ESTIMATES OF SNOWMELT RUNOFF

IN THE

EASTERN ARCTIC

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by

A.R. Vieira-Ribeiro, B. Eng.

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AUTHOR : Augusto R. Vieira-Ribeiro, B. Eng.

SUPERVISOR : Dr. Wm. James

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ABSTRACT :

The purpose of this thesis is to set up simple computational models which require limited climatical data as input, in order to provide estimates of runoff during the spring-summer melt season for drainage basins in the Baffin Region. Due to the limitation of meteorological data in Arctic areas, the models were developed with only the major components of the hydrologic cycle, the components chosen on a logical, physical basis with the restriction that the number of parameters be kept to a minimum.

The models were used to generate daily average flows for the Duval River drainage basin. Unlike southern areas the major contribution of precipitation is snow which is retained until the ablation season which lasts from one to four months in Arctic areas. Observed and simulated results were found to be in agreement in terms of both volume and time distribution.

As the optimised parameters are kept to a minimum it is hoped that it can be expanded for use on ungauged basins.

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Finally the author would like to acknowledge the encouragement provided by his wife for the final completion of the dissertation.

DEDICATION

This thesis is dedicated to the Inuit people of Baffin Island where there is a scarcity of water. The author was motivated to undertake this study in the hope of lessening some of the disparity between the Inuit and non-Inuit people. This study covers only a small part of the entire hydrological system. However, the inventory process involved in this thesis is an important start in the collection of the information required for a concrete development program. A possible development program would be a regular and continuous water system which the Inuit people could avail themselves of, if they so desire.

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CHAPTER I. INTRODUCTION

1.1 Purpose of Study

The Canadian Arctic has long attracted explorers and traders, and the fur trade particularly has brought enduring contact between the Inuit (Eskimo) and Kabloona (non-Eskimo). With this contact the Inuit way of life has changed in two ways which are important to this study. First, increase in health care and the adoption of western standards has caused a population increase. Second, establishment of Hudson Bay Company tradeposts attracted Inuit camps around them. The once small independent camps grew with governmental encouragement to large settlements, now highly dependent upon governmental economic assistance. This increase in population and concentration in permanent settlements has led to many local problems, one of which is that of insufficient water supply.

Perhaps the social impact of western technology on the north should be given much greater attention in the planning stages. The growth in settlement population increases the burden of water supply in the Canadian Arctic which has a low mean annual precipitation. It is unfortunate that little progress has been made to alleviate the water shortage, even though the problem has existed for many years. However, it can be foreseen that much development will take place in Arctic areas. The resources in the north appear more promising as the natural resources further south are depleted at an ever increasing rate.

Water supply is just one problem facing northern settlements. The collection and distribution of water to the community is a major task of the settlements [Heinke and Deans, 1] . Few studies have been made on the hydrology of Arctic rivers [Cogley and McCann, 7] . The collection of data began, with very limited funds in 1972 on the Duval River (fig. 1.2). Extension to Apex River and Broughton Creek in 1973 was made possible by a National Research Council grant and assistance from the Department of Environment who supplied four Stevens A-7, water level recorders (fig. 1.3). For location of all three sites see fig. 1.1.

The purpose of this study is to collect data for, and to develop a disaggregated deterministic and a first order linear regression snowmelt runoff model. The models will be elaborated in later studies as more data are collected. With the present short data base further refinements would be unrealistic [James, 40] . These models are to predict daily flows, given the precipitation on the area in the past winter and the expected average daily temperatures. Such models would then make it possible for engineers and planners to study different rivers in the area, for water supply, power generation potential and design flood parameters.

Since there is little hydrometeorological data available in the Eastern High Arctic the models should clearly require a minimum input of topographic parameters, and meteorological data. It should be noted that there is at present no acceptable method for estimating the engineering hydrology of catchments in the Baffin region, and it is expected that design engineers would use these early models appropriately.

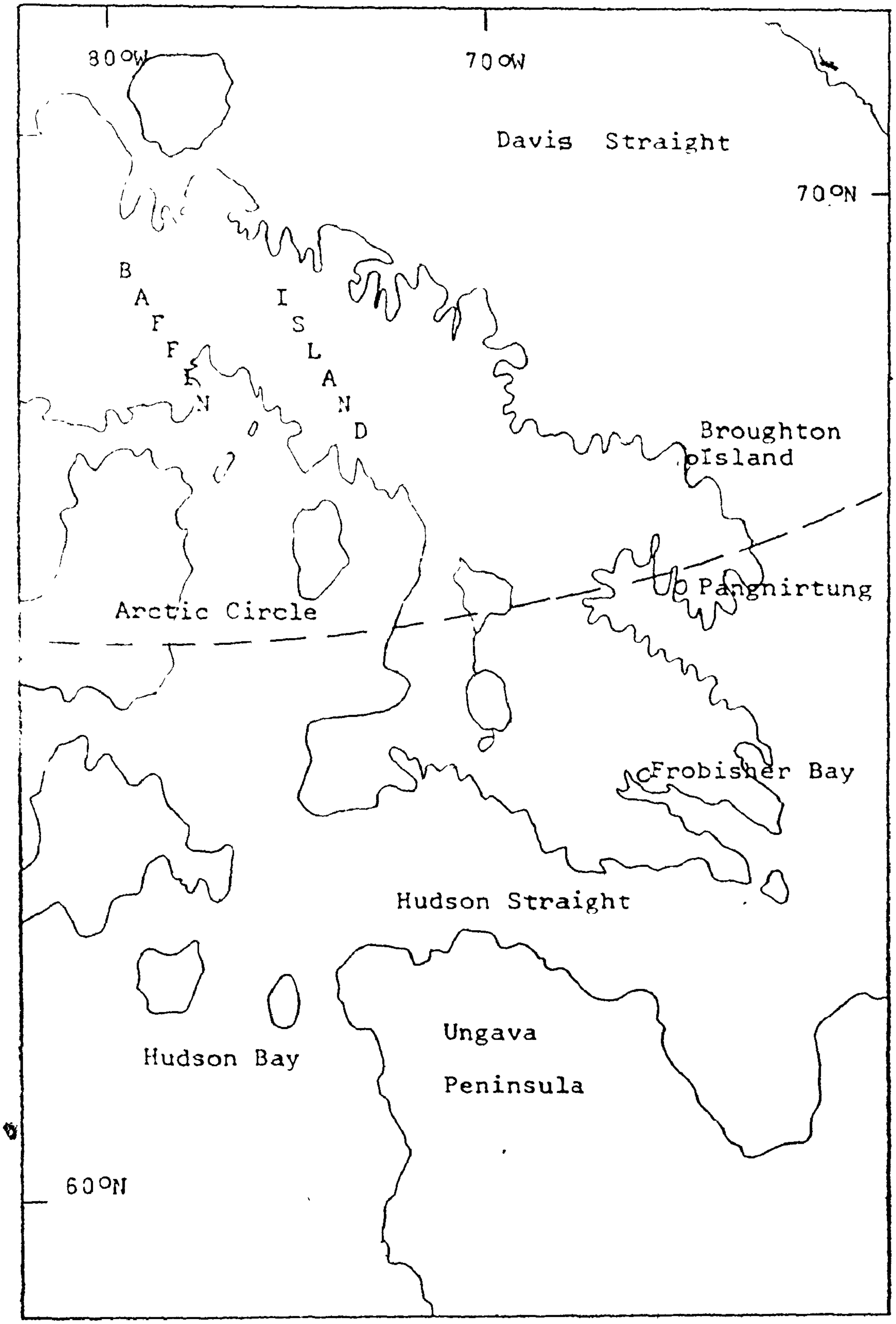
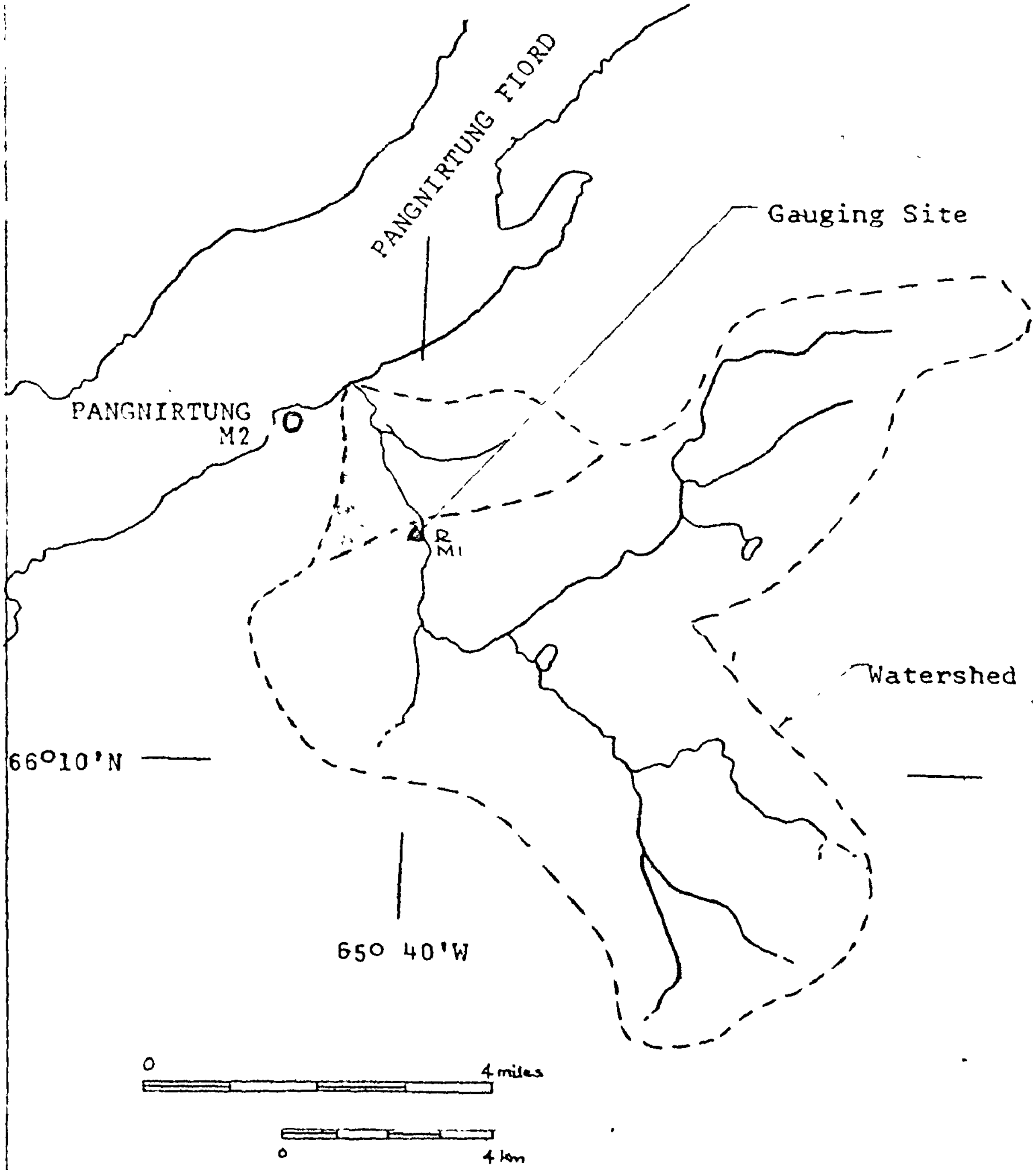


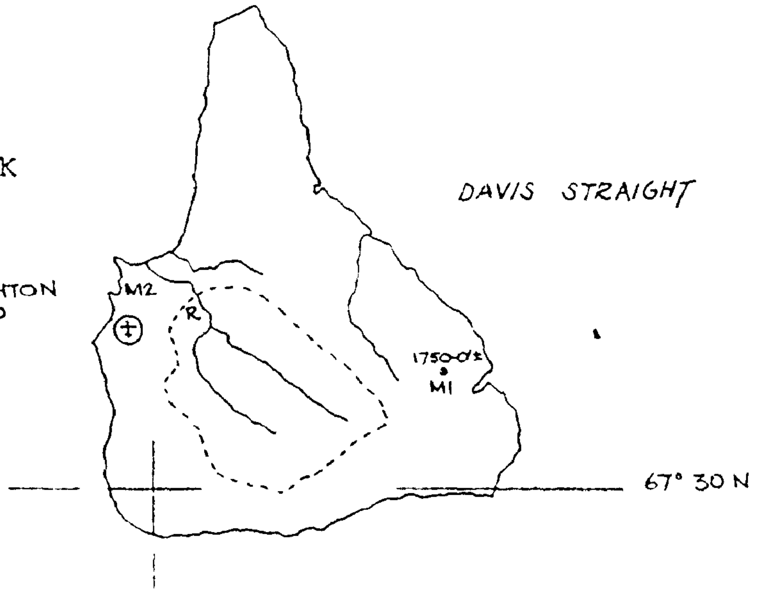
FIG. 1.1 LOCATION OF STUDY CATCHMENTS



M1 - Weather Data Collected in the field
M2 - A.E.S. Automatic weather station
Area of catchment = 39.3 sq. miles, 101 km^2
Area from recorder = 35.4 sq. miles, 92 km^2

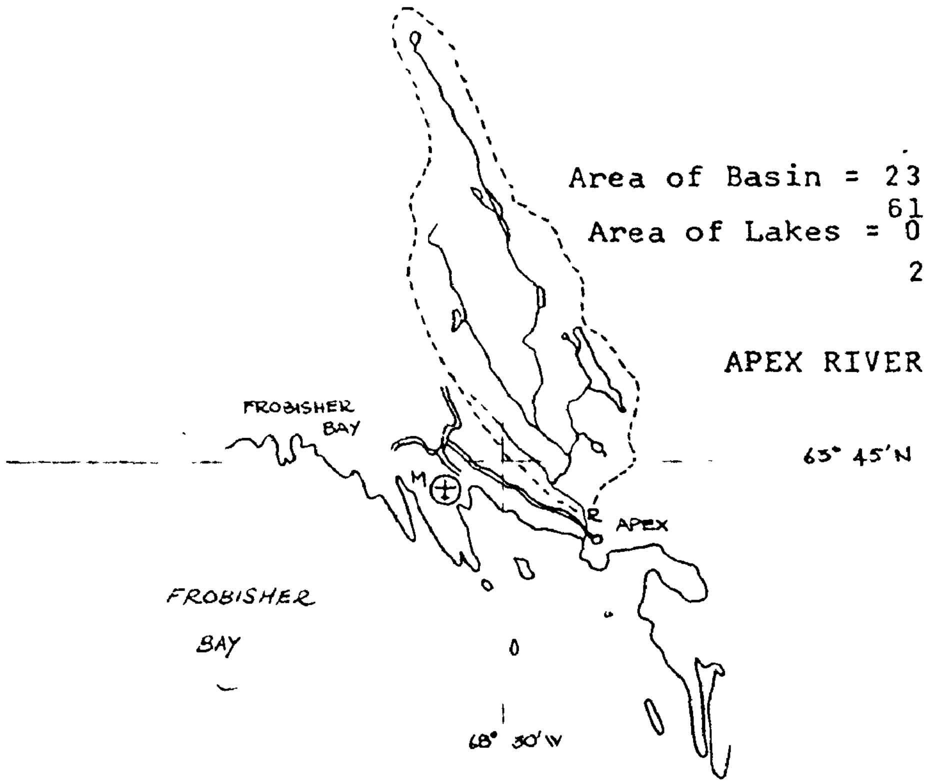
FIG. 1.2 DUVAL RIVER CATCHMENT

FIG. 1.3 BROUGHTON CREEK CATCHMENT



R - Recorder
M - AES Station
M1 - DEW Line Station
M2 - INSTAAR Station

Area of Basin = 11.83 sq. miles
30.6 km^2



Area of Basin = 23.8 miles^2
61.6 km^2
Area of Lakes = 0.8 miles^2
2.1 km^2

APEX RIVER CATCHMENT

1.2 Review of Design Problems

Arctic hydrology is dominated by a short snowmelt runoff season. Within three months 80% - 90% of winter precipitation in the form of snow melts and runs off; most flow in Arctic rivers occurs in the summer months, June to August. This gives rise to three basic problems in engineering design.

The first problem is water supply in Arctic settlements. Abstraction of water from rivers can take place only from spring thaw to fall freeze. The winter supply is therefore made up from unfrozen underground springs, lakes and icebergs. Some form of storage has to be provided for many settlements. Two common methods are excavated reservoirs, taking into account the 7 - 8 ft. of ice cover in winter, and heated storage tanks (steel and wooden). River water may be abstracted in summer by syphon or pumping. In most areas water trucks are being used to transport water from the river to the settlement. In any event the actual period of runoff is of vital economic importance.

The second problem is the generation of sufficient power. Most northern settlements are highly dependent upon electrical power for lighting and heating. Unfortunately in summer when the potential for hydro-power generation is highest sunlight is available for 20-24 hours per day and temperatures are extremely mild in comparison with the winter months. Lakes deeper than (say) 10 ft. can be tapped for hydro-electrical power generation, and damming of rivers and lakes could also provide enough water for power generation.

The third problem is the spring flood. In Pangnirtung in 1971 and in 1968, two bridges built across the mouth of the Duval River were washed away by floods. In Broughton Island, an earth dam was washed away by springmelt in 1973. Another purpose of this study is therefore to produce a design flood method for use in these areas.

1.3 Baffin Region Climate and Data

The three catchments studied lie in a line NNE from Frobisher Bay through Pangnirtung to Broughton Island. The latitude varies from 63°44'N to 67°34'N and longitude varies from 63°59'W to 68°28'W (fig. 1.1). In this section the general climate of the study area is discussed, however special emphasis is placed on the main study basin at Pangnirtung. Much of central Baffin Island is a rolling upland plateau at 400 to 700 meters above sea level with a glaciation level of 700 to 900 meters above sea level.

The meteorological station inventory for Northwest Territories indicates that over 30 stations have been in operation on or around Baffin Island area since 1881 when a German scientific expedition kept observations at Kingawa (67°18'W, 66°36'N) during the first International Polar Year. Eight of the twelve stations in the table are currently operational. As of summer 1973, the Atmospheric Environment Service has begun operating an automatic meteorological station at Pangnirtung.

For the purpose of this study, two seasons are recognized - a summer or ablation season (June, July and August) and a winter or accumulation season (September to May). For runoff purposes this division is adequate; any melting of snow or ice on Baffin Island is almost entirely restricted to the three summer months selected [Bradley, 34].

TABLE 1.1 METEOROLOGICAL STATIONS ON BAFFIN ISLAND

Station	Latitude	Longitude	Elevation (m)	Mean Temperature (1959-69) (deg C) Winter	Mean Temperature (1959-69) (deg C) Summer	Mean Precipitation (1959-69) (cm/w.c.) Winter	Mean Precipitation (1959-69) (cm/w.c.) Summer
1. Arctic Bay *	73°00'	85°18'	11	-20.0	4.4	7.7	4.9
2. Broughton Island	67°33'	64°03'	581	-15.5	2.6	24.4	6.6
3. Cape Dyer "A"	66°35'	61°37'	376	-14.3	3.6	52.3	13.7
4. Cape Hooper	68°26'	66°47'	401	-16.0	2.3	18.5	7.1
5. Clyde	70°27'	68°33'	3	-16.9	3.0	13.2	7.1
6. Dewar Lakes (mid-Baffin Island)	68°39'	71°10'	518	-18.2	3.2	10.9	9.4
7. Frobisher Bay "A"	63°45'	68°33'	21	-14.1	5.9	26.9	15.5
8. Lake Harbour **	62°50'	69°55'	16	-12.3	6.8	22.8	11.5
9. Longstaff Bluff (Foley)	68°67'	75°18'	162	-17.9	4.7	10.9	7.9
10. Nottingham Island	63°07'	77°56'	16	-13.2	4.5	17.0	7.9
11. Pangnirtung **	66°08'	65°44'	13	-14.1	6.1	25.7	13.0
12. Resolution Island *	61°18'	64°53'	39	- 8.8	2.5	18.5	10.6

* Values of mean temperature and total precipitation for 1951-60

** Values of mean temperature and total precipitation for 1931-40

Refer to reference [20]

CHAPTER II. BACKGROUND REVIEW

2.1 Historical Background

Most models for snowmelt runoff predictions that could relate to the climatic conditions of the study were developed for the northern areas of the United States. No models have been developed for, or applied to, snowmelt in the Baffin area. On the other hand, several studies on water resources in the Arctic and sub-Arctic areas have been carried out. Dingman [5] studied the hydrology of the Glen Creek Watershed in Central Alaska (1971) and Cogley and McCann [6, 7] performed hydrological observations on a small Arctic catchment on Devon Island (1972). Derikx and Loijens [45] from the Glaciology Subdivision of Inland Waters Branch developed a model for runoff from glaciers (1971). Their approach to the hydrology of the glacier is similar to the approach to snowmelt taken in this dissertation. The hydrology is considered to be linear, energy (and mass) being the input and runoff being the output. The Frozen Sea Research Group [32] has also produced a paper on the hydrology of a small basin in North Ellesmere Island (1973), but they have not attempted to produce a predictive model on their results.

There was no significant progress in snowmelt prediction techniques prior to 1940. Light [24] and Wilson [25, 26] developed equations for snowmelt at a point, using thermodynamic processes. Their investigation concentrated on the various factors influencing the transmission of heat to the snow-mantle by turbulent diffusion of warm moist air. Geiger [27] indicated that the physical features of a basin, for example, vegetal cover, aspect and basin slope, affect the microclimate of the catchment and therefore have to be taken into account before the snowmelt process at a point can be extended to that over the whole catchment. Linsley [28] related snowmelt runoff to degree-days above freezing using a semi-empirical model. His model utilizes readily available data for most areas to predict runoff. The mean air temperature and the elevation of snowline is used to compute the volume of runoff. The degree-day factor technique is similar to that developed by Collins [29]. The estimated melt and rainfall, if any, was routed through the basin by the coefficient method [2], where they assume storage is directly proportional to runoff.

Garstka et al [14] utilized degree-day factor and recession analysis to predict snowmelt. They applied statistical correlation techniques to hydrometeorological data, such as, temperature, wind velocity, dew point, relative humidity, radiation and duration of temperature above datum base. They concluded that,

> "The temperature factor alone is at least as good as, and in many cases better than a combination of other factors used in correlation studies."

The U.S. Corps of Engineers [9] completed extensive research upon three catchments in the Western United States, with different climatic conditions and physical environments. They produced the classic treatise "Snow Hydrology" [9] in 1956, and the work was summarized with emphasis on engineering design in 1960 [10]. Davar and Bray [23] applied regression analysis and an index plot to the Tobique Basin in

New Brunswick.

Various sophisticated continuous snowmelt runoff prediction models have been developed in recent years. Anderson and Crawford, 1964 [34] employed a temperature index method to determine melt quantities; this is the snowmelt routine in the Stanford Watershed Model [35]. Here air temperature is the primary meteorological input. The Ohio River Forecast Center Model, 1965 Winston, [37], computes snowmelt and the related snowpack parameters on the basis of hourly meteorological observations taken by the U.S. Weather Bureau. The data used by the model are cloud conditions (as an index of radiation), air temperature, and wind velocity. The energy budget involves heat transfers due to radiation, convection, and condensation/sublimation. The model output is excess water reaching the ground every six hours. The University of California (Davis) Model, 1966, Amorocho and Espildora, [38], utilizes a comprehensive representation of the snowpack heat budget to simulate the snow melting process. Because of the complexity of input data requirement, (hourly data of solar radiation, air temperature, dew point temperature, wind velocity and precipitation) great restriction of its use is engendered. Also daily observations of cloud type and cover are needed. The Anderson Model, 1968, was an important extension of the snowmelt process in the Stanford Watershed Model. Anderson [4, 36] divided each day into two 12 hour periods; during each day he computes melt, while at night he computes the snowpack surface temperature. The M.I.T. Continuous Snowmelt Model, 1972, Laramie and Schaake, [33] was developed with flexibility of data input in mind, so that the empirical and theoretical equations encompassed have a wide range of applicability.

2.2. Snowmelt Process

Snow when new is a fine crystalline form of ice, with a density of 0.056 - 0.15, averaging 0.10 in subhumid areas. The usual value used in this thesis is 10 ins.of snow = 1 in. of water. Schaefer [30] defines snow as:

> "..... the solid form of water which grows while
> floating, rising, or falling in the free air of
> the atmosphere."

The Commission on Snow and Ice of the International Association of Scientific Hydrology [31] has classified ten types of snow at time of fall. The types of particle with their symbols in brackets are; plate (F1), stellar crystal (F2), column (F3), needle (F4), spatial dendrite (F5), capped column (F6), irregular crystal (F7), grouped (F8), ice pellet (F9) and hail (F0). These are in turn given the following modifying features with their symbol subscripts in brackets; broken crystals (p), rine coated crystals (r), clusters (f) and wet (w). Further subclassification to grain nature, hardness and wetness is described by the U.S. Army Corps of Engineers [46].

The process whereby a snowpack undergoes a change to coarse crystalline structure and is ready to melt is called "ripening". Ripening is a combination of four processes, (i) settling due to gravity, (ii) wind action in compression of snow, (iii) melting and refreezing of pack, (iv) addition of water by precipitation, or condensation on to a pack. Care should be taken to distinguish between water equivalent and water content, which cannot exceed 5% by weight of the snowpack.

The melting of snow is caused by absorption of heat energy from solar radiation. This energy is introduced to the snowpack from the atmosphere or the ground. In Arctic areas, due to permafrost, the major contribution to snowmelt is from the atmosphere. The heat input from rain is not as significant as is commonly believed. It is the warm air, strong winds, and high humidity which accompany rainfall that are responsible for cases of rapid melt during rainstorms [22]. If wet bulb temperature is 50°F, 1 in. of rain will only melt 0.12 in. of water from snow.

Laramie and Schaake [33] developed the following heat budget relationship:

$$H_{rs} + H_{rl} + H_{cv} + H_{cn} + H_p + H_g + H_q + H_s = 0 \text{ ——— } (2.2 - 1)$$

where

H_{rs} = Absorbed shortwave radiation
H_{rl} = Net longwave radiation exchange between the pack and its environment
H_{cv} = Convective heat transfer from the air above
H_{cn} = Heat supplied by condensate
H_p = Heat content of precipitation
H_g = Conductive heat from the ground
H_q = Change in stored heat of snowpack
H_s = Heat involved in change of state

If the quantity $H_q + H_s$ is represented by H_t, it can be shown that the total heat flux applied to the snowpack to produce changes in its energy content as well as its state can be expressed as follows:

$$H_t = H_{rs} + H_{rl} + H_{cv} + H_{cn} + H_p + H_g \text{ ——————— } (2.2 - 2)$$

2.3 Snowmelt Prediction Techniques

The method used should be appropriate for the following criteria: (i) the purpose of prediction, (ii) the accuracy required for the forecast, (iii) the forecast time available for effective use, (iv) the variability of basin hydrological characteristics, (v) the availability of meteorological data, and (vi) the availability of electronic computers.

There are basically two approaches to snowmelt prediction techniques. The first, which was the only method readily available before the use of digital computers, is the input of known meteorological data directly into equations. These equations were developed from the analysis of the physical processes involved in snowmelt. One of the earliest, and one that is still used in some form or other, is the degree-day formula. This equation is equivalent to the rational formula used in hydrology. The degree-day factor is analogous to the runoff coefficient and is similarly simplistic. A basic assumption is that temperature alone is the only significant parameter in predicting snowmelt. More complicated formulae were developed which made use of all sources of heat input involved in snowmelt [27] . The M.I.T. continuous snowmelt model, for example, makes use of air temperature, dew point temperature, solar radiation, wind velocity, precipitation, cloud type index, and cloud cover. The second approach is the use of statistical techniques [15, 16] . The difficulty in obtaining solutions by these complex techniques was overcome by the general availability of computers. Regression analysis and correlation of many parameters could be achieved rapidly [19] . The U.S. Bureau of Reclamation and Corps of Engineers made full use of these methods. It is shown in this study that the latter is a much more powerful method, and can take into account topographic data, elevation effects, and recession of snowpack, thus allowing its use on different catchments in areas that are meteorologically homogeneous.

2.3-1 Temperature Index, Degree-Day Factor

Bray and Pysklywec [21] used the following two equations.

$$M = C(T_a - T_b) \text{ in/day} \text{ ——— } (2.3 - 1)$$

where

C = snowmelt coefficient, 0.06 for open areas and 0.05 for forested areas

T_a = average daily temperature, °F

T_b = base temperature, usually 32°F

and

$$\text{D.D.F.} = \frac{\text{Volume of daily snowmelt}}{\text{No. of degree-days}} \text{ in/degree-day — } (2.3 - 2)$$

where

D.D.F. = degree-day factor, the value obtained was 0.05 - 0.15 in/degree-day, 0.08 is commonly used for preliminary analysis

2.3-2 Degree-Day and Recession Analysis

The fundamental feature of this method, developed by the U.S. Bureau of Reclamation [14], is an equation for the recession limb of diurnal hydrographs inherent in snowmelt. The following parameters were derived by correlations between degree-days and streamflow: (i) the volume of streamflow from snowmelt, (ii) the recession volume of streamflow from the snowmelt, (iii) the height of the hydrograph peak from the previous trough, (iv) the height of the hydrograph trough above the previous trough (fig. 2.1).

$$V_1 = b_1T_1 + b_3T_3 - C_1 \quad \text{(acre-feet)} \text{ ——————— } (2.3 - 3)$$

where

V_1 = the first day's volume in acre-feet

T_1 = the maximum temperature at a selected station

T_3 = accumulated maximum temperature at the selected station

b_1, b_3, C_1 = statistically derived constants

$$Q_1 = bV_1 + C_2 \quad \text{(feet)} \text{ ——————— } (2.3 - 4)$$

$$Q_2 = b_4V_1 + C_3 \quad \text{(feet)} \text{ ——————— } (2.3 - 5)$$

where

Q_1 = height to peak above trough

Q_2 = height to trough above previous trough

b, b_4, C_2, C_3.= statistically derived constants

Use of this method was found to be good in heavily forested areas, and areas where melt due to rain is insignificant. Naturally the above method is useful where a day-to-day operational forecast is needed, and also where extensive meteorological data are absent.

2.3-3 Generalized Snowmelt Equations

The Corps of Engineers [9] proceeded from the physics of heat transfer and used experimental observations from three catchments in the Western United States. They derived regression coefficients for snowmelt, breaking up the energy contributions as follows:

$$M_i = \frac{Q_i}{750B_i} \quad \text{(in./day)} \quad \text{———} \quad (2.3 - 6)$$

where

M_i = in./day from the ith heat input source

Q_i = energy in B.t.u./ft^2

B_i = quality as decimal fraction

and

$$M = \sum \frac{Q_i}{750B_i} \quad \text{(in./day)} \quad \text{———} \quad (2.3 - 7)$$

$$M = M_c + M_{co} + M_{rs} + M_{rl} + M_p + M_g \quad \text{(in./day)} \quad \text{———} \quad (2.3 - 8)$$

where

M = total snowmelt in in./day

M_c = melt from energy input as convection and molecular conduction

M_{co} = melt from energy input from condensation of water vapor onto snowpack

M_{rs} = melt from energy input from shortwave radiation

M_{rl} = melt from energy input from longwave radiation

M_p = melt from energy input from rain

M_g = melt from energy input from ground

all the above melt is in in./day of snowmelt

The authors [9] further developed the following algorithms from regression analysis for each energy contributor:

$$M_c + M_{co} = 0.0084KV_w (T_a - 32) \quad \text{———} \quad (2.3 - 9)$$

where

K = 1 to 0.54 from open to heavily forested

V_w = wind speed in M.P.H. @ 50 ft. above ground level

The energy from M_{rs} is proportional to the power of the body's temperature (°K), (Stefan's Law of emission of black-body radiation). The sun and earth being considered as black bodies, M_{rs} was found to be 0.09 in./day.

$$M_{rl} + M_{rs} = 0.029 (T_a - 32) + 0.09 \text{ (in./day)} \quad \text{———} \quad (2.3 - 12)$$

The contribution from rainfall is:

$$M_p = \frac{P_r (T_w - 32)}{144} \quad \text{———} \quad (2.3 - 11)$$

where

P_r = one day's rainfall in inches

T_w = wet bulb temperature in °F

In this case the contribution of energy by conduction from the ground M_g, will be insignificant due to the permafrost in Arctic areas. Combining the above equations and simplifying we get:

$$M = (0.029 + 0.084KV_2 + 0.007P_r)\ (T_a - 32) + 0.09 \text{ —— } (2.3\ \text{-}12)$$

2.3-4 Index Plot and Regression Analysis

Davar and Bray [8, 23] found that (i) the degree-day relations were simple and satisfactory when determined from the local conditions, (ii) the Corps of Engineers generalized snowmelt equation (2.3 - 12), though sound in theory could not accurately predict daily snowmelt in the Tobique Basin in New Brunswick. (These two equations are used later in this study as a basis for comparison of results), (iii) the regression equation using the same basic meteorological parameters as above, but derived for local conditions, gave best representation of the actual snowmelt sequence. Pysklywec's equation [21] for the Tobique Basin was:

$$M = 0.615 + 0.0373n + 0.00607R_b + 0.0021\ (T_a - 36)V_w$$
$$+ 0.0437(R_h)V_w + 0.007P_r\ (T_a - 32) \text{ ———— } (2.3 - 13)$$

where

n = sunshine, hr./day

R_b = longwave radiation, ly./day

R_h = relative humidity

It should be pointed out that a regression analysis for a particular basin would be expected to yield good results for that basin.

2.4 Additional Processes

2.4-1 Ground Melt, Hydrograph Synthesis and Routing

Under normal climatic conditions, snowpack recedes to elevations where the lapse-rate has lowered the temperature to the level where no more snowmelt is possible for the season. Below the level of active percolation, the groundwater contribution from the active layer should contribute to baseflow until the end of the melt season. Because of the low annual precipitation in the Arctic areas, and the short length of the melt season, the active layer should have a very low moisture content when refreezing begins. Thus under normal conditions, the runoff during the snowmelt season should be basically contributed by the snowpack and groundwater runoff should normally be negligible (fig. 2.2).

Unlike catchments in more temperate regions, the Arctic Basins are subjected during much of the melt season to diurnal freeze-thaw cycles. A large amount of snow and ice that is melted during the day but not runoff, is refrozen during the night. This freeze-thaw cycle which extents over most of the melt season in the Arctic would be substantiated later in this thesis when it is shown that D.D.F. values for the Arctic basins are smaller than that of basins further south. This diurnal freeze-thaw cycle is naturally more predominant at the beginning and end of the ablation season.

Unit hydrograph theory is applicable where storm event rainfall is a major contribution to runoff. In the high Arctic annual runoff

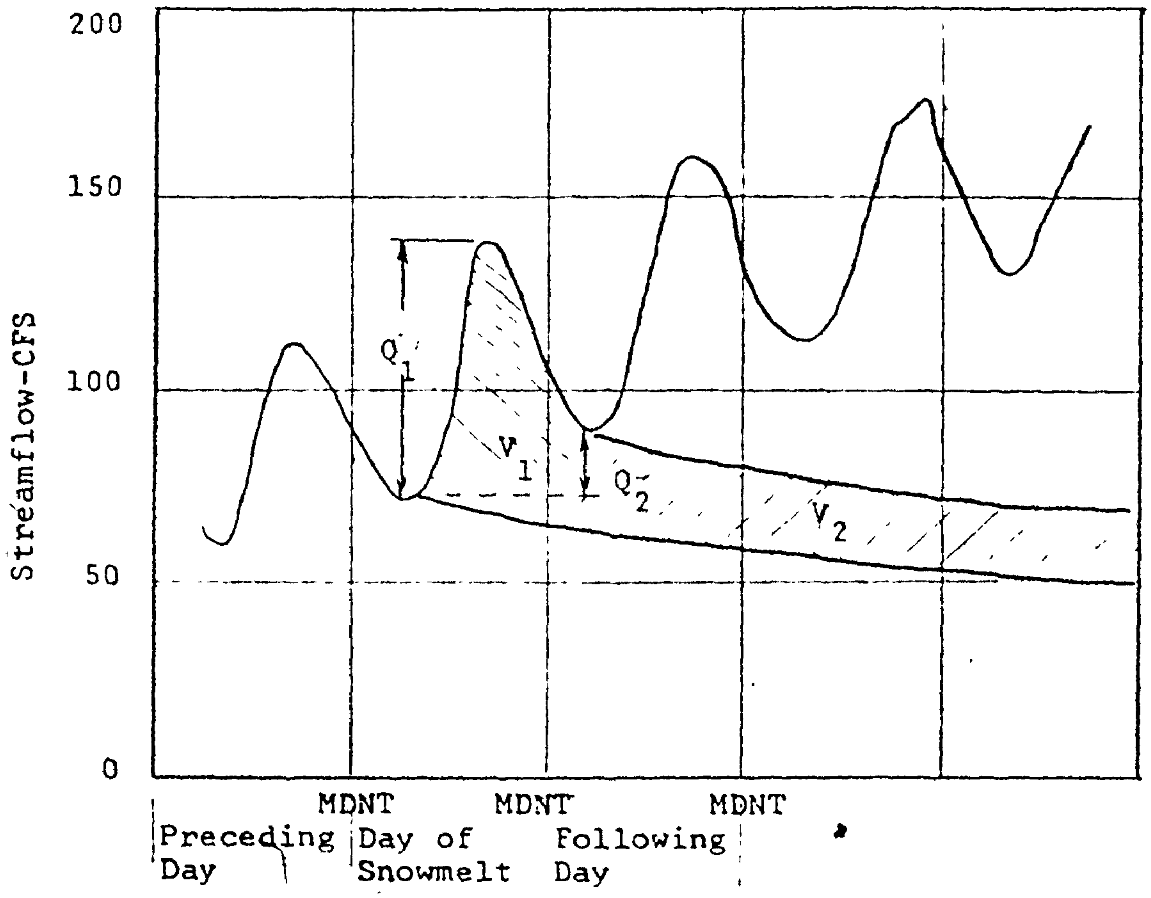


FIG. 2.1 RECESSION ANALYSIS WITH DEGREE-DAYS(GARSTKA,1959)

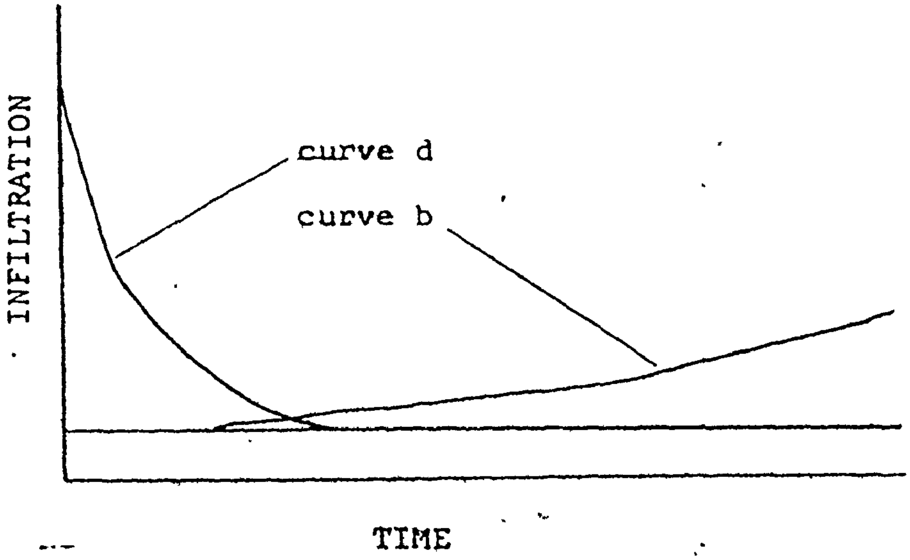


FIG. 2.2 [illegible] OF

from precipitation is generally small in comparison to snowmelt, but one would use linear theory to apply to rare flood events, especially for storms such as the highest recorded at Pangnirtung, (1.49 inches in 24 hours, [17]). Phase routing can be achieved empirically by trial fitting of synthesized hydrographs to historical data, which are scarce in our area.

2.4-2 Infiltration in Frozen Soils

The quantity and size of ice-free pores are major parameters governing the infiltration rate in frozen soils. Therefore the moisture content of a soil at time of freezing is an important factor. Gray [39] summarizes the works of several Russian workers, Larken (1962), Kuenik and Baemenov (1963) and others who report that if a soil is frozen when its moisture content is greater than the field capacity, it's infiltration rate is very low. If it is saturated, then there is almost no infiltration. Willis et al (1962) completed some studies on several snow plots in North Dakota, and found that as much as 90% of snowmelt was lost as surface runoff when these plots were frozen at high moisture content. Gillies (1968) in a study on prairie snowpacks found:

$$d = 53.5 - 0.65\ MC\ (\%) \qquad (2.4 - 1)$$

where

d = percentage of total water content of the overlying snowpack which could infiltrate the ground

MC = initial soil moisture content prior to melt

Zavodchikov (1962) noted that for the case of saturated soils (moisture content 70 - 80%) the infiltration rate increased during the melting period to 6 - 8 times the initial rate, due to poremelt by melt water. (See curve B, fig. 2.2) In time, however, the infiltration will again decrease due to its high moisture content. In the case of soil initially frozen at low moisture content, and where the soil temperature at the time of snowmelt is well below freezing, water entering the soil is frozen in the pores and movement is inhibited. (See curve D, fig. 2.2)

2.4-3 Permafrost and Active Layer

The definition of permafrost is ground that is perennially below the freezing temperature [2] . The irregular surface representing the upper limit of the permafrost is the permafrost table. The ground above the permafrost table is known as the suprapermafrost. It has been found that the thickness of the permafrost layer is approximately proportional to the mean annual temperature. Possible permafrost areas are frequently indicated by various ground configurations such as polygons, pingos, stone rings and stone stripes, collectively known as patterned ground.

Construction, in Arctic areas, is confronted with the problem of building foundations in order that the permafrost below the building remains permanently frozen. Instability caused by construction or other local disturbances can cause thawing and refreezing. This may initiate subsurface ground water channels; these in turn cause thawing, resulting in progressive differential settlement in summer and excessive heave in winter. The impounding of water, behind dams constructed on permafrost, may cause leakage and subsequent collapse because of thawing of the permafrost foundation.

The surface layer of ground (active layer) normally thaws during the summer and refreezes during the winter, but permafrost below remains frozen and impermeable. In areas mantled with peat or dense material of living vegetation, the active layer is thin. In areas of gravel or exposed rock, the active layer may be quite deep. Permafrost is absent or lies at great depths beneath lakes or ponds because these bodies of standing water readily absorb the sun's heat during summer.

2.4-4 Evaporation and Precipitation

The evaporation process is similar to snowmelt. Radiation and winds predominate in both. Therefore it is expected that correlations between causes of snowmelt and streamflow will automatically include the effect of evaporation. In other words one has a reproduceable model between meteorological factors causing both snowmelt, evaporation and streamflow. Since in the Eastern High Arctic there is a short ablation season, and very little open water storage one would expect snowmelt to considerably predominate over evaporation. For these reasons the model in this thesis has been referred to as a snowmelt runoff model.

There is poor correlation for storm events observed at different elevations in mountainous terrain. Since rainfall in this area is generally small and rainfall data sparse, it is difficult to see how this can be incorporated in a simple engineering model. Many simple techniques exist for deriving design storms and design floods. Where runoff obviously results from rain (no diurnal fluctuation), it should be removed from observed hydrograph. One should in that case correlate with runoff to estimate whether rain observation is significant or not.

CHAPTER III. FIELD PROGRAM

3.1 Catchment Selection

The objective of the field program was the collection of minimal streamflow and meteorological data from different catchments on Baffin Island. The data were to be used to develop the deterministic and regression models.

The choice of catchments was necessarily limited to those areas where easy access is available by air transport. Frobisher Bay and Fort Chimo can be reached by first class air carrier (fig. 1.1), and from there one can reach Lake Harbour, Cape Dorset, Pangnirtung and Broughton Island by secondary carrier. As a change of latitude is more significant than longitude due to the range in change of climate, a north-south study zone was decided upon from Frobisher Bay to Broughton Island. Further expansion in other directions is desirable if manpower and economic resources are made available.

From topographical data of the area, the Duval Catchment was selected (fig. 1.2). A preliminary field study was organized in the summer of 1972. The topography was found to be accurately represented by the maps and the aerial photographs. The catchment was found to be favourable to stream gauging and automatic level recorders. The decision was made to extend the study to Broughton Island and Frobisher Bay in the summer of 1973.

3.2 Description of Three Catchments

3.2-1 Broughton Island Field Station (63°59'W, 67°34'N)

This is the smallest and most accessible of the three catchments (fig. 1.3). Due to its size, lack of lakes within the basin and the availability of good meteorological data from both Distant Early Warning Line stations and INSTAAR (Institute of Arctic and Alpine Research) it should be highly suitable for a pilot/test basin. The recorders used in the 1973 study were Steven's, type A, Model 71. One of the recorders was located at the washed out hamlet damsite about 2 km. ESE of the mouth of the creek, about 0.3 km. upstream from the D.E.W. line road. Table 3.1 lists hydrographic data for all three catchments.

3.2-2 Apex River Field Station (68°28'W, 63°44'N)

This catchment contains the largest number of lakes (fig. 1.3). It is long and narrow in shape, in comparison with the other two catchments. The mouth of the Apex River is about 5 km. ESE from the Frobisher Bay Airport. The river is accessible by the road to the Apex settlement. The river passes under a bridge, approximately 0.5 km. from the settlement. The site of the recorder is about 0.4 km. upstream from the bridge on the western side of the river. The recorder is fixed in a storage box on an eight-foot stilling well by means of 1/4" steel cable and rock bolts. Two bench marks have been implanted in the rock outcrop alongside (3 m. off in a NW direction). The fragile stilling wells (1/4" plywood) cannot withstand the winter

TABLE 3.1 HYDROGRAPHIC DATA FOR STUDY CATCHMENTS

LOCATION: CATCHMENT:	Broughton Island Broughton Creek *	Frobisher Bay Apex River	Pangnirtung Duval River
1. Length of longest reach	8.8 km	19.9 km	17.4 km
2. Area of catchment	30.64 km^2	61.7 km^2	101.8 km^2
3. Area of catchment from recorder	30.64 km^2	61.7 km^2	91.7 km^2
4. Average elevation of catchment	161.5 m.a.s.l.	213.4 m.a.s.l.	548.6 m.a.s.l.
5. Maximum elevation of catchment	487.7 m.a.s.l.	381.0 m.a.s.l.	1280.2 m.a.s.l.
6. Area of lakes	-	2.07 km^2	0.16 km^2

* Broughton Creek, evidently now named Kurulak Creek

ice conditions. Sturdier stilling wells constructed with thicker wood or metal could be placed in the same location for a more permanent site in the future. Meteorological data are available from the A.E.S. in Frobisher Bay; the location of the meteorological station should be suitable for the studies (fig. 1.3).

3.2-3 Duval River Field Station (66°08'N, 65°44'W)

The Duval catchment is the largest in area of the three catchments (fig. 1.2). Continuous data were collected for 1972 and 1973 ablation seasons. It is the catchment of major concern in this dissertation. It contains two small lakes. A larger lake, about 8 km. south of the settlement in another catchment,may be applicable to power generation and water supply. The mouth of the river is located about 1 km. ENE from the airstrip at Pangnirtung. The field station is located 3.5 km. upstream from the mouth on the south bank of the river. The recorder is located about 0.5 km. from the point where the river slope begins to level off into an open valley about 600 m. long and 300 m. wide (fig. 1.2). The gauging site is 25.6 m. wide, approximately 0.6 m. deep, located 1 m. downstream of the recorder. It is a long straight section of boulder strewn river, rather than a well-defined control. Meteorological data have not been available in the past at Pangnirtung, and A.E.S. has set up a remote automated weather station at the western end of the town in 1973. Therefore observations on temperature, wind, cloud cover, etc., were made in the field.

3.3 Data Collection and Presentation

3.3-1 Streamflow

In the summer of 1972 streamflow was observed hourly by members of the research group. A graduated staff was implanted in a recessed section of the bank. Attenuation of the wave ripples was attempted by means of a stilling basin of rocks around the staff. The location of the stake was selected such that the observer could read it fairly easily from the bank. The best section was located about one hundred meters from the campsite. In 1973 the same location was utilized for the automatic recorder. Figure 1.2 indicates this location.

In 1973, four Steven's A-7 continuous water level recorders were installed. The negator spring drove a clockwork mechanism which can run for three months without need to rewind. The recorder holds a year's strip chart for the recorder.

With the help of automatic water-level recorders the researchers could achieve greater mobility, not having to remain on site to note information manually. The disadvantage of these recorders was their bulk. The complete recorder-box-well system weighed in excess of 68 kg. (150 lb.). The inhospitable terrain of soggy tundra and wet snow made the transportation of the instruments quite difficult.

The three recorders set up performed quite satisfactorily with no malfunctioning during the whole period. Minor icing of the well occurred in Broughton Island due to frazil ice conditions in the initial thawing at the start of the ablation season. The data are translated into flows in figures E.2 and E.3 (a & b).

3.3-2 Stage Discharge Observations

Reliance on hand held current meters limited the points on the stage discharge to a maximum depth of 32 inches. On Broughton Island, however, one member of the party used an inflatable rubber dinghy to gauge the river at higher stages. At the Apex River current meters were used, and the Department of the Environment utilized fluorometry to obtain some further points of the rating curve. All methods gave similar results. Figures E.4, E.5 and E.6 show the stage discharge relationship for all three catchments. The stage discharge curves used in this study have been evaluated and adopted by Environment Canada, Water Survey Branch, and are the official rating curves for the three stations. Further rating points are being added to these curves from time to time.

For further stage discharge relationships the use of fluorometry is highly recommended to obtain higher points on the stage discharge curves on the more conveniently located, but steep and rough cross-sections. The current meters used were the small portable Ott current meters, No. 10.152 (further details are given in Appendix B).

3.3-3 Meteorological Data

Meteorological data for Frobisher Bay may be obtained from the Atmospheric Environment Service. Similarly at Broughton Island meteorological data may be obtained from the D.E.W. line station or INSTAAR (Institute for Arctic and Alpine Research) University of Colorado. The D.E.W. line station data are those available in "Meteorological Data of Canada" [18] . The location of the D.E.W. line station is at elevation 1955 ft. (594 m.). The catchment has an average elevation of about 750 ft. (197 m.), and the INSTAAR station is a few feet above M.S.L. (see fig. 1.3).

At Pangnirtung there had not been any systematic climatic data collection. The R.C.M.P. collected some meteorological data up till 1950 [17] . The A.E.S. with the help of National Parks Service set up an automatic weather station at Pangnirtung in the summer of 1973. The unit was a MRI, Mechanical Weather Station. This station collected information on wind speed, direction and temperature. Provision for precipitation is allowed but not active on this unit (fig. 1.2).

In the ablation season in 1972, the research party made use of a non-recording thermometer, the temperature being noted at the same time as stage were recorded. Also at the same hour, wind speed, direction and cloud cover were recorded. The wind anemometer was built in the field as indicated in a popular science article [43] . The anemometer comprises a table tennis ball, thread and a protractor. As all competition balls are of standardised weight and dimensions under rigid control and the length of thread being as indicated, the deflection is a function of wind velocity. By rotating the anemometer to achieve maximum deflection the wind direction and velocity is obtained [44].

In 1973, automatic temperature recorders were used (Pacific Transducer Corp. Model 6.15F, 7 day). These were 7-day, negator spring wound, coil recorders, range of temperature -30°F to 70°F, and -70°F to 130°F. Because of lack of personnel to spread over three catchments hourly observations were forfeited. As the model was to apply to daily flows, climatic information was aggregated into 4 categories: clouded, semi-clouded, sunny or raining, in order of increasing importance to runoff. These were given values of zero to three respectively in the regression model and denoted "weather factor". The temperature observations are plotted in figures E.7 and E.8 (a & b).

CHAPTER IV. MODEL DEVELOPMENT

4.1 Degree-Day Algorithm

In North America, a degree-day is a unit expressing the amount of heat in terms of the persistence of a temperature for a 24-hour period of one-degree-Fahrenheit departure from a reference temperature. In snowmelt studies, the degree-day is computed by substracting from the average of the daily maximum and the daily minimum 32°F or a specified datum [2] . For example, if the daily mean computed was 40°F, there would be an 8 degree-day; a daily mean of 36°F, would yield 4 degree-days. Degree-days above 32°F and above other reference temperatures have been used in point-snowmelt and snowmelt runoff computations. An accurate computation of degree-days could be made from hourly observations or from a chart of recording temperatures. In Arctic areas there is a fair probability that the drop to the minimum may be sufficiently great to yield means below 32°F, indicating no degree-days, whereas snowmelt conditions may have prevailed during the day when air temperatures were above the freezing point. Garstka et al [14] used the maximum and minimum temperatures to estimate degree-days. For open sites, the Corps of Engineers [10] derived the daily springtime melt M in inches by correlation, as a function of mean daily temperature T_a, and the maximum daily temperature T_m,

$$M = 0.06\ (T_a - 24)\ \text{inches/day} \qquad (4.1 - 1)$$

$$M = 0.04\ (T_m - 27)\ \text{inches/day} \qquad (4.1 - 2)$$

where the equations are for T_a from 34 - 66°F and T_m from 44 - 76°F.

It should be pointed out that the above equations are for point melt values. In applying the same theory to snowmelt over a basin, the basin-index melt values are utilised. The average rate of snowmelt M, inches per day, is

$$M = K\,(T_a - 32) \text{ inches/day} \qquad (4.1 - 3)$$

where,

T_a = mean air temperature in °F

K = degree-day factor, 0.02 to 0.11 with maximum 0.30

Watt and Hsu [41], further extended this idea with the inclusion of decreasing areal extent of snowcover after extensive periods of intensive melting:

$$M = K\,(T_a - 32)\,A_s \qquad (4.1 - 4)$$

where,

K = 0.022in/day °F, this value is in the range (0.021 - 0.024) suggested by the Corps of Engineers (1956)

A_s = function of ratio of total snowmelt quantity M, to the total snowfall to date, $\sum S$. A_s was set at 1.0 for $\sum M/\sum S$ less that BC, the bare coefficient, and was assumed to vary linearly from 1.0 to 0.0 as $\sum M/\sum S$ increased from BC to 1.0.

It was decided to test these equations against the data obtained from the Duval River at Pangnirtung in 1973. Modifications were made to the first two equations to give snowmelt over the area of the basin. The dry-adiabatic lapse rate of -5.5°F/1000 ft. as developed by Hauritz (1941) was utilised to obtain the average temperature of the catchment. The recorder was at 243.8 m.a.s.l.; the 50 percentile of the area above the recorder was at 548.6 m.a.s.l. The results are plotted in fig. 4.1.

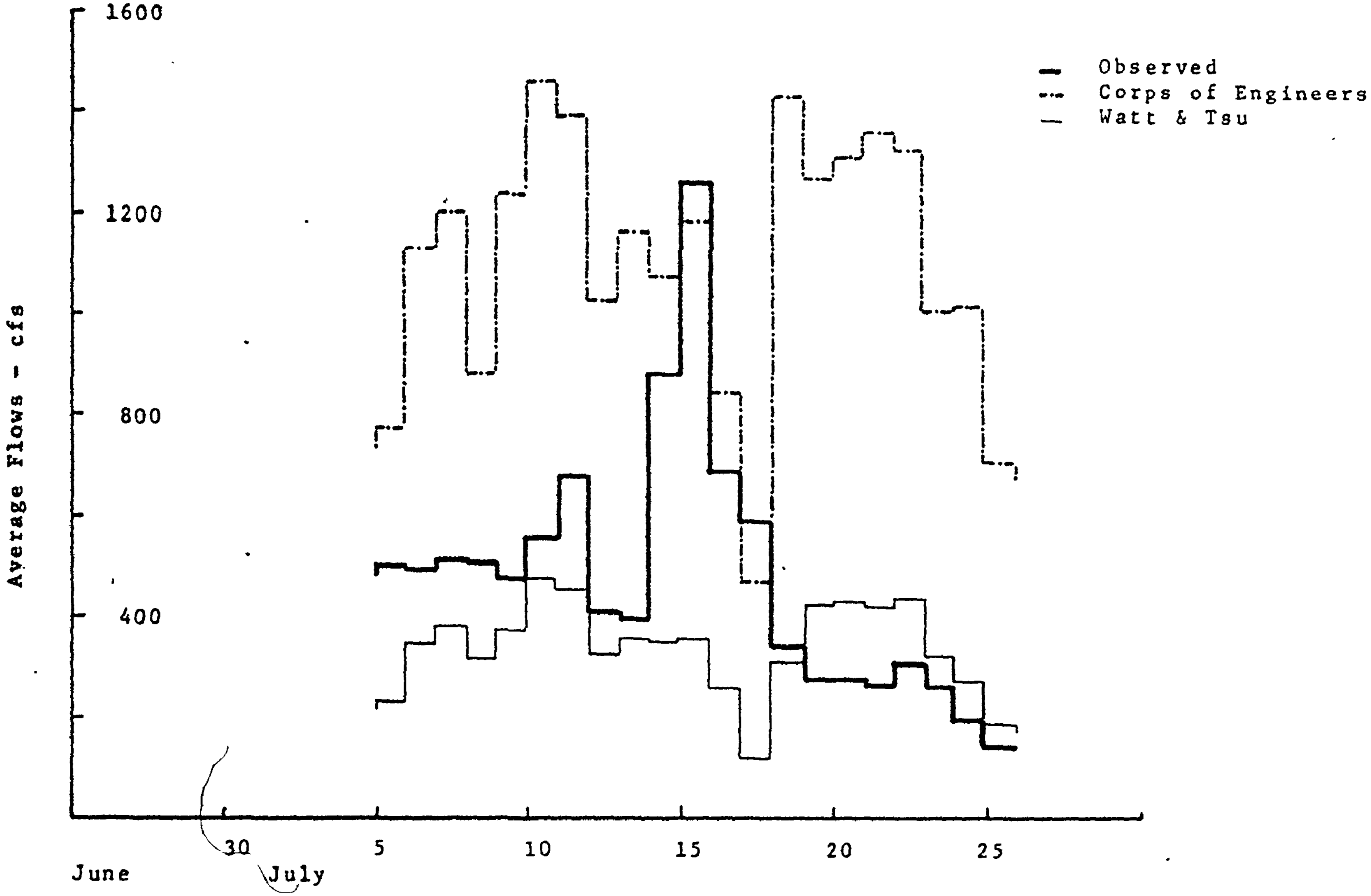


FIG. 4.1 COMPARISON OF FLOWS FROM ALGORITHMS DERIVED BY CORPS OF ENGINEERS & WATT & TSU

The Corps of Engineers equations (4.1 - 1, 4.1 - 2) consistently overpredicted the flows, except for two days, especially in the latter part of the season, where it overpredicted the daily flows by about 400%. The maximum predicted, however, only exceeded the maximum observed by 13%.

Watt and Hsu's equations, however, consistently underpredicted the daily flows. The maximum error was an underprediction of about 33%. The maximum flow predicted by Watt and Hsu's equations amount to only 38% of the observed value.

4.2 Regressions (air temperature, wind, cloud)

Researchers on snowmelt in the United States and Canada have reported difficulty in applying sophisticated models to catchments other than test basins for lack of detailed meteorological (namely radiation) data. Highly complex, accurate, pilot models are usually non-transferable, without applying many assumptions and modifications. Thus for the Arctic area with such sparse meteorological information available, a simple practical snowmelt runoff model which can easily be applied should be used.

Arctic catchments have a short ablation season, in which a major portion of the snow melts and runs off. Due to this unique phenomenon, it is believed that a simple degree-day model can be applied. However, as Bray [21] has proved, new coefficients must be established for each study area, which must have homogeniety of climate and topography.

Added assets to the researcher in the Arctic are the shallow active layer, dwarfed vegetation and diurnal temperature fluctuations. These simplify the heat balance phenomena thus aiding in the formulation of the degree-day model by regression analysis. Unlike the snowmelt process in more temperate zones, precipitation in winter is retained on the ground as snow even though some redistribution takes place, and negligible ripening or run-off occurs prior to the ablation season.

Regression analysis allows one to take snowmelt and consider it as a function of other variables (air temperature, wind, cloud cover, etc.)

[11, 12, 13] . The degree of sophistication is only limited by the number of parameters available. At this initial stage of data collection, the model was limited to a linear first-order regression. Important variables taken into account are degree-days, weather factor (a combination of wind, cloud and precipitation) and recession of snowpack. See table 4.1 for input data used in the regression program (for listing see Appendix C).

The weather factor used in table 4.1 has the following weights:

(i) 0 - for a day with full cloud cover and little wind

(ii) 1 - for a day that is semi-clouded with some wind

(iii) 2 - for a day that is clear

(iv) 3 - for a day with measurable precipitation

The output data are set up as follows:

Column one, NPAR = 1, Y is regressed against X2

Column two, NPAR = 2, Y is regressed against X2 and X3

Column three, NPAR = 3, Y is regressed against X2, X3 and X4

Column four, NPAR = 4, Y is regressed against X2, X3, X4 and X5

For explanation of symbols in table 4.3 see Appendix A.

TABLE 4.1 INPUT DATA

FLOW CFS	X1	X2	X3	X4	X5
150.54	1	4.00	0	100	2
179.75	1	5.67	0	70	3
249.79	1	7.58	2	10	3
389.79	1	8.17	2	0	6
327.21	1	4.75	0	70	2
290.37	1	14.83	1	30	5
564.58	1	13.33	2	10	4
482.50	1	13.50	1	30	2
475.62	1	14.75	2	10	3
517.29	1	16.46	2	0	4
556.87	1	14.96	2	10	6
672.08	1	18.79	1	60	4
585.42	1	16.21	0	90	2
566.46	1	14.54	2	20	2
365.00	1	13.92	2	20	3
296.96	1	12.71	2	20	2
333.54	1	10.08	3	80	1
308.83	1	7.88	0	100	4
172.37	1	6.71	0	90	6
130.29	1	6.04	0	100	1

X1 = Unit constant used in regression program

X2 = Degree-day above 32°F

X3 = Weather factor

X4 = % of cloud cover

X5 = Wind velocity in MPH

TABLE 4.2 OUTPUT DATA

NPAR=1	NPAR=2	NPAR=3	NPAR=4
159.80	158.58	174.53	178.66
210.74	209.03	226.59	227.86
269.00	272.26	279.78	280.48
287.00	290.09	298.10	289.04
182.68	181.24	199.82	204.30
490.15	488.56	493.08	488.36
444.39	446.00	447.09	445.05
449.58	448.38	454.38	459.44
487.71	448.90	488.40	489.81
539.87	540.57	539.31	537.68
494.11	495.25	494.51	486.03
610.94	608.21	604.84	603.53
532.24	527.50	530.97	536.38
481.30	482.56	481.14	485.73
462.39	463.83	463.10	464.33
425.48	427.27	427.89	432.31
345.26	350.56	339.78	346.02
278.15	275.81	287.43	285.33
242.46	240.46	254.54	245.81
222.03	220.21	129.97	129.11

TABLE 4.3 STATISTICAL CHECKS ON REGRESSION

NO. OF PARAMETERS	1	2	3	4
B0	37.786975	37.716126	69.692263	80.979766
B1	30.503026	30.214761	29.097193	29.195136
B2	–	2.760089	-4.658541	-5.318001
B3	–	–	-0.115471	-0.124904
B4	–	–	–	-3.304317
S.E.E.	90.41	93.00	92.64	95.52
F. TEST	43.97	20.79	14.34	10.13
M.C.C. R1YK	.84	.84	.85	.85
P.C.C. RYX2	.84	.83	.80	.81
RYX3	–	.02	-.03	-.03
RYX4	–	–	-.15	-.17
RYX5	–	–	–	-.03

F-TEST CRITICAL VALUES

(n=20, k=1, 4)	95%	4.41	3.59	3.24	3.06
	99%	8.29	6.11	5.29	4.89

4.3 Progressive Increase of Lag during a Streamflow Season in the High Arctic

Analysis of diurnal fluctuations of temperature and streamflow data from the Duval catchment indicates that the concept of fixed lag between insolation and streamflow, does not hold true for larger catchments. The data clearly show that the lag may increase progressively during the season, and, in the case of the Duval River, by as much as 100% of the lag at the beginning of the season.

Cross-correlation is a technique that can be used to determine time lags of maximum correlation between hydrologic time series [43] . The cross-covariance was computed between the temperature and streamflow time-series for lags of 0 to 1200 minutes increasing in steps of 60 minutes. This was repeated for truncated segments of the series as follows:

(a)	whole series	(day 1 - 20)
(b)	first ten days	(day 1 - 10)
(c)	last ten days	(day 11 - 20)
(d)	first five days	(day 1 - 5)
(e)	last five days	(day 14 - 18)

For each of the five series a graph of the cross-covariance was plotted against lag. The lag of maximum correlation was then measured to the nearest 30 minutes as follows:

(a) whole series : 420 minutes
(b) first half series : 360 minutes
(c) second half series : 510 minutes

(d) first quarter series : 300 minutes

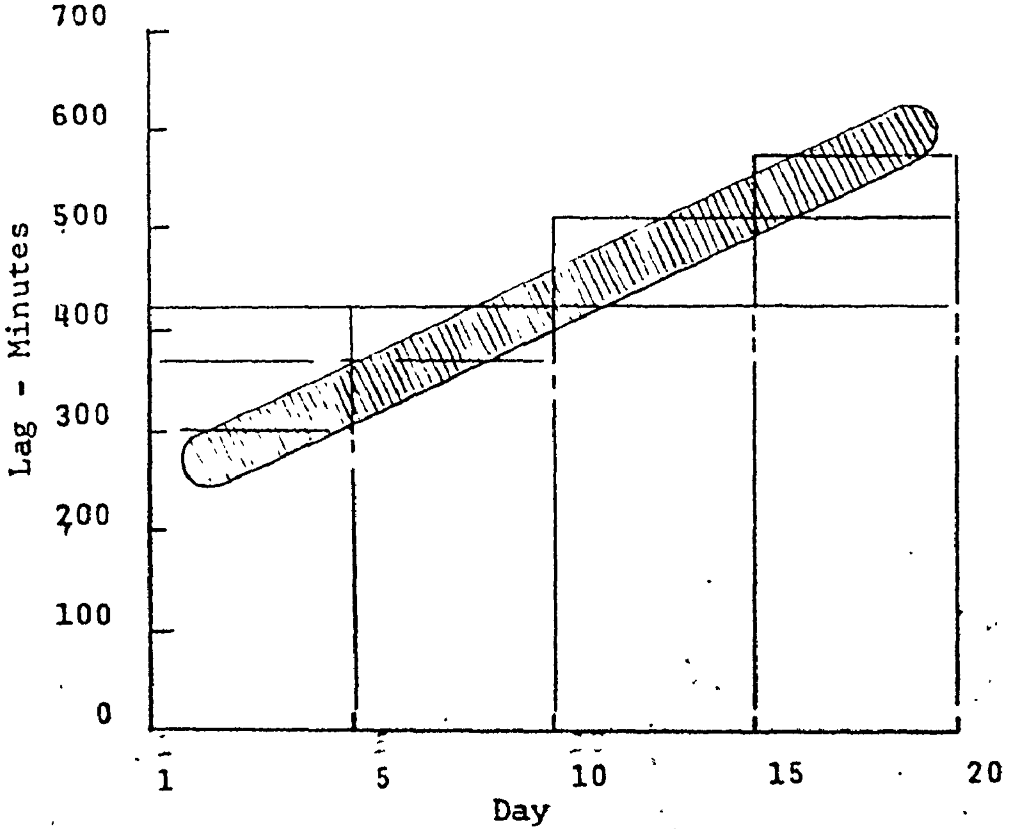
(e) last quarter series : 370 minutes

The results are presented in the bar chart, fig. 4.2, and indicate an approximately linear growth in lag from 4 hours at the onset of the 1972 melt season, to 10 hours at the end of that season.

An obvious cause of lag increase is the depletion of snowpack, and of groundwater stored in the active layer, during the melt season. For example, the snowpack tends to melt at lower elevations first, and hence the centre of snow mass moves steadily upstream from the gauging site. Groundwater (although limited in the High Arctic catchment) similarly drains from the active layer on slopes adjacent to the lower river reaches first.

Many simulation models will be insensitive to a variable lag, but it is evident that the phenomenon should be incorporated in "bare" coefficent routines. Certainly references to a fixed lag should be made with caution. Such references are widespread in the literature at present time.

FIG. 4.2 PROGRESSIVE INCREASE OF LAG



4.4 Systematic Development of a Deterministic Model

A dissertation on modelling would be incomplete without reviewing the deterministic approach. Bray [23] concluded from his intensive study of the Tobique Basin (1965) in New Brunswick, that attempted reconstitutions of snowmelt for the entire season, based on historically-determined degree-day factors have proved uncertain due to seasonal bias. An attempt is made here to systematically develop a deterministic model based on degree-day factors from the 1972 data collected at Pangnirtung. Discussion of the results is presented as the model is developed.

$$\text{D.D.F.} = \frac{\text{Volume of daily snowmelt}}{\text{No. of degree-days}} \text{ in/degree-day} \text{ ———— } (2.3 - 2)$$

where

D.D.F. = degree-day factor, value usually 0.05 - 0.15 in/degree-day, 0.08 is commonly used for preliminary analysis

Figure 4.3, shows some typical seasonal results from New Brunswick [39].

The deterministic model is systematically developed in the following manner with the D.D.F. as the objective function; (i) disaggregation in time : a seasonal value will be developed, then 5-day block values will be ascertained, and finally daily values, (ii) disaggregation in space : the entire area of the catchment will be used in (i), then the area will be disaggregated into four equal areas for the daily values.

4.4-1 Seasonal, Multi-day block and Daily Models

For the first phase of development of the D.D.F. model in time, the melt contribution will be taken from the area encompassing the entire basin area. The term "season" used in this subsection shall be taken to mean the period of 20 days over which data was collected at Pangnirtung in 1972 for this dissertation.

a. Seasonal Model

The seasonal value of D.D.F. (S.D.D.F.) is obtained by taking the total volume of daily snowmelt in inches over the observed season and dividing it by the total degree-days over the same season:

$$\text{S.D.D.F.} = \frac{\sum_{i=1}^{n} \text{Volume of daily snowmelt}}{\sum_{i=1}^{n} \text{No. of degree-days}} \text{ in/degree-day} \quad \text{—— (4.4 - 1)}$$

$$= 0.0552$$

where

n = no. of days in the season, 20

For the total no. of degree-days the values were derived from the application of the dry-adiabatic lapse rate of - 5.4°F/1000 ft. (-9.8°C/Km) rise in elevation applied to the 50% area of catchment elevation as shown in figure 4.4 (p. 59). The value obtained (0.0552 in/degree-day) is low compared to the average value (0.08 in/degree-day) obtained in basin studies further south [23].

b. Multi-day block Model

The multi-day block chosen for this example was arbitrarily taken to be 5-day units. The equation for the model is shown below,

$$\text{M.D.D.F.}_i = \frac{\sum_{j}^{k} \text{Volume of daily snowmelt}}{\sum_{j}^{k} \text{No. of degree-days}} \qquad (4.4 - 2)$$

where

M.D.D.F._i = Multi-day degree-day factor of ith unit

n = no. of days in one unit

j = $n(i - 1) + 1$

k = $n\,i$

The values obtained were:

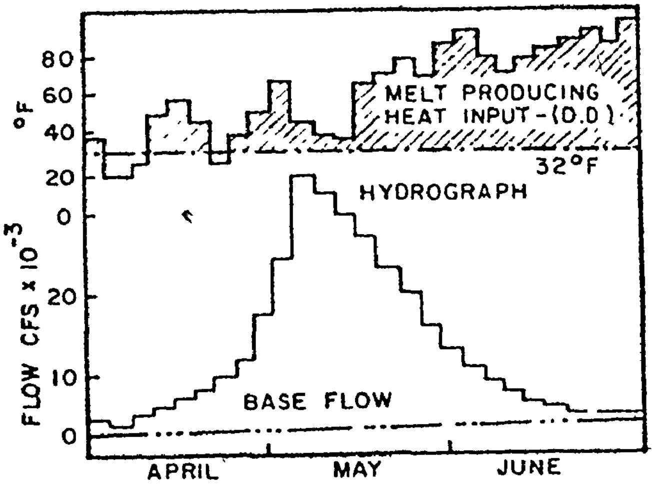
M.D.D.F._1 = 0.1344 in/degree-day

M.D.D.F._2 = 0.0463 in/degree-day

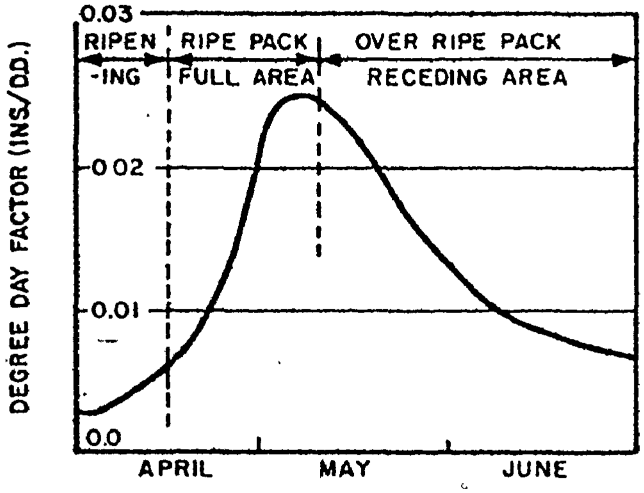
M.D.D.F._3 = 0.0494 in/degree-day

M.D.D.F._4 = 0.0557 in/degree-day

The flows in block 1 were rising and comparable to the ripening limb of the D.D.F. curve in fig. 4.3, when the D.D.F. has by far the highest value. In block 4 the D.D.F. has the next highest value, and this agrees with the receding limb of fig. 4.3. Blocks 2 and 3 which contribute the bulk of the flow have an average value of 0.04785 in/degree-day. Blocks 2 and 3 also have the highest runoff values; if the



TYPICAL HYDROGRAPH OF SNOWMELT OR STREAMFLOW



TYPICAL SEASONAL DEGREE DAY FACTOR IN N.B.

FIG. 4.3 THE DEGREE-DAY FACTOR METHOD

of p.

seasonal value of 0.0552 in/degree-day were applied, an error of 15.36% in the estimation of runoff would result. A better value of D.D.F. is achieved by this time resolution.

c. Daily Model

The D.D.F. formula was applied to daily results obtained from the 1972 field data. The results are tabulated in table 4.4. A careful study of the D.D.F. generated in table 4.4 would show that the high value obtained in block 1 is attributed to the results of the 5th day. The value of 0.457 in/degree-day is much greater than any results cited in the literature. In this case one would seriously consider that antecedent temperatures were important factors in producing this result.

To investigate this, the term "recession-flow" is used to mean melt which is contributed by antecedent temperature conditions. It is the melt which is retarded in the pores of the soil above the permafrost or in the interstices of the snowpack. It is suggested that such recession-flow especially in the first and last five days of the 1972 data season, might affect the D.D.F. quite radically. This is calculated in table 4.4.

Two reasons for the difference in results from this and the study on the Tobique Basin (fig. 4.3) are evident. Firstly, degree-day values in Arctic basins are small; small changes in temperature have a proportionately larger effect on snowmelt. Further south, as in New Brunswick, once the temperature trend rises above zero degree-day, it continues steadily to increase, to a value much greater than that observed in the Arctic areas. Fluctuation in temperature of a few

TABLE 4.4 DAILY DEGREE-DAY FACTORS OF THE DAILY MODEL

DEGREE-DAY (°F)	RUNOFF (in)	D.D.F. (in/degree-day)	
0.00	0.158	-	
1.67	0.189	0.113	0.1853
3.58	0.262	0.073	
4.17	0.409	0.098	
0.75	0.343	0.457	
10.83	0.305	0.028	
9.33	0.593	0.064	
9.50	0.506	0.053	
10.75	0.500	0.047	
12.46	0.543	0.044	
10.96	0.585	0.053	
14.79	0.706	0.048	
12.21	0.615	0.050	
10.54	0.595	0.056	
9.92	0.383	0.039	
8.71	0.312	0.036	
6.08	0.350	0.058	
3.88	0.324	0.083	
2.71	0.181	0.067	
2.04	0.137	0.067	

degrees is a small percentage of total degree-day. Secondly, the size of the basin and the large degree-day values mask the effects of recession flow, which will be shown to be critical for the Arctic basins.

In table 4.5, the D.D.F. for daily degree-day values is tabulated for values of recession-flow of 50 cfs to 100 cfs. (This estimate seems reasonable for most of the season). Furthermore, it seems likely that the ripening process took place before July 11, day one in the 1972 season. The 1973 data, which covered a larger base, supports this assertion (see fig. 3.2 and 3.3). Table 4.5 indicates that a constant recession-flow of 50 - 100 cfs over the whole season produces a better D.D.F. (In table 4.5 flows have been adjusted to account for the extraction of recession-flow)

Recession-flow should be computed from a knowledge of lag, but no attempt has been made here to take this into account. However, as shown in Section 4.3, increasing lag was found to be statistically significant, and future work should investigate this possibility.

In table 4.5, an infinitely large value of the D.D.F. is needed to generate any flow at all due to the lack of a degree-day value. The D.D.F. values then drop to a steady level averaging 0.049 in/degree-day. At the end of the season the D.D.F. increases again. Recession-flow has the effect of lowering the high D.D.F. values occurring in the first and last five days. Neglecting day one, the first 4 days average D.D.F. value is lowered from 0.185 in/degree-day to

TABLE 4.5. DAILY DEGREE-DAY FACTORS WITH RECESSION CONSIDERATION, OF THE DAILY MODEL

RECESSION (cfs)

0	50	100	
-	-	-	
0.113	0.082	0.050	0.121
0.073	0.059	0.044	
0.098	0.085	0.073	
0.457	0.387	0.317	
0.028	0.023	0.018	
0.064	0.058	0.052	
0.053	0.048	0.042	
0.047	0.042	0.037	
0.044	0.039	0.035	
0.053	0.049	0.044	
0.048	0.044	0.041	
0.050	0.046	0.042	
0.056	0.051	0.046	
0.039	0.033	0.028	
0.036	0.030	0.024	
0.058	0.049	0.040	
0.083	0.070	0.056	
0.067	0.047	0.028	
0.067	0.041	0.016	

0.121 in/degree-day, a decrease of 52.9%. For mid-season, the change is from 0.049 in/degree-day to 0.039 in/degree-day a decrease of 25.3%. Similarly for the last four days the average value was lowered from 0.069 in/degree-day to 0.035 in/degree-day, a decrease of 96.4%. These values are slightly small because no adjustment has been made to account for the recession-flow reduction from the D.D.F., and hence one may conclude that this recession-flow concept is very important for low flow conditions in basins where lag is one day or more.

Furthermore, it is interesting to note that for a recession-flow of 100 cfs, the D.D.F. values in table 4.5 show a similar trend to that given in fig. 4.3. This supports the assertion that ripening had taken place prior to the collection of data for the 1972 season.

For disaggregation on a daily basis, the derived D.D.F. values with consideration for recession-flow, vary from 0.070 in/degree-day to 0.016 in/degree-day through the season. It can be immediately seen that application of these values necessitate a knowledge of the time in the melt season. Large errors could occur if the factors are not applied properly, and further work is necessary to relate D.D.F. to melt season duration.

Evidently the D.D.F. will rise to 0.070 in/degree-day, the peak value for the ripening limb, then gradually fall. Without knowledge of melt season duration, an average value of 0.050 in/degree-day (seasonal D.D.F.) could be used.

4.4-2 Areal Disaggregation of the Daily Model

It is felt that for this study daily resolution is the smallest useful time unit due to the fact that temperature data are readily available only as daily averages. James [40] showed in his paper on development of simulation models (1972) that there is a limit to which models can be resolved in time and space. It is felt that further resolution of the 1972 field observations would lead to the questioning of the integrity of that data. However, the catchment has a shorter response than this, unfortunately the field observations cannot warrant further discretization. Areal disaggregation into more than four equal areal units is therefore not warranted, but this should indicate whether areal disaggregation is likely to be significant. There is an alternate method of areal disaggregation which could also be used. The elevation could be chosen and the contributing area then established for it. With that method the contributing areas would vary and a factor would have to be established and used for each area. By the choice of equal areas compilation with the model is simplified. No attempt can be made to reach an optimum disaggregation; this may also form a useful line of enquiry for future researchers in this field.

From figure 4.4, the average elevation of each of the four equal areas, I to IV, is obtained. Table 4.6 shows the adjusted degree-days for each of the areas; the adiabatic lapse rate lowers the number of degree-days progressively for areas I to IV. With disaggregation we find that I and II contribute to melt before areas III and IV which may have zero degree-days. Areal disaggregation allows melt contribution

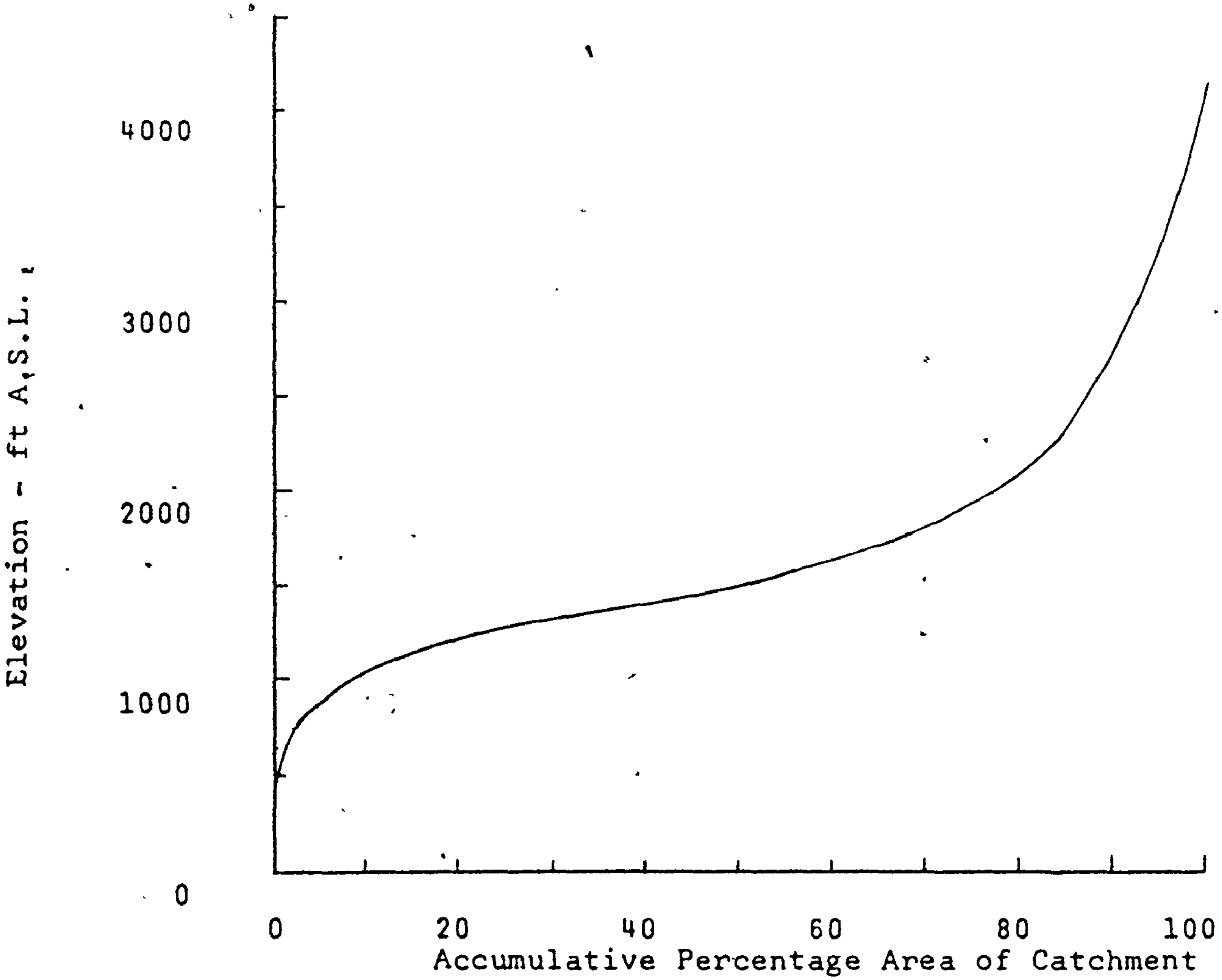


FIG 4.4 PERCENTAGE AREA - ELEVATION CURVE, DUVAL BASIN

TABLE 4.6 DEGREE-DAY VALUES AREAS I TO IV *

I	II	III	IV
2.27	0.87	0.00	0.00
3.94	2.54	0.92	0.00
5.85	4.45	2.83	0.00
6.44	5.04	3.42	0.00
3.02	1.62	0.00	0.00
13.10	11.70	10.08	5.43
11.60	10.20	8.58	3.93
11.77	10.37	8.75	4.10
13.02	11.62	10.00	5.35
14.73	13.33	11.71	7.06
13.23	11.83	10.21	5.56
17.06	15.66	14.04	9.39
14.48	13.08	11.46	6.81
12.81	11.41	9.79	5.14
12.19	10.79	9.17	4.52
10.98	9.58	7.96	3.31
8.35	6.95	5.33	0.68
6.15	4.75	3.13	0.00
4.98	3.58	1.96	0.00
4.31	2.91	1.29	0.00

* Average elevations in feet above sea level are 1120, 1380, 1680 and 2540 respectively for areas I to IV.

from the lower elevation despite the fact that the average overall value of the D.D.F. applied to the entire catchment yields no melt.

At the beginning of the season there is greater melt from the lower elevations. This is borne out from the observation of increasing lag due to the receding snowpack as shown in section 4.3. This fact may be utilized to obtain the D.D.F. values for the basin. Linearity is assumed and snowmelt is assumed to be proportional to the value of the respective degree-days to allow application of the same D.D.F. for the day over the entire basin. On this basis, as disaggregation approaches an infinite number of areas, the optimal value of D.D.F. will be achieved. The D.D. F. values obtained in this way are shown in table 4.7.

The four areas were arbitrarily given a uniform cover of snow equivalent of 8 inches of water (this is the amount of melt that occurred over the season). Melt was terminated when the total melt reached 8 inches from that area; melt is allowed only from the areas which theoretically still had snow cover. In actuality the snow cover is not distributed uniformly over the entire basin. During the accumulation season the snow is dispersed unevenly by the wind. More snow accumulates in the plateau and valley areas than on the exposed slopes. Without snow course data and detailed photogrammetric interpretation, no attempt will be made here to redistribute the snow cover. However, it must be pointed out that proper distribution of snow cover would enhance the accuracy and sensitivity of the model. Snowpack accumulates in the same areas within the catchment. Local people

TABLE 4.7. DISAGGREGATED DAILY DEGREE-DAY FACTORS FOR AREAS I TO IV

DEGREE-DAY (°F above 32°F)	RUNOFF (in)	D.D.F. (in/degree-day)
2.27	0.457	0.201
3.94	0.402	0.102
5.85	0.468	0.080
6.44	0.708	0.110
3.02	0.895	0.296
13.10	0.397	0.030
11.60	0.802	0.069
11.77	0.682	0.058
13.02	0.651	0.050
14.73	0.684	0.046
13.23	0.758	0.057
17.06	0.858	0.050
* 13.08	1.026	0.078
11.41	1.031	0.090
10.79	0.676	0.063
9.58	0.573	0.060
6.95	0.752	0.108
4.75	0.782	0.165
3.58	0.468	0.131
2.91	0.379	0.130

* Flow contribution from area I is assumed terminated at this point, areas II to IV are assumed contributing for rest of season.

(e.g. traders) and air photos could indicate such parts of the basins and this information could easily be incorporated in the deterministic model at the next order of disaggregation. In line with the redistribution of snow cover, the degree-day information for different area elevation relationships could be improved by adjustment to the "equivalent latitude" which Dingman [5] illustrated in his report on the Hydrology of the Glenn Creek Watershed (1971).

In table 4.7, no account is taken of recession-flow or lag, and the D.D.F. values from the first and last five days of the season are high. For uniform recession-flow over the entire season of 50 cfs and 100 cfs respectively, the D.D.F. is shown in table 4.8 and plotted in fig. 4.5 for both recession-flows.

The curves indicate that the D.D.F. values tend to approach a constant value for the entire season. This implies that a method based on a single-valued D.D.F. can be derived. In many cases it may be useful to estimate snowpack recession. In table 4.7, at day 12 melt from area I exceeded 8 inches of water equivalent, and on day 13 of season, the runoff was considered from areas II to IV only. The D.D.F. prior to this was 0.050 in/degree-day, on day 13 it increased by 0.020 in/degree-day. This could occur if there were more than 8 inches of potential melt from area I. The very cold winter would incur a larger amount of redistribution of snow by wind. Drifts would be deep in the incised gulleys in the lower catchment. This would account for a greater flow contribution for lower elevations. This adds to the complexity of the model, and as little snow cover information is available, a uniform cover was assumed for this exercise.

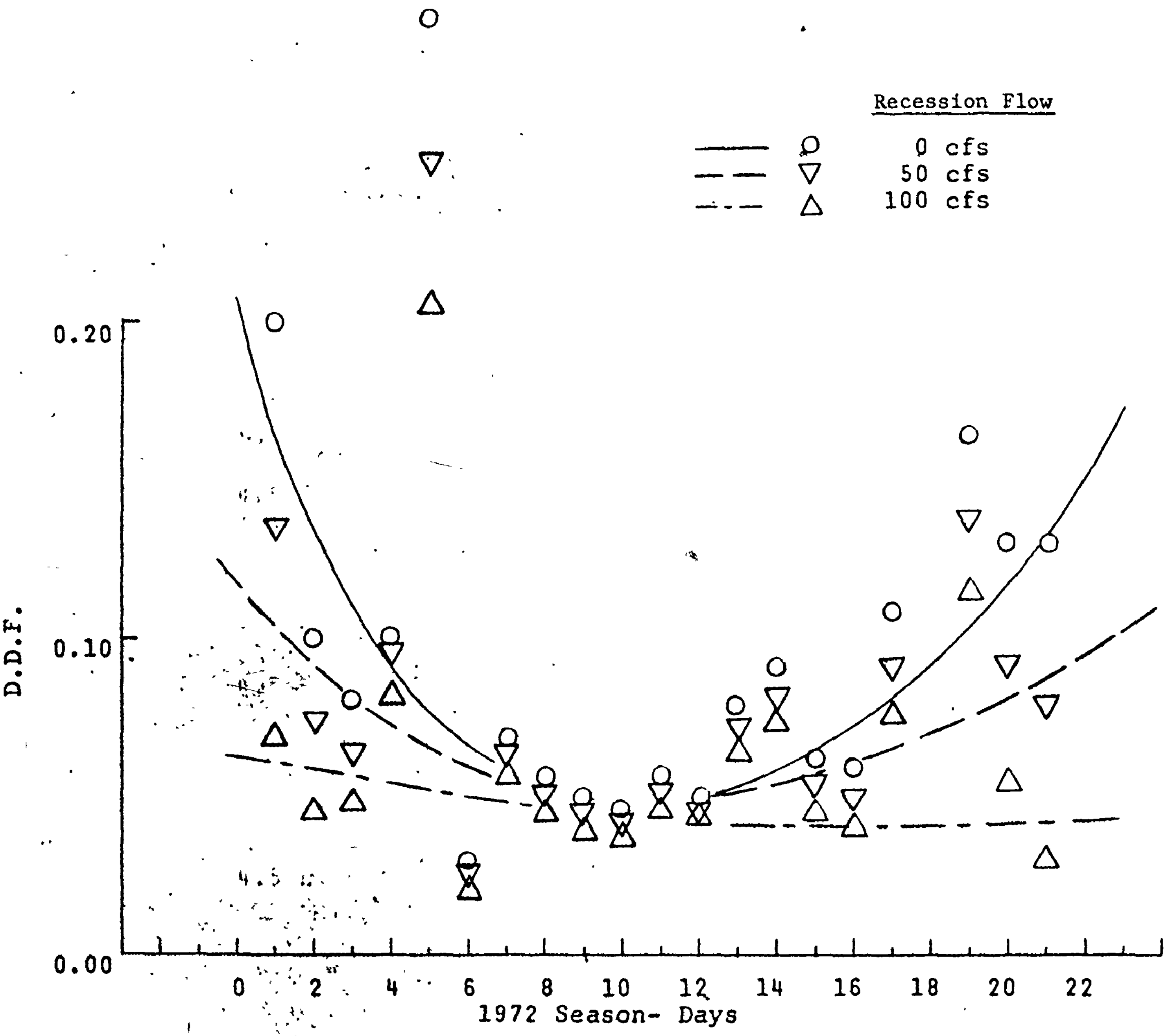


FIG. 4.5 D.D.F. CURVES, DUVAL BASIN 1972

DAILY DISAGGREGATED MODEL
TABLE 4.8. DISAGGREGATED DEGREE-DAY FACTORS, WITH RECESSION CONSIDERATION

RECESSION (cfs)		
0	50	100
0.201	0.135	0.068
0.102	0.074	0.045
0.080	0.064	0.048
0.110	0.096	0.082
0.296	0.251	0.206
0.030	0.025	0.020
0.069	0.063	0.057
0.058	0.052	0.046
0.050	0.045	0.039
0.046	0.042	0.037
0.057	0.052	0.047
0.050	0.047	0.043
0.078	0.072	0.065
0.090	0.082	0.074
0.063	0.054	0.045
0.060	0.050	0.040
0.108	0.090	0.076
0.165	0.138	0.114
0.131	0.093	0.055
0.130	0.080	0.030

From fig. 4.5, the limiting value of D.D.F. is 0.045 in/degree-day, for the Duval basin from 1972 data. The results of a spatially disaggregated model would be much better than those of a model with rising and falling D.D.F. where the entire basin is assumed to be contributing. No estimation of ripening duration or of receding limb is necessary. Because of areal disaggregation, the influence of the ripening process is distributed through the ablation season, and up the catchment. Continuity of flow from contributing areas and the monitoring of the receding snowpack can be automatically taken into account. Improvements of knowledge of recession-flow and snowpack distribution would greatly enhance the accuracy of the results that could be generated by this method. Improvements could be made to the model by taking into account adjusted daily values of recession-flow. This can be accomplished by making it a function of antecedent temperature conditions.

Further studies to obtain a deterministic value of the limiting D.D.F. value are recommended, as it is evident that this method could prove to be a powerful tool for snowmelt prediction.

4.4-3 Application of D.D.F. Model to 1973 Pangnirtung Data

As an example of operational use the 1972 D.D.F. model is applied to 1973 Pangnirtung data. The methodology will be outlined in general with specific references made to the sample problem. The D.D.F. model should be developed in the following steps:

(i) Disaggregate the basin into "n" equal areas (a_i, $i = 1,n$). the example n = 4; the areas are numbered I to IV downstream to upstream and are given in square miles ($a_i = 8.85 \text{mi}^2$)

(ii) Obtain the average elevation for each area area. For the example the elevation from areas I to IV are 1120, 1380, 1680 and 2540 ft. respectively.

(iii) Apply the adiabatic lapse and obtain the adjusted degree-day temperatures ($t_{i,j}$, $i = 1,n, j = 1,e$, where j = jth day of the season) at each area from the observed degree-days. For the example the adjustment to the observed degree-days are - 1.73, - 3.13, - 4.75 and - 9.4°F for areas I to IV respectively (table 4.9).

(iv) Apply the chosen D.D.F. to the adjusted degree-day (table 4.9) to obtain the runoff ($q_{i,j}$, $i = 1,n$, $j = 1,e$) in inches from each of the areas

$$q_{i,j} = t_{i,j} \text{ (D.D.F.)} \text{ ——————— } (4.4 - 3)$$

For the example the runoff is tabulated in table 4.10 for each sub-area. D.D.F. = 0.05 in/degree-day.

(v) Sum the runoff for the jth day of the season for $i = 1,4$. Divide that by n and multiply by Kddf, the conversion factor

TABLE 4.9 DAILY DEGREE-DAYS FROM 1973 PANGNIRTUNG DATA

	I	II	III	IV
evation Feet	1120	1380	1680	2540
	5.81	4.41	2.79	0.00
	4.94	3.54	1.92	0.00
	15.60	14.20	12.55	7.93
	17.44	16.04	14.42	9.77
	9.27	7.87	6.25	1.60
	14.81	13.41	11.79	7.14
	16.77	15.37	13.75	9.10
	10.89	9.49	7.87	3.22
	15.94	14.54	12.92	8.27
	21.19	19.79	18.17	13.52
	20.06	18.66	17.04	12.39
	13.77	12.37	10.75	6.10
	15.35	13.95	12.33	7.68
	14.77	13.37	11.75	7.10
	15.35	13.95	12.33	7.68
	10.48	9.08	7.46	2.81
	3.98	2.58	0.96	0.00
	13.06	11.66	10.04	5.39
	17.98	16.58	14.96	10.31
	18.60	17.20	15.58	10.93
	18.23	16.83	15.21	10.56
	18.98	17.58	15.96	11.31
	13.23	11.83	10.21	5.65
	10.69	9.29	7.67	3.02
	7.10	5.70	4.08	0.00

TABLE 4.10 PREDICTED RUNOFF (INCHES) FROM CONTRIBUTING AREAS AND TOTAL RUNOFF (CFS) FROM ENTIRE BASIN

I		II		III		IV		
$q_{1,j}$ (in)	$\Sigma q_{1,j}$ (in)	$q_{2,j}$ (in)	$\Sigma q_{2,j}$ (in)	$q_{3,j}$ (in)	$\Sigma q_{3,j}$ (in)	$q_{4,j}$ (in)	$\Sigma q_{4,j}$ (in)	Ob_j (cfs)
0.291	0.291	0.221	0.221	0.140	0.140	0.000	0.000	166.71
0.247	0.538	0.177	0.398	0.096	0.236	0.000	0.000	123.81
0.780	1.318	0.710	1.108	0.628	0.864	0.397	0.397	598.57
0.872	2.190	0.802	1.910	0.721	1.585	0.489	0.886	686.22
0.464	2.654	0.394	2.304	0.313	1.898	0.080	0.966	297.36
0.741	3.395	0.671	2.975	0.590	2.488	0.357	1.323	561.04
0.839	4.234	0.769	3.744	0.688	3.176	0.455	1.778	654.33
0.545	4.779	0.475	4.219	0.394	3.570	0.161	1.939	374.64
0.797	5.576	0.727	4.946	0.646	4.216	0.414	2.353	614.83
1.060	6.636	0.990	5.936	0.909	5.125	0.676	3.029	864.71
1.003	7.639	0.933	6.869	0.852	5.977	0.620	3.649	810.92
0.689	8.328	0.619	7.488	0.538	6.515	0.305	3.954	511.54
0.768	9.096	0.698	8.186	0.617	7.132	0.384	4.338	586.74
0.739	9.835	0.669	8.855	0.588	7.720	0.355	4.693	559.14
0.768	10.603	0.698	9.553	0.617	8.337	0.384	5.077	586.74
0.524	11.127*	0.454	10.007	0.373	8.710	0.141	5.218	354.95
		0.129	10.136	0.048	8.758	0.000	5.218	42.12
		0.583	10.719	0.502	9.260	0.270	5.488	322.35
		0.829	11.548*	0.748	10.008	0.516	6.004	498.10
				0.779	10.787	0.547	6.551	315.56
				0.761	11.548*	0.528	7.079	306.64
						0.566	7.645	134.70
						0.278	7.923	66.16
						0.151	8.074	35.96
						0.000	8.074	0.00

for converting inches of runoff to flow in cfs.

$$Qb_j = Kddf\ \left(\frac{\sum_{i=1}^{4} q_{i,j}}{n}\right) \quad \text{———————} \quad 4.4\ \text{-}4$$

where

Qb_j = Average flow for entire basin on the jth day of the season

For the example Kddf = 951.87 cfs/inch, and the results of Qb_j are plotted in table 4.10.

(vi) As the total runoff for the observed flows for the 1973 season was 10.86 in. of water equivalent, the runoff contribution from each area is considered to cease when it exceeded 11.0 in.

$$\sum_{j=1}^{k-1} q_{i,j} \leqslant 11.0 \text{ in.} \leqslant \sum_{j=1}^{k} q_{i,j} \quad \text{———————} \quad 4.4 - 5$$

where

k = last day in the season contributing to flow from the ith area

For the example $\sum_{j=1}^{k} q_{i,j}$ for i = 1,4 is noted in table 4.10 with an asterisk (*)

The results of predicted average flows (Qb_j) in table 4.10 is plotted against observed flows in fig. 4.6. The predicted results follow

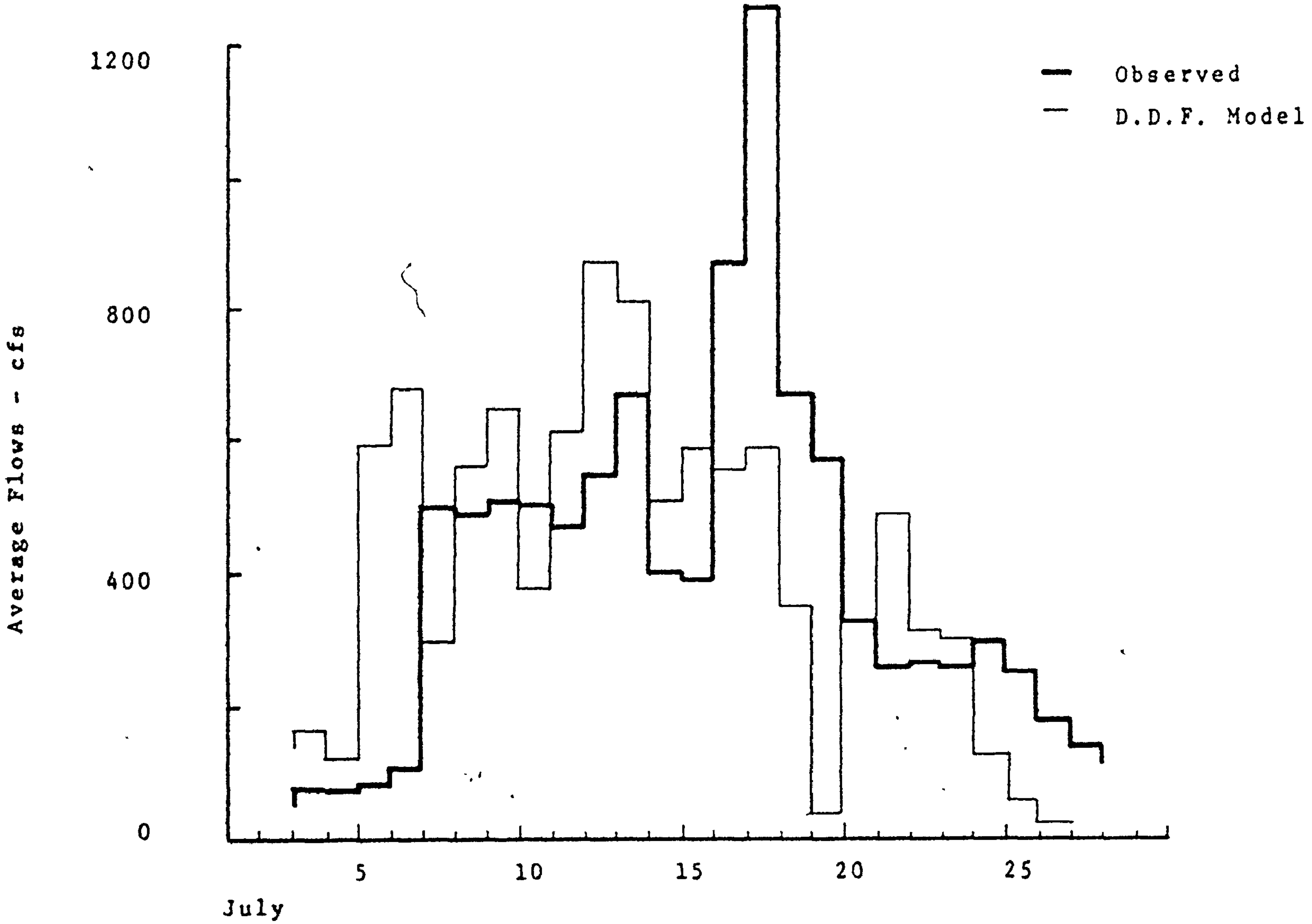


FIG. 4.6 PLOT OF DAILY FLOWS, OBSERVED AND 1972 D.D.F. MODEL FOR PANGNIRTUNG

the trend of observed flows. Unlike the conventional D.D.F. method where the D.D.F. is applied to the entire basin and knowledge of seasonal duration is needed, the D.D.F. model here has built in adjustments to continuity with which the receding snowpack is takin into account and decreasing flows with high degree-days are taken into account as shown in fig. 4.6.

No recession flows or redistribution of snow cover were considered in this excercise. As was discussed in subsection 4.4-2, these would improve and enhance the accuracy of the predicted flows. Thus it can be concluded from the development and the above example in this section that the deterministic D.D.F. model has great potential and further studies in this line should definitely be encouraged.

CHAPTER V. REGRESSION ANALYSIS AND APPLICATION OF 1972 MODEL TO 1973 DATA

5.1 Regressions to 1973 Data

A computer program was developed for regressing the field data, [11, 42] . It was also applied to the data obtained from the field trip in 1973. The data collected were modified to suit the automatic method from which the flows were derived. Where possible temperature and weather data were obtained for Frobisher Bay and Broughton Island [18] from the Atmospheric Environment Service. Data from the A.E.S. "mechanical weather station" (MRI) at Pangnirtung set up in the summer of 1973 could not be used for this study. Instead, temperature data collected by means of Pacific Transducer Corporation Model 6.15F, 7-day temperature recorders were used. The input data for the three reaches were set up as follows:

Column one, variable Y = observed average flow (CFS),
Column two, variable X1 = constant set to unity,
Column three, variable X2 = degree-day in °F above 32°F,
Column four, variable X3 = weather factor : 0, clouded day to 3, wet, cloudy day
Column five, variable X4 = maximum temperature of the day °F
Column six, variable X5 = minimum temperature of the day °F

The input data for the Duval River, the Broughton Creek and the Apex River are tabulated respectively in tables 5.1, 5.4 and 5.7

The output data from the regression program are tabulated for the above reaches respectively in tables 5.2, 5.5 and 5.8. The results are average predicted flows (CFS) and are developed from linear least squares regressions. The output data are set up as follows:

Column one, NPAR = 1, Y is regressed against X2 above
Column two, NPAR = 2, Y is regressed against X2 and X3
Column three, NPAR = 3, Y is regressed against X2, X3 and X4
Column four, NPAR = 4, Y is regressed against X2, X3, X4 and X5

In the testing of the regressed models developed in this chapter the use of the F-test or the F-null hypothesis is applied [11, 12, 13]. The linearity of the regression relation is tested whereby several observations of Y are made for each combination of x_1, x_2 ....x_k. One can test the hypothesis that all true partial regression coefficients equal zero by an F-test of the variance accounted for by regression, relative to the error variance. If the F-value calculated is greater than the F-value tabulated then one can reject the hypothesis concluding that the variance accounted for by regression is more than could be reasonably expected if all the true partial regression coefficients were zero [13].

5.1-1 Pangnirtung, Duval River 1973

The F-test results shown in table 5.3 indicates that except for NPAR = 1, one can reject the hypothesis. This indicates that where more relevant variables are added the predictability of the results is improved. However, for NPAR = 1, the only variable applied is degree-day above 32°F, from automatic coil temperature recorders. In comparison to 1972 data (temperature observed on alcohol thermometer) the F-value calculated (43.97) was very much greater than the F-value (8.29) for a 99% confidence in rejecting the hypothesis.

However, when variables X3, X4 and X5 are applied additionally NPAR = 2, NPAR = 3, NPAR = 4, respectively, one finds that the hypothesis can be rejected with 99% confidence. It should be pointed out that the additional variables above were extracted from field notes from temperature charts from the researcher's own equipment.

5.1-2 Broughton Island, Broughton Creek 1973; Frobisher Bay, Apex River 1973

The results in two tests are similar, and are compared in this part of the dissertation.

The results from tables 5.6 and 5.9 show that in no case can the null hypothesis be rejected with 99% confidence. In only two cases for the Apex River where three and four variables are applied can the null hypothesis be rejected with a 90% confidence.

The difference between Broughton Creek, Apex River and the Duval River is that for the latter, the data for regression were extracted from the researcher's own field equipment and observations. Data for the two former reaches were obtained from the Atmospheric Environment Services observations [18]. The results obtained in 1972, table 4.3, showed that data from non-automated equipment produced the necessary sensitivity needed to produce good regression coefficients for extraction of a generalized model for predicting snowmelt. The data from automated equipment for temperature recording and A.E.S. data do not give the necessary sensitivity to produce regression coefficients that even satisfy the F-test with 90% confidence with just one variable.

Similarly field extraction of weather data provides the researcher with much greater accuracy of information as shown in the results for the Duval River 1973 (and 1972), where for NPAR = 2 to NPAR = 4, in all cases the F-test was satisfied with 99% confidence. In no cases where weather information were extracted from the A.E.S. data were the regressions able to satisfy the F-test with 99% confidence.

5.2 Development of Daily Model with 1972 Data

From the regressed information given in tables 5.1 through 5.9, it was concluded that the temperature and weather data collected from 1973 were of insufficient sensitivity to be utilised to develop a good model (detailed discussion in Chapter VI). As the 1972 data was statistically the best of the four sets of data, it was used as the basis for a daily flow model.

The regression coefficients (table 4.3) from the computer program applied to Pangnirtung 1972 data, were used on the input data, X2, tables 5.1, 5.4 and 5.7 (see equation 5.2-1).

$$Y_i^x = 1.0714\ A_x + 0.8647\ A_x\ (T_i^x) \qquad (5.2\text{-}1)$$

where

Y_i^x = predicted daily average flow of xth catchment (cfs)

A_x = area of xth study catchment (mi^2)

T_i^x = degree-day above 32°F (from column X2)

Summing the predicted flows obtained from equation 5.2-1, and dividing by the sum of observed flows one obtains the "correction ratio" L_x for the xth study catchment. In this study L_P, L_B, and L_F denote the correction ratios of the study basins at Pangnirtung, Broughton and Frobisher Bay respectively. When the logs of the correction ratios (log L_P, log L_B and log L_F) for the three reaches were plotted against latitude they were found to be statistically linear. Regressing the logs of the correction ratios yields

$$\log L_X = 18.6151 - 0.2823\ (L_X) \tag{5.2-2}$$

where

$\log L_X$ = log of the correction ratio of the xth catchment

L_X = latitude in degrees north of the xth catchment

Thus to obtain the correction value of a catchment at latitude L_X the following equation is developed,

$$L_X = \left[\frac{1}{e^{2.3026\ (\log L_X)}}\right] \tag{5.2-3}$$

where

L_X = correction ratio, sum of predicted over observed.

Combining equations 5.2-1 through 5.2-3 results in a latitude corrected model from 1972 data,

$$Y_i^{\,x} = \frac{[1.07141\ A_x + 0.86472\ A_x\ (T_i^{\,x})]}{e^{2.3026\ [18.6151\ -\ 0.2823\ (L_X)]}} \tag{5.2-4}$$

5.3 Application of 1972 Model to 1973 Data

5.3-1 Frobisher Bay, Apex River (63.75°N, 61.7 km^2)

The algorithm developed from equation 5.2-4, was utilised for the Apex River:

$$Y_i = [25.4266 + 20.52\ (T_i)]\ 4.160884 \text{———————} (5.3\text{-}1)$$

This was applied to 1973 data and the results are tabulated on fig. 5.1.

5.3-2 Pangnirtung, Duval River (66.13°N, 91.7 km^2)

The algorithm developed from equation 5.2-4 was similarly applied to the Duval catchment:

$$Y_i = [37.78957 + 30,49942\ (T_i)]\ 0.885798 \text{—————} (5.3\text{-}2)$$

This was applied to 1973 data and the results are tabulated on fig. 5.2.

5.3-3 Broughton Island, Broughton Creek (67.55°N, 30.64 km^2)

The algorithm developed from equation 5.2-4 was similarly applied to the Broughton Creek catchment.

$$Y_i = [12.626744 + 10.190864\ (T_i)]\ 0.351951 \text{———————} (5.3\text{-}3)$$

This was applied to 1973 data and the results are tabulated on fig. 5.3.

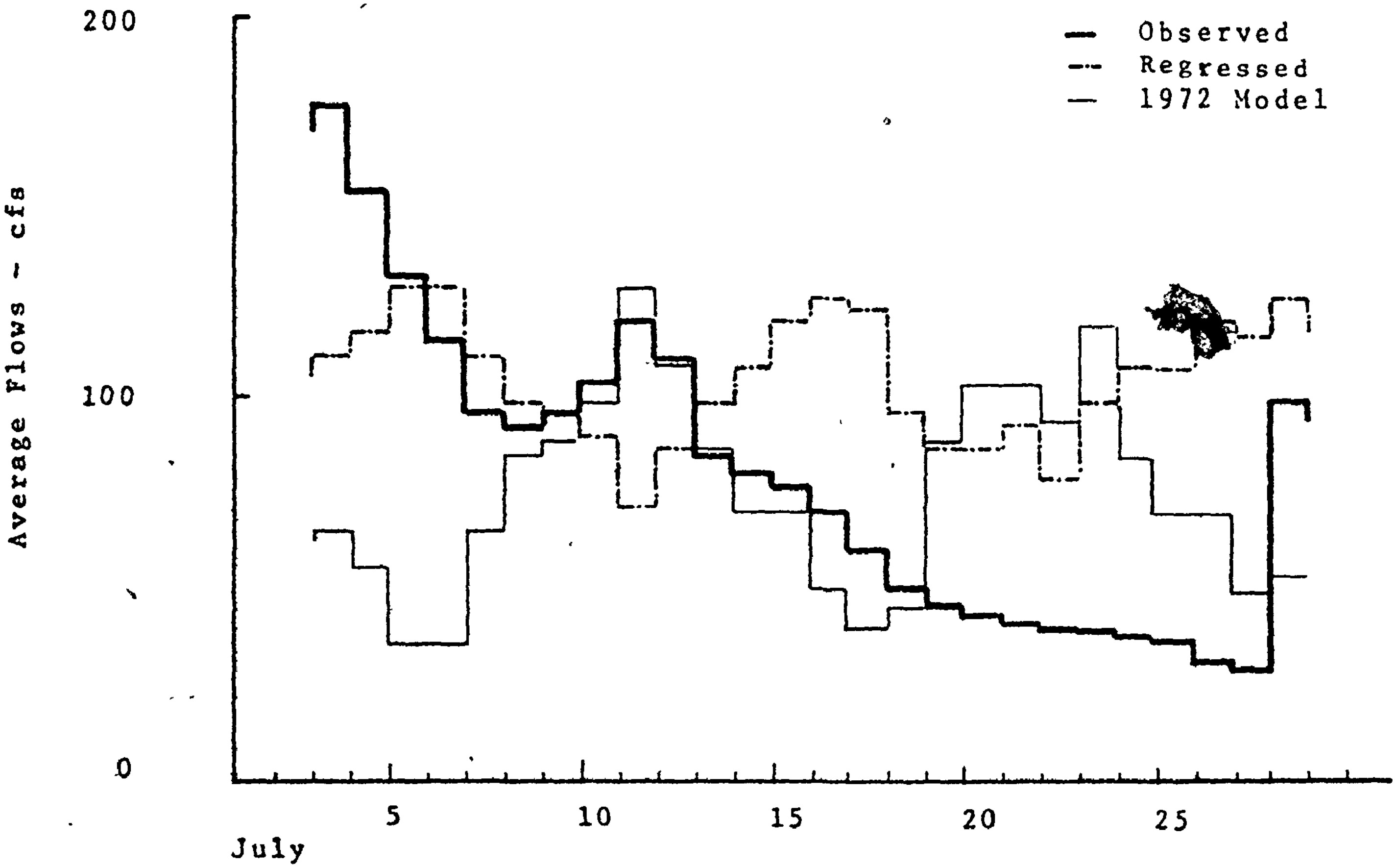


FIG. 5.1 PLOT OF DAILY FLOWS, OBSERVED, REGRESSED AND 1972 MODEL FOR FROBISHER

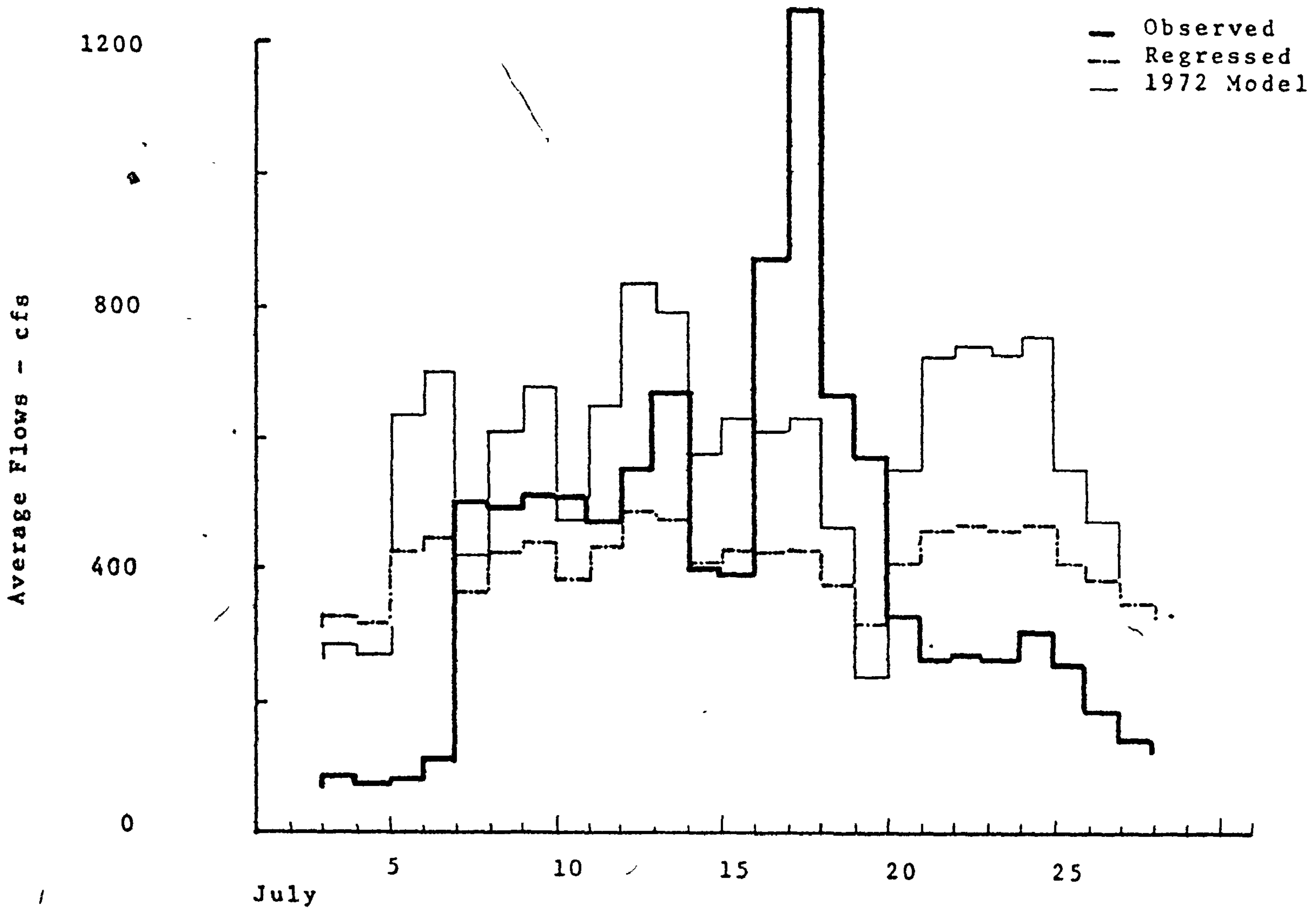


FIG. 5.2 PLOT OF DAILY FLOWS, OBSERVED, REGRESSED AND 1972 MODEL FOR PANGNIRTUNG

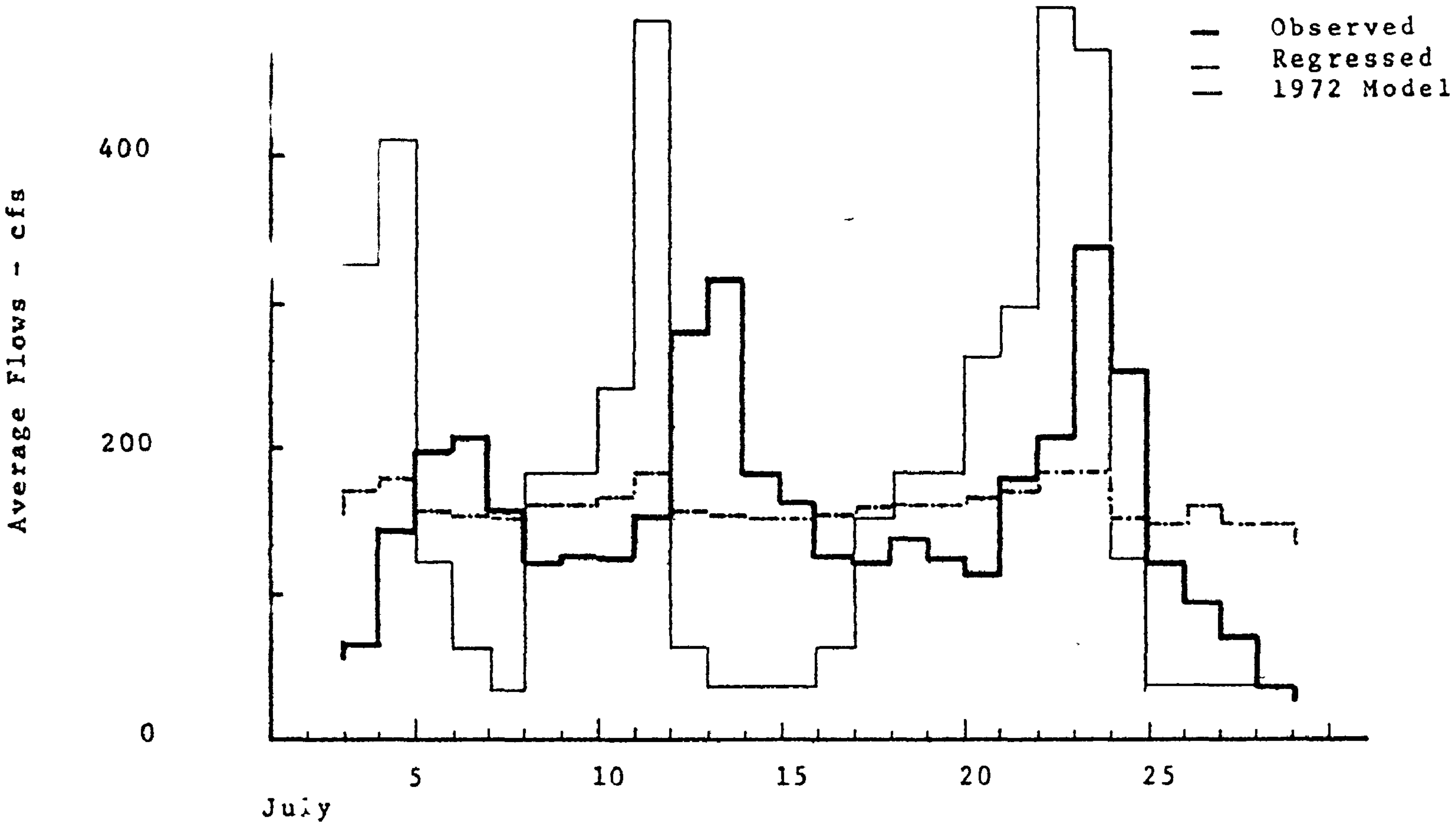


FIG. 5.3 PLOT OF DAILY FLOWS, OBSERVED, REGRESSED AND 1972 MODEL FOR BROUGHTON

CHAPTER VI. DISCUSSION OF THE MODEL

6.1 Discussion of the Results of the Deterministic D.D.F. Model

The following is a summary of the discussion stated in section 4.4. It was shown there that disaggregation of the D.D.F. model improved the accuracy of the predicted results. This disaggregation can take place in time and space. The results showed a definite improvement when the model was resolved from seasonal (20 days) to daily time units. Similarly the predicted results improved with areal discretization. The problem of optimization of the disaggregated units have been left to future studies.

The current deterministic model used in the estimation of snowmelt streamflow is the D.D.F. Method. This model is applied to the entire catchment, because of this the D.D.F. values change over the season. By varying the D.D.F. value, ripening at the beginning and the depletion of snowpack at the end of the season is taken into account (fig. 4.3). Therefore, this method necessitates the knowledge of the duration of the melt season.

In the operational use of the disaggregated D.D.F. Model a knowledge of the duration of the season is not required. A single D.D.F. value is applied for the entire season. All that is required in order to use the model is the precipitation during the winter accumulation and the temperatures of the operational season. Mass balance is taken into account for receding snowpacks with areal discretization in the model. Similarly ripening is taken into account with elevation-temperature-area considerations. For an example of operational use see subsection 4.4-3.

It was the intention of this dissertation to show that the disaggregated D.D.F. model improves predicted results. The results from the development in section 4.4, substantiated this intention. It also showed that it is a sensitive operational model which is simple to use.

6.2 Discussion of the Results of the Regressed Model

The regressed model (equation 5.2-4, with degree-day above 32°F and latitude) is developed to a limited extent due to the fact that a more elaborate algorithm cannot be justified on the basis of the limited field data.

From the results in Chapter V one can conclude that incorporation of the additional variables of weather factor, maximum and minimum temperatures, enhance the sensitivity of the model. These had been chosen primarily because they are readily available to the researcher from government agencies.

Another conclusion from this thesis is that data extracted from government publications should be used with caution as a data base for the creation of models. Good data have to be collected in order to extract a good model. The results also show that more elaborate automated temperature recorders do not give better results than painstaking manual extraction from inexpensive, yet sensitive equipment. However, that is an economic decision based on the availability of manpower and funds.

6.3 Recommendation for Further Work

In the development of the disaggregated deterministic and regressed models, many factors, that could have been included, were discarded due to time limitations. Thus the applicability is necessarily limited, and these models must be used carefully.

For the deterministic D.D.F. model, further data should be collected to establish a better D.D.F. value for the Duval basin. As outlined in section 4.4, further research should be initiated to: optimize the number of disaggregated units, snow cover distributions, equivalent latitude and recession flows. Where rain occurs a separate model should be used. Evaporation should be removed from the net mass balance of the snowpack as it may be significant in the distribution of snowmelt. Other basins should also be studied in a similar manner as data become available.

Further collection of data from other catchments in this study should be continued and field temperature data should be collected as a basis of comparison to information collected and issued by A.E.S. This could then be used to extend the existing information on the two catchments using operational hydrological models.

The importance of latitude shown in the results should be checked in future studies. The linearity of the logs of correction ratios versus latitude should be examined in greater detail as more flow data become available.

The above comments have been confined to the broad hydrological aspects of Arctic Basins, however, the sub-basin aspects such as the progressive increase of lag during a streamflow season in the Arctic areas, 4.3, and the processes of ripening, should not be neglected, as they form a vital part in the complex process of snowmelt.

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APPENDICES

APPENDIX A

NOMENCLATURE

A. NOMENCLATURE

The symbols listed below are in the order of occurrence in the text, and have the following meaning:

H_{rs}	absorbed shortwave radiation.
H_{rl}	net longwave radiation exchange between the pack and its environment
H_{cv}	convective heat transfer from the air above
H_{cn}	heat supplied by condensate
H_p	heat content of precipitation
H_g	conductive heat from the ground
H_q	change in stored heat of snowpack
H_s	heat involved in change of state
M	snowmelt (inches/day)
C	snowmelt coefficient
T_a	average temperature (°F)
T_b	base temperature (usually 32°F)
D.D.F.	degree-day factor (in/degree-day)
V_1	volume of snowmelt (acre-feet)
T_1	maximum temperature (°F)
T_3	accumulated maximum temperature (°F)
b, b_1, b_3, b_4, C_1, C_2, C_3	statistically derived constants
Q_1	height to peak above trough
Q_2	height to trough above previous trough
M_i	snowmelt from i^{th} heat source (in/day)
Q_i	energy (B.t.u./ft^2)
B_i	quality as decimal fraction

M_c	melt from energy input convection and molecular conduction
M_{co}	melt from energy input from condensation of water vapor onto snowpack.
M_{rs}	melt from energy input from shortwave radiation
M_{rl}	melt from energy input from longwave radiation
M_p	melt from energy input from rain
M_g	melt from energy input from ground
K	variable coefficient
V_w	wind speed (M.P.H. @ 50 ft. above ground level)
P_r	one day's rainfall (inches)
T_w	wet bulb temperature (°F)
n	sunshine (hr/day)
R_b	longwave radiation (ly/day)
R_h	relative humidity
d	percentage of total water content of the overlying snowpack which could infiltrate the ground
MC	initial soil moisture content prior to melt
T_m	maximum daily temperature (°F)
K	degree-day factor
A_s	function of ratio of total snowmelt to total snowfall
X1	unit constant used in regression program
X2	degree-day above 32°F
X3	weather factor
X4	% of cloud cover or maximum temperature °F
X5	average wind velocity (M.P.H.) or minimum temperature °F
BO-B4	regression coefficients
S.E.E.	standard error of estimate
M.C.C.	multiple correlation coefficient

P.C.C.	partial correlation coefficient
Y	observed average flows (CFS)
Y_i^x	predicted daily average flow of the x^{th} catchment (CFS)
A_x	area of x^{th} study catchment (mi^2)
T_i^x	degree-day above 32°F
L_x	latitude correction ratio

APPENDIX B

GAUGING

B. GAUGING

The gauging for the Duval River and Broughton Creek was performed manually with the aid of an Ott current meter model No. 10.152. Counters were provided by means of bicycle horns with a 1.5 volt d-c source hooked up to the meter contacts. The number of revolutions of the propeller was coincident with the number of beeps. The meter operator noted depth of channel and distance from bank at each counting station. The assistant on the bank noted the information down. The results of two typical gauging experiments are tabulated on table B.1.

The flow information gathered were plotted in a stage-discharge relationship for the two respective creeks as shown in figures 3.4 and 3.5. (The two gaugings in 1973 coincided very well with the curve provided by the 1972 gauging.) The stage-discharge curve for the Apex River was provided by the Department of Environment who obtained their curve by means of fluorometry.

TABLE B.1 GAUGING DATA

DATE : Saturday, July 21, 1973

LOCATION : Duval River, Pangnirtung

W/L : Recorder 1.505' Stake 16"

TEMPERATURE : 50°

[prop # 14937]
[bomb # 19230]

DISTANCE OUT (FT)	DEPTH (FT)	n REV/SEC	v FPS	Q CFS
6	1.17	0.50	0.92	3.23
9	1.33	0.90	1.55	6.18
12	1.08	0.70	1.24	4.02
15	0.83	1.00	1.70	4.23
18	1.42	0.48	0.89	3.79
21	1.75	1.08	1.86	9.77
24	1.75	0.94	1.60	8.40
27	1.67	0.60	1.07	5.36
30	1.17	1.54	0.98	3.44
33	2.33	1.12	1.90	13.28
36	1.33	1.42	2.39	9.54
39	1.67	1.08	1.86	9.32
42	1.83	0.74	1.29	7.08
45	1.17	1.32	2.20	7.72
48	1.42	1.10	1.87	7.97
51	–	–	–	–
54	1.67	1.84	3.07	15.38
57	1.67	0.52	0.93	4.66
60	1.67	1.54	2.58	12.93
63	1.67	0.56	1.00	5.10
66	1.75	0.32	0.64	3.36
69	1.75	0.70	1.24	6.51
72	1.92	1.84	3.08	17.74
75	1.17	1.62	2.70	9.48
78	1.75	1.34	2.25	11.81
81	2.00	1.30	2.18	13.08
84	1.83	0.94	1.60	8.78
87	–	–	–	–
90	0.50	0.70	1.24	1.86
93	0.50	0.70	1.24	1.86
			TOTAL	215.88

APPENDIX C

PROGRAM LISTING

C. PROGRAMS

The following pages in this appendix contain the listing of the driver and the subroutine programs used to derive the coefficients for the regressed model. The coefficients of the model are obtained by the application of matrix theory [42] to regression analysis.

Statistical routines were also built into the overall program. Specifically tests relevant to regression were developed in subroutines OUTSTAT [13] and DRAPER [11].

A sample of the data input is shown in page C16. The output printout was not shown due to the number of pages involved; however, the summary of the results of the statistical data are tabulated in chapters IV and V.

Subroutine MATINV was taken from Matrix Methods of Structural Analysis by C.K. Wang [42]. All other subroutines were written by the author.

```
      PROGRAM TST(INPUT,OUTPUT,TAPE7,TAPE8,TAPE5=INPUT,TAPE6=OUTPUT)        000100
                                                                            000110
C *******************************************************************      000120
C     THIS IS REGRESSION MODEL WITH STATISTICAL TESTS                       000130
C *******************************************************************      000140
                                                                            000150
C    THIS IS A DRIVER PROGRAM WHICH UTILISES MATRIX THEORY TO ANALYSE      000160
C    MULTIPLE LINEAR REGRESSION MODELS                                      000170
C    BUILT INTO IT ARE MATRIX ROUTINES WHICH MULTIPLY ≠MATMUL≠,            000180
C    TRANSPOSE ≠MATRAN≠,AND INVERT ≠MATINV≠                                 000190
                                                                            000200
C     NVAR     IS THE NO. OF VARIABLES                                      000210
C     NPAR     IS THE NO. OF PARAMETERS                                     000220
C     FLOW     IS THE DAILY FLOW IN CFS-DAY                                 000230
C     X(I,1)   IS DUMMY VARIABLE ALWAYS ONE                                 000240
C     X(I,2)   IS TEMPERATURE VALUES IN DEGREE FAHRENHEIT                   000250
C     X(I,N)   IS OTHER VARIABLES TO BE SPECIFIED                           000260
                                                                            000270
C    IF NPAR EXCEEDS ≠5≠ REDO READX                                         000280
                                                                            000290
C    ----------------------------------------------------------------      000300
C     READING IN DATA                                                       000310
C    ----------------------------------------------------------------      000320
                                                                            000330
      DIMENSION FLOW(25),X(25,5),XT(5,25),B(5),XPROD(5,5),                  000340
     + XPINV(5,5),XTPRO(5,1),DUMMY(5,5),INDEX(5,2)                          000350
      DIMENSION BT(1,5),SSRG(1,1),YT(1,25),Y1(25,1),YPRO(1,1)               000360
      DIMENSION STAT(25),RESID(25)                                          000365
      REAL MSR,MSE,MSBO,MSRBO                                               000370
                                                                            000380
      NVAR=25                                                               000390
      NPAR=4                                                                000400
      NR1=7                                                                 000410
      REWIND NR1                                                            000420
      CALL READX (NVAR,NPAR,FLOW,X)                                         000422
      CALL WRITX (NVAR,NPAR,FLOW,X)                                         000424
      CALL SUMVAR (NVAR,NPAR,FLOW,X,STAT)                                   000426
                                                                            000430
C    ZERO MATRICES, DUMMY,XPINV,B                                           000440
                                                                            000450
      DO 1 I=1,5                                                            000460
      DO 1 N=1,5                                                            000470
      DUMMY(I,N)=0.0                                                        000480
      XPINV(I,N)=0.0                                                        000490
      B(I)=0.0                                                              000500
    1 CONTINUE                                                              000510
                                                                            000520
      NSTOP=NPAR                                                            000530
      NPAR=1                                                                000532
    3 CONTINUE                                                              000534
      NPAR=NPAR+1                                                           000536
      NPARX=NPAR-1                                                          000537
      WRITE(6,2005) NPARX                                                   000538
 2005 FORMAT(1H1,//,2X,* THE NUMBER OF PARAMETERS = *,I4,//)                000540
                                                                            000570
C    ----------------------------------------------------------------      000580
C     OBTAIN PRODUCT OF TRANSPOSED X AND X, XPROD                           000590
```

```
      C     -------------------------------------------------------------------
            CALL MATRAN (NVAR,NPAR,X,XT)



            CALL MATMUL (NPAR,NVAR,NPAR,XT,X,XPROD)



      C     -------------------------------------------------------------------
      C     OBTAIN INVERSE OF XPROD, XPINV
      C     -------------------------------------------------------------------

            CALL MATINV (NPAR,XPROD,DUMMY,INDEX,DUMMY,XPINV)



      C     -------------------------------------------------------------------
      C     OBTAIN PRODUCT OF XT, AND Y
      C     -------------------------------------------------------------------

            CALL MATMUL (NPAR,NVAR,1,XT,FLOW,XTPRO)


       2004 FORMAT(//,1X,F10.3)

      C     -------------------------------------------------------------------
      C     OBTAIN ELEMENTS OF B VECTOR
      C     -------------------------------------------------------------------

            CALL MATMUL (NPAR,NPAR,1,XPINV,XTPRO,B)

      C     -------------------------------------------------------------------
      C     WRITE OUT VALUES OF VECTOR B
      C     -------------------------------------------------------------------

            WRITE(6,3002)
       3002 FORMAT(1H1,//,1X,*   REGRESSION COEFFICIENTS   *,/)
            WRITE(6,2000) B(1)
       2000 FORMAT(//,1X,* THE VALUE FOR B0 = *,F12.6)
            WRITE(6,2001) B(2)
       2001 FORMAT(//,1X,* THE VALUE FOR B1 = *,F12.6)
            IF(NPAR.LT.3) GO TO 8
            WRITE(6,2002) B(3)
       2002 FORMAT(//,1X,* THE VALUE FOR B2 = *,F12.6)
            IF(NPAR.LT.4) GO TO 8
            WRITE(6,2006) B(4)
       2006 FORMAT(//,1X,* THE VALUE FOR B3 = *,F12.6)
            IF(NPAR.LT.5) GO TO 8
            WRITE(6,2007) B(5)
       2007 FORMAT(//,1X,* THE VALUE FOR B4 = *,F12.6)
          8 CONTINUE

            WRITE(6,3003)
       3003 FORMAT(//,5X,*  OBSERVED     PREDICTED   RESIDUALS   PERCENTAGES*)
            DO 2 I=1,NVAR
            X1=FLOAT(I)
```

```
      Y=B(1)+X(I,2)*B(2)+X(I,3)*B(3)+X(I,4)*B(4)+X(I,5)*B(5)          001200
      RESID(I)=FLOW(I)-Y                                              001210
      PERCENT=RESID(I)*100.0/FLOW(I)                                  001212
      CALL PLOTPT(X1,FLOW(I),3)                                       001214
      CALL PLOTPT(X1,Y,4)                                             001216
      WRITE(6,3001) FLOW(I),Y,RESID(I),PERCENT                        001220
 3001 FORMAT(5X,F10.2,3X,F10.2,3X,F10.2,3X,F10.2,*  *)                001230
                                                                      001260
    2 CONTINUE                                                        001270
                                                                      001280
      CALL OUTPLT                                                     001282
      CALL OUTSTAT (NVAR,NPAR,STAT)                                   001283
      CALL CHEKREG (NVAR,NPAR,STAT,RESID,B)                           001285
      CALL RELVAR (NVAR,NPAR,STAT,B)                                  001286
      IF(NPAR.EQ.NSTOP) STOP                                          001287
      GO TO 3                                                         001288
      STOP                                                            001289
      END                                                             001290
```

```
      SUBROUTINE DRAPER (NVAR,NPAR,FLOW,B,BT,XTYPRO)                    001312
      DIMENSION FLOW(NVAR),B(5),BT(1,5)                                 001314
      DIMENSION SSRG(1,1),YT(1,25),Y1(25,1),YPRO(1,1)                   001316
      REAL MSR,MSE,MSBO,MSRBO                                           001318
C                                                                       001320
      CALL MATRAN (NPAR,1,B,BT)                                         001330
C                                                                       001340
      CALL MATMUL (1,NPAR,1,BT,XTPRO,SSRG)                              001350
      XNVAR=FLOAT(NVAR)                                                 001360
      XNPAR=FLOAT(NPAR)                                                 001370
      MSR=SSRG(1,1)/XNPAR                                               001380
      CALL MATRAN(NVAR,1,Y1,YT)                                         001390
      CALL MATMUL (1,NVAR,1,YT,Y1,YPRO)                                 001400
      RESIDU=YPRO(1,1)-SSRG(1,1)                                        001410
      MSE=RESIDU/(XNVAR-XNPAR)                                          001420
      YTOT=0.0                                                          001430
      YSQ=0.0                                                           001440
C                                                                       001450
      DO 10 I=1,NVAR                                                    001460
      YTOT=YTOT+FLOW(I)                                                 001470
      YSQ=YSQ+(FLOW(I)**2.)                                             001480
   10 CONTINUE                                                          001490
      SSBO=(YTOT**2.)/XNVAR                                             001500
      SSRBO=SSRG(1,1)-(YSQ/XNVAR)                                       001510
      MSBO=SSBO                                                         001520
      MSRBO=SSRBO/(XNPAR-1.)                                            001530
      R2=SSRBO/(YPRO(1,1)-SSBO)                                         001540
C                                                                       001550
      WRITE(6,2009) MSR                                                 001560
      WRITE(6,2010) MSE                                                 001570
      WRITE(6,2011) MSBO                                                001580
      WRITE(6,2012) MSRBO                                               001590
      WRITE(6,2013) R2                                                  001600
 2009 FORMAT(1X,///,* MEAN SQUARE OF REGRESSION = *,F10.2,/)            001610
 2010 FORMAT(1X,* MEAN SQUARE OF RESIDUAL = *,F10.2,/)                  001620
 2011 FORMAT(1X,* CORRECTION FACTOR MEAN OF Y = *,F10.2,/)              001630
 2012 FORMAT(1X,* SS OF REG. CONTR. ALLOW FOR BO = *,F10.2,/)           001640
 2013 FORMAT(1X,* COEFF OF MUL DET R2 = *,F10.2,/)                      001650
      RETURN                                                            001660
      END                                                               001670
                                                                        001680
```

```
      SUBROUTINE READX (NVAR,NPAR,FLOW,X)                                 001690
                                                                          001700
C    X(I,1) IS DUMMY VARIABLE AWAYS EQUAL TO UNITY                        001710
C    X(I,2) IS THE TEMPERATURE VALUES                                     001720
C    X(I,3) IS THE PRECENTAGE OUTFLOWED                                   001730
C    X(I,4) IS THE CLOUD COVER VALUED FROM 0 TO 10                        001740
C    X(I,5) IS THE WIND VELOCITY IN MPH                                   001750
                                                                          001760
      DIMENSION FLOW(NVAR),X(NVAR,5)                                      001770
      READ(7,1000) (FLOW(I),I=1,NVAR)                                     001780
      DO 1 I=1,NVAR                                                       001790
    1 X(I,1)=1.0                                                          001800
      READ(7,1000) (X(I,2),I=1,NVAR)                                      001810
 1000 FORMAT(10F6.2)                                                      001820
      DO 3 I=1,NVAR                                                       001830
      X(I,3)=0.0                                                          001840
      X(I,4)=0.0                                                          001850
      X(I,5)=0.0                                                          001860
    3 CONTINUE                                                            001870
      IF(NPAR.LT.3) GO TO 2                                               001880
      READ(7,1000) (X(I,3),I=1,NVAR)                                      001890
      IF(NPAR.LT.4) GO TO 2                                               001900
      READ(7,1000) (X(I,4),I=1,NVAR)                                      001910
      IF(NPAR.LT.5) GO TO 2                                               001920
      READ(7,1000) (X(I,5),I=1,NVAR)                                      001930
    2 CONTINUE                                                            001940
      RETURN                                                              001950
      END                                                                 001960
                                                                          001970
                                                                          001980
                                                                          001990
```

```
      SUBROUTINE MATRAN (MR,NC,A,AT)                                    002000
C    MATRIX TRANSSPOSE MATRIX A OF MR*NC,TO AT OF NC*MR                 002010
                                                                        002020
      DIMENSION A(MR,NC),AT(NC,MR)                                      002030
                                                                        002040
      DO 1 I=1,NC                                                       002050
      DO 1 J=1,MR                                                       002060
      AT(I,J)=A(J,I)                                                    002070
    1 CONTINUE                                                          002080
                                                                        002090
                                                                        002100
      RETURN                                                            002110
      END                                                               002120
                                                                        002130
                                                                        002140
```

```
      SUBROUTINE MATMUL (L,M,N,A,B,C)                                   00002150
                                                                        00002160
C     MATRIX A IS L*M                                                   00002170
C     MATRIX B IS M*N                                                   00002180
C     MATRIX C IS A*B, L*N                                              00002190
                                                                        00002200
      DIMENSION A(L,M),B(M,N),C(L,N)                                    00002210
                                                                        00002220
      DO 1 I=1,L                                                        00002230
      DO 1 J=1,N                                                        00002240
                                                                        00002250
      C(I,J)=0.                                                         00002260
                                                                        00002270
      DO 2 K=1,M                                                        00002280
    2 C(I,J)=C(I,J)+A(I,K)*B(K,J)                                       00002290
    1 CONTINUE                                                          00002300
                                                                        00002310
      RETURN                                                            00002320
      END                                                               00002330
                                                                        00002340
                                                                        00002350
```

```
      SUBROUTINE MATINV (N,A,B,INDEX,C,D)
C     MATRIX INVERSION BY GAUSS-JORDAN ELIMINATION METHOD
C     THE A SQUARE MATRIX IS REPLACED BY ITS INVERSE THE C MATRIX
C     MATRIX CANNOT EXCEED 30 UNLESS REDIMENSION

      DIMENSION A(N,N),B(N,N),C(N,N),INDEX(N,2),D(N,N)

      DO 7 I=1,N
      DO 7 J=1,N
    7 B(I,J)=A(I,J)

      DO 8 I=1,N
    8 INDEX(I,1)=0

      II=0

    9 AMAX=-1.

      DO 10 I=1,N

      IF(INDEX(I,1)) 10,11,10

   11 DO 12 J=1,N

      IF(INDEX(J,1)) 12,13,12

   13 TEMP=ABS(A(I,J))
      IF(TEMP-AMAX) 12,12,14

   14 IROW=I
      ICOL=J
      AMAX=TEMP


   12 CONTINUE

   10 CONTINUE

      IF(AMAX) 125,15,16

   16 INDEX(ICOL,1)=IROW

      IF(IROW-ICOL) 19,18,19

   19 DO 20 J=1,N

      TEMP=A(IROW,J)
      A(IROW,J)=A(ICOL,J)
   20 A(ICOL,J)=TEMP

      II=II+1

      INDEX(II,2)=ICOL

   18 PIVOT=A(ICOL,ICOL)
```

```
      A(ICOL,ICOL)=1.0                                          00293000
      PIVOT=1./PIVOT                                            00294000
                                                                00295000
      DO 21 J=1,N                                               00296000
   21 A(ICOL,J)=A(ICOL,J)*PIVOT                                 00297000
                                                                00298000
      DO 22 I=1,N                                               00299000
                                                                00300000
      IF(I-ICOL) 23,22,23                                       00301000
                                                                00302000
   23 TEMP=A(I,ICOL)                                            00303000
      A(I,ICOL)=0.0                                             00304000
                                                                00305000
      DO 24 J=1,N                                               00306000
   24 A(I,J)=A(I,J)-A(ICOL,J)*TEMP                              00307000
                                                                00308000
   22 CONTINUE                                                  00309000
                                                                00310000
      GO TO 9                                                   00311000
                                                                00312000
   25 ICOL=INDEX(II,2)                                          00313000
      IROW=INDEX(ICOL,1)                                        00314000
                                                                00315000
      DO 26 I=1,N                                               00316000
                                                                00317000
      TEMP=A(I,IROW)                                            00318000
      A(I,IROW)=A(I,ICOL)                                       00319000
   26 A(I,ICOL)=TEMP                                            00320000
                                                                00321000
      II=II-1                                                   00322000
                                                                00323000
  125 IF(II) 25,27,25                                           00324000
                                                                00325000
   27 CONTINUE                                                  00326000
                                                                00327000
C     THE A MATRIX ABOVE IS THE INVERSE A MATRIX                00328000
                                                                00333000
      DO 6 I=1,N                                                00334000
C     THE C MATRIX ABOVE IS THE UNIT MATRIX                     00334200
                                                                00334400
      DO 6 J=1,N                                                00335000
    6 D(I,J)=A(I,J)                                             00336000
      DO 30 I=1,N                                               00337000
      DO 30 J=1,N                                               00338000
                                                                00339000
      C(I,J)=0.                                                 00340000
                                                                00341000
      DO 30 K=1,N                                               00342000
   30 C(I,J)=C(I,J)+B(I,K)*A(K,J)                               00343000
                                                                00344000
      GO TO 34                                                  00345000
                                                                00346000
   15 WRITE(6,2000)                                             00347000
 2000 FORMAT(//,1X,*   ZERO PIVOT   *,//)                       00348000
                                                                00349000
   34 RETURN                                                    00350000
      END                                                       00351000
```

```
      SUBROUTINE SUMVAR (NVAR,NPAR,FLOW,X,STAT)                         004000
      DIMENSION FLOW(NVAR),X(NVAR,NPAR),STAT(NVAR)                      004010
      DIMENSION SUMX(5),SUMXY(5),SUMXX(5)                               004020
      DO 1 J=2,NPAR                                                     004030
      SUMX(J)=0.0                                                       004040
      SUMXX(J)=0.0                                                      004050
      SUMXY(J)=0.0                                                      004060
      DO 1 I=1,NVAR                                                     004070
      SUMX(J)=SUMX(J)+X(I,J)                                            004080
      SUMXX(J)=SUMXX(J)+(X(I,J)**2.0)                                   004090
    1 SUMXY(J)=SUMXY(J)+(FLOW(I)*X(I,J))                                004100
      SUMY=0.0                                                          004110
      SUMYY=0.0                                                         004120
      DO 2 I=1,NVAR                                                     004130
      SUMY=SUMY+FLOW(I)                                                 004140
    2 SUMYY=SUMYY+(FLOW(I)**2.0)                                        004150
      STAT(1)=SUMY                                                      004160
      STAT(2)=SUMYY                                                     004170
      STAT(3)=SUMXY(2)                                                  004180
      STAT(4)=SUMX(2)                                                   004190
      STAT(5)=SUMXX(2)                                                  004200
      IF(NPAR.LT.3) GO TO 9                                             004210
      STAT(6)=SUMXY(3)                                                  004215
      STAT(7)=SUMX(3)                                                   004220
      STAT(8)=SUMXX(3)                                                  004230
      IF(NPAR.LT.4) GO TO 9                                             004240
      STAT(9)=SUMXY(4)                                                  004245
      STAT(10)=SUMX(4)                                                  004250
      STAT(11)=SUMXX(4)                                                 004260
      IF(NPAR.LT.5) GO TO 9                                             004270
      STAT(12)=SUMXY(5)                                                 004275
      STAT(13)=SUMX(5)                                                  004280
      STAT(14)=SUMXX(5)                                                 004290
    9 RETURN                                                            004330
      END                                                               004340
```

```
      SUBROUTINE OUTSTAT (NVAR,NPAR,STAT)                                 004350
      DIMENSION STAT(NVAR)                                                004360
      WRITE(6,3000)                                                       004362
      WRITE(6,3001)                                                       004363
      WRITE(6,3002)                                                       004364
      WRITE(6,2000)  STAT(1)                                              004370
      WRITE(6,2001)  STAT(2)                                              004380
      WRITE(6,2002)  STAT(3)                                              004390
      WRITE(6,2003)  STAT(4)                                              004400
      WRITE(6,2004)  STAT(5)                                              004410
      IF(NPAR.LT.3)  GO TO 9                                              004420
      WRITE(6,2005)  STAT(6)                                              004430
      WRITE(6,2006)  STAT(7)                                              004440
      WRITE(6,2007)  STAT(8)                                              004450
      IF(NPAR.LT.4)  GO TO 9                                              004460
      WRITE(6,2008)  STAT(9)                                              004470
      WRITE(6,2009)  STAT(10)                                             004480
      WRITE(6,2010)  STAT(11)                                             004490
      IF(NPAR.LT.5)  GO TO 9                                              004500
      WRITE(6,2011)  STAT(12)                                             004510
      WRITE(6,2012)  STAT(13)                                             004520
      WRITE(6,2013)  STAT(14)                                             004530
 2000 FORMAT(//,1X,* SUM OF Y(I)                   = *,F12.2)             004540
 2001 FORMAT(/,1X,*  SUM  OF  Y(I)  SQUARED       = *,F12.2)              004550
 2002 FORMAT(/,1X,*  SUM  OF  X(I,2)Y(I)          = *,F12.2)              004560
 2003 FORMAT(/,1X,*  SUM  OF  X(I,2)              = *,F12.2)              004570
 2004 FORMAT(/,1X,*  SUM  OF  X(I,2)  SQUARED     = *,F12.2)              004580
 2005 FORMAT(/,1X,*  SUM  OF  X(I,3)Y(I)          = *,F12.2)              004590
 2006 FORMAT(/,1X,*  SUM  OF  X(I,3)              = *,F12.2)              004600
 2007 FORMAT(/,1X,*  SUM  OF  X(I,3)  SQUARED     = *,F12.2)              004610
 2008 FORMAT(/,1X,*  SUM  OF  X(I,4)Y(I)          = *,F12.2)              004620
 2009 FORMAT(/,1X,*  SUM  OF  X(I,4)              = *,F12.2)              004630
 2010 FORMAT(/,1X,*  SUM  OF  X(I,4)  SQUARED     = *,F12.2)              004640
 2011 FORMAT(/,1X,*  SUM  OF  X(I,5)Y(I)          = *,F12.2)              004650
 2012 FORMAT(/,1X,*  SUM  OF  X(I,5)              = *,F12.2)              004660
 2013 FORMAT(/,1X,*  SUM  OF  X(I,5)  SQUARED     = *,F12.2)              004670
 3000 FORMAT(1H1,//,*--------------------------------------*)             004672
 3001 FORMAT(*     STATISTICAL  TESTS    *)                               004673
 3002 FORMAT(*-----------------------------------*)                       004674
    9 RETURN                                                              004680
      END                                                                 004690
```

```
      SUBROUTINE CHEKREG (NVAR,NPAR,STAT,RESID,B)                       004700
      DIMENSION STAT(NVAR),RESID(NVAR),B(5)                             004710
      COMMON /A/ AYY,A2Y,A3Y,A4Y,A5Y                                    004712
      COMMON /S/ S1Y1,S1X2,S1X3,S1X4,S1X5                               004714
      REAL NUM                                                          004716
      XNPAR=FLOAT(NPAR)                                                 004720
      XNVAR=FLOAT(NVAR)                                                 004730
      DENOM=XNVAR*(XNVAR-1.0)                                           004740
      S2Y1=(XNVAR*STAT(2)-(STAT(1)**2.0))/DENOM                         004750
      S1Y1=SQRT(S2Y1)                                                   004760
      S2X2=(XNVAR*STAT(5)-(STAT(4)**2.0))/DENOM                         004770
      S1X2=SQRT(S2X2)                                                   004780
      WRITE(6,2000) S2Y1,S1Y1                                           004782
      WRITE(6,2001) S2X2,S1X2                                           004783
      AYY=XNVAR*STAT(2)-(STAT(1)**2.0)                                  004784
      A2Y=XNVAR*STAT(3)-STAT(4)*STAT(1)                                 004790
      A3Y=0.0                                                           004800
      A4Y=0.0                                                           004810
      A5Y=0.0                                                           004820
      IF(NPAR.LT.3) GO TO 9                                             004830
      S2X3=(XNVAR*STAT(8)-(STAT(7)**2.0))/DENOM                         004840
      S1X3=SQRT(S2X3)                                                   004850
      A3Y=XNVAR*STAT(6)-STAT(7)*STAT(1)                                 004860
      WRITE(6,2002) S2X3,S1X3                                           004862
      IF(NPAR.LT.4) GO TO 9                                             004870
      S2X4=(XNVAR*STAT(11)-(STAT(10)**2.0))/DENOM                       004890
      S1X4=SQRT(S2X4)                                                   004895
      A4Y=XNVAR*STAT(9)-STAT(10)*STAT(1)                                004900
      WRITE(6,2003) S2X4,S1X4                                           004902
      IF(NPAR.LT.5) GO TO 9                                             004910
      S2X5=(XNVAR*STAT(14)-(STAT(13)**2.0))/DENOM                       004920
      S1X5=SQRT(S2X5)                                                   004930
      A5Y=XNVAR*STAT(12)-STAT(13)*STAT(1)                               004940
      WRITE(6,2004) S2X5,S1X5                                           004942
    9 CONTINUE                                                          004950
      ERRSQ=0.0                                                         004960
      DO 1 I=1,NVAR                                                     004970
    1 ERRSQ=ERRSQ+RESID(I)*RESID(I)                                     004980
      ERRSQ=ABS(ERRSQ)                                                  004985
      WRITE(6,3000) ERRSQ                                               004986
 3000 FORMAT(/,4X,* ERRSQ = *,F10.1)                                    004987
C      STANDARD ERROR OF ESTIMATE                                       004990
      NUM=AYY-B(2)*A2Y-B(3)*A3Y-B(4)*A4Y-B(5)*A5Y                       004991
      DEN=XNVAR*(XNVAR-XNPAR)                                           004992
      S2YK1=NUM/DEN                                                     004993
      WRITE(6,2005) S2YK1                                               004994
      S2YK=(ERRSQ)/(XNVAR-XNPAR)                                        005000
      S1YK=SQRT(S2YK)                                                   005010
      WRITE(6,2005) S2YK                                                005012
      WRITE(6,2006) S1YK                                                005014
C     ----------------------------------                                005020
C       F-TEST FOR REGRESSION                                           005030
C     ----------------------------------                                005040
      FN=B(2)*A2Y+B(3)*A3Y+B(4)*A4Y+B(5)*A5Y                            005050
      WRITE(6,3001) FN                                                  005052
 3001 FORMAT(/,3X,* VALUE OF FN = *,F12.1)                              005054
      FD=(XNPAR-1.0)*XNVAR*S2YK                                         005060
```

```
           WRITE(6,3002) FD                                                    005062
      3002 FORMAT(/,3X,* VALUE OF FD = *,F12.1)                                005064
           F=FN/FD                                                             005070
           WRITE(6,2007) F                                                     005072
      2000 FORMAT(//,1X,* VARIANCE OF Y  =*,F14.1,* STD DEV OF Y  =*,F10.2)    005080
      2001 FORMAT(/,1X,* VARIANCE OF X2 =*,F14.1,* STD DEV OF X2 =*,F10.2)     005090
      2002 FORMAT(/,1X,* VARIANCE OF X3 =*,F14.1,* STD DEV OF X3 =*,F10.2)     005100
      2003 FORMAT(/,1X,* VARIANCE OF X4 =*,F14.1,* STD DEV OF X4 =*,F10.2)     005110
      2004 FORMAT(/,1X,* VARIANCE OF X5 =*,F14.1,* STD DEV OF X5 =*,F10.2)     005120
      2005 FORMAT(//,3X,* STANDARD ERROR OF ESTIMATE =*,F14.1)                 005130
      2006 FORMAT(//,3X,* ROOT OF S.E.E. =*,F10.2)                             005140
      2007 FORMAT(///,3X,*  F-TEST FOR REGRESSION =*,F10.2)                    005150
           RETURN                                                              005160
           END                                                                 005170
                                                                               005180
```

```
      SUBROUTINE WRITX (NVAR,NPAR,FLOW,X)                                       005190
      DIMENSION FLOW(NVAR),X(NVAR,5)                                            005200
      WRITE(6,2003)                                                             005205
      WRITE(6,2000)                                                             005210
      WRITE(6,2004)                                                             005212
      WRITE(6,2001)                                                             005220
      WRITE(6,2004)                                                             005224
      DO 1 I=1,NVAR                                                             005230
    1 WRITE(6,2002) FLOW(I),X(I,1),X(I,2),X(I,3),X(I,4),X(I,5)                  005240
 2000 FORMAT(//,2X,*  PRINTOUT OF THE INPUT DATA *)                             005250
 2001 FORMAT(1X,*  FLOW CFS           X1           X2           X3              005260
     +X4           X5*)                                                         005261
 2002 FORMAT(1X,F10.2,2X,F10.2,2X,F10.2,2X,F10.2,2X,F10.2,2X,F10.2)             005270
 2003 FORMAT(1H1)                                                               005275
 2004 FORMAT(/)                                                                 005276
      RETURN                                                                    005280
      END                                                                       005290
```

```
      SUBROUTINE RELVAR (NVAR,NPAR,STAT,B)                              005300
      DIMENSION STAT(NVAR),B(5)                                         005310
      COMMON /A/ AYY,A2Y,A3Y,A4Y,A5Y                                    005320
      COMMON /S/ S1Y1,S1X2,S1X3,S1X4,S1X5                               005330
C   ----------------------------------------                            005340
C      MULTIPLE CORRELATION COEFF R2YK                                  005350
C   ----------------------------------------                            005360
      XNUM=B(2)*A2Y+B(3)*A3Y+B(4)*A4Y+B(5)*A5Y                          005370
      DEN=AYY                                                           005380
      R2YK=XNUM/DEN                                                     005390
      R2YK=ABS(R2YK)                                                    005395
      R1YK=SQRT(R2YK)                                                   005400
      WRITE(6,2000) R1YK                                                005410
C   -----------------------------------------                           005420
C     PARTIAL CORRELATION OCEFF RY21,ETC.,                              005430
C   -----------------------------------------                           005440
      RYX2=(B(2)*S1X2)/S1Y1                                             005450
      WRITE(6,2001) RYX2                                                005460
      IF(NPAR.LT.3) GO TO 9                                             005470
      RYX3=(B(3)*S1X3)/S1Y1                                             005480
      WRITE(6,2002) RYX3                                                005490
      IF(NPAR.LT.4) GO TO 9                                             005500
      RYX4=(B(4)*S1X4)/S1Y1                                             005510
      WRITE(6,2003) RYX4                                                005520
      IF(NPAR.LT.5) GO TO 9                                             005530
      RYX5=(B(5)*S1X5)/S1Y1                                             005540
      WRITE(6,2004) RYX5                                                005550
    9 CONTINUE                                                          005560
 2000 FORMAT(//,1X,* MULTIPLE COR. COF. R1YK = *,F10.2)                 005570
 2001 FORMAT(/,1X,* PARTIAL COR. COF. RYX2 = *,F10.2)                   005580
 2002 FORMAT(/,1X,* PARTIAL COR. COF. RYX3 = *,F10.2)                   005590
 2003 FORMAT(/,1X,* PARTIAL COR. COF. RYX4 = *,F10.2)                   005600
 2004 FORMAT(/,1X,* PARTIAL COR. COF. RYX5 = *,F10.2)                   005610
      RETURN                                                            005620
      END                                                               005630
```

```
PRINTOUT OF THE INPUT DATA

 FLOW CFS          X1           X2           X3          X4          X5

    86.29         1.00         7.54         0.00        51.00        0.00
    83.13         1.00         6.67         0.00        50.00        0.00
    86.00         1.00        17.33         0.00        68.00        0.00
   115.58         1.00        19.17         0.00        63.00        0.00
   556.12         1.00        11.00         0.00        50.00        0.00
   496.88         1.00        16.54         0.00        62.00        0.00
   516.37         1.00        18.50         2.00        53.00        0.00
   514.67         1.00        12.62         2.00        50.00        0.00
   472.25         1.00        17.67         2.00        65.00        0.00
   558.71         1.00        22.92         2.00        70.00        0.00
   675.08         1.00        21.79         1.00        64.00        0.00
   405.25         1.00        15.50         1.00        56.00        0.00
   395.54         1.00        17.08         2.00        63.00        0.00
   876.96         1.00        16.50         3.00        55.00        0.00
  1256.33         1.00        17.08         2.00        52.00        0.00
   676.83         1.00        12.21         0.00        52.00        0.00
   579.92         1.00         5.71         0.00        38.00        0.00
   331.08         1.00        14.79         0.00        70.00        0.00
   265.83         1.00        19.71         1.00        50.00        0.00
   272.37         1.00        20.33         0.00        65.00        0.00
   265.79         1.00        19.96         0.00        58.00        0.00
   309.21         1.00        20.71         0.00        51.00        0.00
   258.71         1.00        14.96         1.00        51.00        0.00
   190.67         1.00        12.42         0.00        59.00        0.00
   143.08         1.00         8.83        -0.00        51.00        0.00
```

APPENDIX D

SENSITIVITY ANALYSIS ON COIL THERMOMETERS

D. SENSITIVITY ANALYSIS OF P.T.C. 7-DAY, COIL THERMOMETERS

D.1 Objective

1.1 To observe recorder temperatures versus control temperatures

1.2 To observe the sensitivity of rate of change of automatic recorders

D.2 Experimental Approach

The three Pacific Transducer Corporation model 6.15 F, 7-day, negator spring wound, coil thermometers, two of range -30°F to 70°F and one -70°F to 130°F used in the 1973 Arctic field work were correlated with an FR, alcohol thermometer range -10°F to 120°F. They were placed outdoors in a 12 x 7 x 4 inch box, with two rows of 2 x 0.5 inch slots, three feet above ground, five feet from a wall. Readings were taken approximately every three hours during the day, for the duration of one week. At the end of the week the recorders were taken indoors and the temperature of the thermometers were tabulated till room temperature was attained (fig. D.1). A summary of the daily temperatures is given in table D.1.

D.3 Results and Discussion

With respect to differences between the temperatures of the control thermometer and the P.T.C. thermometers, it was found that the P.T.C. thermometers never exceeded the control temperature by more than 2.5°F, however, they fell short of the maximum daily temperature attained by the control thermometer by -10°F in the worst case. From table D.1, one finds that the temperatures of the control thermometer were consistently under-predicting. There were only two occasions whereby one out of three of the temperatures were not following the trend of being consistently over or under. Only four of the fourteen tabulated observations have two or more temperatures reading above that of the control temperature. Eight of the nine maximums were under predicted.

The second part of the experiment will help clarify the above results. The sensitivity to rate of change of temperature is shown on fig. D.1. The 28°F change from outdoor to indoor temperatures took the alcohol control thermometer 15 minutes to attain equilibrium; the P.T.C. thermometers took 120 minutes to attain it. The final temperature attained was 4°F below that of the alcohol thermometer after three hours.

D.4 Conclusion of the Experiment

The results indicate that the temperatures reached by the P.T.C. thermometers if allowed to attain equilibrium is ± 2.5 °F for the one of range -70°F to 130°F and ± 2°F for the two of range - 30°F to 70°F. However, the experimental results indicate that the resistance to high rates of change of temperature make these recorders underestimate the maximum. The rate of change of the P.T.C. thermometer was found to be 40 min/°F rate of rise where the differential is 7°F or less. This indicates that if there is a change in external temperature of 5°F, the P.T.C. thermometers will take 200 min to attain that temperature.

In Arctic areas the diurnal temperature fluctuation creates high rates of change of temperature. The P.T.C. thermometers as utilised in the 1973 field trip are thus inefficient and incapable to giving the sensitive record of temperatures as necessitated by the type of data required.

TABLE D.1 SUMMARY OF DAILY TEMPERATURES

DECEMBER	CONTROL TEMP	P.T.C. 1	P.T.C. 2	P.T.C. 3
19	22	23 (+1)	23 (+1)	20 (-2)
20	20	20	18 (-2)	18 (-2)
21	24	23 (-1)	24	19 (-5)
22	28	27 (-1)	23.5(-4.5)	23 (-5)
23	32	27 (-5)	24 (-6)	25 (-7)
24	30	24 (-6)	20 (-10)	20 (-10)
26	41	38 (-3)	38 (-3)	36 (-5)
27	69	66 (-3)	65 (-4)	68 (-1)
	max	+ 2.5	+ 1	+ 2
	min	- 6	- 10	- 10

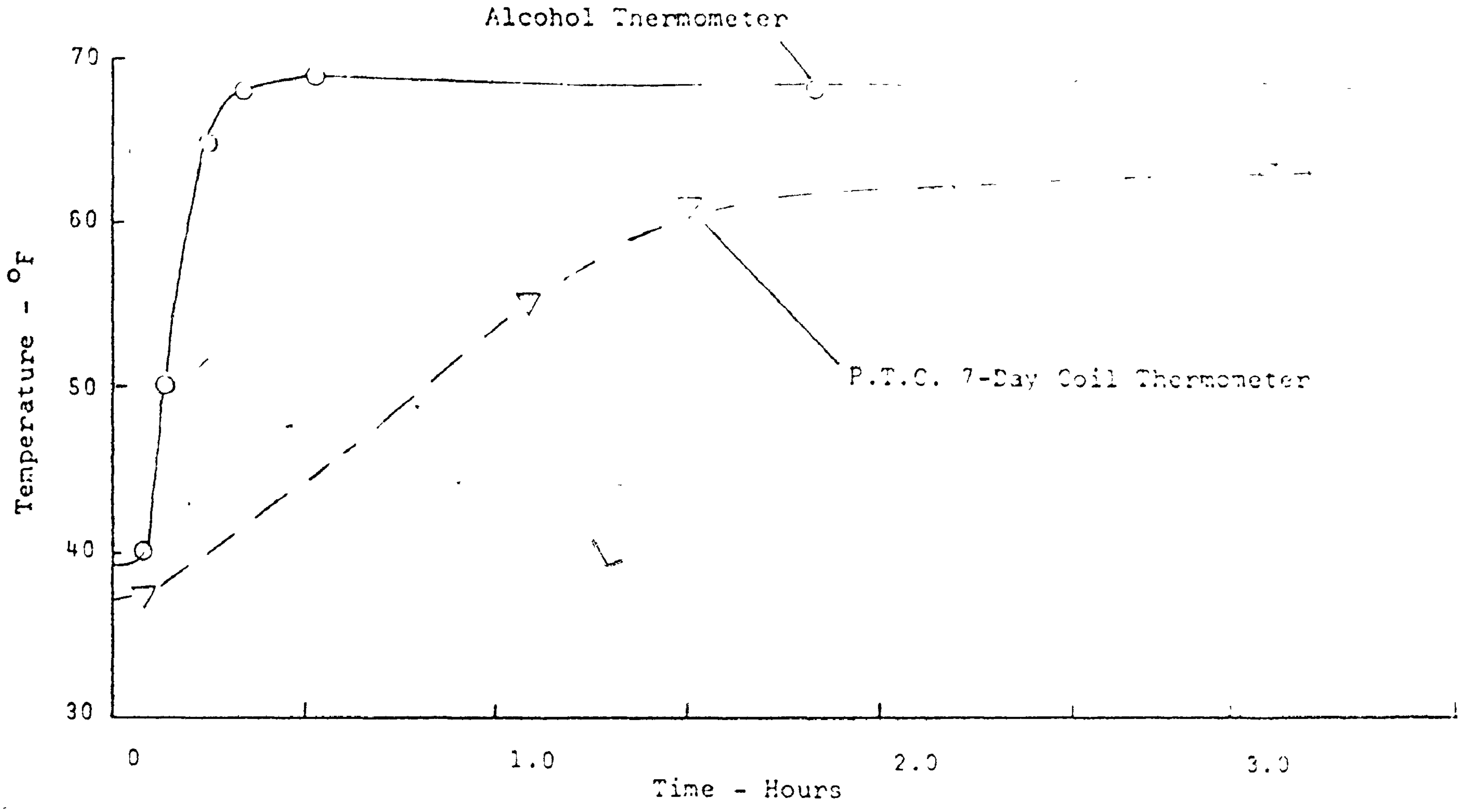
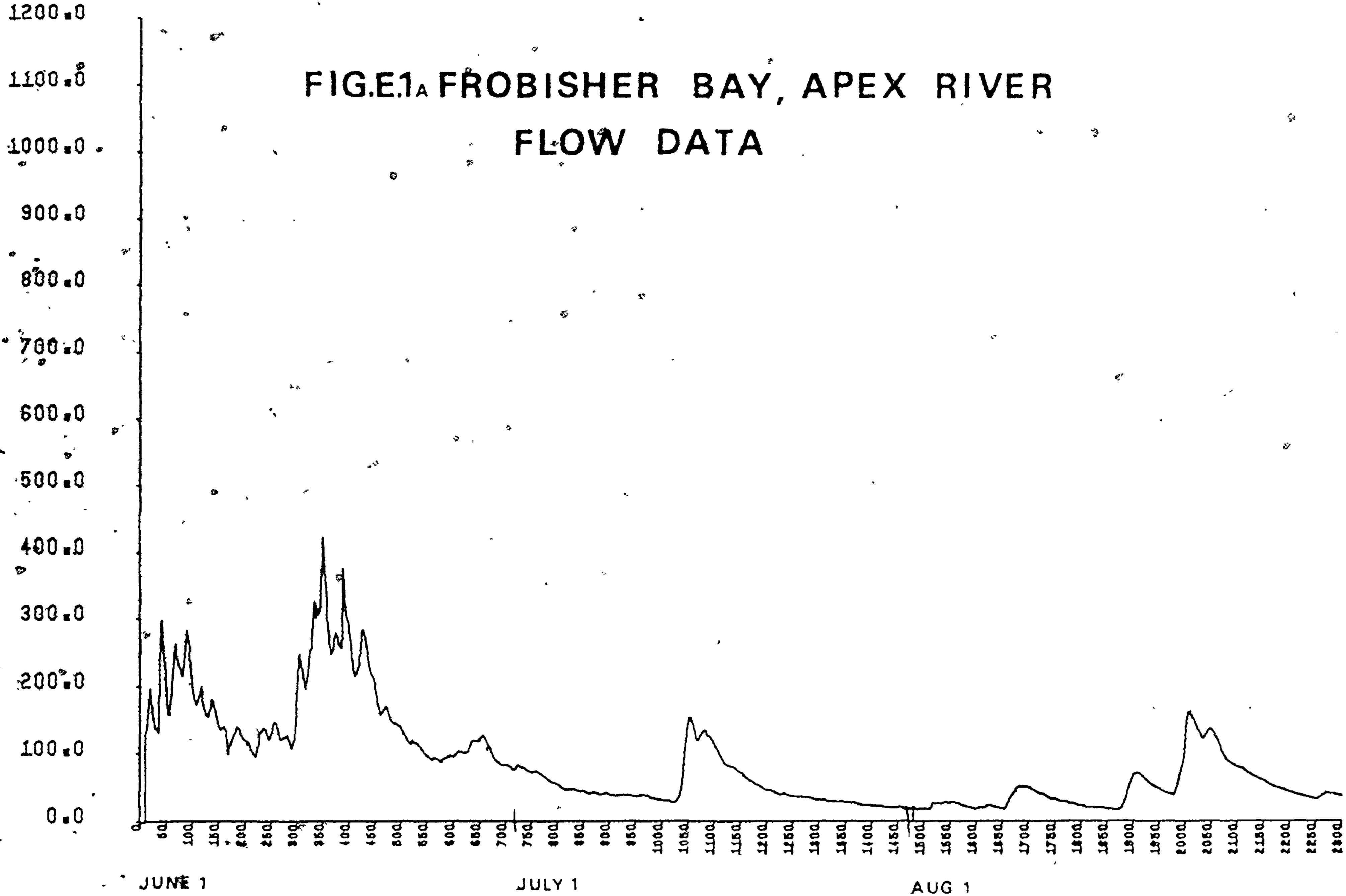


FIG. D.1 RATE OF CHANGE OF TEMPERATURE OF COIL VERSUS ALCOHOL THERMOMETERS

APPENDIX E

FIELD OBSERVATIONS AND DATA PROCESSING

FIG.E.1A FROBISHER BAY, APEX RIVER FLOW DATA



1973

FIG.E.1B BROUGHTON ISLAND FLOW DATA

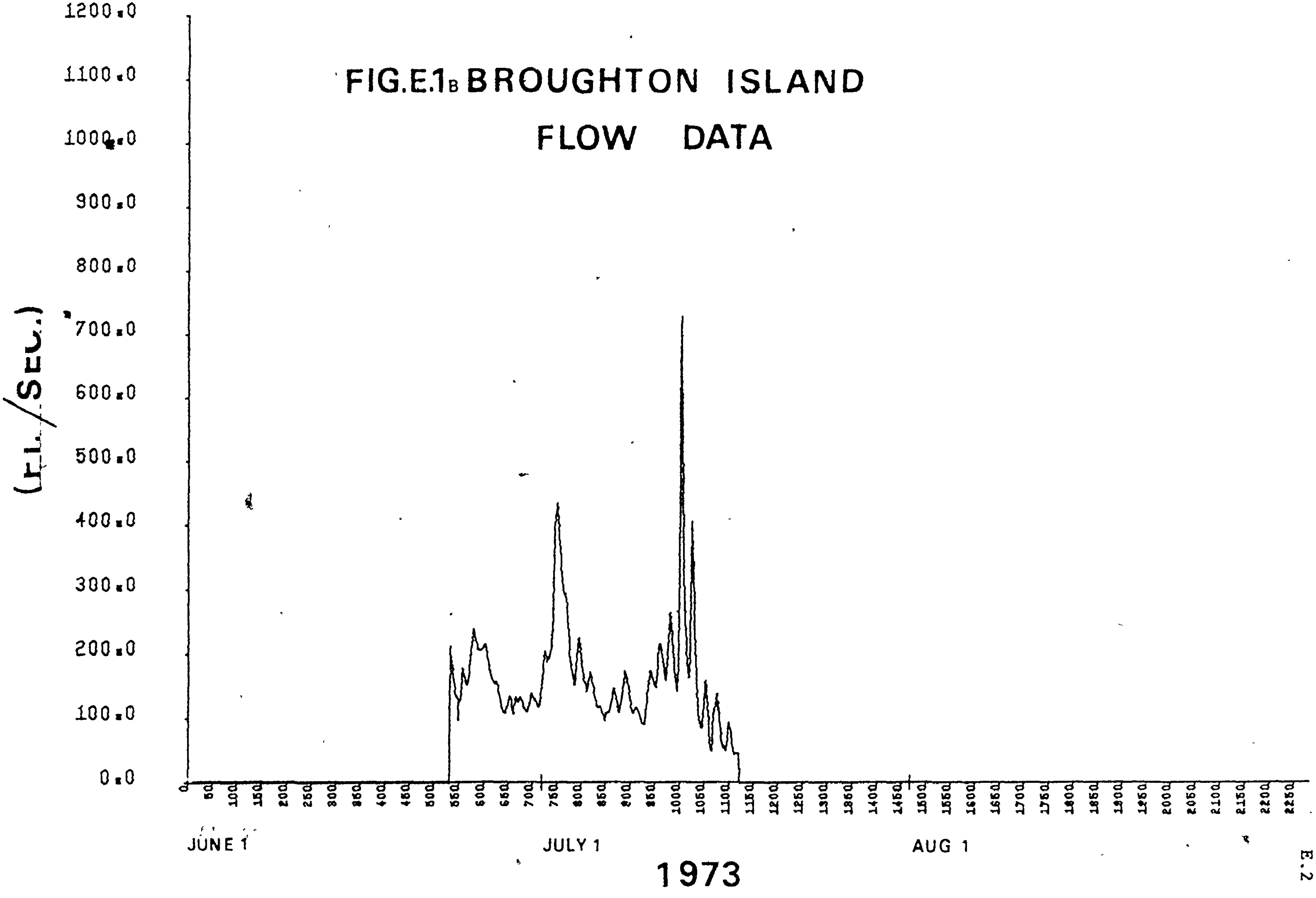


FIG. E.2 PANGNIRTUNG FLOW DATA (1972)

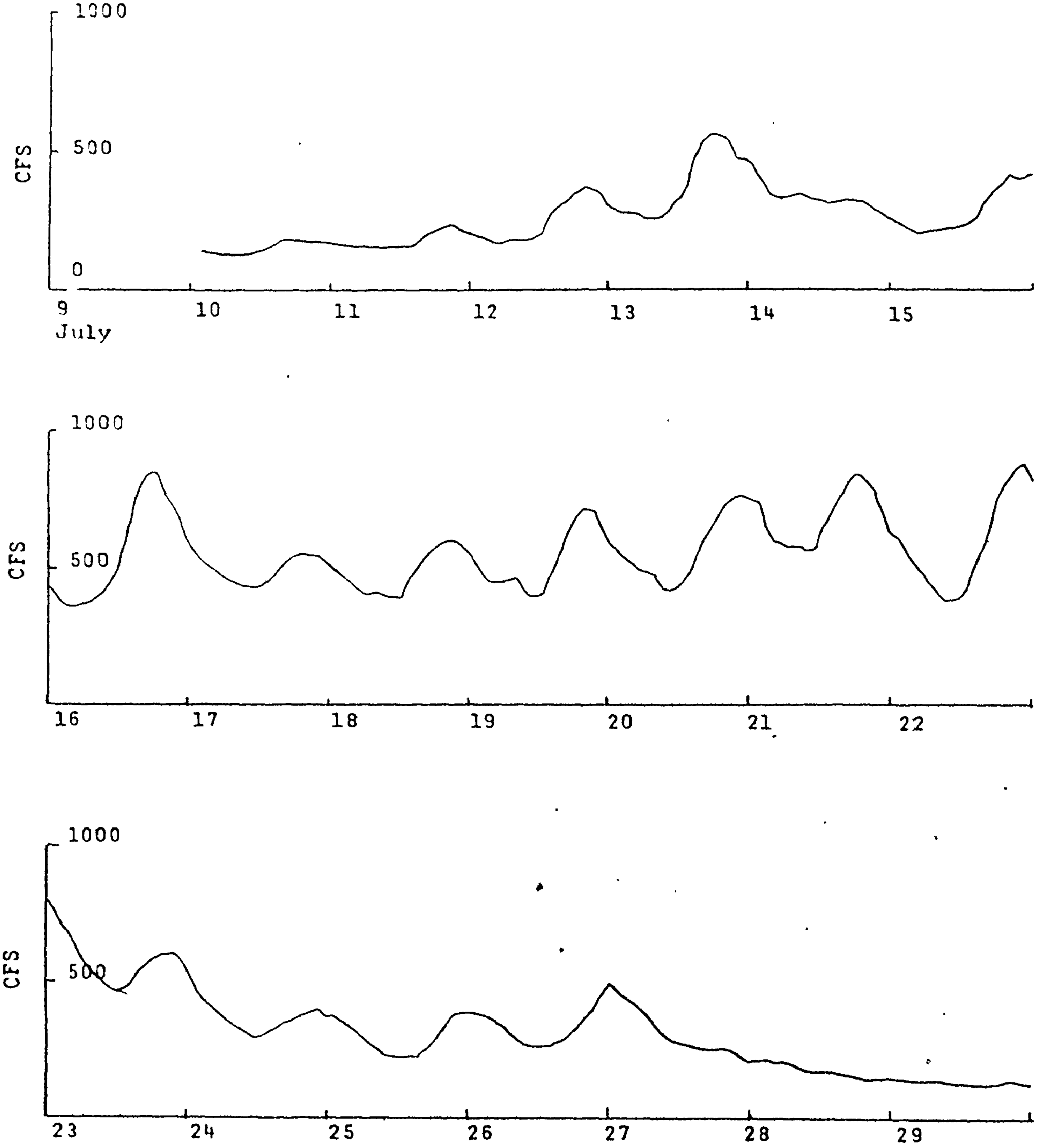


FIG. E.3a PANGNIRTUNG FLOW DATA (1973)

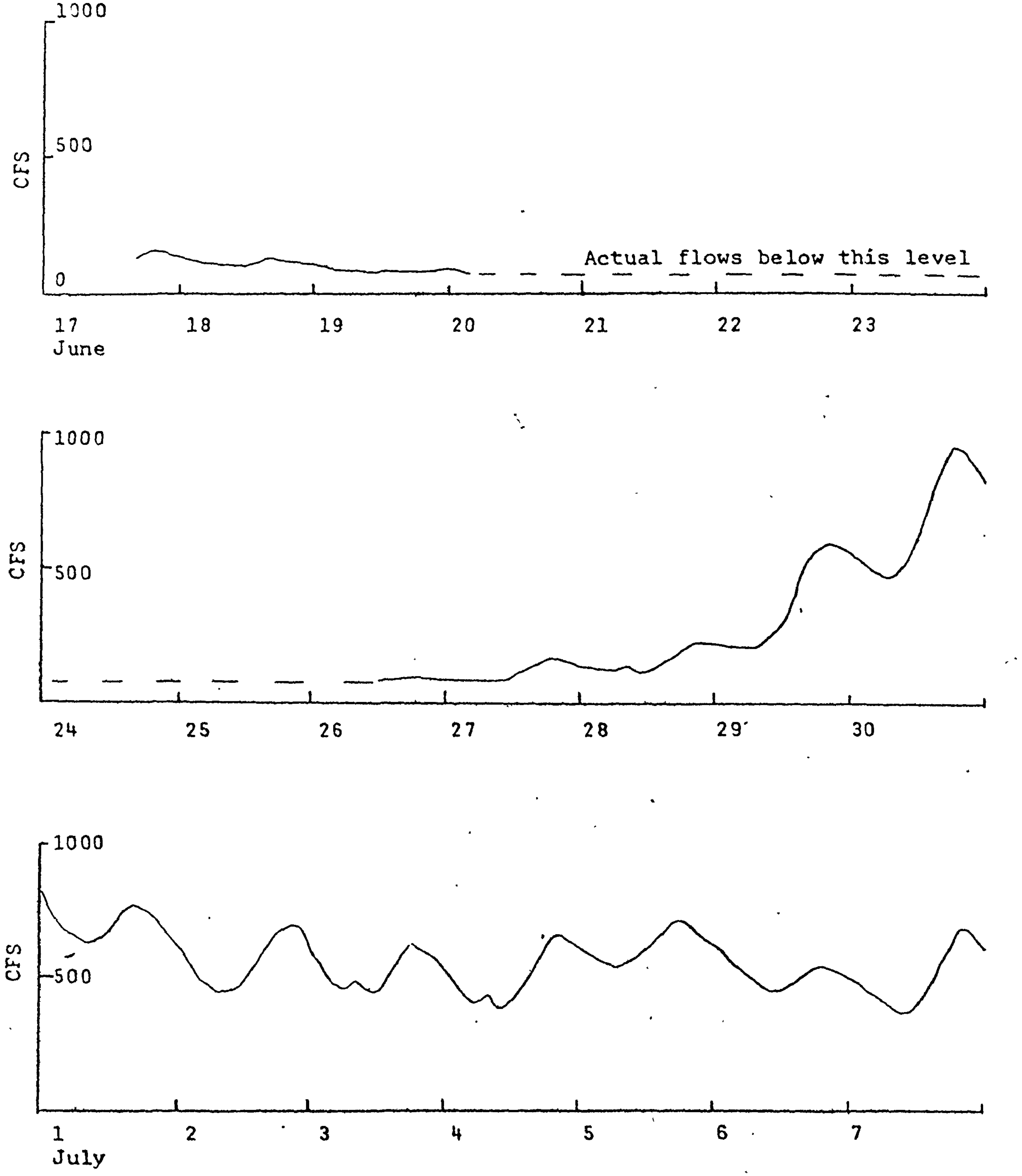
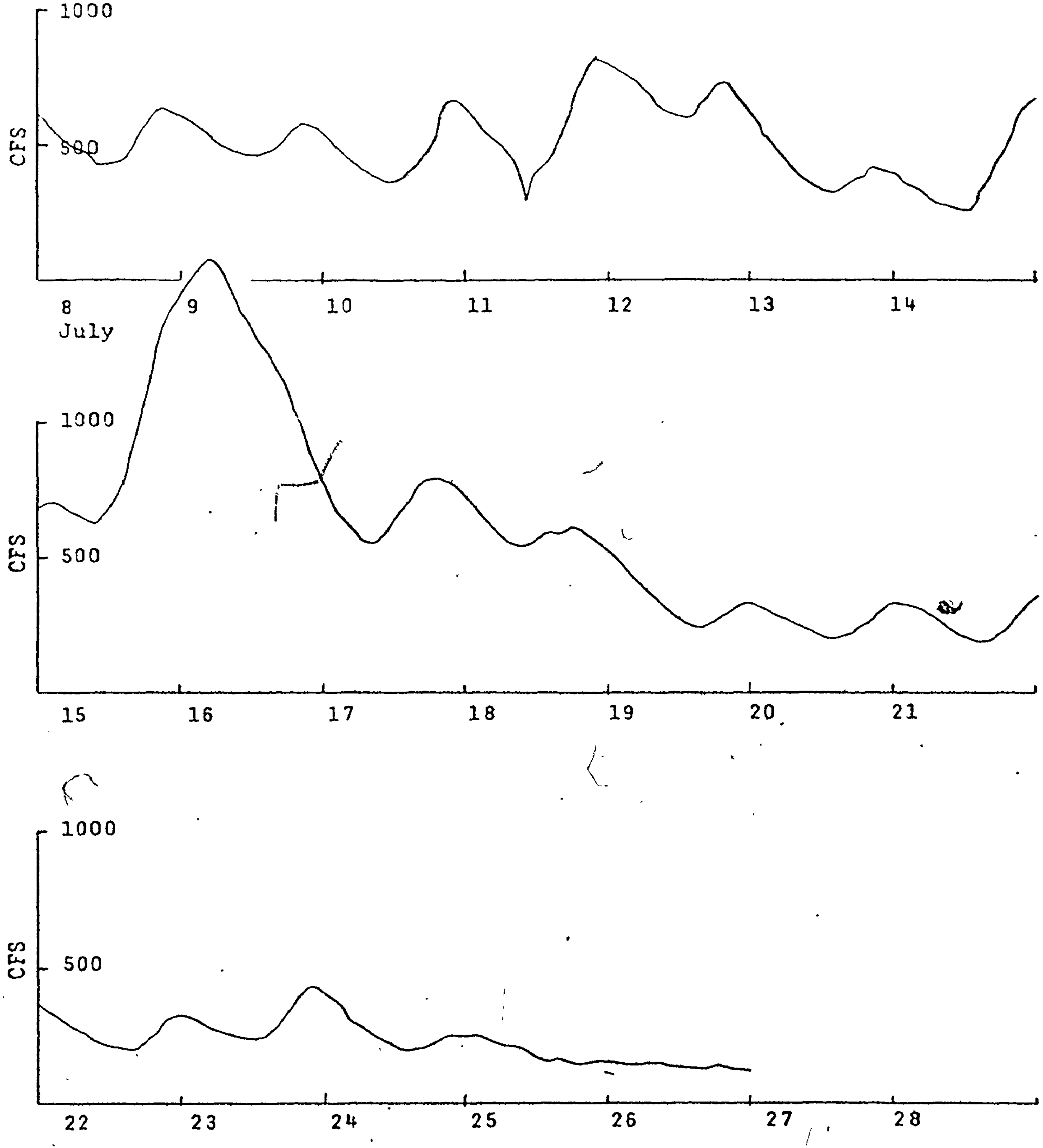


FIG. E.3b PANGNIRTUNG FLOW DATA (1973) CONTINUED



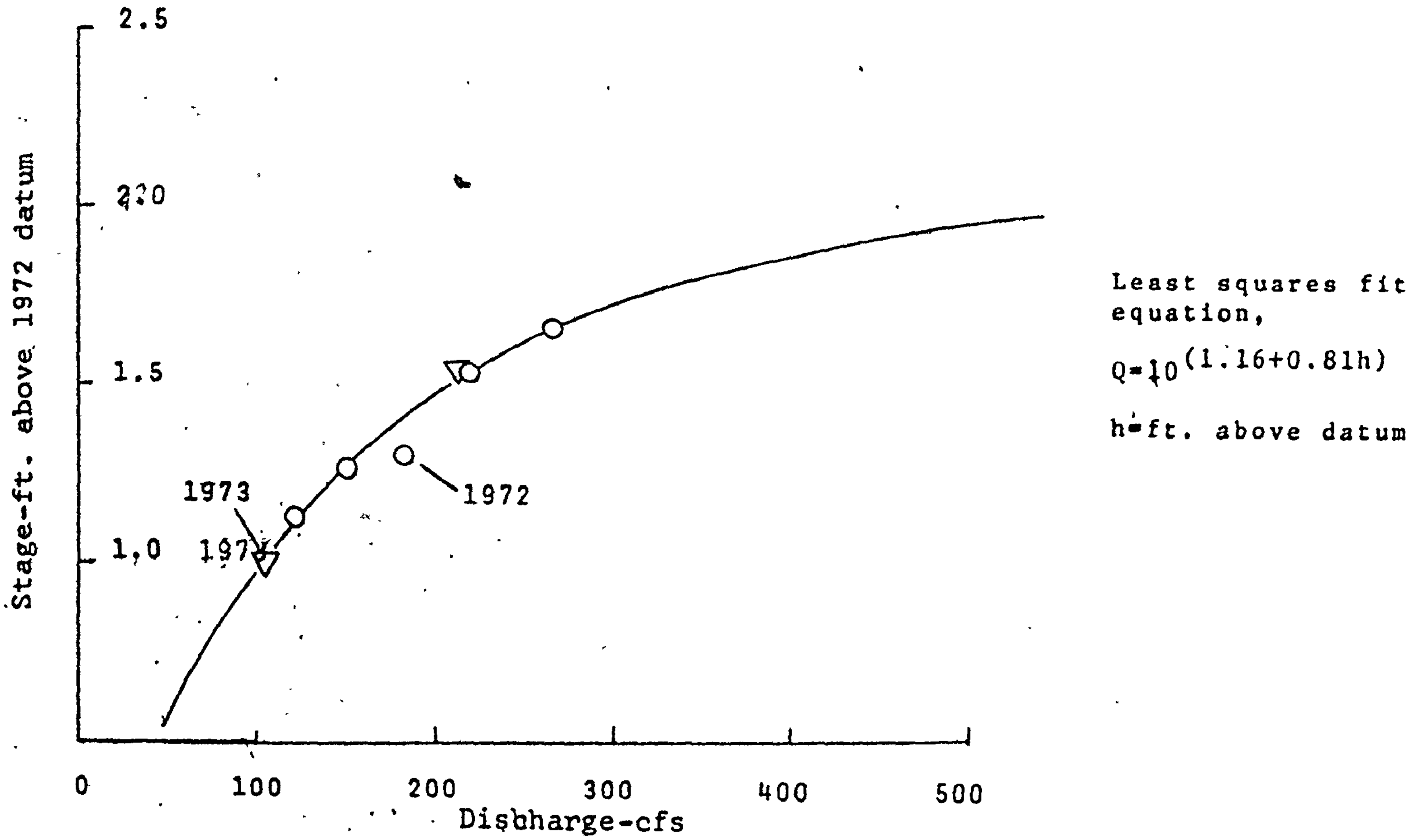


FIG. E.4 STAGE-DISCHARGE CURVE DUVAL RIVER (1972/3)

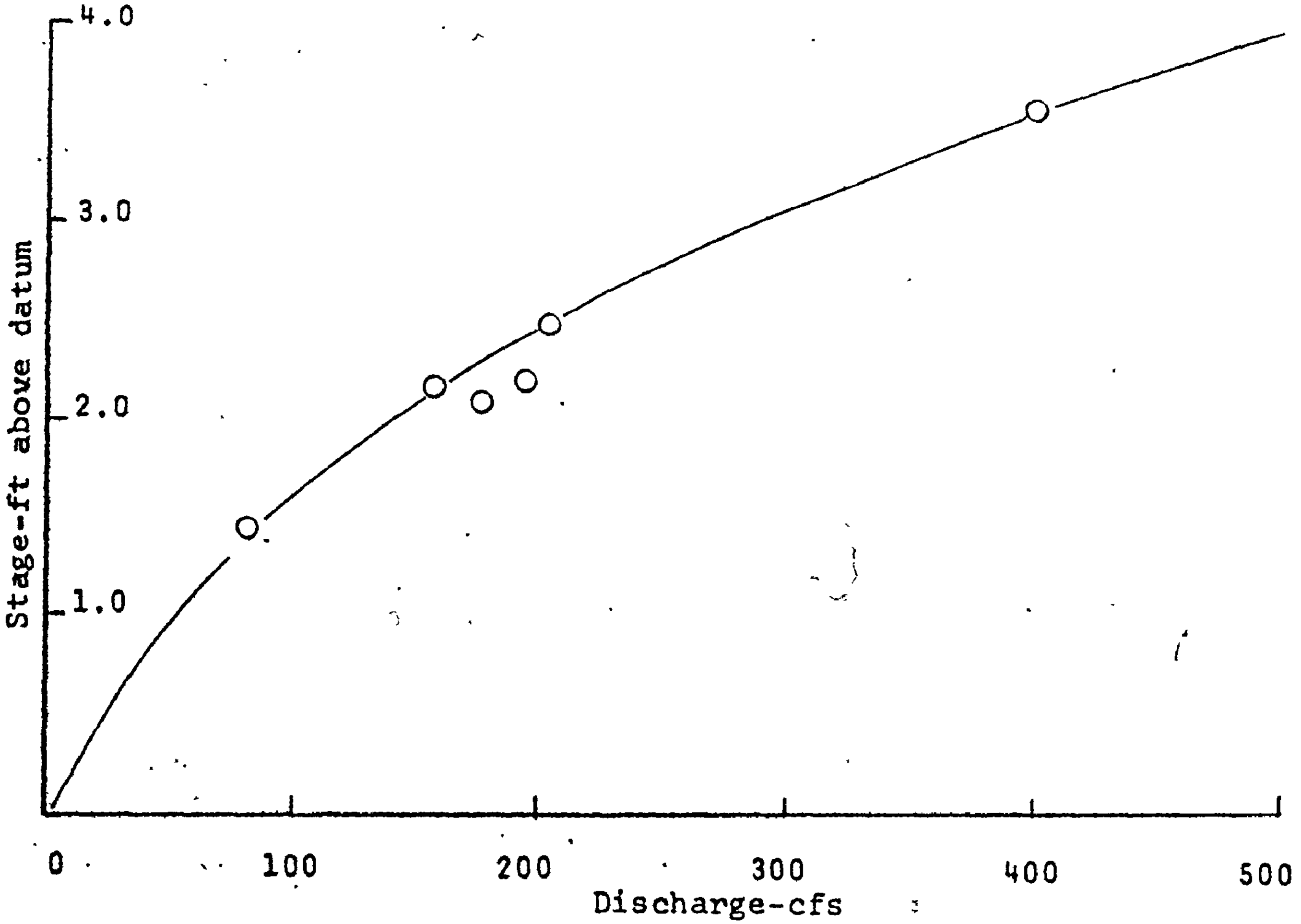


FIG. E.5 STAGE-DISCHARGE CURVE BROUGHTON CREEK (1973)

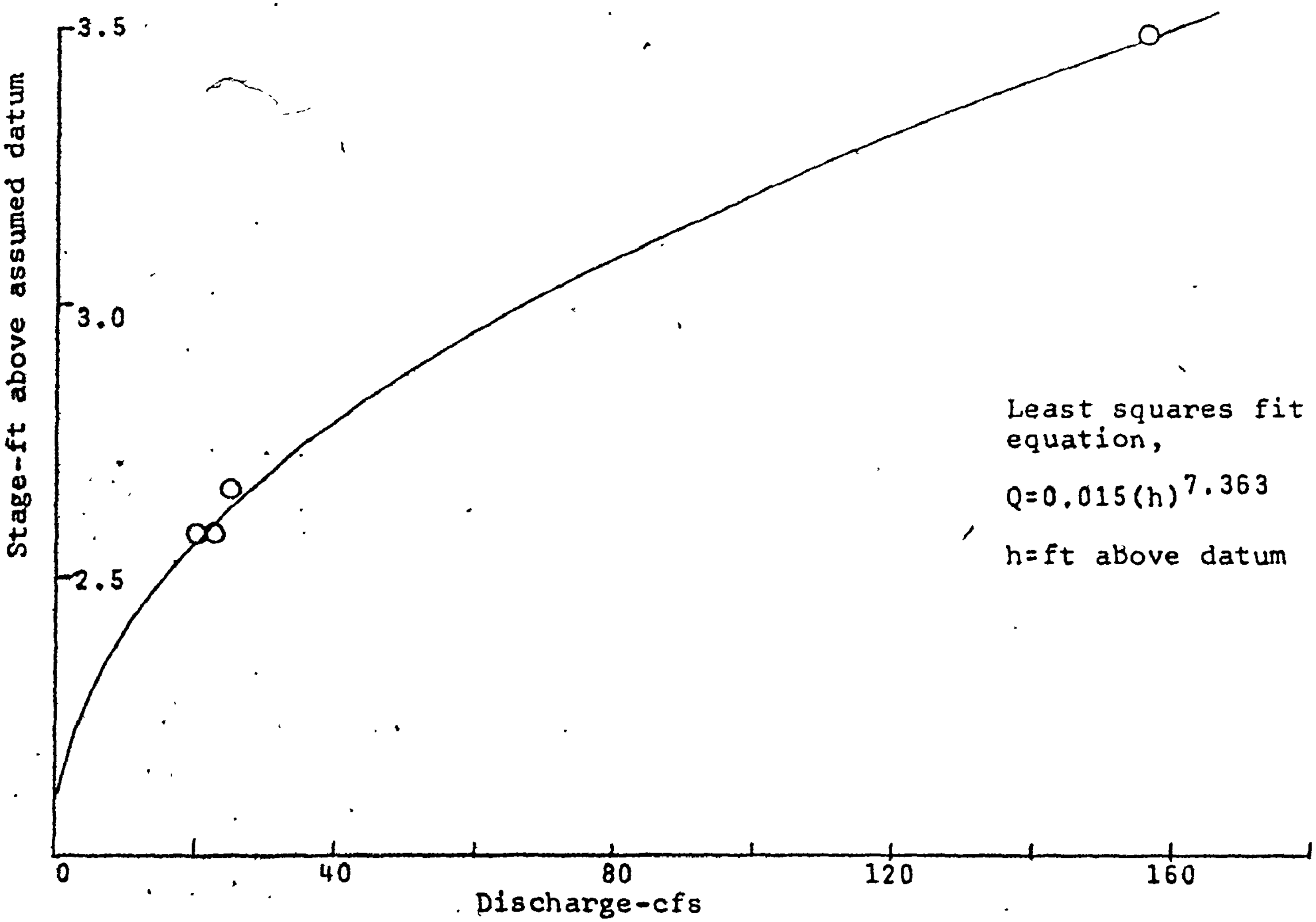


FIG. E.6 STAGE-DISCHARGE CURVE APEX RIVER (1973)

FIG. E.7 PANGNIRTUNG,DUVAL RIVER, TEMPERATURE DATA 1972

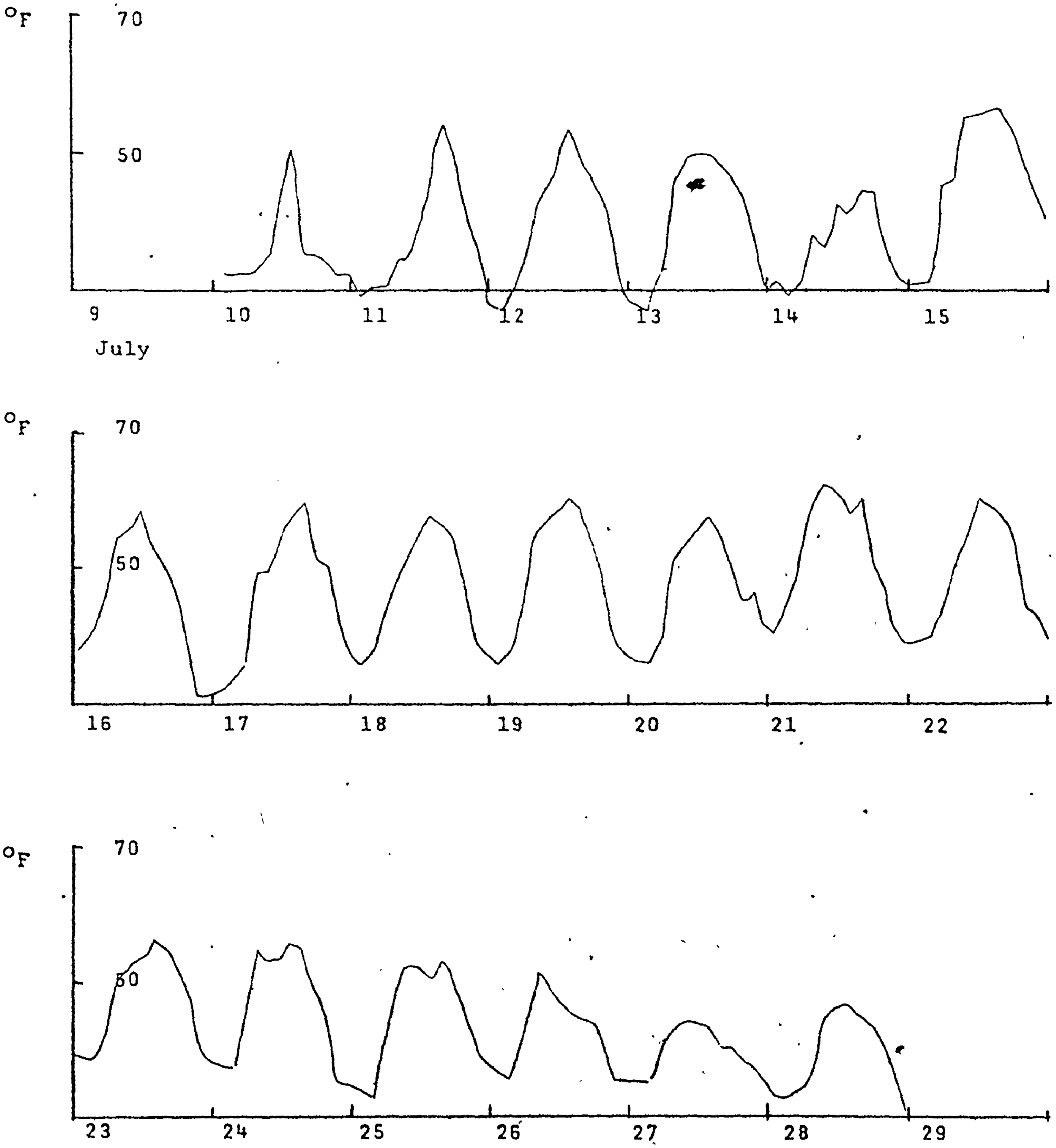


FIG. E.8a PANGNIRTUNG, DUVAL RIVER, TEMPERATURE DATA 1973

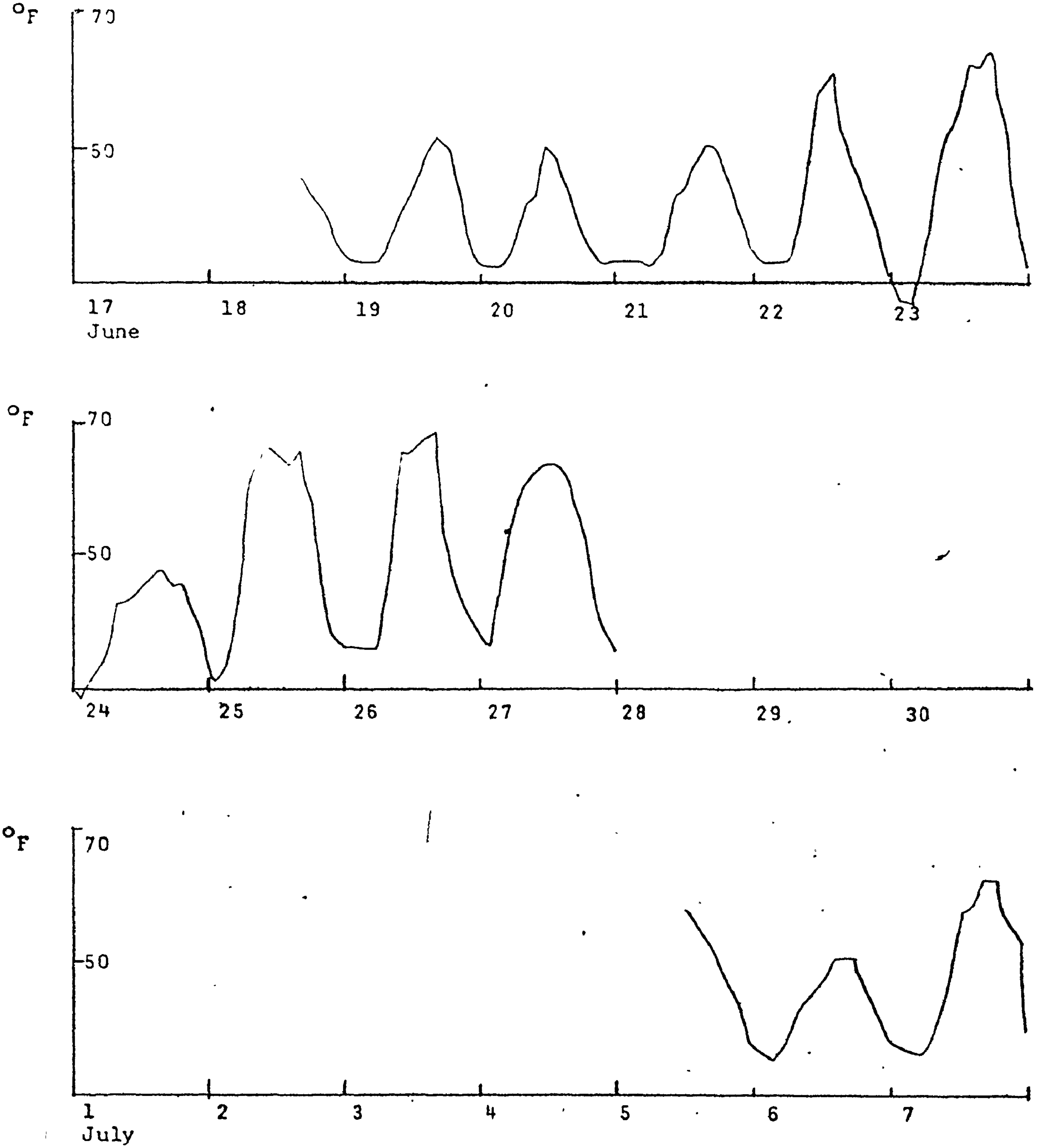


FIG. E.8b PANGNIRTUNG, DUVAL RIVER, TEMPERATURE DATA 1973 cont.

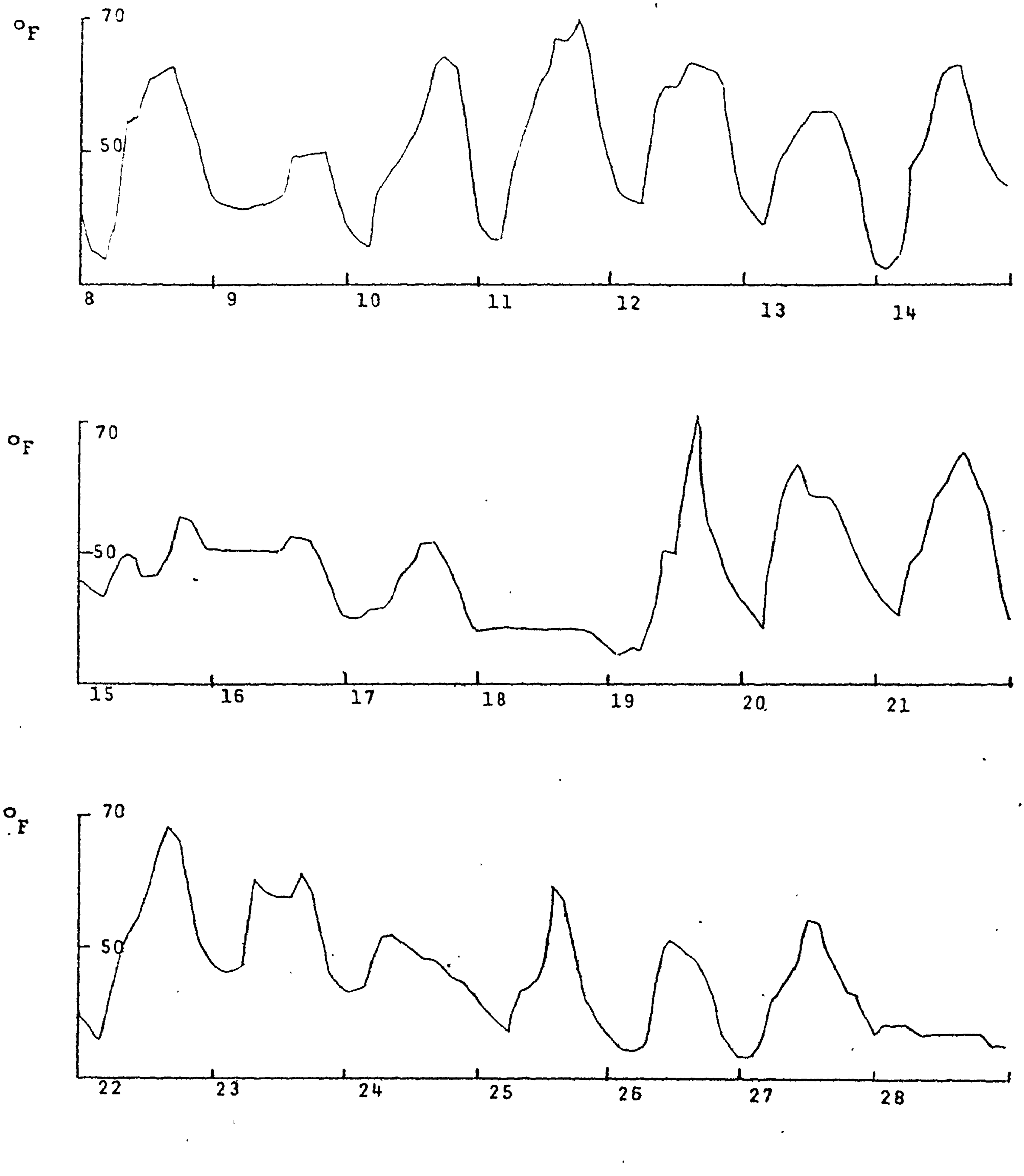


TABLE E.1 INPUT DATA PANGNIRTUNG 1973

Y CFS	X1	X2 °F - DAY	X3 W	X4 °F MAX	X5 °F MIN
86.29	1.0	7.54	0	51	33
83.13	1.0	6.67	0	50	32
86.00	1.0	17.33	0	68	36
115.58	1.0	19.17	0	63	36
506.12	1.0	11.00	0	50	35
496.88	1.0	16.54	0	62	36
516.37	1.0	18.50	2	63	34
514.67	1.0	12.62	2	50	41
472.25	1.0	17.67	2	65	36
558.71	1.0	22.92	2	70	37
675.08	1.0	21.79	1	64	42
405.25	1.0	15.50	1	56	39
395.54	1.0	17.08	2	63	32
876.96	1.0	16.50	3	55	43
1256.33	1.0	17.08	2	52	40
676.83	1.0	12.21	0	52	40
579.92	1.0	5.71	0	38	38
331.08	1.0	14.79	0	70	34
265.83	1.0	19.71	1	60	38
272.37	1.0	20.33	0	65	40
265.79	1.0	19.96	0	68	36
309.21	1.0	20.71	0	61	43
258.71	1.0	14.96	1	51	42
190.67	1.0	12.42	0	59	37
143.08	1.0	8.83	0	51	34

TABLE E.2 OUTPUT DATA PANGNIRTUNG 1973

NPAR=1	NPAR=2	NPAR=3	NPAR=4
330.35	295.75	231.14	218.42
321.26	297.11	226.54	203.58
432.65	280.42	157.49	178.65
451.88	277.54	322.52	281.98
366.51	290.33	358.08	320.32
424.40	281.66	264.45	252.79
444.88	621.38	563.85	513.71
383.43	630.58	668.98	709.44
436.21	622.68	494.98	500.64
491.07	614.46	545.34	530.11
479.26	444.84	511.13	536.82
413.53	454.68	494.67	503.87
430.04	623.60	520.71	460.27
423.98	795.91	808.56	867.39
430.04	623.60	760.82	739.59
379.15	288.44	351.19	385.91
311.23	298.61	459.31	451.66
406.11	284.40	36.67	77.49
457.52	448.09	535.25	500.77
464.00	275.73	314.11	331.82
460.13	276.31	237.39	222.38
467.97	275.13	412.96	441.07
407.89	455.53	587.40	612.36
381.34	288.11	204.77	242.84
343.83	293.73	270.33	254.78

TABLE E.3 STATISTICAL CHECKS IN REGRESSION PANGNIRTUNG 1973

REGRESSION COEFFICIENTS		NPAR=1	NPAR=2	NPAR=3	NPAR=4
B_0		251.56	307.55	1115.29	342.77
B_1		10.45	- 1.56	30.38	16.63
B_2			171.39	130.84	136.35
B_3				-21.83	-14.55
B_4					14.91
S.E.		268.80	218.61	212.92	209.96
F-TEST		0.80	6.16	6.78	5.12
M.C.C.	RIYK	0.18	0.60	0.70	0.71
P.C.C.	RYX2	0.18	- .03	0.53	0.29
	RYX3		0.61	0.46	0.48
	RYX4			- .64	- .43
	RYX5				.18
F-TEST CRITICAL VALUES	95%	4.28	3.44	3.07	2.87
(n=25, k=1,4)	99%	7.88	5.72	4.87	4.43

	STANDARD DEVIATION		CORRELATION COEFFICIENT		REGRESSION COEFFICIENT
Y	273.26				
X2	4.79	RX2	0.1832	BX2	10.45
X3	0.97	RX3	0.5989	BX3	168.71
X4	8.03	RX4	0.0032	BX4	- 0.11
X5	3.35	RX5	0.4652	BX5	129.28

TABLE E.4 INPUT DATA BROUGHTON 1973

Y	X1	X2	X3	X4	X5
68.20	1.0	10	0	50	33
145.81	1.0	13	0	52	38
199.31	1.0	3	1	37	32
206.75	1.0	1	1	35	31
156.43	1.0	0	1	36	28
120.99	1.0	5	0	42	32
125.37	1.0	5	0	43	30
123.90	1.0	7	0	46	31
152.74	1.0	16	1	59	36
280.92	1.0	1	1	37	29
314.21	1.0	0	0	35	28
188.02	1.0	0	0	35	29
163.75	1.0	0	1	35	27
124.04	1.0	1	1	37	28
169.44	1.0	4	1	43	29
138.36	1.0	5	1	41	32
123.16	1.0	5	1	42	31
115.40	1.0	8	1	43	36
177.70	1.0	9	0	44	37
205.58	1.0	16	0	55	40
338.43	1.0	15	0	53	40
252.25	1.0	3	1	42	28
120.25	1.0	0	1	32	27
96.89	1.0	0	0	33	27
71.09	1.0	0	1	36	21
35.45	1.0	0	1	28	20

TABLE E.5 OUTPUT DATA BROUGHTON 1973

NPAR=1	NPAR=2	NPAR=3	NPAR=4
170.30	176.90	183.74	111.07
176.24	180.97	179.99	190.88
156.44	150.44	144.29	188.68
152.48	147.72	144.35	197.92
150.50	164.37	151.70	175.17
160.40	170.10	172.93	186.67
160.40	170.10	176.59	161.56
164.36	172.82	180.18	157.67
182.18	168.10	176.77	138.71
152.48	147.72	151.67	178.16
150.50	163.31	165.78	176.21
150.50	163.31	165.78	191.45
150.50	146.37	148.04	154.57
152.48	147.72	151.67	162.93
158.42	151.80	162.54	157.51
160.40	153.16	151.54	174.91
160.40	153.16	155.19	165.03
166.34	157.23	147.79	193.78
168.32	175.54	165.49	203.18
182.18	185.05	179.89	184.63
156.44	183.69	176.27	191.52
150.50	150.44	162.57	154.52
150.50	146.37	137.08	138.50
150.50	163.31	158.47	150.26
150.50	146.37	151.70	68.51
150.50	146.37	122.45	10.42

TABLE E.6 STATISTICAL CHECKS IN REGRESSION - BROUGHTON 1973

REGRESSION COEFFICIENTS	NPAR=1	NPAR=2	NPAR=3	NPAR=4
B_0	150.50	163.31	37.83	-437.90
B_1	1.98	1.36	- 3.69	- 17.60
B_2		-16.94	-17.74	- 6.40
B_3			3.64	5.36
B_4				15.24
S.E.E.	72.53	72.05	71.62	57.43
F-TEST	0.51	0.39	0.34	2.63
M.C.C. RIYK	0.14	0.18	0.21	0.6207
R.C.C. RYX2	0.14	0.10	- 0.27	I
RYX3		- 0.12	- 0.12	- 0.04
RYX4			0.38	0.56
RYX5				I
F-TEST CRITICAL VALUES 95%	4.26	3.42	3.05	2.84
(n=26, k=1,4) 99%	7.72	5.57	4.72	4.26

STANDARD DEVIATION		CORRELATION COEFFICIENTS		REGRESSION COEFFICIENTS	
SX2	5.35	RX2	0.1446	BX2	1.98
SX3	0.50	RX3	-0.1130	BX3	-16.55
SX4	7.67	RX4	0.1685	BX4	1.61
SX5	4.96	RX5	0.4055	BX5	5.99

TABLE E.7 INPUT DATA FROBISHER 1973

Y	X1	X2	X3	X4	X5
198	1.0	8	0	49	31
206	1.0	10	0	50	33
243	1.0	7	0	44	34
195	1.0	6	1	43	33
170	1.0	7	1	44	33
147	1.0	5	0	41	32
124	1.0	5	1	43	31
123	1.0	4	1	40	31
112	1.0	5	0	44	30
134	1.0	7	1	46	31
129	1.0	6	1	45	31
150	1.0	10	0	50	34
227	1.0	12	0	51	37
332	1.0	18	0	63	36
289	1.0	20	0	62	42
297	1.0	22	0	65	43
239	1.0	17	2	54	43
250	1.0	10	2	45	38
177	1.0	12	0	51	37
154	1.0	10	0	48	36
131	1.0	6	1	40	36
115	1.0	6	1	41	35
97	1.0	12	0	50	37
92	1.0	16	0	54	41
97	1.0	17	0	55	42
104	1.0	19	1	58	43
121	1.0	25	0	70	44
110	1.0	20	0	58	46
85	1.0	16	0	56	40
80	1.0	13	1	48	41
77	1.0	13	1	50	39
71	1.0	9	2	46	35
60	1.0	7	1	43	34
50	1.0	8	0	45	34
46	1.0	17	0	58	40
43	1.0	20	0	58	45
41	1.0	20	0	58	46
40	1.0	18	1	55	44
39	1.0	23	0	66	44
38	1.0	16	0	53	42
36	1.0	13	0	51	39
32	1.0	13	1	51	38
30	1.0	9	1	46	36
105	1.0	10	1	48	36
131	1.0	7	1	42	35
124	1.0	5	1	39	34
94	1.0	8	1	44	36
78	1.0	11	0	49	36

TABLE E.7 INPUT DATA FROBISHER 1973 (cont'd)

Y	X1	X2	X3	X4	X5
65	1.0	12	0	51	37
52	1.0	16	0	57	38
45	1.0	25	0	66	47
40	1.0	26	0	71	44
37	1.0	15	0	53	40
35	1.0	17	0	58	39
32	1.0	18	0	60	40
30	1.0	22	0	64	44
29	1.0	22	0	59	48
26	1.0	17	0	57	41
24	1.0	18	0	59	40
21	1.0	19	0	61	40
20	1.0	10	1	46	37

TABLE E.8 OUTPUT DATA FROBISHER 1973

NPAR=1	NPAR=2	NPAR=3	NPAR=4
123	120	162	164
117	114	135	123
126	122	110	117
129	130	143	151
126	127	136	129
132	128	108	97
132	132	163	170
135	135	140	132
132	128	151	154
126	127	165	155
129	130	171	178
117	114	135	140
111	109	109	116
93	92	159	146
87	87	104	112
81	81	107	114
96	104	103	103
117	123	116	115
111	109	109	116
117	114	106	114
129	130	99	112
129	130	114	125
111	109	95	85
99	98	71	63
96	95	65	58
90	94	93	90
72	73	117	125
87	87	47	59
99	98	99	107
108	110	72	69
108	110	101	96
120	126	157	147
126	127	122	115
123	120	104	94
96	95	108	115
87	87	47	42
87	87	47	59
93	97	71	69
78	78	101	109
99	98	56	50
108	106	88	97
108	110	115	109
120	121	124	135
117	119	133	143
126	127	108	102
132	132	105	100
123	124	116	127
114	111	101	91
111	109	109	116

TABLE E.8 OUTPUT DATA FROBISHER 1973 (cont'd)

NPAR=1	NPAR=2	NPAR=3	NPAR=4
99	98	114	103
72	73	60	54
69	70	111	102
102	100	77	69
96	95	108	98
93	92	116	123
81	81	92	101
81	81	20	17
96	95	93	101
93	92	102	92
90	89	110	100
117	119	104	99

TABLE E.9 STATISTICAL CHECKS IN REGRESSION FROBISHER 1973

REGRESSION COEFFICIENTS	NPAR=1	NPAR=2	NPAR=3	NPAR=4
B_0	146.34	141.82	-380.91	-1436.57
B_1	-2.96	-2.76	-20.40	-53.13
B_2		4.42	26.44	29.23
B_3			14.40	30.48
B_4				17.18
S.E.E.	75.68	76.29	72.37	72.54
F-TEST	3.30	1.65	3.7	2.95
M.C.C. RIYK	.23	.23	.40	I
R.C.C. RYX2	-.23	-.21	I	.83
RYX3		.03	.20	.22
RYX4			I	I
RYX5				I
F-TEST CRITICAL VALUES 95%	4.0	3.15	2.76	2.53
(n=61, k=4) 99%	7.08	4.98	4.13	3.65

STANDARD DEVIATION		CORRELATION COEFFICIENTS		REGRESSION COEFFICIENTS	
SX2	6.0	RX2	0.2299	BX2	-2.96
SX3	0.59	RX3	0.1311	BX3	17.13
SX4	8.0	RX4	-0.1531	BX4	-1.47
SX5	4.61	RX5	-0.3149	BX5	-5.27