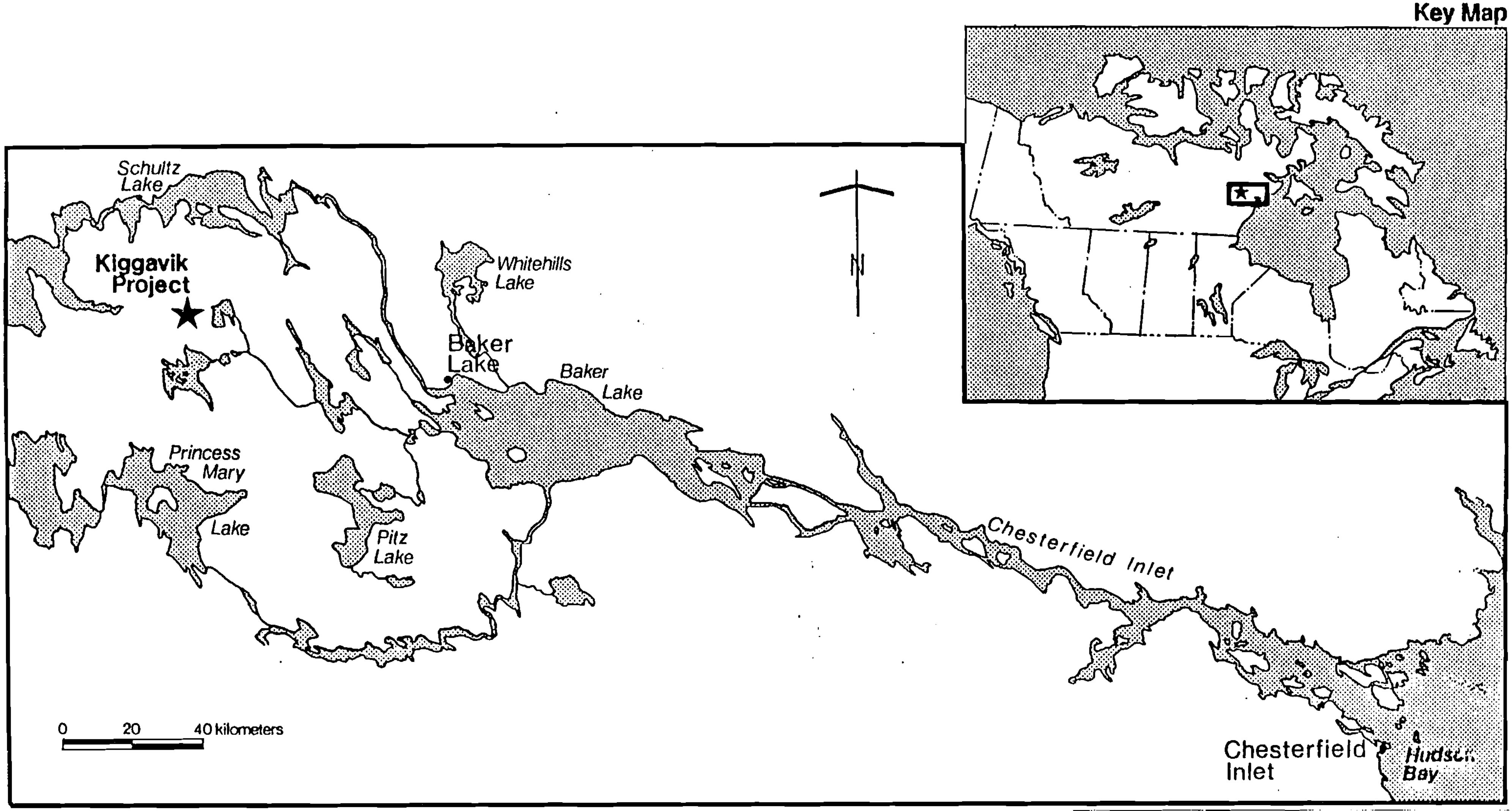


Figure 1.1: **LOCATION MAP**

(District of Keewatin Northwest Territories)

URANGESELLSCHAFT
Kiggavik Uranium Project
Baker Lake, Northwest Territories

The area is thus characterized by long, cool winters, very short transitional seasons, and short warm summers.

The climate is classified as cold continental, and the region is dominated by Arctic pressure systems. The dominant factors determining the climate are:

- the character of the solar energy input,
- the surface topography and nature of the ground surface, and
- the dominant weather systems.

The nearest Atmospheric Environment Service (AES) climatological station to the Kiggavik site is at Baker Lake. The station opened in 1946 although hourly observations have been made only since 1962. A summary of the (30-year normal) climatic data for Baker Lake is shown in Figure 1.2. A more complete discussion of climate for the area can be found in Supporting Document No. 3 on climatology and meteorology.

The Kiggavik site lies at an elevation of 180 m and is approximately 80 km west of the Baker Lake meteorological station (elevation at 12 m). The intervening terrain is undulating and contains lakes and river valleys oriented in a northwesterly direction. The highest ground between the project site and Baker Lake rises to 230 m, approximately 30 km due east of the site. There are likely to be some differences in the meteorological conditions between the two sites because of:

- the higher elevation of the Kiggavik site, and
- the effect of Baker Lake during the ice-free season.

The difference in elevation may cause temperatures to be slightly lower at Kiggavik because of probable slight increases in wind speeds. There may also be a slight increase in precipitation at Kiggavik because of low clouds and fogs.

The presence of a large cool body of water during the ice-free season (July and August for Baker Lake) will have a modifying effect at Baker Lake. The small shallow lakes near the project site would not be expected to have as marked an effect. Spring and summer temperatures would be kept lower at Baker Lake, while fall temperatures would likely be higher.

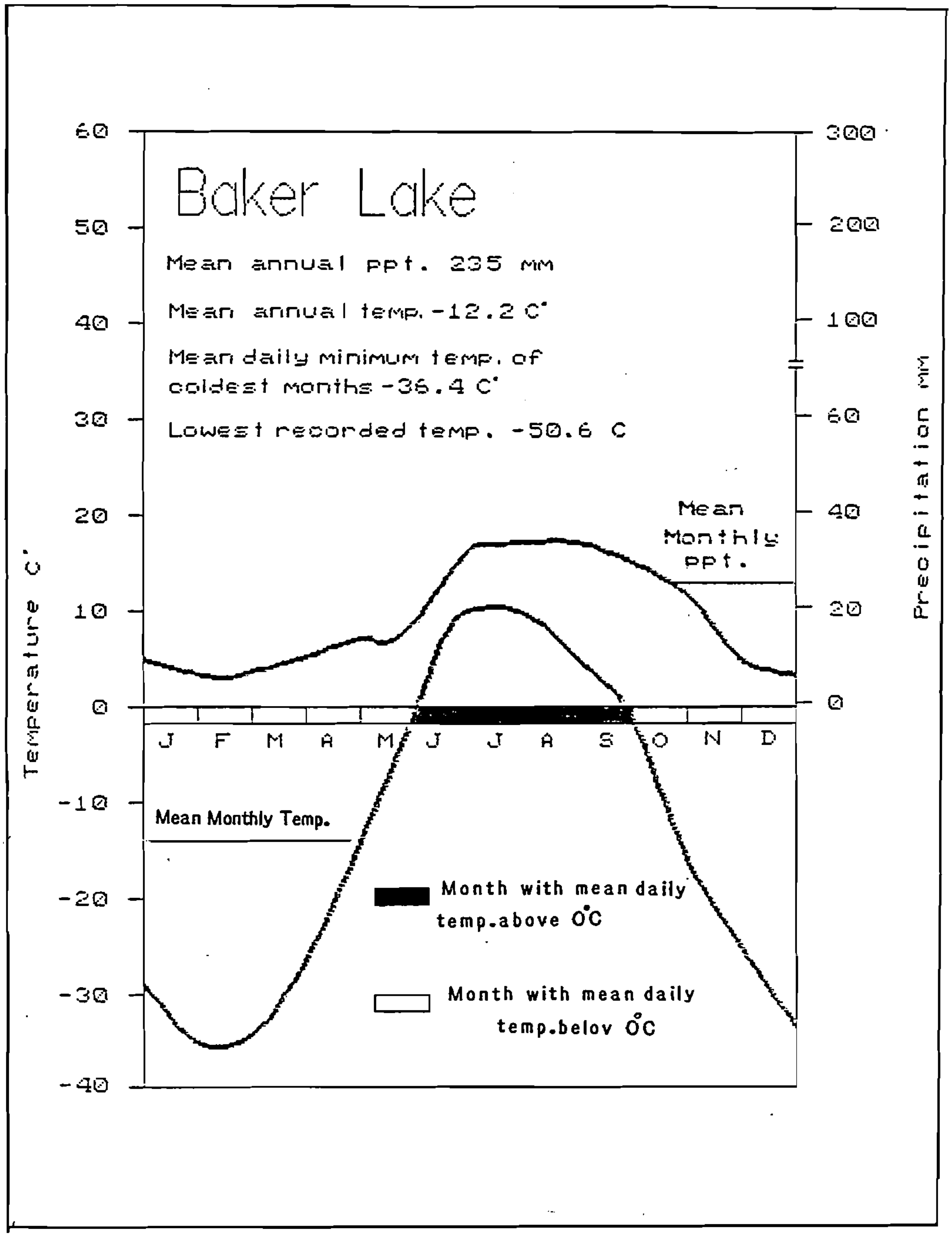
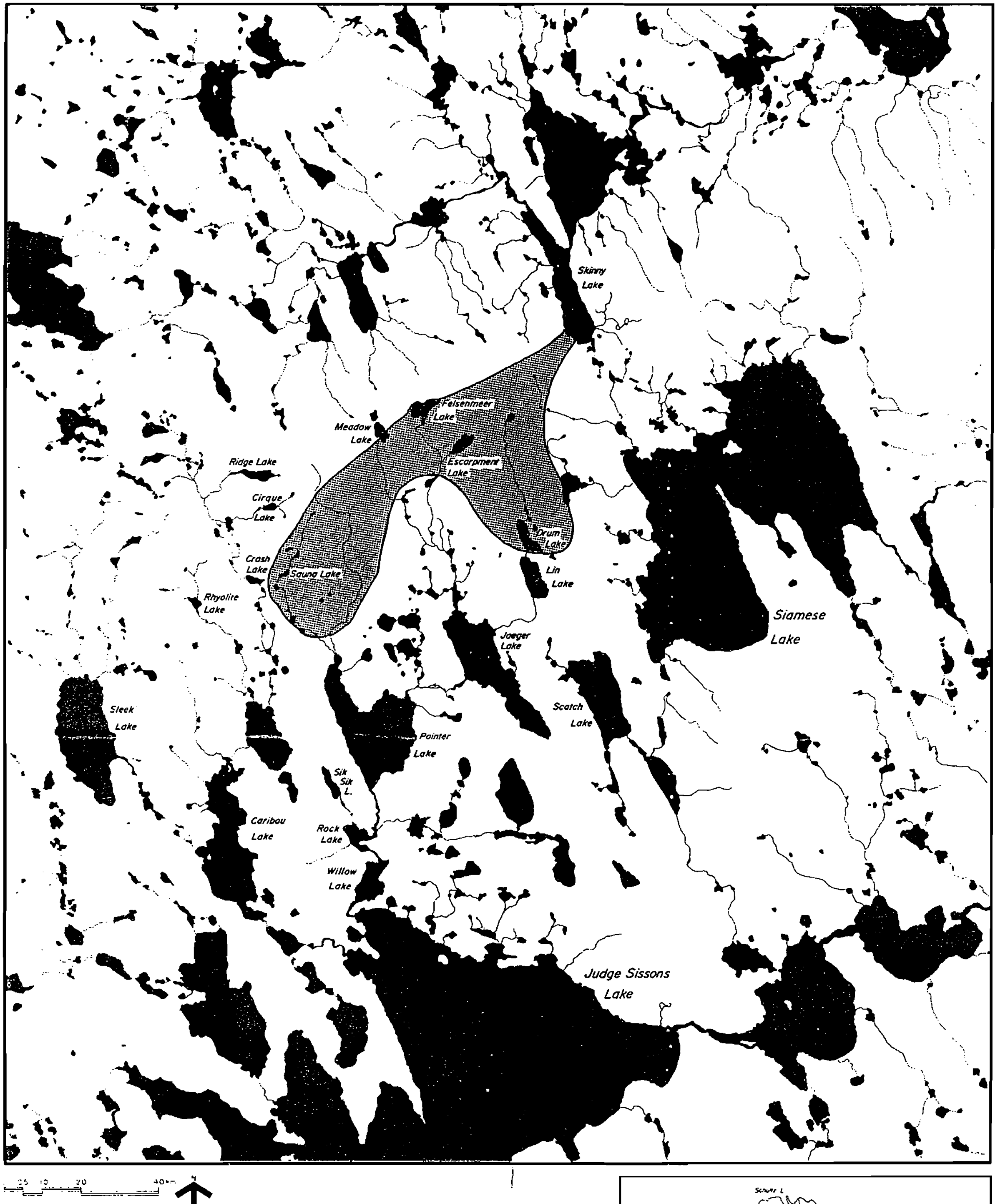


Figure 1.2 : SUMMARY CLIMATOLOGICAL DATA



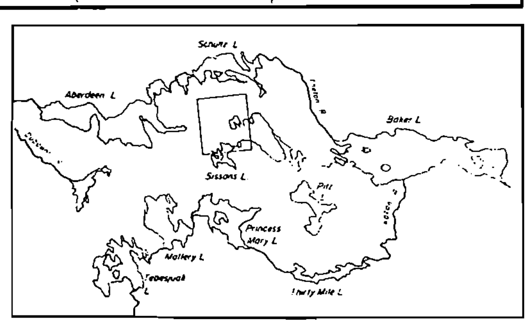


FIGURE 1.3
Project Location Map
Kiggavik Project Site

Project Development Area

1.2.3 Geology

1.2.3.1 Bedrock

The Kiggavik site is situated at the eastern end of the Thelon Basin, which formed approximately 1,800 million years ago. The basin was subsequently filled in with a thick deposit of clastics and small amounts of felsic volcanics. The pre-Thelon clastic rocks are mainly arkosic quartzites, with intercalated orthoquartzites and chlorite-sericite schist units. Except for the chemically inert orthoquartzites, all the metasediments are host to uranium mineralization.

1.2.3.2 Surficial Materials:

The surficial materials in the study area can be grouped into three major deposits:

- o glacial deposits, including tills and glaciofluvial materials,
- o fluvial deposits, resulting from recent activity, and
- o organic deposits, resulting from gradual accumulation of peats.

1.2.4 Soils

The site lies in a zone of continuous permafrost, with regional thicknesses greater than 200 m. The active layer reaches about 0.50 m to 1.25 m on well-drained tills, and about 0.80 m on wet peatlands. The soils are generally dominated by clay-rich till, although organic cryosols and fibric- to mesic-peats are present in wetter areas. A large proportion of the area is wetland, with the remainder being occupied by lakes and dry upland tundra. Cryogenic processes, especially cryoturbated soils, are evident and associated with patterned ground features such as polygons, stripes and hummocks.

1.2.5 Vegetation

The region is north of the treeline and so is composed of a variety of foliose, squamulose and fruticose lichens, together with various moss species in the surface layers, by ericaceous shrub and heath species, and by a variety of herbs, grasses and sedges. Further information on soils and vegetation can be found in Supporting Document No. 2.

1.2.6 Hydrology

Major water resources in the Kiggavik region include the Thelon River system and Judge Sissons Lake, the latter which flows into the Anigaq River. Both the Thelon and Anigaq rivers flow eastward into the western end of Baker Lake. Numerous smaller lakes, ranging from small shallow ponds to deep lakes with surface areas exceeding 25 km^2 are distributed throughout the region (Figure 1.3). The basin and lake areas for watersheds within the Kiggavik site are listed in Table 1.1. Particulars of a few select lakes are given in Figure 1.4.

Runoff and streamflow characteristics in the region are governed by topography, soil and plant communities and meteorological conditions. The cold Arctic climate results in the development of a thick layer of ice on surface water for about eight months of the year. By the end of winter in May, the thickness of ice in the project area generally exceeds 2 m. Runoff during these periods is negligible, and streamflow is greatly diminished or ceased completely.

There are generally three major periods of hydrologic activity in the central Keewatin region:

- **Spring snowmelt:** the largest source of water to regional watersheds (Roulet, 1985). Peak runoff occurs when meltwater exceeds the storage capacity of upland and lowland (wetland) soils. Snowmelt generally causes rapid rises in discharge hydrographs, with peak times reached only a matter of days after the initiation of melt. This results because of the very low storage capacities of soils at this time.
- **Early and mid summer:** the period when most of the basin snow cover is depleted and evapotranspiration is active. The basin dries out gradually, leading to a decrease in the permafrost groundwater table. As the frost table deepens, there is greater storage capacity in the active layer and so streamflow is reduced. The exception during this period is the wetlands, which undergo slow thawing and usually receive lateral inflows to maintain saturated conditions.
- **Rainy periods of late summer:** when evapotranspiration decreases due to an increase in cloudiness and a decrease in daylight hours. At low-lying

TABLE 1.1: BASIN AND LAKE AREAS FOR WATERSHEDS WITHIN THE KIGGAVIK REGION

Watershed	Basin Area (km^2)	Lake Area (km^2)
Escarpment	2.4	0.13
Pointer	82	3.7
Ridge	2.3	0.17
Jaeger	56	2.8
Cirque	1.1	0.06
Skinny	122	2.0
Crash	14	0.08
Fox	29	1.28
Caribou	80	3.41
Felsenmeer	1.4	2.08
Meadow	4.1	0.13
Drum	5.4	0.14
Lin	7.6	0.25
Scotch	19	0.48
Sik Sik	2.4	2.01
Willow	104	0.16
Kavisilik	156	0.55
Siamese	85	27.5
Judge Sissons	680	95.5
Anigaq River (at mouth) (including Pitz Lake drainage)	5,250	-

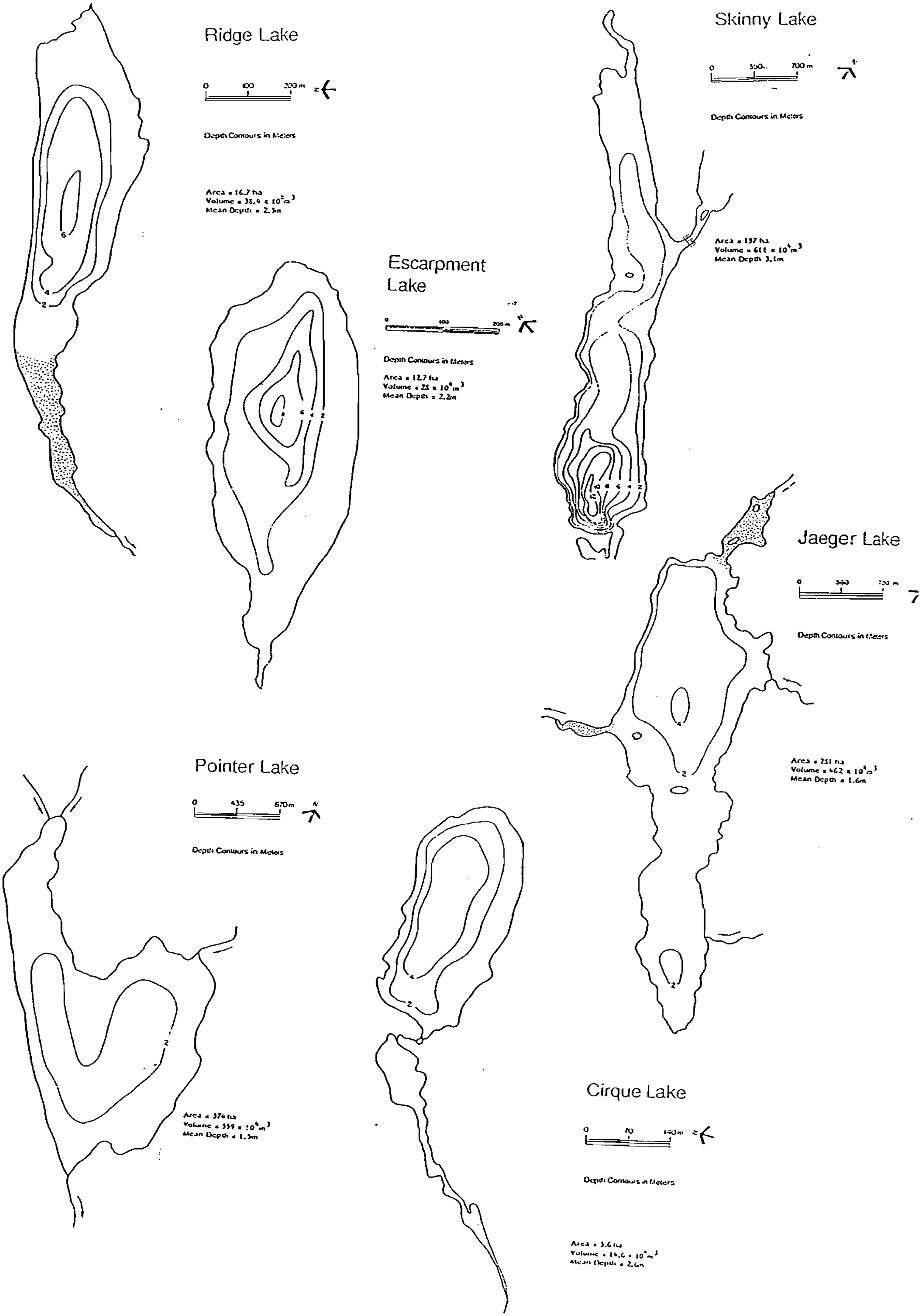


Figure 1.4 Characteristics of Select Lakes

areas, the watertable may rise to the ground surface, so that moderate to heavy rainstorms can generate sporadic high flow events (SOF mechanism).

1.3 Hydrologic Assessment of Surface Waters in Kiggavik

1.3.1 Purpose and Objectives of the Study

The purpose of this section of the report is to provide an analysis of the surface water hydrology for predictive purposes. The objective is to carry out such an investigation. There are a number of aspects about the hydrology of the study site that must be known and assessed. These involve quantifying responses to the following questions:

Q1. The nearest meteorological station to Kiggavik is Baker Lake, which is about 80 km away. Can the Baker Lake data be used to estimate conditions and inputs at the Kiggavik site?

Q2. What is the response of watersheds in the study site to snowmelt? (i.e. How long does it take the snow, after it melts, to leave the watersheds?)

Q3. What is the response time of the system to reach peak discharge after the initiation of snowmelt?

Q4. What proportion of the total available water is lost by evapotranspiration and what proportion is lost by runoff?

Q5. Can flow mechanisms be inferred from any of the hydrologic data?

Q6. What is the total discharge from the Kiggavik area?

Q7. Are the surface waters interconnected within the study site, so that changes in one watershed can affect all others?

All of the above questions may be answered, at least in part, with the data available for this analysis. Many assumptions have been made, which will be discussed in a later section.

1.3.2 Methodology

The objectives of this report will be fulfilled by a detailed analysis of the available data. The methodology used for quantifying each of the objectives (Section 1.3.1) is listed below.

Objective 1:

To determine whether or not the Baker Lake meteorological data can be used to reasonably estimate inputs to the study site, daily mean air temperatures measured at Baker Lake in 1982 and 1983 can be compared with those measured within the study site over the same period by Roulet and Woo (1986).

Objective 2:

The response of the study site can be calculated from six watersheds where runoff data are available (i.e., Ridge, Pointer, Jaeger, Skinny, Cirque and Escarpment). The response ratio is computed as the net runoff divided by the total available water from each watershed. This equation is complicated because allowances have to be made for:

- o weirs located at lake outflows, instead of the inflows, and
- o rain events that occurred during the snowmelt and runoff periods.

Before responses can be calculated, the snowmelt period has to be defined. There is generally no definitive means of determining this period, so for this report, it is assumed to occur from the time of first hydrograph response (average about June 8/88) to the time the hydrograph recession "levelled off" (about July 31/88).

The total available water (TAW) can then be computed as the sum of:

- o snow water equivalents (both on the basins and lakes),
- o precipitation (only from after the time the snow transect data were collected until June 8/88), and
- o active layer melt (assumed to contribute 3 cm of runoff).

The net runoff attributed to snowmelt (NR) can be computed by calculating the area under the hydrographs (from June 8 to July 31/88) and then by subtracting all precipitation events occurring during this period.

The response ratio can then be calculated for each watershed as NR/TAW.

Objective 3:

Specifics about time-to-peak and other hydrologic variables can be determined by analysis of the outflow hydrographs.

Objective 4:

The proportional losses of total available water to evaporation and runoff can be determined by calculating a water balance for each watershed (i.e., by comparing total water inputs and outputs).

The total water inputs during melt (i.e., the total available water) will have already been calculated to satisfy Objective 2. The same applies for the amount of water lost as runoff.

The water lost by evapotranspiration (ET) can be estimated by a number of methods. In this exercise ET refers to water losses from:

- o free water bodies (i.e., wetlands, streams, etc.),
- o transpiration (i.e., vegetative water loss), and
- o bare soils

For areas with limited data (such as for Kiggavik), either the Thornthwaite or Blaney-Criddle formulae may be used.

Thornthwaite

The Thornthwaite method uses air temperature as an index of the energy available for ET. It assumes that air temperature is correlated with the integrated effects of net allwave radiation and other controls of ET, and that the available energy is shared in fixed proportion between heating the atmosphere and ET.

The Thornthwaite method requires that mean monthly air temperatures be available for the year of interest. For the Kiggavik area, these data are available for 1988 (at Baker Lake) (Table 2.10). The Thornthwaite equations are given below:

$$I = \sum_{i=1}^{12} \frac{Tai}{5}^{1.514}$$

where: I = annual heat index

Ta_i = mean monthly air temperature (°C) for each month of the year

$$Et = 1.6\left[\frac{10(Ta)}{I}\right]^{a}$$

$$a = 0.49 + (1.79 \times 10^{-2})I - (7.71 \times 10^{-5})I^2$$

where: Et = uncorrected potential ET (cm/mo),

Ta = mean monthly air temperature for the month of interest (°C), and

a = coefficient as a function of I.

The value of Et must then be adjusted to account for the number of days of sunlight in each month and the length of day, both of which are a function of latitude. Correction factors are available in standard hydrologic texts (e.g., Dunne and Leopold, 1978). Water losses for each month by potential evapotranspiration (PET) are then computed as the product between Et and the correction factor.

Blaney-Criddle

The Blaney-Criddle formula was originally developed for estimating consumptive use of irrigated crops in the western USA. It is based on the same assumptions as Thornthwaite's method, and also uses air temperature and day-length as the major independent variables. The equation is given as follows:

$$Et = (0.142Ta + 1.095)(Ta + 17.8)kd$$

where:

Et = PET (cm/mo)

Ta = mean monthly air temperature (°C).

k = empirical crop factor

d = monthly fraction of annual hours of daylight

Neither the Thornthwaite or Blaney-Criddle equations were developed for Tundra regions such as Kiggavik, but where limited data are available, they may offer an approximation.

Objective 5:

Flow mechanisms can be inferred from knowledge of site conditions and from analysis of the hydrographs. Frozen soil conditions and rapid hydrograph peaks are generally considered to be indicative of overland flow mechanisms, while hydrograph recessions are generally a function of subsurface flows.

Objective 6:

The total discharge from the study site may be estimated if the following data are available (or can be computed):

- o drainage areas for each lake in the study area,
- o total annual precipitation, and
- o response ratios for the area.

The total discharge from each watershed in the study area may be computed by multiplying the response ratio by the total annual precipitation to give a volume per unit time per unit area ($m^3\ s^{-1}\ km^{-2}$). This value can then be multiplied by the area of each watershed to give a discharge. The total discharge from the Kiggavik site is simply the sum of all individual values from each watershed in the area. For comparative purposes, this value can be compared with measured discharge values at some of the Environment Canada measuring locations into which water from the study region drains (e.g., the Anigaq River downstream of Audra Lake).

2.0 SURFACE WATER HYDROLOGY: DATA ANALYSIS

2.1 Representativeness of Baker Lake Data

The nearest meteorological station to the Kiggavik study site is Baker Lake, which is about 80 km west. The assessment of the surface water hydrology within the study area is based on the 1988 flow records. No precipitation or air temperatures were measured at the site during this year, so Baker Lake data must be used. The purpose of this section is to determine whether the Baker Lake data can reasonably be used to estimate conditions/inputs to the Kiggavik site.

For this analysis, mean daily air temperatures from Kiggavik and Baker Lake were used for comparison (largely because these records were most complete for the years of interest). Hydrologic and climatological data were collected from within the Kiggavik site during the spring to fall period of 1982 and 1983 (Roulet and Woo, 1986).

Daily mean air temperatures for June and July of 1982 and 1983 from both sites are listed in Tables 2.1 to 2.4 respectively. The data were compared statistically by regression analysis, and significant differences were determined by the sample size and correlation coefficient. Regressions for June and July 1982 are shown in Figures 2.1 and 2.2 respectively. Both regressions show a significant positive correlation in daily mean air temperatures recorded at both sites. For both months, the daily mean air temperature recorded at Baker Lake is approximately 10% lower than that recorded at Kiggavik. This is probably related to the fact that air temperature was measured at the Kiggavik site over a wetland (i.e., in a topographic low). That recorded at Baker Lake was open to winds blowing across the lake, and so daily mean temperatures are slightly higher.

There is much more scatter in the data for July than June probably because Baker Lake thaws in July, and so there is a much more modifying influence on air temperature recorded at Baker Lake than in Kiggavik, where the lakes are very much smaller.

In summary, although the relationship is not ideal, conditions at Baker Lake are reasonably similar for Kiggavik for at least eight months of the year. Furthermore, daily mean air temperatures are not significantly different between the two sites, at least for the 1982 and 1983 seasons. Based on this brief analysis, the Baker Lake data may reasonably be used to estimate climatic conditions in the Kiggavik area.

TABLE 2.1: MEAN DAILY AIR TEMPERATURES MEASURED IN JUNE 1982 WITHIN KIGGAVIK AND AT BAKER LAKE

June	Kiggavik Mean Daily Air Temperature (^{o}C)	Baker Lake Mean Daily Air Temperature (^{o}C)
01	-3	-4.6
02	-4	-4.5
03	-3	-4.7
04	-3	-6.2
05	-2	-4
06	0	-0.6
07	-1	-2.9
08	-1	-4.6
09	0	-0.9
10	2	0.5
11	3	2.1
12	4	3.7
13	3	4.3
14	6	4.5
15	5.5	4.3
16	8	7.5
17	4.5	5.5
18	8	6.8
19	5	4.9
20	5.5	6.1
21	6	6
22	5	4.3
23	4.5	5.2
24	5	4.8
25	5	4.6
26	5.5	5.9
27	8	6.9
28	10	10.3
29	15	12.9
30	15	15.9

Regression Analysis:

Constant	1.147649
Standard Error of Y Estimate	0.971923
R Squared (r^2)	0.961094
No. of Observations	30
X Coefficient(s)	0.873090
Standard Error of Coefficient	0.033197

TABLE 2.2: MEAN DAILY AIR TEMPERATURES MEASURED IN JULY 1982 WITHIN KIGGAVIK AND AT BAKER LAKE

July	Kiggavik Mean Daily Air Temperature (^oC)	Baker Lake Mean Daily Air Temperature (^oC)
01	13	11.8
02	12	10.4
03	15	15.5
04	10	9.9
05	8	8.3
06	9	9.3
07	12	12.3
08	8	9.3
09	8	7.2
10	7	8.2
11	8.5	9.4
12	10	10.8
13	12	9.7
14	11	14.1
15	10	10.3
16	10	8.5
17	12	13.6
18	15	12.4
19	16	15.1
20	8	9.1
21	9	8.8
22	15	12.2
23	20	16.1
24	17	17.1
25	16	18.1
26	15	13.2
27	14	9.4
28	13	10.1
29	12	8.1
30	10	6.8
31	9	6.4

<u>Regression Analysis:</u>

Constant	2.444313
Standard Error of Y Estimate	1.920837
R Squared (r^2)	0.655326
No. of Observations	31
X Coefficient(s)	0.845464
Standard Error of Coefficient	0.113860

TABLE 2.3: MEAN DAILY AIR TEMPERATURES MEASURED IN JUNE 1983 WITHIN KIGGAVIK AND AT BAKER LAKE

June	Kiggavik Mean Daily Air Temperature (^{o}C)	Baker Lake Mean Daily Air Temperature (^{o}C)
09	3.5	0.6
10	4	2
11	4	3.8
12	5.5	4.2
13	5.5	6.3
14	5.5	7
15	5.5	3.1
16	5	5.9
17	5	5.5
18	5	5.3
19	5	5.9
20	7.5	7.7
21	8	8.4
22	10	10.7
23	9.5	10.8
24	5	6.5
25	4	3.9
26	7	9.6
27	11	12.5
28	12	14.8
29	7.5	7
30	7.5	5.7

<u>Regression Analysis:</u>

Constant	2.156027
Standard Error of Y Estimate	0.947973
R Squared (r^2)	0.850521
No. of Observations	22
X Coefficient(s)	0.645838
Standard Error of Coefficient	0.060541

TABLE 2.4: MEAN DAILY AIR TEMPERATURES MEASURED IN JULY 1983 WITHIN KIGGAVIK AND AT BAKER LAKE

July	Kiggavik Mean Daily Air Temperature (°C)	Baker Lake Mean Daily Air Temperature (°C)
01	8	4.9
02	6	5.9
03	5	5.6
04	5	4.8
05	5	7
06	5.5	6.7
07	9	9.5
08	10	15
09	11.5	9.9
10	10	6.5
11	9	5.4
12	8.5	4.6
13	9	6.4
14	9	8.8
15	10	8.4
16	10	7.3
17	10.5	7.2
18	10.5	8.3
19	10	12.8
20	9.5	15.8
21	8	16.8
22	10.5	18
23	10	12.9
24	8.5	13.6
25	7	14.2
26	8.5	15.6
27	8.5	16.2
28	8	8.8
29	9.5	9.5
30	9	10.1
31	8	9.3

Regression Analysis:

Constant	7.224302
Standard Error of Y Estimate	1.716956
R Squared (r^2)	0.106120
No. of Observations	30
X Coefficient(s)	0.140880
Standard Error of Coefficient	0.077269

FIGURE 2.1
A Regression of Mean Air Temperatures Recorded in in June 1982 at Kiggavik and Baker Lake

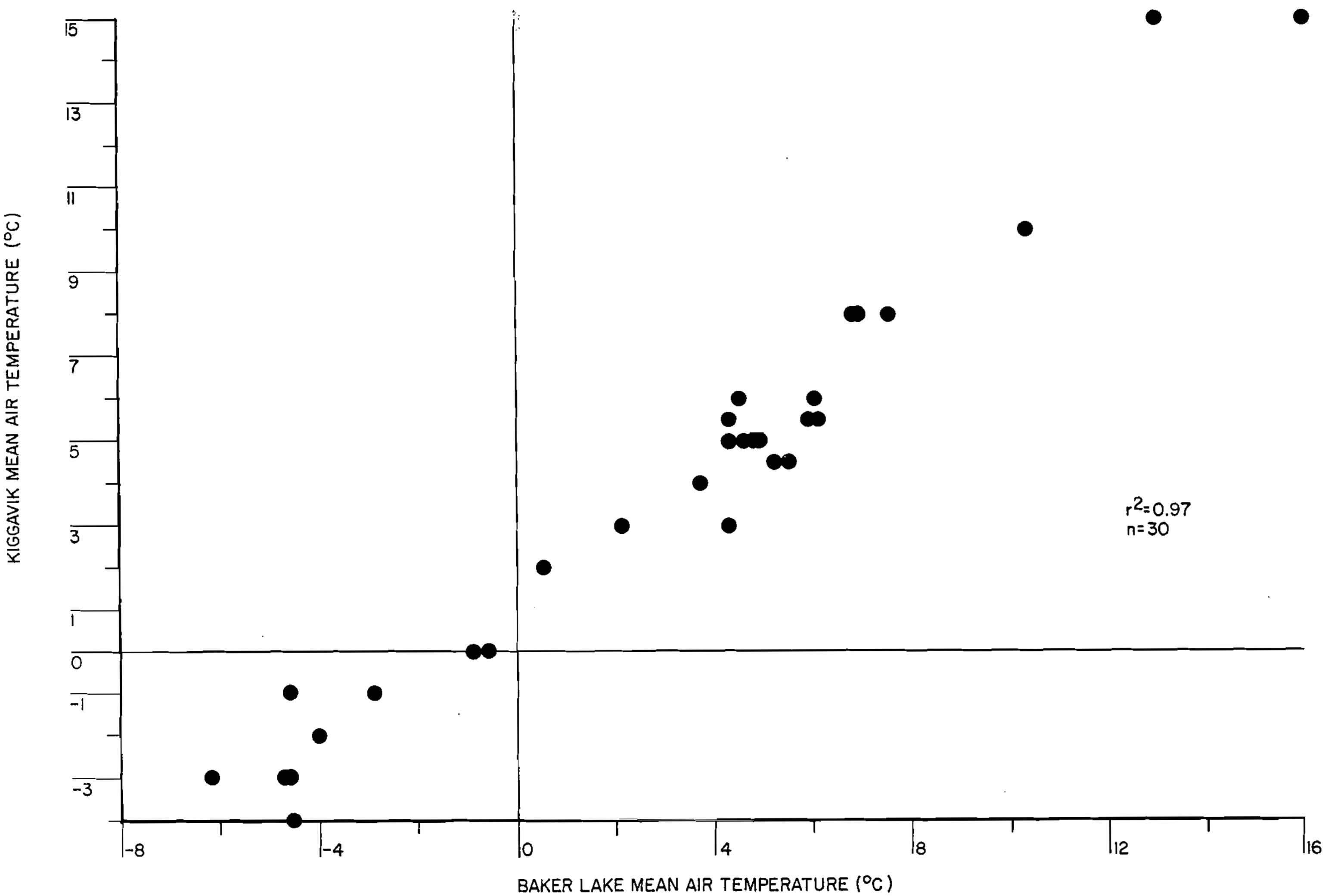
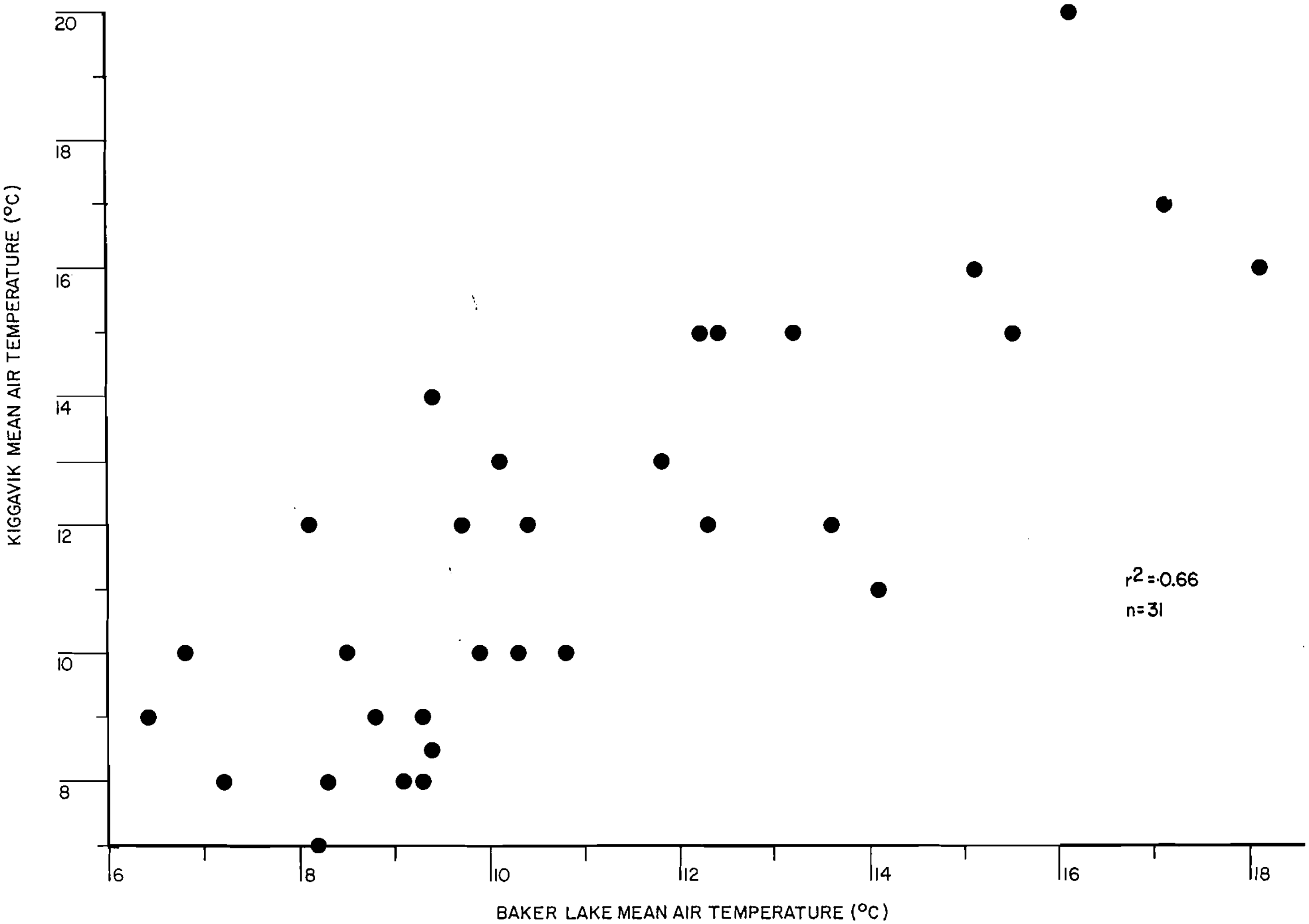


FIGURE 2.2
A Regression of Mean Air Temperatures Recorded
in July 1982 at Kiggavik and Baker Lake



2.2 Representativeness of 1988 Data

Since much of the analysis of surface water hydrology will be based on the 1988 flow measurements, it is useful to know how representative this year was relative to the 30-year normals for the region. This can be checked by comparing the 1988 precipitation and air temperature records from Baker Lake to the 30-year normals recorded at the same location (1951-1980).

The mean monthly air temperatures for 1988 and for the 30-year normals are listed in Table 2.5. A regression between these two variables is shown in Figure 2.3. There is a significant positive relation between the two sets of data, indicating that, at least with respect to mean monthly air temperatures, 1988 is a very representative year for Baker Lake records.

The 1988 and 30-year normal monthly (total) precipitation records for Baker Lake are listed in Table 2.6. The correlation is much less 1:1 than for mean daily air temperatures (Figure 2.4), and shows that 1988 total precipitation is approximately 25% higher than the 30-year normals. This suggests that a greater amount of precipitation occurred in 1988, compared with the 30-year normal.

In summary then, 1988 was a fairly representative year in terms of mean monthly air temperatures, but in terms of precipitation, it was higher than normal.

2.3 The Snowmelt Period of 1988

There is considerable debate as to how the snowmelt period should be defined. While some feel that air temperature is the responsible variable, others argue that hydrograph response is the determining factor. For this report, snowmelt was defined as the time the hydrographs first reported any flow (about June 8/88) to the time the recession "levelled off" (about July 31/88). After July 31/88, the hydrograph recession continued, but became increasingly affected by summer rain events. This thus defines the influence that an accumulated snow pack has on the hydrograph and not the time by which the majority of snow has melted on the landscape, which has generally occurred by the end of June.

TABLE 2.5: MEAN MONTHLY AIR TEMPERATURES (°C) RECORDED AT BAKER LAKE

Month	1988	30-year Normals (1951-1980)
January	-34.2	-33
February	-33.5	-32.6
March	-25.6	-27.9
April	-15.7	-17.3
May	-8.5	-6.4
June	4.8	4.1
July	11.6	11
August	10.6	9.7
September	4.3	2.3
October	-6.3	-7.7
November	-22	-20.3
December	-29.9	-28.2

Regression Analysis:

Constant	-0.66344
Standard Error of Y Estimate	1.480199
R Squared (r^2)	0.992673
No. of Observations	12
X Coefficient(s)	0.958023
Standard Error of Coefficient	0.026026

FIGURE 2.3
A Regression of Mean Monthly Air Temperatures at Baker Lake for 1988 and 30-Year Normals

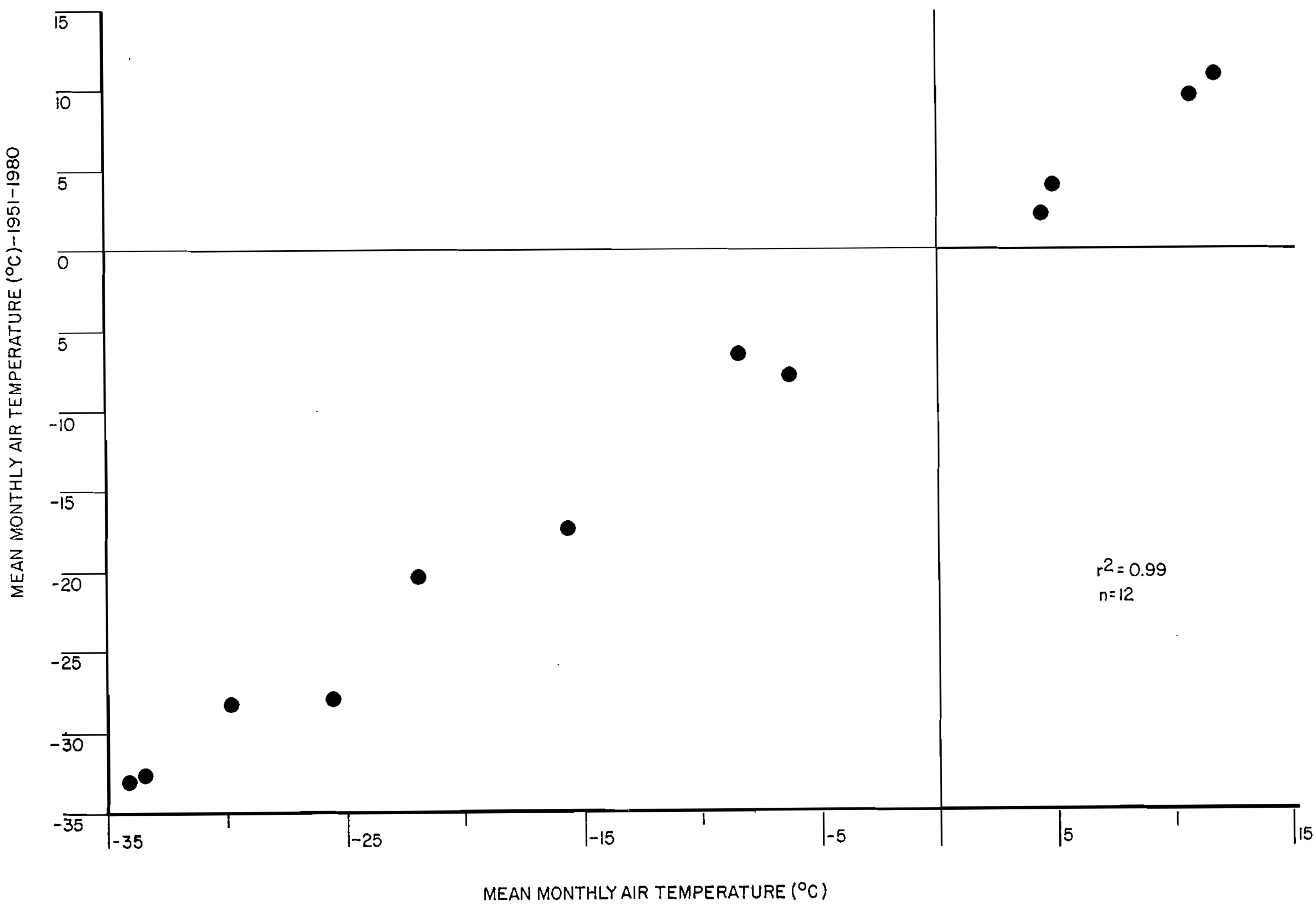


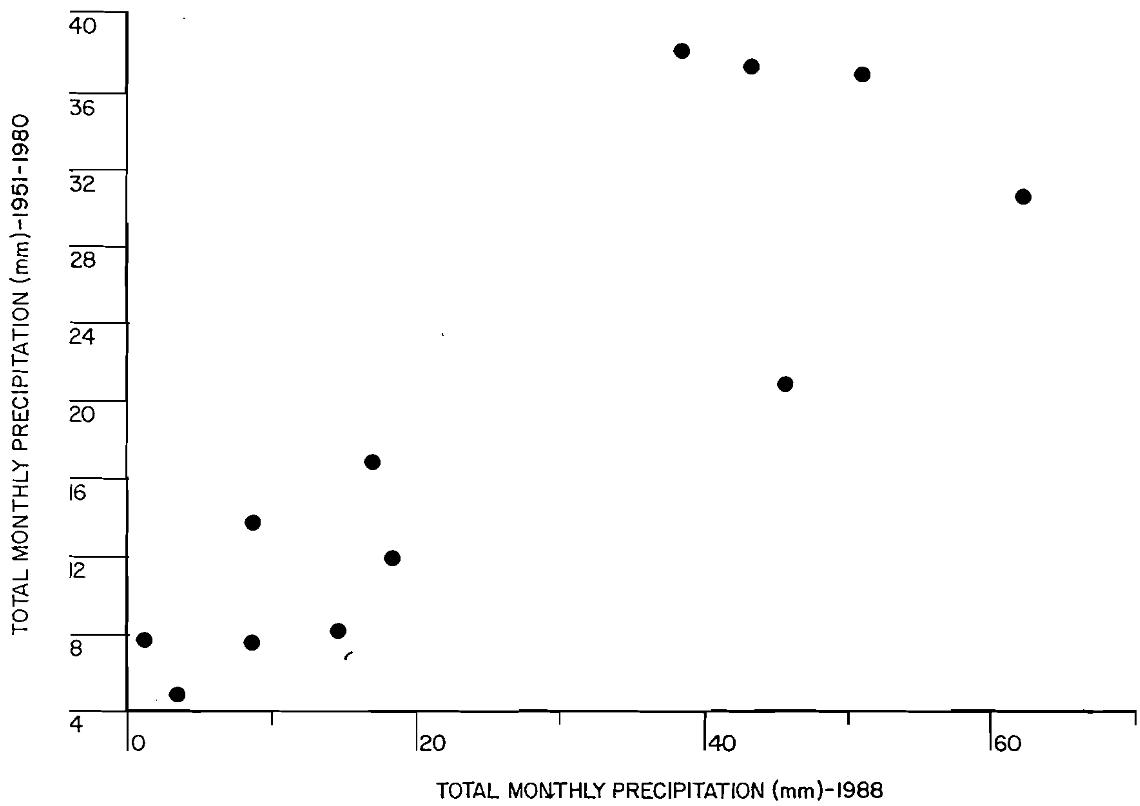
TABLE 2.6: MEAN MONTHLY PRECIPITATION (mm) RECORDED AT BAKER LAKE

Month	1988	30-year Normals (1951-1980)
January	1.2	7.7
February	3.4	4.9
March	8.5	7.6
April	8.6	13.8
May	18.4	12
June	45.6	20.9
July	38.4	38.1
August	43.3	37.3
September	51	37
October	62.2	30.6
November	17	16.9
December	14.6	8.2
TOTAL	312	235

Regression Analysis:

Constant	5.722598
Standard Error of Y Estimate	6.750410
R Squared (r^2)	0.748428
No. of Observations	12
X Coefficient(s)	0.532763
Standard Error of Coefficient	0.097676

FIGURE 2.4
A Regression of Total Monthly Precipitation Recorded at Baker Lake for 1988 and 30-Year Normals



2.4 Hydrologic Data Available For 1988

The Kiggavik study site contains a large number of small lakes (Figure 1.3). Hydrologic data (for 1988) are available for six of these lakes (i.e., Ridge, Pointer, Jaeger, Skinny, Cirque and Escarpment). The following data are available for these lakes:

- o snow water equivalents from a number of transects for all lakes except Cirque, and
- o lake outflow hydrographs.

Other available data include:

- o drainage basin and lake area estimates, and
- o Baker Lake meteorological records from 1951 to 1988.

Snow water equivalents are listed for some watersheds in Table 2.7. Note that in those instances where more than one transect was done, mean snow water equivalents were computed. The mean water equivalent for the whole region is approximately 0.09 m, which compares well with the 0.1 m 30-year normal recorded at Baker Lake.

Outflow hydrographs for Ridge, Pointer, Jaeger, Skinny, Cirque and Escarpment lakes are given in Figures 2.5 to 2.10 respectively. The total volume discharged from each watershed was determined by computing the area under each hydrograph (from 08 June to 31 July 1988) (i.e., the snowmelt period). The calculated runoff volumes for each watershed are listed in Table 2.8.

Drainage basin and lake areas were estimated for each watershed in the Kiggavik study area (Table 1.1). Areal estimates were made from the 1:50,000 topographical maps available for the area. Because of the scale of these maps, there is potentially a major source of error in estimating basin, lake areas and catchment characteristics for small watersheds (such as Cirque).

Baker Lake meteorological data are available from 1951 to 1988. Thirty-year normals (Table 2.9) and 1988 data (Table 2.10) will be used for analysis in this report.

TABLE 2.7: SNOW WATER EQUIVALENTS FOR SELECT WATERSHEDS IN KIGGAVIK

Watershed	Date of Transect(s)	Transect Water Equivalent 1	2	3	4	Mean Water Equivalent (m)
Ridge	01 June 1988	0.09	0.06			0.08
Pointer	01 June 1988	0.07	0.04	0.07	0.06	0.06
Jaeger	01 June 1988	0.08	0.06			0.07
Skinny	02 June 1988	0.10	0.15			0.13
Escarpment	02 June 1988	0.09				0.09

FIGURE 2.5
Discharge Hydrograph at the Outlet of Ridge Lake-1988

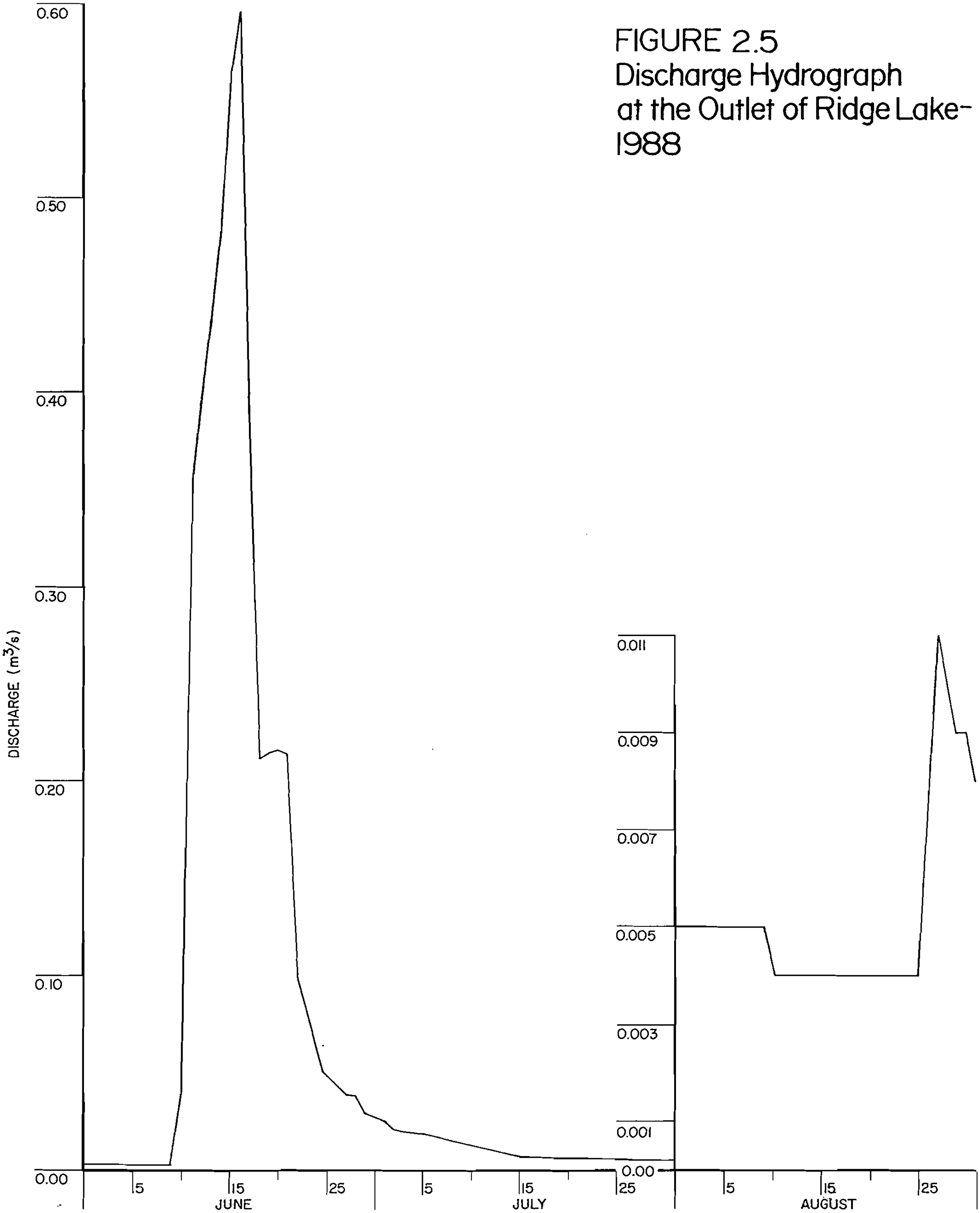


FIGURE 2.6
Discharge Hydrograph at the Outlet of Pointer Lake

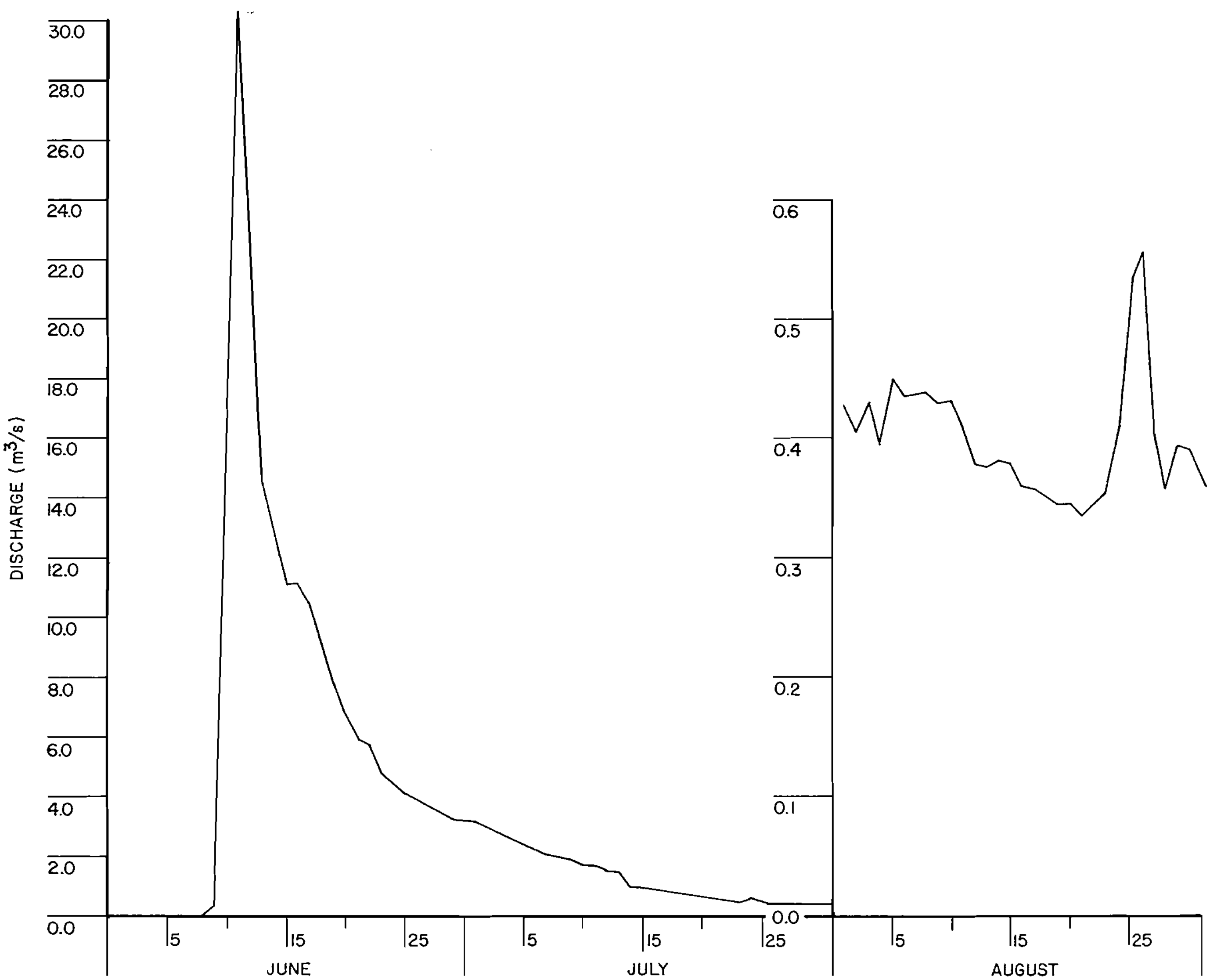


FIGURE 2.7
Discharge Hydrograph at the Outlet of Jaeger Lake

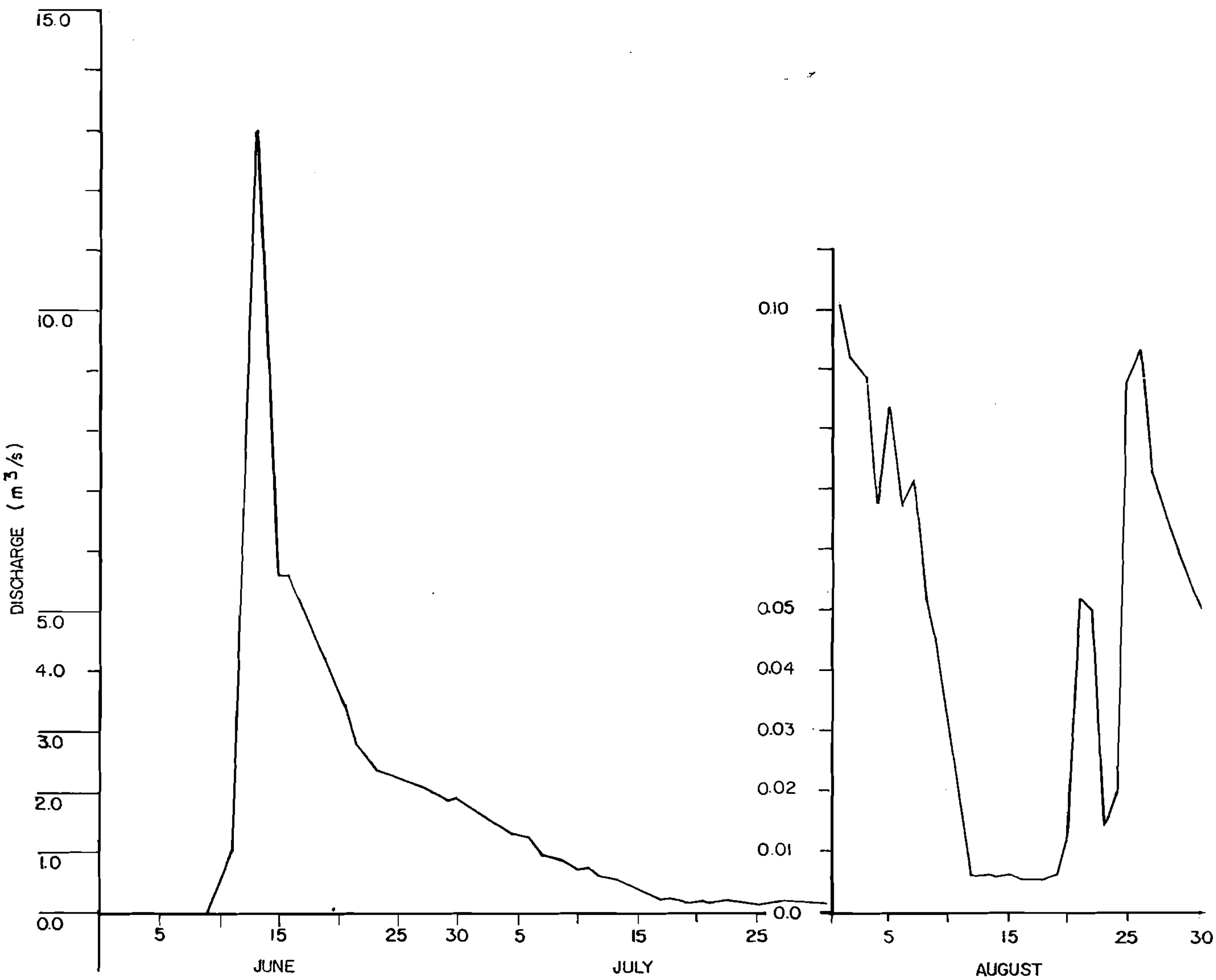
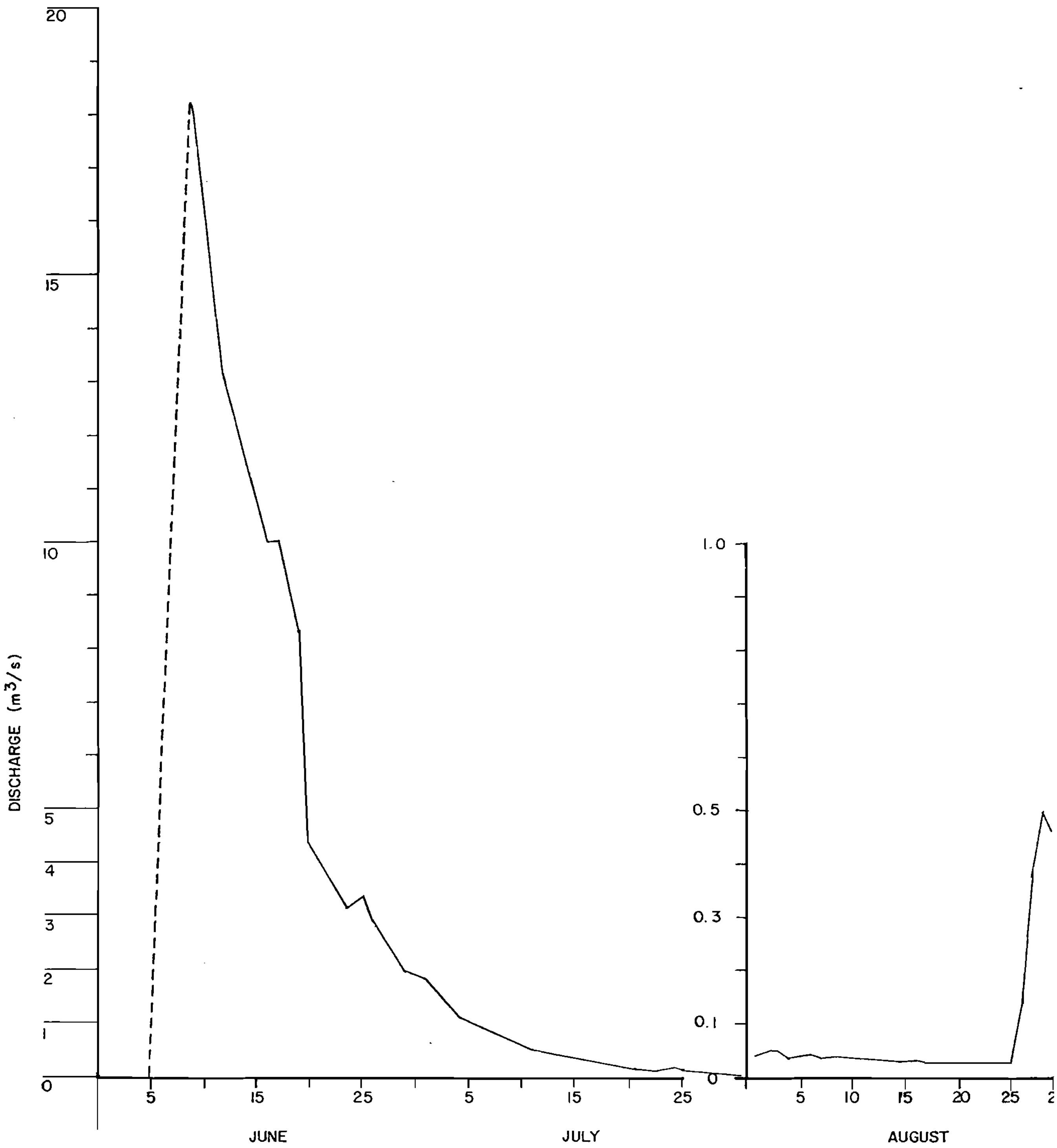


FIGURE 2.8
Discharge Hydrograph at the Outlet of Skinny Lake



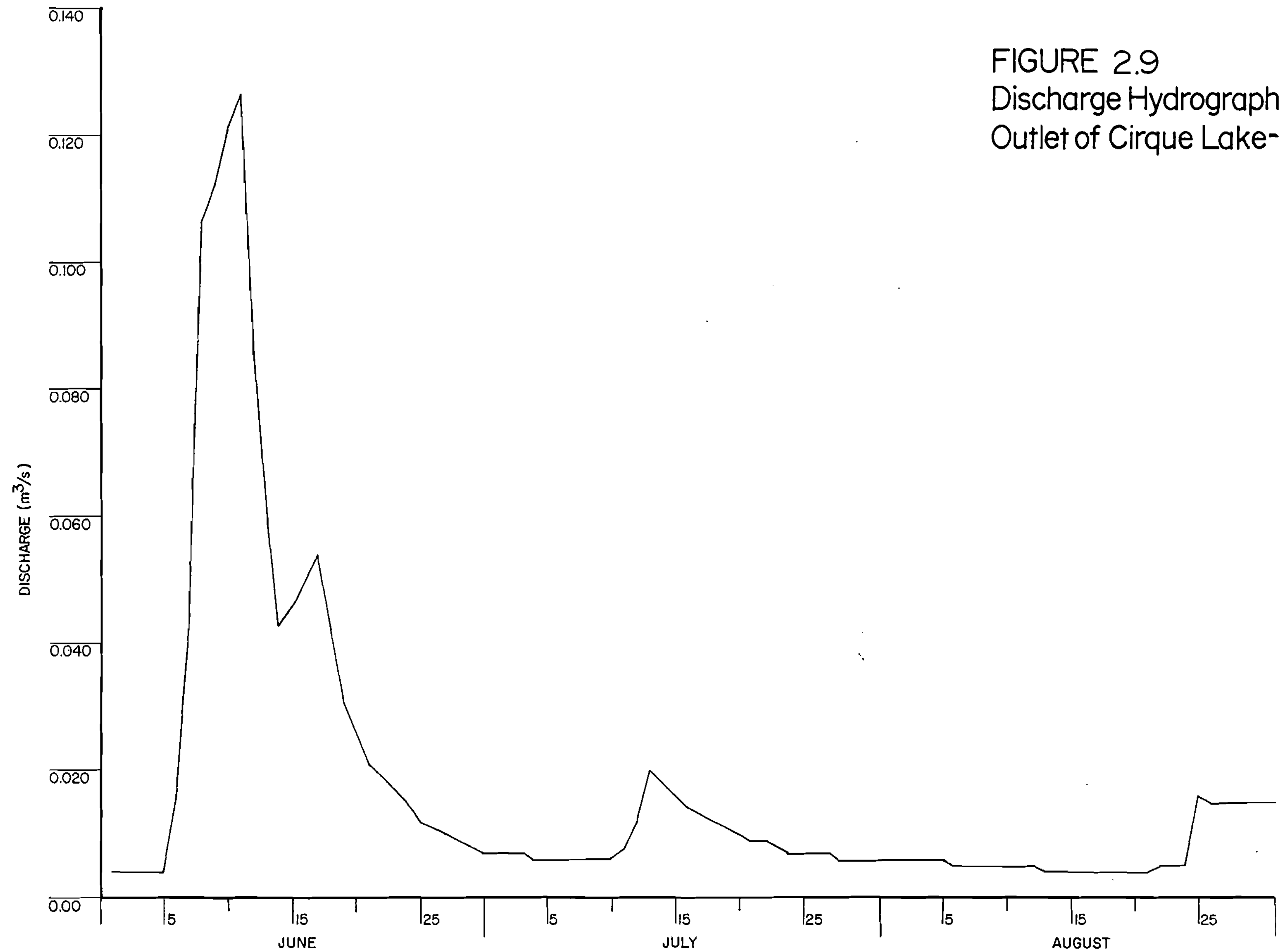


FIGURE 2.9
Discharge Hydrograph at the
Outlet of Cirque Lake-1988

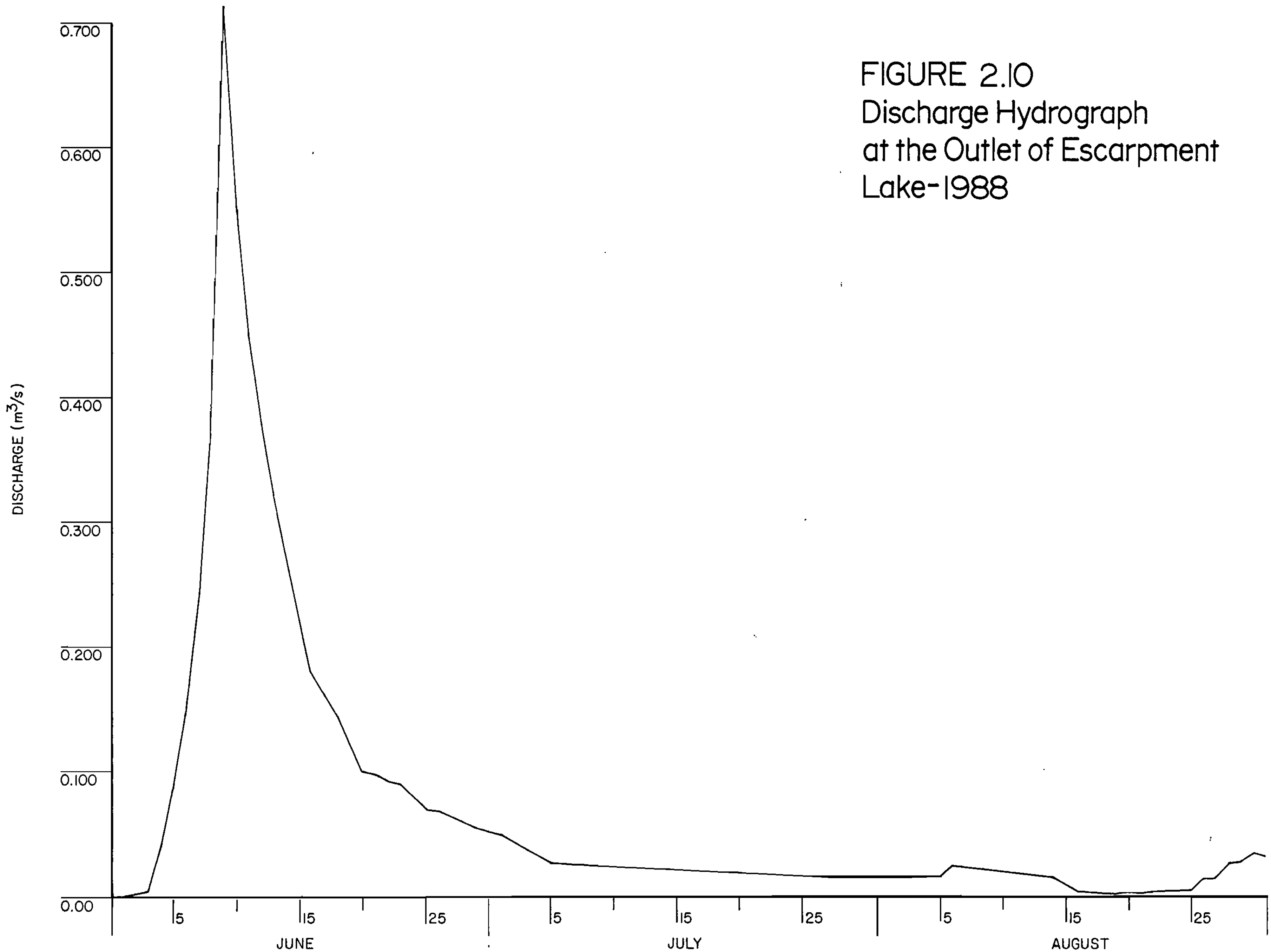


FIGURE 2.10
Discharge Hydrograph
at the Outlet of Escarpment
Lake-1988

TABLE 2.8: RUNOFF VOLUMES[1] FROM HYDROGRAPHS MEASURED AT LAKE OUTLET

Watershed	Runoff Volume (m^3)
Cirque	1.1×10^5
Pointer	1.7×10^7
Jaeger	8.2×10^6
Escarpment	5.5×10^5
Ridge	3.8×10^5
Skinny	1.8×10^7

[1] For the period of 08 June to 31 July 1988.

TABLE 2.9: TEMPERATURE AND PRECIPITATION NORMALS AT BAKER LAKE (1951-1980)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature (°C)													
Mean	-33.0	-32.6	-27.9	-17.3	-6.4	4.1	11.0	9.7	2.3	-7.7	-20.3	-28.2	-12.2
Maximum	-29.5	-29.2	-23.7	-12.5	-2.6	7.9	16.0	13.8	5.3	-4.4	-16.4	-24.7	-8.3
Minimum	-36.4	-36.0	-32.0	-22.1	-10.2	0.2	6.0	5.5	-0.7	-11.0	-24.0	-31.6	-16.0
Precipitation (mm)													
Rainfall	0.0	0.0	0.0	0.4	5.9	18.1	38.1	36.9	31.4	7.5	T	T	138.3
Snowfall	8.0	5.4	8.3	13.6	6.3	2.8	0.0	0.4	5.9	23.2	17.4	8.7	100.0
Total Precipitation	7.7	4.9	7.6	13.8	12.0	20.9	38.1	37.3	37.0	30.6	16.9	8.2	234.6

T = Trace, less than 0.1 mm of rain or less than 0.1 cm of snow.

TABLE 2.10: PRECIPITATION AND AIR TEMPERATURE RECORDS FOR 1988 AT BAKER LAKE

1988 Mean Monthly Air Temperatures (^oC)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-34.2	-33.5	-25.6	-15.7	-8.5	4.8	11.6	10.6	4.3	-6.3	-22	-29.9

Rain Events Occurring from June to August 1988

Date		Amount of Rain (mm)
June	03	11
	09	2.4
	10	15
	16	0.4
	29	0.4
	30	7.6
July	04	4.8
	20	0.8
	21	0.6
	22	10
	23	13.8
	27	6.4
	28	1.6
	29	0.4
August	02	1.8
	04	3.2
	05	5.8
	06	0.8
	08	0.2
	13	0.2
	14	0.8
	22	22
	23	10
	24	0.2
	25	7.4
	26	10

2.5 Calculating Total Available Water

The method used for computing total available water (TAW) from each watershed in Kiggavik is discussed in Section 1.3.2. The following is an outline of how TAW was calculated for one watershed (i.e., Ridge Lake), as TAW will be calculated for the other watersheds in a similar manner.

Total available water was calculated as the sum of:

- o snow water equivalent on the basin and lake (since weirs were located at lake outflows),
- o precipitation (occurring after the time the snow surveys were done to just before the beginning of the melt period), and
- o active layer melt from the basin.

2.5.1 Snow Water Equivalent

Two snow surveys were carried out on the Ridge Lake watershed on June 1/88 (Table 2.7). Mean water equivalent was 0.08 m. The total area of the basin is 2.3×10^6 m^2 and lake is 1.7×10^5 m^2 (Table 1.1). The volume of water in the snowpack was computed as the product of basin area and mean water equivalent (MWE) (for the basin), and lake area and MWE (for the lake). It was assumed here that the snow depth on the basin was similar to that on the lake. Since the area is generally flat, this may be a reasonable assumption. So, for Ridge Lake, the total volume of water available from the basin was 1.8×10^5 m^3, and from the lake was 1.4×10^4 m^3. The total volume available from the snowpack over the entire watershed was computed simply as the sum of these two values, or 1.9×10^5 m^3.

2.5.2 Precipitation

The snowmelt period is defined here from June 8/88 to July 31/88 (Section 2.3). Since the snow survey was carried out at Ridge Lake on June 1/88 (Table 2.7), only those precipitation events occurring after this time but before June 8/88 should be included. Only one (11 mm) event was recorded at Baker Lake during this period (Table 2.10). This event was converted to a volume of water by multiplying by the basin area (for total basin volume) and by the lake area (for total lake volume). Precipitation from the basin was therefore 2.5×10^4 m^3 and 1.9×10^3 m^3 from the lake.

2.5.3 Active Layer Melt

Because it is not possible to assess water volumes lost from the active layer using the available data, it was assumed that only 3 cm of the approximately 1 m deep active layer would be available for runoff. This was then converted to a volume by multiplying by the basin area, to give 6.9×10^4 m^3.

The available water from each component within each watershed is listed in Table 2.11.

2.6 Calculating Net Runoff

The method used for computing net runoff from each watershed is discussed in Section 1.3.2. The following is an outline of how net runoff was computed for each of the six watersheds in Kiggavik where data were available. For consistency, Ridge Lake is given as an example. Runoff from all others are computed in a similar manner.

Net runoff is computed as the difference between: (i) total (hydrograph) runoff (from 08 June to 31 July 1988), and (ii) total precipitation occurring between 08 June and 31 July 1988.

The total volume of water flowing past the outflow weirs from June 8 to July 31/88 may be determined by computing the area under the hydrograph curves for this time period. For Ridge Lake, this volume is 3.8×10^5 m^3. The total precipitation recorded during this period was 0.064 m (Table 2.10), which was converted to a volume of water by multiplying by the basin area (for the basin volume) and by the lake area (for lake volume). For Ridge Lake, these volumes are 1.5×10^5 m^3 and 1.1×10^4 m^3, respectively. Table 2.12 lists outflow volumes and calculated precipitation volumes for each of the six watersheds in Kiggavik.

It should be noted at this point that the calculated precipitation volumes are probably overestimates of what actually reaches the outflow weirs. This is because a portion of the incident rainfall will be intercepted or absorbed by the vegetation. Because no

TABLE 2.11: TOTAL AVAILABLE WATER (m^3) FROM SELECT WATERSHEDS IN KIGGAVIK DURING SNOWMELT

Watershed	Snow Water Equivalents		Precipitation Inputs		Active Layer Melt	Total Available Water
	Basin	Lake	Basin	Lake		
Ridge	$1.8x10^5$	$1.4x10^4$	$2.5x10^4$	$1.9x10^3$	$6.9x10^4$	$2.9x10^5$
Pointer	$4.9x10^6$	$2.2x10^5$	$9.0x10^5$	$4.1x10^4$	$2.5x10^6$	$8.6x10^6$
Jaeger	$3.9x10^6$	$2.0x10^5$	$6.2x10^5$	$3.1x10^4$	$1.7x10^6$	$6.5x10^6$
Skinny	$1.6x10^7$	$2.6x10^5$	$1.3x10^6$	$2.2x10^4$	$3.7x10^6$	$2.1x10^7$
Cirque	$8.3x10^4$	$4.2x10^3$	$1.2x10^4$	$6.2x10^2$	$3.3x10^4$	$1.3x10^5$
Escarpment	$2.2x10^5$	$1.2x10^4$	$2.6x10^4$	$1.4x10^3$	$7.2x10^4$	$3.3x10^5$

TABLE 2.12: CALCULATION OF NET RUNOFF (m^3) FROM SELECT WATERSHEDS IN KIGGAVIK AS THE DIFFERENCE BETWEEN OUTFLOW VOLUMES AND PRECIPITATION INPUTS DURING THE MELT PERIOD

Watershed	Outflow Volumes (at Weir)	Precipitation Inputs During Melt Period: Basin	Precipitation Inputs During Melt Period: Lake	Net Runoff
Ridge	$3.8x10^5$	$1.5x10^5$	$1.1x10^4$	$2.2x10^5$
Pointer	$1.7x10^7$	$5.2x10^6$	$2.4x10^5$	$1.2x10^7$
Jaeger	$8.2x10^6$	$3.6x10^6$	$1.8x10^5$	$4.4x10^6$
Skinny	$1.8x10^7$	$7.8x10^6$	$1.3x10^5$	$1.0x10^7$
Cirque	$1.1x10^5$	$7.0x10^4$	$3.6x10^3$	$3.6x10^4$
Escarpment	$5.1x10^5$	$1.5x10^5$	$8.3x10^3$	$3.5x10^5$

reasonable data were available on interception rates in this area, this point is simply noted.

2.7 Calculating Water Losses By Evapotranspiration

2.7.1 Thornthwaite

The method used for computing evapotranspirational water losses using Thornthwaite is discussed in Section 1.3.2. Mean monthly air temperatures for 1988 are the only data required for this exercise. These are given in Table 2.10.

For mean monthly air temperatures less than $0^{o}C$, the Thornthwaite method assumes no evapotranspiration. The calculated annual heat index (I) is therefore 8.13. The constant a is then 0.64 and Et for June and July is 4.98 cm/mo and 8.77 cm/mo respectively. The correction factor for the Baker Lake site is 1.56 and 1.55 for June and July respectively (Dunne and Leopold, 1978). Potential evapotranspirational (PET) losses for these months are therefore 7.7 cm/mo and 13.6 cm/mo respectively. By similar calculations, PET losses for August and September are 9.5 cm and 4.8 cm, respectively. Total seasonal PET losses are therefore approximately 36 cm.

The limited available data restrict calculation of actual evapotranspirational losses (AET), which are most likely smaller than PET rates. Calculated water losses by ET are therefore upper-limit values. These losses (cm/mo) are then computed to volumes of water by multiplying with basin areas. These are given for each of the six watersheds in Kiggavik in Table 2.13.

2.7.2 Blaney-Criddle

The method for computing evapotranspirational water losses by the Blaney-Criddle method is discussed in Section 1.3.2. Only the mean monthly air temperatures for June and July 1988 are required. These are given in Table 2.10.

For this exercise it was assumed that the crop factor (k) was equal to unity, and that the monthly fraction of daylight hours (d) was 0.124 (Dunne and Leopold, 1978). Calculated water losses by Et for June and July are 4.98 cm/mo and 10.0 cm/mo respectively. PET

TABLE 2.13: WATER LOSSES FROM SELECT WATERSHEDS IN KIGGAVIK BY EVAPOTRANSPIRATION USING THE THORNTHWAITE METHOD

Watershed	Water Losses by Evapotranspiration (m^3) June	July	Total Water Loss
Ridge	$1.8x10^5$	$3.1x10^5$	$4.9x10^5$
Pointer	$6.3x10^6$	$1.1x10^7$	$1.7x10^7$
Jaeger	$4.3x10^6$	$7.6x10^6$	$1.2x10^7$
Skinny	$9.4x10^6$	$1.7x10^7$	$2.6x10^7$
Cirque	$8.5x10^4$	$1.5x10^5$	$2.4x10^5$
Escarpment	$1.8x10^5$	$3.3x10^5$	$5.1x10^5$

losses for August and September are 9.2 cm and 4.7 cm, respectively. Total seasonal losses are therefore 29 cm. These values are similar to those computed using Thornthwaite (Section 2.7.1).

2.7.3 Checking The Validity of Thornthwaite and Blaney-Criddle Equations

Estimates of water loss by evapotranspiration were made in the Kiggavik area in June and July of 1982 and 1983 by Roulet and Woo (1986). They estimated evaporation rates using both evaporation pans and the Bowen-ratio energy balance approach (Price and Dunne, 1976).

Mean monthly air temperatures for these periods, recorded at Baker Lake, are given in Table 2.14. Using the Thornthwaite equation (Section 2.7), PET losses for June and July 1982 were 5.9 cm/mo and 11.2 cm/mo respectively. The Blaney-Criddle equation resulted in 6.5 cm/mo and 9.5 cm/mo respectively. Total ET losses (sum of June and July values) were 17.1 cm and 16.0 cm using the Thornthwaite and Blaney-Criddle equations respectively. Both of these values compared well with the 18.3 cm measured in Kiggavik during this same period (Roulet and Woo, 1986).

By similar calculations, total ET losses for June and July of 1983 were 20.5 cm by Thornthwaite and 13.7 cm using the Blaney-Criddle equation. The ET value measured within Kiggavik during this period was 22.3 cm (Roulet and Woo, 1986).

The water loss by ET estimated using both the Thornthwaite and Blaney-Criddle equations appear to give reasonable estimates of measured values. Either results could thus be used for the following analysis, but since the Thornthwaite estimates were slightly closer to the measured values, they will be used for the following analysis.

TABLE 2.14: MEAN MONTHLY AIR TEMPERATURES RECORDED AT BAKER LAKE IN 1982 AND 1983

Month	1982 (^{o}C)	1983 (^{o}C)
January	-37.8	-31.0
February	-32.5	-34.7
March	-29.8	-28.1
April	-20.8	-18.7
May	-6.2	-11.3
June	3.1	5.1
July	11.0	9.8
August	9.4	9.6
September	1.8	5.0
October	-4.8	-6.0
November	-25.6	-16.4
December	-31.6	-29.1

3.0 SURFACE WATER HYDROLOGY: INTERPRETATION OF THE DATA

3.1 Basin Responses to Snowmelt

The watershed runoff response ratios are a good measure of how responsive the basin is to spring melt. Response ratios are computed as net runoff (Section 2.6) divided by the total available water (Section 2.5). The total available water and net amounts of runoff are listed, for the six watersheds in Kiggavik, in Table 3.1. Response ratios range from 0.28 (for Cirque Lake) to 1.4 (for Pointer Lake). Because the Cirque Lake watershed is so small and local relief so great, there is a high degree of uncertainty in snow pack response. Cirque Lake has a large snow drift area in its basin which may never melt during some years, thus prolonging snowmelt response. Pointer Lake, on the other hand, is in a large flat basin where snowmelt occurs relatively rapidly and completely. A good estimate of basin and lake areas is essential for this analysis because all equivalent water depths are converted to volumes by multiplying with basin and lake areas (see Section 1.3.2).

If these six watersheds are representative of the entire Kiggavik region, then an average response ratio for these watersheds should approximate an average for the region. The mean response ratio was 0.78 (Table 3.1), indicating that approximately 80% of the total available water leaves the region as runoff, leaving about 20% for evaporation (evaporation and transpiration) or storage.

Roulet (1985) provided a review of runoff ratios, defined here as total runoff divided by total precipitation, for Arctic watersheds. He found mean response ratios for the central Keewatin were between 0.60 to 0.75. These ratios are not quite the same as those computed for the snowmelt period (this report). The analysis for this report has considered only the melt period (as it is when much of the water leaves the watersheds) and so calculated response ratios will probably be higher than those estimated by Roulet (1985). Based on this fact, the mean response ratio during the melt period (i.e., 0.78) is reasonable compared with those computed by Roulet (1985) for the region.The above calculations have shown that approximately 80% of the available water from Kiggavik leaves the region as runoff. It is also necessary to know how quickly this volume leaves the area. This may be approximated by the time it takes for the hydrograph to reach peak discharge, and can be measured directly from the hydrographs (Figures 2.5 to 2.10).

TABLE 3.1: CALCULATION OF MELT RESPONSE RATIOS FOR SELECT WATERSHEDS IN KIGGAVIK AS NET RUNOFF DIVIDED BY TOTAL AVAILABLE WATER

Watershed	Total Available Water During Melt (TAW) (m^3)	Net Runoff During Snowmelt (NRO) (m^3)	Melt Response Ratio (NRO/TAW)
Ridge	$2.9x10^5$	$2.2x10^5$	0.76
Pointer	$8.6x10^6$	$1.2x10^7$	1.4
Jaeger	$6.5x10^6$	$4.4x10^6$	0.68
Skinny	$2.1x10^7$	$1.0x10^7$	0.48
Cirque	$1.3x10^5$	$3.6x10^4$	0.28
Escarpment	$3.3x10^5$	$3.5x10^5$	1.1

These data show that, on average, it takes about 5 days for the maximum discharge to be reached. This suggests that, not only are very large volumes of water lost during the melt period, but much of it occurs within a short period of time. The Kiggavik area is thus highly responsive during the snowmelt period.

3.2 Proportional Losses of Available Water

The hydrologic character of a region may be determined by considering the amount of available water lost from the area by various pathways. This can best be accomplished by calculating water balances for each watershed (i.e., by comparing total water inputs and outputs). This can be computed for only the snowmelt period and on a seasonal basis.

3.2.1 Water Balance for the Snowmelt Period

The total water inputs (i.e., the total available water) are listed, for each watershed in Kiggavik, in Table 3.1. Water losses as runoff are listed in Table 3.1 and as evapotranspiration in Table 2.13. Summary values for each of these components are given, for the six watersheds in the area, in Table 3.2.

The results show that, for all watersheds during the snowmelt period, total water inputs are less than the total water outputs (Table 3.2), suggesting that either additional water is leaving the watersheds (i.e., from storage in snow drifts that may never melt or annual fluctuations in the depth of the active zone), or that there are errors in estimating water inputs and outputs. A discussion of potential sources of errors in the data collection and analysis is warranted and will follow (see Section 3.6).

3.2.2 Seasonal Water Balance

Seasonal water balances can be computed for each watershed as the difference between total water inputs and total outputs, for the period of 01 June to 31 August 1988. Although the thaw period lasts into September, runoff data were only available to 31 August, which limited the extent of this analysis.

Total (seasonal) water inputs to Kiggavik are calculated as the sum of snow water equivalent and precipitation occurring through the season. Total water outputs are by

TABLE 3.2: CALCULATION OF A WATER BALANCE FOR WATERSHEDS IN KIGGAVIK AS THE DIFFERENCE BETWEEN TOTAL WATER INPUTS (Total Available Water) AND OUTPUTS (Net Runoff and Evapotranspiration) DURING THE MELT PERIOD

	Water Inputs (I)	Water Outputs (O)		
Watershed	Total Available Water at Melt (TAW) (m^3)	Net Runoff (NR) (m^3)	Evapotranspirational Losses (ET) (m^3)	Net Change (I-O) (m^3)
Ridge	2.9×10^5	2.2×10^5	4.9×10^5	-4.2×10^5
Pointer	8.6×10^6	1.2×10^7	1.7×10^7	-2.0×10^7
Jaeger	6.5×10^6	4.4×10^6	1.2×10^7	-9.9×10^6
Skinny	2.1×10^7	1.0×10^7	2.6×10^7	-1.5×10^7
Cirque	1.3×10^5	3.6×10^4	2.4×10^5	-1.5×10^5
Escarpment	3.3×10^5	3.5×10^5	5.1×10^5	-5.3×10^5

evapotranspiration and runoff. Values for each of these pathways have been computed for each watershed (Table 3.3).

The results are similar to those computed only for the snowmelt period, in that seasonal total water outputs exceed total inputs, suggesting either water loss from storage or errors in estimating water inputs and outputs.

The only information that can be inferred from these results is that total water inputs and outputs from Kiggavik are large and probably equal on an annual basis. Runoff losses probably demand much of the available water, although ET (evaporation and transpiration) losses may also be significant.

3.3 Basin Responses to Summer Rains

The Kiggavik region is highly responsive to snowmelt, with large volumes of water leaving the area by runoff over a very short period of time (Section 3.1). The purpose of this section of the report is to see how responsive the region is to summer rain events.

During the summer period, the snow has melted and the active layer is in the order of 1 m deep. Evapotranspiration is reduced because of an increase in cloudy skies and a general shortening of daylight hours. Hydrographs from each of the watersheds show rapid increases towards the middle-to-end of August/88 (Figures 2.5 to 2.10). The amplitude of these hydrograph rises are very much less than for the snowmelt period.

The snowmelt response (peak discharge) ranges from 7 times (for Cirque Lake) to 130 times (for Jaeger Lake) greater than the summer runoff peaks. Snowmelt peaks are, on average, 50 times greater than the summer runoff peaks. This is obviously related to the much greater volume of water available for runoff during the spring melt period. It is evident, however, that late summer rain events can cause sporadic high flow events during this period.

3.4 Mechanisms of Runoff

Although the precise mechanisms of runoff cannot be defined, they may be inferred from hydrographs and knowledge of site conditions. The following is a speculative summary of likely flow mechanisms operating throughout the year in the Kiggavik region.

TABLE 3.3: SEASONAL WATER BALANCES (01 JUNE TO 31 AUGUST 1988)

	Total Water Inputs (m^3)		Total Water Losses (m^3)		
Watershed	Snow Water Equivalent	Rain	ET	Runoff	Inputs-Outputs
Ridge	$2.0x10^5$	$3.5x10^5$	$7.8x10^5$	$3.8x10^5$	$-6.5x10^5$
Pointer	$5.2x10^6$	$1.2x10^7$	$2.7x10^7$	$1.8x10^7$	$-2.8x10^7$
Jaeger	$4.1x10^6$	$8.3x10^6$	$1.8x10^7$	$8.3x10^6$	$-1.4x10^7$
Skinny	$1.6x10^7$	$1.7x10^7$	$3.7x10^7$	$1.8x10^7$	$-2.2x10^7$
Cirque	$1.1x10^5$	$1.7x10^5$	$3.7x10^5$	$1.3x10^5$	$-2.2x10^5$
Escarpment	$2.3x10^5$	$3.5x10^5$	$7.8x10^5$	$5.9x10^5$	$-8.2x10^5$

3.4.1 Spring Snowmelt

During the spring melt period, large volumes of water are rapidly released to lakes and streams. This is evident by the very large peaks recorded at lake outlets. The almost instantaneous response of watersheds to this period suggests that much of the water moves from watersheds as overland flow, occurring when the rate of meltwater rate exceeds the IC of the soil. Much, if not all, of the soil is frozen, or near-frozen, at this time, thereby significantly reducing the IC of the soil. Snowmelt occurs quite rapidly and at a rate that exceeds the soil's IC, and water leaves the watershed by overland flow. Response times for subsurface flows are very much lower than for overland flows (Dunne and Black, 1970ab), further suggesting an overland flow mechanism for peak discharges during spring runoff.

The recession limb of the melt hydrograph becomes progressively less influenced by overland flows as the active layer melts and the ground can store more water (i.e., the IC of the soil increases). For this period, water infiltrating into the soil can encounter a layer of low permeability (i.e., the permafrost surface) and a saturated layer can form atop this impermeable surface. Once a critical depth of water is reached (defined by Darcy's Law), subsurface (saturated) flow can occur within the soil to the lakes or streams. Subsurface flows are very much slower than surface routes because water must first percolate into the soil and be stored before the saturated lense can develop. Subsurface flow can only occur if the saturated lense develops. As an increasing amount of water infiltrates into soils, or as the active layer deepens, the subsurface pathway contributes larger amounts of water to surface water bodies. The subsurface stormflow (SSSF) generally contributes to much of the hydrograph recession.

3.4.2 Early and Mid-Summer

During the early-to-mid summer period, there are no major hydrograph events (Figures 2.5 to 2.10). The hydrograph continues to recede as less water is available from the subsurface pathway (because the active layer can store a larger amount of water as it deepens).

3.4.3 Late Summer

During the late summer period, a number of sporadic (but low-volume) hydrograph peaks are evident (Figures 2.5 to 2.10). At low-lying areas, the capillary fringe (or tension saturated zone) and/or the water table are very near the ground surface because of the expanding active layer. As a result, a relatively small rain event can infiltrate into the soil and very quickly bring the capillary fringe and/or water table to the ground surface (Abdul and Gillham, 1984). When this occurs, a seepage face develops along the ground surface and saturation overland flow (SOF) can occur. A seepage face at atmospheric pressure results in outwardly-directed hydraulic gradients from the soil (Gillham, 1984), thereby causing water from within the soil to quickly leave by this route. In addition, any precipitation falling directly onto the saturated areas can move as overland flow to surface waters. The mechanisms of return flow and precipitation onto saturated areas are known collectively as saturation overland flow.

Speculative Summary

During the spring snowmelt period, overland flow (HOF), initiated when meltwater rates exceed the frozen soil IC, is responsible for hydrograph peaks, while subsurface stormflow (SSSF), initiated after a saturated lense develops above an impermeable frost surface in the soil, generates the recession limb of the hydrograph. During early-to-mid summer, few events are recorded on hydrographs because of evapotranspirational losses because there is much storage within the system (wetlands and active layer and because of low rainfall). The rainy period of late summer can cause sporadic high flows by saturation overland flow (SOF), that is, by development of a seepage face in low-lying areas. All of the above mechanisms result in a rather complex, yet hydrologically responsive, system within Kiggavik.

3.5 Regional Discharges From Kiggavik

3.5.1 Annual Discharges

The water budgets of several local watersheds must be known for estimating dilution and dispersion of any liquid discharges, and for predicting impacts in watersheds that are to be affected by site development. On an annual basis, water budgets can be estimated from data on:

- o total annual precipitation,
- o total watershed area, and
- o watershed response ratio.

The total annual precipitation for 1988 was 312 mm, the mean response ratio for watersheds in Kiggavik is 0.78, and watershed areas are given in Table 1.1. Calculated discharges for key watersheds in the Kiggavik region are shown in Figure 3.1. These calculated budgets are in reasonable agreement with Environment Canada (1988) streamflow data for the Anigaq River downstream of Audra Lake. This station had a mean discharge of 18 m^3/s over 12 months. Using the above technique, this location is estimated to have a mean annual discharge of about 24 m^3/s.

The discharge from the entire Kiggavik study site, defined as the outflow from Judge Sisson's Lake into the Anigaq River, averages 5 m^3/s on an annual basis. This represents 12% of the total flow of the Anigaq River at the point of discharge into Baker Lake. This information on the annual hydrologic response of the Kiggavik region is critical in evaluating the effects of any site development on local and regional water quality.

3.5.2 Discharges During The Snowmelt Period

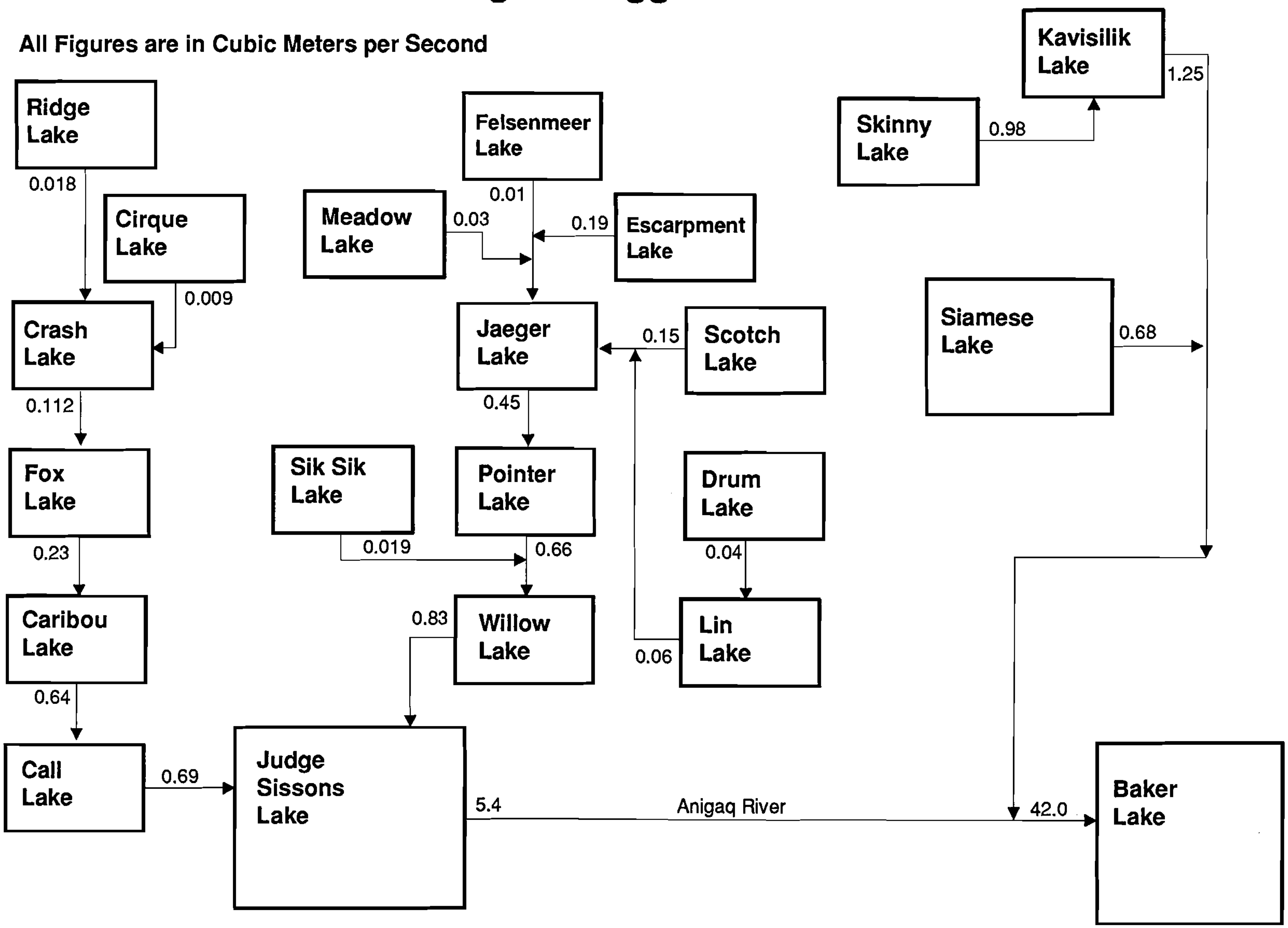
The preceding analysis allowed for determination of regional hydrology on an annual basis. It would be of interest to calculate regional discharges only for the snowmelt period, and to compare these with the annual discharges. Although it is expected that these results will be similar, there is no means of assessing this until the calculations have been made.

Total discharges from Kiggavik during the snowmelt period can be estimated using the values of net runoff computed for the six monitored watersheds. By dividing the net runoff during snowmelt by the watershed areas, a mean value of runoff per unit area can be calculated. This value is 9.8×10^4 m^3/km^2.

The discharge from the entire Kiggavik region during the snowmelt period is therefore 6.7×10^7 m^3, and represents about 13% of the total flow of the Anigaq River at the point of discharge into Baker Lake. This proportion is similar to the annual proportion largely because the snowmelt period dominates much of the hydrologic activity in Kiggavik for the year.

FIGURE 3.1 Schematic Representation of Local Drainage at Kiggavik

All Figures are in Cubic Meters per Second



3.6 Assumptions and Potential Sources of Error

A number of assumptions had to be made for the analysis to be carried out on such a limited data set. There are also potential sources of error in the measurement of various characteristics of the system (i.e., basin and lake areas, weir outflow discharges, etc.). These will be discussed in the following sections.

3.6.1 Basin and Lake Areas

Perhaps the most important source of error in this analysis is the value used for basin and lake areas. Because all water depths were converted to volumes by multiplying with basin and lake areas, any error in estimating these areas will be incorporated into each step of the analysis. As discussed in a previous section, areas were estimated from 1:50,000 topographic maps of the region, and no specific allowance was made for local snow pack anomalies, and so small watershed areas (such as Cirque Lake) may be expected to show significant deviations from the mean for the region. These anomalies are useful, however, in that site modifications such as building construction, pit development, waste rock piles, etc. will all result in local drifting of snow and shift local watershed response from the Pointer Lake response more toward the Cirque Lake basin response.

3.6.2 Baker Lake Data

Although the Baker Lake data have been shown to be similar to estimates made in the Kiggavik site, the relationships are not 1:1 and have been assessed only for 2 months of 2 years. Roulet and Woo (1986) measured various hydrologic and meteorological parameters at a small lake within the Kiggavik region. The representativeness of this one location to the entire region has not been shown. Furthermore, there were no available data with which to compare precipitation inputs. These are likely to be at least as variable between Kiggavik and Baker Lake as air temperature. Since both air temperature and precipitation inputs from Baker Lake had to be used in this analysis, more comparisons between the two locations should be made.

3.6.3 Snow Water Equivalents

Snow water equivalents for each watershed were, in most cases, taken from one snow survey. Certainly a much greater number of transects would be required, at least for the larger watersheds, to more precisely determine the water equivalent. It would also be useful to carry out surveys during the melt period so that direct comparisons could be made between water equivalents and watershed runoff.

It was assumed that the snow water equivalent recorded on basins was the same over the lakes. This was necessary because weirs were located at lake outlets, and so snow on the lakes had to be accounted for. This could be verified with a snow survey across the lake, or eliminated by placing a weir at the lake inlets for those lakes which have defined inlets.

3.6.4 Location of Weirs

It would have been useful to have a weir located at the lake inflow so that discharges from the basin could be measured directly, without having to account for lake effects. Certainly some portion of the lake will store runoff water that it receives from the surrounding basins, introducing a lag time between the onset of melt and the hydrograph response. The volume recorded may also represent an underestimate if significant amounts of water are stored by the lake.

3.6.5 Snowmelt Period and Runoff

It was assumed that the spring melt period started on June 8/88 and continued until July 31/88. Because weirs were located at lake outlets, a significant volume of water may have melted prior to June 8/88 (when the hydrograph first responded). This volume may not have reached the flow monitoring location because of retention on the lake surface. This will introduce a lag time, which will influence the time-to-peak and other hydrologic characteristics of the watershed, such as response ratios. Because of these lags, the Kiggavik watersheds are even more responsive than these data signify, with the responsiveness of each watershed being dependent on variables such as depth, and hence melt time of local snow drifts and lake surface area to watershed ratios.

4.0 PREDICTIONS OF SURFACE WATER RESPONSES DURING SNOWMELT

The preceding analysis has revealed some interesting aspects of the surface water hydrology in Kiggavik. Of particular interest is the fact that snowmelt generates a large and rapid response, and so controls the hydrologic character of the region. This information is critical for evaluating potential effects associated with land use changes.

In most cases, the probable responses to events of varying size and recurrence are a necessary prerequisite for planning purposes. That is, engineering and geomorphic structures are designed to account for system responses to some large infrequent event. The occurrence of these events, and associated system responses, are therefore necessary for practical purposes.

The following is a highly speculative exercise designed for predicting surface water responses (during snowmelt) for snowmelt events with a given recurrence interval. The analysis is based on sound fundamental hydrologic principles, but is extended beyond practical limitations to allow for a full interpretation for predictive purposes.

The analysis is carried out by the following logic and assumptions. Sections 2 and 3 have outlined surface water responses to hydrologic conditions (i.e., snowmelt release) dictated by a total annual precipitation of 312 mm. If the total precipitation inputs were to change (i.e., from one year to the next), then the system responses (to a different volume of snowmelt) would change accordingly. If it were possible to predict the total annual precipitation responsible for a snowmelt event with a given recurrence interval (or probability), then surface water responses to these events could be predicted (using the 1988 responses as a reference).

For this analysis, surface water responses to snowmelt events of a given size will be defined as the total volume of runoff during the snowmelt period.

4.1 Predicting the Total Annual Precipitation Responsible for a Snowmelt Event of a Given Magnitude and Recurrence

As discussed above, system responses to snowmelt events of a given size (and recurrence interval) can be determined if the total annual precipitation, responsible for such events, can be predicted.

It may be necessary at this point to discuss what is meant by a "snowmelt event of a given size and recurrence interval". One may wish to know the hydrologic response to a 50-year snowmelt event. This does not refer to a snowmelt event of a given size occurring once every 50 years, but instead refers to the probability of occurrence of an event of a given magnitude. For a 50-year snowmelt event, the probability of occurrence is 2%. Two 50-year snowmelt events can occur in successive years, although the probability is extremely low. These melt events are generated in years having a given total annual precipitation. The purpose of this exercise is to be able to predict the total annual precipitation responsible for snowmelt events of a given magnitude and return period.

Note that these analyses are generally computed for rain events of a given intensity and duration, but since snowmelt is the dominant hydrologic event of the year in Kiggavik, this technique was modified to account for snowmelt events instead of rain events.

For this exercise, the total annual precipitation is required for all available years of record. Table 4.1 lists total annual precipitation recorded at Baker Lake from 1952 to 1988. The recurrence interval (T) of each precipitation total is computed as follows:

- o all precipitation totals are ranked by size. The largest event is ranked m=1 and the smallest is ranked m=n, where n is the number of years of record;
- o if several precipitation totals are the same, each is assigned the same rank; for example, if three years have the same total precipitation which should have been ranked 4,5,6, the rankings are then 1,2,3,5,5,5,7;
- o a return period (recurrence interval) is computed for each precipitation total as:

$$T = \left[\frac{n+1}{m}\right]$$

The recurrence interval and associated precipitation totals are plotted as natural logarithm of T vs total annual precipitation in Figure 4.1. The relationship is a significant one (r^2=0.91, n=37) although not simply linear. However, a best-fit line can be made for predictive purposes.

TABLE 4.1: TOTAL ANNUAL PRECIPITATION AND RECURRENCE INTERVALS FOR BAKER LAKE RECORDS (1952-1988)

Year	Total Precipitation (mm)	Rank (m)	Recurrence Interval (T)
1952	232	23.0	1.65
1953	207	29.0	1.31
1954	154	37.0	1.03
1955	295	10.0	3.80
1956	183	32.5	1.17
1957	182	34.0	1.12
1958	228	26.0	1.46
1959	247	19.0	2.00
1960	208	28.0	1.36
1961	230	24.0	1.58
1962	250	17.0	2.24
1963	191	31.0	1.23
1964	193	30.0	1.27
1965	176	35.0	1.09
1966	173	36.0	1.06
1967	300	9.0	4.22
1968	274	11.0	3.45
1969	214	27.0	1.41
1970	316	4.0	9.50
1971	250	17.0	2.24
1972	183	32.5	1.17
1973	243	21.0	1.81
1974	264	14.0	2.71
1975	334	3.0	12.67
1976	236	22.0	1.73
1977	363	2.0	19.00
1978	266	12.0	3.17
1979	246	20.0	1.90
1980	250	17.0	2.24
1981	229	25.0	1.52
1982	314	5.0	7.60
1983	265	13.0	2.92
1984	257	15.0	2.53
1985	369	1.0	38.00
1986	312	7.5	5.07
1987	313	6.0	6.33
1988	312	7.5	5.07

Now that the hydrológic inputs associated with snowmelt events of a given return period can be predicted, the system responses to these events can now be determined. The system response was defined as the total volume of water released as runoff during the snowmelt period because snowmelt is the single largest hydrologic event of the year. All other times of the year are comparatively inactive hydrologically.

4.2 Predicting Watershed Discharges in Response to Snowmelt Events of a Given Magnitude and Return Period

Surface water responses to specific snowmelt events will be determined by considering the following information about individual watersheds in Kiggavik:

- o net runoff (calculated as the total discharge through outflow weirs during snowmelt, minus any precipitation occurring during this period);
- o total depth of water available as snowmelt (calculated as the ratio between the total available water and total watershed area);
- o total watershed area (calculated as the sum of basin and lake areas); and
- o total annual precipitation.

Predictive equations can be developed for each watershed in Kiggavik where data are available, and then averaged to allow for prediction of hydrologic responses for the entire Kiggavik region. These equations are most useful for predictive purposes if they are simplified for unit system characteristics. For this exercise, an equation is developed to allow for prediction of total runoff during snowmelt for a unit depth of available water; a unit watershed area, and for 100 mm of total annual precipitation. That depth of total annual precipitation was chosen for simplification of later computations.

For each watershed, the net runoff, total available water and total annual precipitation input are tabulated (Table 4.2). The total volume of runoff during snowmelt is computed for a unit depth of available water; unit watershed area, and for 100 mm of total annual precipitation by dividing the runoff volume by each respective term. For example, the Ridge Lake watershed, having an area of 2.5×10^6 m^2 and 0.12 m of total available water, lost 2.2×10^5 m^3 of water as runoff during the 1988 snowmelt year. The predictive equation would be: $2.2 \times 10^5/0.12/2.5 \times 10^6/3.12$, or 0.24 $m^3/m/m^2/100$ mm. The equations for the other watersheds are as follows:

TABLE 4.2: SUMMARY OF HYDROLOGIC DATA FOR SELECT WATERSHEDS IN KIGGAVIK

Watershed	Net Runoff (m^3)	Total Available Water (m^3)	Total Area (Lake + Basin) (m^2)	Depth of Available Water (m)	Total Annual Precipitation (mm)
Ridge	$2.2x10^5$	$2.9x10^5$	$2.5x10^6$	0.12	312
Pointer	$1.2x10^7$	$8.6x10^6$	$8.6x10^7$	0.10	312
Jaeger	$4.4x10^6$	$6.5x10^6$	$5.9x10^7$	0.11	312
Skinny	$1.0x10^7$	$2.1x10^7$	$1.2x10^8$	0.18	312
Cirque	$3.6x10^4$	$1.3x10^5$	$1.2x10^6$	0.11	312
Escarpment	$3.5x10^5$	$3.3x10^5$	$2.5x10^6$	0.13	312

- o Ridge: 0.24 $m^3/m/m^2/100$ mm
- o Pointer: 0.44 $m^3/m/m^2/100$ mm
- o Jaeger: 0.22 $m^3/m/m^2/100$ mm
- o Skinny: 0.15 $m^3/m/m^2/100$ mm
- o Cirque: 0.09 $m^3/m/m^2/100$ mm
- o Escarpment: 0.35 $m^3/m/m^2/100$ mm

The mean coefficient for these watersheds (representing a mean for the entire Kiggavik region) is 0.25.

The surface water response to a 50-year snowmelt event may thus be determined for a given watershed in Kiggavik (or for the entire region) as follows.

A 50-year snowmelt event corresponds to an annual total precipitation of about 370 mm (Figure 4.1). Supposing that the watershed of interest is Judge Sisson's Lake, the total area is 6.8×10^8 m^2 (Table 1.1). The depth of available water has to be estimated and, based on the 30-year normals, a depth of 0.10 m is appropriate. The total runoff from Kiggavik during snowmelt for hydrologic conditions associated with a 50-year snowmelt event is therefore calculated as:

$$0.25 \times 0.10 \times 6.8 \times 108 \times 3.7 = 6.3 \times 10^7 \ m^3$$

This value is surprisingly similar to the estimated discharge from Kiggavik calculated in Section 3.5.2, suggesting that the snowmelt event of 1988 was similar in magnitude to the 50-year snowmelt event. This is not a poor assumption as the 1988 total annual precipitation was almost 80 mm higher than the 30-year normals for Baker Lake.

5.0 SUMMARY AND IMPLICATIONS FOR SITE DEVELOPMENT

The preceding analysis has outlined some important features of the surface water hydrology in Kiggavik. There are generally three hydrologic periods during the year and each is characterized by distinct responses and flow mechanisms. The most important of these, hydrologically, is the spring snowmelt period, in which large volumes of water are lost from watersheds over very short periods of time, probably by overland flow. Response ratios are very high at this time, indicative of an overland flow mechanism. Early and mid summer is a time with minimal amounts of runoff because of evaporative losses and water storage in the expanding active layer and in wetlands. Late summer is a period of sporadic heavy rain events and, because of restricted evapotranspiration and thawed soils, surface waters can be quite responsive to these rain events by a saturated overland flow mechanism.

This discussion of flow mechanisms is highly speculative, because detailed hydrologic investigations have not been made in the area to support such statements. However, they are based on fundamental knowledge of site conditions and measured hydrologic responses, and so are probably reasonable estimates.

A model is presented for predicting runoff during the snowmelt periods in response to snowmelt events of a given return period. This analysis is also speculative, but offers approximations in an area with limited data. Snowmelt runoff can be predicted if the watershed area and total annual precipitation are known.

The rapid response of the Kiggavik region and the large volumes of water released during snowmelt, suggests that much of the region is hydrologically connected, so that changes in one watershed will likely affect all others. This is especially relevant for the area just west of Pointer Lake, which is characterized by a large number of small lakes and wetlands. In terms of site development, there are a number of points that are deserved of attention. Because the region is highly responsive during the snowmelt period, any activities that involve changing surface conditions within a watershed should be avoided during this time. If significant changes are made during this period, hydrologic conditions throughout the region will be affected, largely because the hydrologic system is probably interconnected. The same applies, although much less so, for very late summers, when the surface water hydrology is responsive to rain events. The most appropriate time to develop site conditions is either after the late summer period or during the early-to-mid summer (i.e., after the snowmelt period). Hydrologic activity is reduced and changes to site conditions will probably have only local effects. The significant point here is to avoid any activity during the snowmelt period. After this period, the Kiggavik region is hydrologically much less responsive to precipitation inputs and so site development will likely cause less damage than during the snowmelt period.

Site modifications such as building construction, pit development, waste rock piles, etc. will result in local drifting of snow. This will still allow for runoff peaks, although volumes will be reduced, as the snowmelt period is extended.

As a final note, it should be stated that much of this analysis is based on a very limited data set. Little information was available on actual site conditions, and so many conclusions are highly speculative. Assumptions and potential sources of error have been discussed, and data required for a more thorough analysis have been outlined. In the absence of a complete data set, the analysis in this report does offer an approximation to surface water conditions within the Kiggavik region.