SNOWMELT AS PREDICTED BY
A SURFACE ENERGY BALANCE

A Thesis

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Master of Science

Civil Engineering

by

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ABSTRACT

From a study of the factors affecting the energy balance of a snow surface it is shown that a simplified form of the energy balance equation involving only the transfers of net radiation, sensible heat, and the latent heat of evaporation is suitable for use in this study. When a mass-transfer type formula ($Q_e = (A + B \cdot V) \cdot (E_a - E_s)$) is used to calculate the latent heat of evaporation it is shown that if "A" is assumed to be zero a suitable value of the evaporative heat transfer coefficient "B" for use in Western Manitoba is 0.18 calories/(cm.^{2} • mile • mb). This transfer coefficient is so small that the accumulated transfer of latent and sensible heat was only 6% of the accumulated net radiation. The results of this research on evaporative heat transfer coefficients over a snow surface are compared with those obtained by Gold and Williams and by Barry. Three semi-empirical methods of estimating snowmelt; a degree - day, a regression equation, and the U.S.C.E. equations, are tried and their results compared with the energy balance approach.

ACKNOWLEDGEMENTS

As a preface to my thesis I wish to acknowledge the assistance I have been given in its preparation. In particular I am grateful for the guidance of my advisor Dr. R. W. Newbury and for the assistance of J. E. Thomlinson in the collection of the basic data on which this thesis is based. I am indebted to the Agassiz Centre for its financial assistance and to the Water Survey of Canada, Department of Energy, Mines and Resources for granting me educational leave to attend university. In closing, I acknowledge the patience of my wife Joan without which this research could not have been done.

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CHAPTER I

INTRODUCTION

The importance of being able to accurately forecast the magnitude and timing of runoff from snowmelt is well recognized. At present most of the approaches to the forecasting of snowmelt are of a semi-empirical nature. In order to see if it is possible to get a realistic estimate of the amount and rate of snowmelt by an energy balance approach, this study was undertaken on the Wilson Creek Basin.

The Wilson Creek Watershed is an International Hydrologic Decade (IHD) Project located in Township 20 Range 16 W.P.M. on the eastern slopes of the Riding Mountain about 150 miles northwest of Winnipeg. The location is indicated in FIGURE 1.

Wilson Creek was ideally suited for such a study as there was an operating weather station equipped to measure relative humidity, air temperature and wind speed. To provide controls for the snowmelt computations, there was a stream gauging station and network of eleven snow courses. The only extra instrumentation needed was a net pyrradiometer to measure all-wave net radiation and pyranometer for measuring total incoming short-wave radiation. These were provided by the Meteorological Branch, Department of Transport. FIGURE 2 shows the location of the meteorological instruments, snow courses and gauging station.

The watershed is covered by a forest that is greater than 95 percent deciduous and contains large areas covered only by a very open decadent forest. Thus the watershed may be considered to be relatively open. MacKay and Stanton (1964) have provided a detailed description of the watershed.

The snowmelt during the spring of 1969 was concentrated in a very short period. On March 26 the snow cover was equivalent to 5.78 inches of water, on April 9 there was still 4.84 inches; however, by April 14 there was only 0.95 inches water equivalent. From the streamflow records it was apparent that significant melting did not occur until the morning of April 12. This high melting rate resulted in an instantaneous peak flow of 282 cfs on the night of April 14 - the highest snowmelt flood recorded since the installation of the Wilson Creek Weir in 1957. The weather from April 12-15 was warm with average daytime temperatures of 55°F and with average nighttime temperatures dropping only to 43°F (approximate).

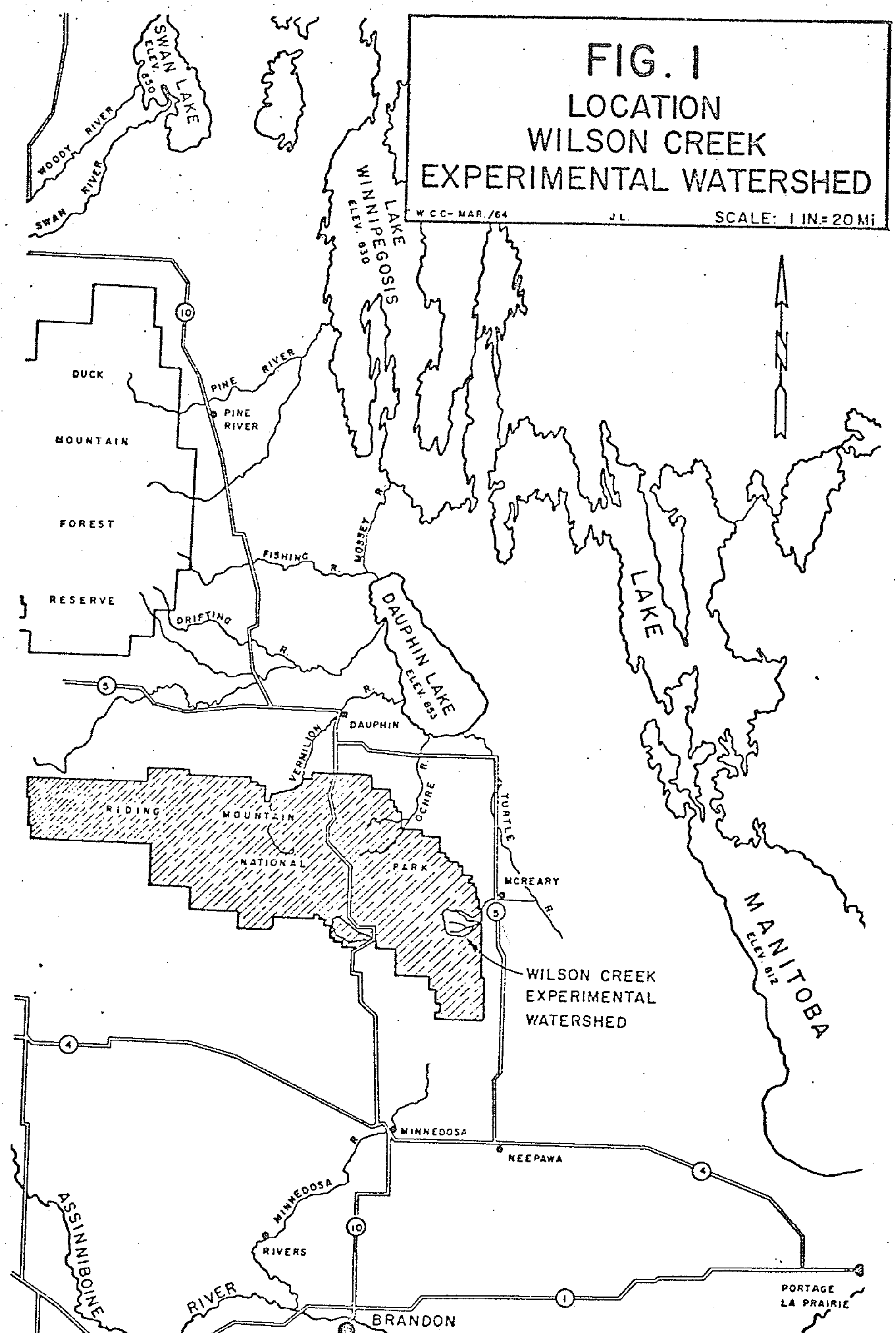


FIG. I
LOCATION
WILSON CREEK
EXPERIMENTAL WATERSHED
W.C.C.-MAR./64
J.L.
SCALE: 1 IN.= 20 Mi
N
SWAN LAKE
ELEV. 850
WOODY RIVER
SWAN RIVER
LAKE WINNIPEGOSIS
ELEV. 830
DUCK
MOUNTAIN
FOREST
RESERVE
PINE RIVER
PINE RIVER
MOSSEY R.
FISHING R.
DRIFTING R.
DAUPHIN LAKE
ELEV. 855
DAUPHIN
VERMILION R.
OCHRE R.
TURTLE R.
RIDING MOUNTAIN NATIONAL PARK
MCREARY
WILSON CREEK
EXPERIMENTAL
WATERSHED
LAKE MANITOBA
ELEV. 812
MINNEDOSA
NEEPAWA
MINNEDOSA R.
RIVERS
ASSINIBOINE RIVER
BRANDON
PORTAGE
LA PRAIRIE
J.L.

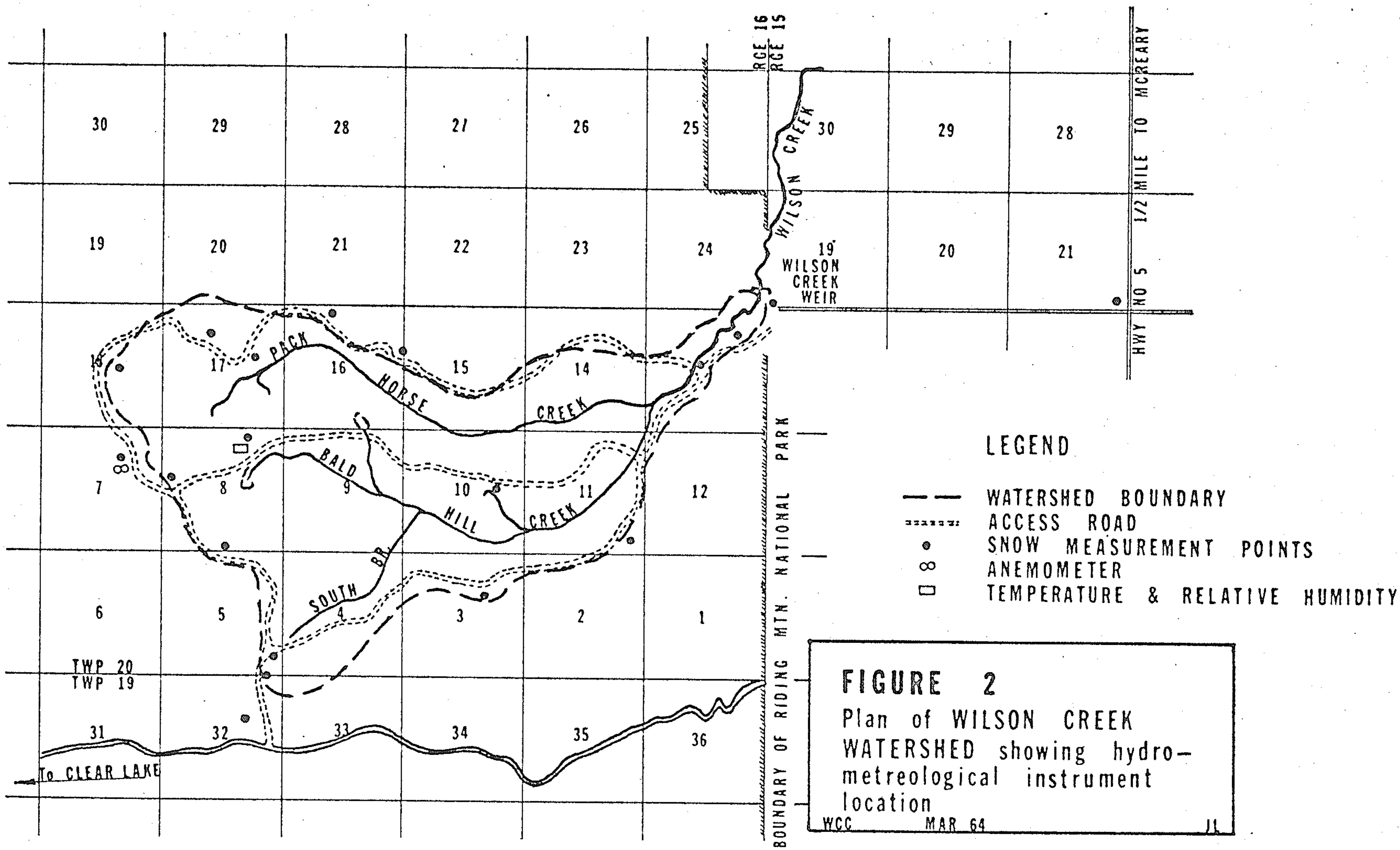


FIGURE 2

Plan of WILSON CREEK WATERSHED showing hydro-metreological instrument location

WCC MAR 64 JL

CHAPTER II

ENERGY BALANCE EQUATION

The amount of snow that melts at any point location is determined by the net exchange of energy between the snow-pack and its surroundings. Before that melt becomes effective as runoff it must travel from the point at which it was created to the stream. The purpose of this section is to present the basic equations for the processes involved in the energy balance along with some simplifying assumptions. The problem of routing the point melt through the snow to the stream and then down the stream channel is not dealt with.

The Energy Balance Equation

The main processes that interact to provide an energy balance at the snow surface are shown in FIGURE 3. Anderson (1968) has expressed this inter-relationship in the following equation.

$$Q_\theta = Q_r + Q_h + Q_e + Q_1 + Q_w \quad \text{-------------------} \quad (1)$$

where:

Q_θ = change in heat storage of the snow pack

Q_r = net radiation transfer

Q_h = sensible heat transfer

Q_e = gain or loss of latent heat caused by evaporation, condensation, or sublimation

Q_1 = gain or loss of latent heat caused by freezing or melting

Q_w = net heat transfer caused by a gain or loss of water.

If it is assumed that no solar radiation penetrates the surface layer of the snowpack and that the heat storage of this layer is negligible, equation (1) may be written:

$$Q_r + Q_h + Q_e + Q_1^1 + Q_c + Q_w^1 = 0 \qquad (2)$$

where:

Q_c = heat transferred to or from surface layer by conduction within the snow pack

1 = denotes the surface layer rather than snow pack as a whole.

Discussion of Individual Terms

Q_w^1 As 32°F is the zero point for computations of heat storage and as water leaving the pack is usually at 32°F, Q_w^1 represents heat transferred to the surface layer by precipitation. As there was no precipitation during this study, $Q_w^1 = 0$.

Q_c Anderson (1968) indicated that Q_c is small because of the low thermal conductivity of snow and may be neglected.

Q_1^1 This term, the loss of latent heat associated with melting, is usually the quantity to be calculated. The melt in inches may be determined by dividing Q_1^1 by the latent heat of fusion required to freeze or melt one inch - (2.54 cm./in. * 79.7 cal/cm^3 = 202.4 cal/cm^2). If the free water content is two percent as suggested by Anderson (1968), then:

$$MELT = Q^1/(202.4)\ (1-0.02) = Q^1/198.352 \text{ inches} \quad (3)$$

$\underline{Q_e}$ The transfer of latent heat by evaporation or condensation is a turbulent exchange process that may be expressed as:

$$Q_e = (A + BV)\ (E_a - E_s) \quad (4)$$

where:

V = wind velocity in miles per hour at a reference height

E_s = saturation vapour pressure at the temperature of snow surface

E_a = vapour pressure of the air at a reference height

A = an empirical evaporative heat transfer constant

B = an empirical evaporative heat transfer coefficient.

In the literature there is a wide range of values for A and B. The problem of choosing the constant and coefficient appropriate to our conditions is discussed later.

$\underline{Q_h}$ The transfer of sensible heat between the air and the snow surface occurs by conduction at the molecular interface between the air and snow. It obviously depends on $(T_a - T_s)$, the temperature gradient and a turbulent exchange function $f_{(v)}$:

$$Q_h = f_{(v)} \cdot (T_a - T_s) \quad (5)$$

where:

T_a = air temperature at a reference height

T_s = surface temperature.

Anderson (1968) points out that thus far it has been impossible to obtain reliable measurements with which to calculate Q_h accurately. An alternative method of calculating Q_h was suggested by Bowen (1926). This method uses the ratio of Q_h to Q_e which can be expressed as:

Bowen Ration = $R = Q_h/Q_e = \gamma \cdot (T_a - T_s)/(E_a - E_s)$ -- (6)

where:

$\gamma = C_p \cdot P_a / (0.622 \cdot L)$ ---------------------- (7)

and

C_p = specific heat of air

L = latent heat of vapourization

P = atmospheric pressure.

If $C_p = 0.133$ calories/(g_m ^oF), L = 597.3 calories/cm^2, and P is in millibars, then $\gamma = 0.00036\ P_a$ millibars/^oF.

There is some controversy concerning the correctness of the Bowen Ratio under some weather conditions. For discussion of this point reference is made to papers by Anderson (1968), Munn (1966, pp 95-97), Pruitt & Lourence (1966) and Brutsaert (1965).

$\underline{Q_r}$ The net radiation transfer was measured directly.

Sign Convention

The sign convention used in this project is that a flux is positive if it tends to add heat to the surface. For example:

(a) Incoming radiation is positive.

(b) Outgoing radiation is negative.

(c) Evaporation causes a negative latent heat flux.

(d) Condensation causes a positive latent heat flux.

Simplified Energy Balance Equation

In equation (2) we wrote:

$$Q_r + Q_h + Q_e + Q_l^1 + Q_c + Q_w^1 = 0$$

If we take $Q_c = Q_w = 0$; as we have just shown, and if we set $Q_m^1 = -Q_l^1$

where:

Q_l^1 = gain or loss of latent heat caused by melting or freezing in surface layers

Q_m^1 = heat causing melting;

we may write:

$$Q_m^1 = Q_r + Q_h + Q_e \quad \text{-----------------------------} \quad (8)$$

Since Q_h is related to Q_e $[Q_h = R \cdot Q_e]$ we may write:

$$Q_m^1 = Q_r + Q_e\,(R + 1) \quad \text{--------------------------} \quad (9)$$

$$\text{Melt} = Q_m^1 / 202.4\ (0.98) \text{ when melt +ve} \quad \text{-----------} \quad (10A)$$

$$\text{Melt} = Q_m^1 / 202.4 \qquad \text{when melt -ve} \quad \text{------------} \quad (10B)$$

Different "effective" latent heats of fusion were used for the two cases because under melting conditions it was assumed the snow pack contained 2 percent free water.

From equation (9) it can be seen that since Q_r was measured it is only necessary to calculate Q_e to be able to calculate Q_m^1 and thus the amount of melt.

Before leaving the theoretical development of the energy balance equation, it may be worthwhile to review the main assumptions that have been used:

It has been assumed that:

(1) During the periods of active melt the snow surface temperature was 32°F;

(2) During the non-melting (nightime) periods the snow surface temperature was that of the ambient air;

(3) There is no negative transfer of sensible heat; i.e. Q_h min. = 0; [Although in assumption (2) it is recognized that the snow surface temperature may drop below 32°F, the amount of heat given up by the snow is neglected. This is not a bad assumption because the low thermal conductivity of snow results in the heat storage capacity of the surface layer being negligible when compared to other components of the energy balance; such as, the net radiation exchange.]

(4) Bowen's ratio holds;

(5) There is no penetration of the surface layer by solar radiation;

(6) The free-water content of a melting snow pack is 2 percent;

(7) All negative Q_m acts to freeze free water in the pack. [In other words, no consideration is taken of the actual water holding capability of the freezing pack.]

<u>Summary</u>

In this section the component terms of the energy balance equation, their relative importance and the main assumptions necessary to their computation have discussed with the result that a simplified energy balance equation

$$Q_m^1 = Q_r + Q_h + Q_e$$
$$= Q_r + Q_e (R + 1)$$

has been presented for use in this analysis of snowmelt.

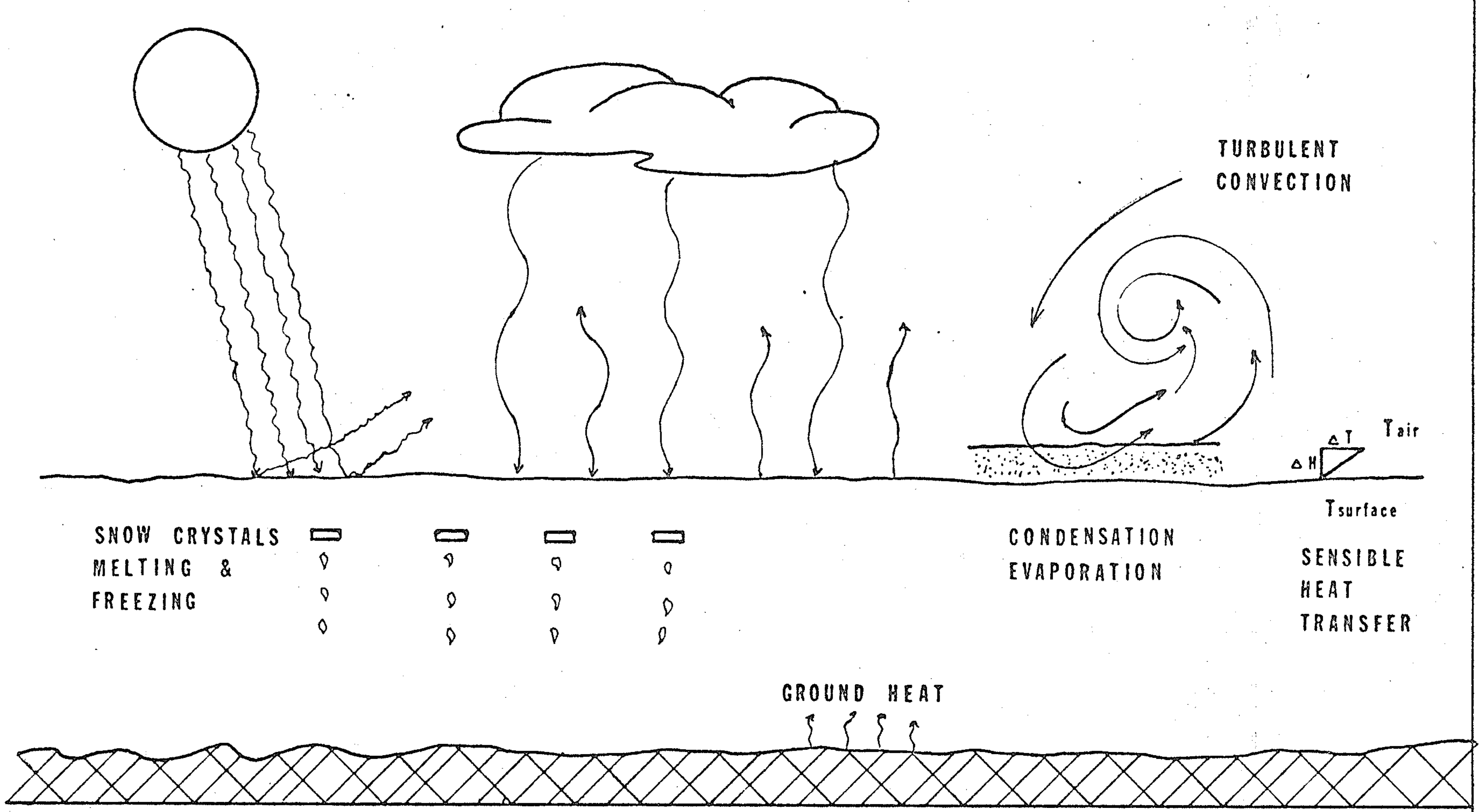


FIGURE 3

FACTORS INFLUENCING ENERGY BALANCE OF A SNOWPACK

CHAPTER III

INSTRUMENTATION

The net radiation was measured in langleys (calories/cm^2) by a net pyrradiometer developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia. Latimer (1963) indicates that with proper care this instrument should be accurate to within ± 5 to ± 10 percent.

Because of the lack of heated facilities on the watershed, it was necessary to locate the instrument at prairie level in the town of McCreary about five miles north of the watershed. This may well be the major source of error in this measurement. The major problem is that the snow cover was less in McCreary and thus it is believed to have disappeared maybe a half-day to a day sooner. The CSIRO net pyrradiometer showed no change in the net radiation that would indicate a drastic change in the albedo of the surface.

The incident solar radiation was measured with a Kipp & Zonen pyranometer that is quoted to have an error of ± 5 percent.

The air temperature and relative humidity were measured and recorded by a hygrothermograph inside a standard shelter 4.5 feet above the ground. The temperature was measured by means of a bimetallic strip and the recorded values were found to agree within $\pm 1^{\circ}$F of those obtained with a standard mercury thermometer. The use of a hair operated mechanism to measure relative humidity cannot be expected to yield a high order of accuracy.

As the wind speed was measured by a three-cup type of anemometer at a reference height of 10 meters, the standards of the World Meteorological Organization (W.M.O. -No. 168TP82) which call for an accuracy of 10.5 meters/sec ($\pm$1.1 m.p.h.) should have been met.

The net radiation, air temperature, relative humidity, and wind speed were used to compute the amount of melt. For control the actual amount of melt was measured by a network of eleven (11) snowcourses. The courses were fairly well distributed throughout the basin but because of access problems were mainly located on the higher ground between valleys. On April 4 and 5 before the start of the melt season traverses were run across three major valleys and it was found that the snow-water equivalent in the valleys averaged about 125 percent of the water equivalent on the interfluves. This distribution of the snow cover was kept in mind when isohyetals of water equivalent were drawn on the basin.

As barometric pressure was not recorded on the watershed, it was necessary to estimate the values of this parameter from records obtained at Dauphin Airport, which is about thirty (30) miles north of the watershed. As the barometric pressure at Dauphin Airport never varied more than four (4) percent from the monthly mean, that mean was used after being adjusted to the approximate mean elevation of the watershed (1800 feet).

From equation (7) it was seen that $\gamma = 0.00036\ P_a$ millibars per ^{o}F. If the average value of P_a = 949.6 millibars, then from Equation 6:

$$R = Q_h/Q_e = 0.342 \cdot (T_a - T_s)/(E_a - E_s) \quad \text{-------} \quad (11)$$

Summary

In summary it can be said that although the relative humidity was not measured as accurately as could be desired, it is felt that the accuracy of this instrumentation (±10 - 15%) was sufficient for the purpose of the exercise. In other words, no major error in the energy budget is due to faulty instrumentation.

CHAPTER IV

ANALYSIS OF OBSERVATIONS

Trial Energy Balance

In CHAPTER II it was shown that it was only necessary to calculate Q_e to be able to calculate Q_m^1 and thus the amount of melt. In order to calculate Q_e by equation (4) it is necessary to obtain estimates of A and B. In order to test the sensitivity of the energy balance to different values of A and B, two sets to transfer coefficients were chosen. They are shown below and represent the low and high ends, respectively, of the range of values given in the literature for transfer coefficients.

(a) Those presented by Ferguson (1968, p. 49)
where: A = 0.000, B = 1.191

(b) Gold & Williams (1961)
where: A = 0.000, B = 7.652.

It should be noted that these coefficients have been adjusted to suit the time increment to be used in this energy balance and to suit the 10m height at which the wind speed was measured. In this study a twelve (12) hour time increment has been used. One period starts at 19.00 hours and runs through the night until 06.00 hours. The daytime period runs from 07.00 hours to 18.00 hours. The wind speed was adjusted by a power law relationship.

$$V_{10m} = V_{meas.} (10m/Z_{meas.})^{P} \text{ ----------------- } (12)$$

Following Ferguson's (1968) reasoning P was taken as 0.25. This assumes that the turbulence created by the wind spilling over Riding Mountain is of the same order of magnitude as that found over the Niagara River. The temperature and relative humidity measurements were not adjusted for the relatively small differences in instrument height.

Using equations 4, 9, 10, and 11 the melt for each twelve hour increment was computed. The computations were started on April 12 at 07.00 as the hydrograph (FIGURE 4) showed that melt started during the 12th. As there was a snow survey on the 14th that is indicative of conditions at about 12.00, the computations were run until that time.

There was also a snow survey on April 8. The amount of snow that disappeared between the 8th and 14th was equivalent to 3.89 in. of water. The energy balance computations for the period April 12, 07.00 to April 14, 12.00 gave the following results:

Evaporative Transfer Coefficient	Acc. Melt
Ferguson	5.31 inches
Gold & Williams	13.54

In the discussion on instrumentation in CHAPTER III it was shown that no major error in the energy budget is due to faulty instrumentation. These results therefore indicate the inaccuracy of melt computations using inappropriate coefficients in equation (4):

$$Q_e = (A + BV) \cdot (E_a - E_s)$$

In addition the results illustrate that significant difference are obtained by the use of two well-recognized sets of values for "A" and "B".

Testing of Mass Transfer Formulae

In the preceding section the importance of the evaporative component in the energy budget was clearly demonstrated. As a result it was decided to try other sets of coefficients that have been proposed. From a literature survey fourteen sets of values for "A" and "B" were found and tested in the energy balance equation for the period April 12, 07.00 - April 14, 12.00. As the primary purpose of these computations was to determine the effect of the evaporative latent heat transfer term on the energy balance, Q_e, Q_h and $Q_e + Q_h$ were calculated in addition to the melt quantity.

From TABLE 1 it is seen that all estimates of "A" + "B" caused the energy balance to overestimate the actual melt of 3.89 in. water equivalent. The differences in the effect of various estimates of "A" and "B" are also clearly shown in the mass curves presented in FIGURE 5, Q_e versus Time; FIGURE 6, Q_h vs Time; and FIGURE 7, $Q_e + Q_h$ vs Time. The bottom portion of FIGURES 5, 6 and 7 are a plot of accumulated Q_e, Q_h and $Q_e + Q_h$ against Time. In the upper portion of these figures are plots of the vapour pressure and temperature differences between the air and snow surfaces that along with the wind speed control the transfer of latent and sensible heat.

For the sake of clarity in FIGURES 4, 5, and 6, equations 1, 2, 10, 11, and 12 of Table 1 are the only ones shown as they were thought to be representative [see APPENDIX B]. These five equations were chosen by eye using preliminary mass curves (not shown) of $Q_e + Q_h$ for all fourteen equations.

It is interesting that the mass curves of $Q_e + Q_h$ are bracketed by those representing the work of two Canadian groups; Barry (1967) and Gold & Williams (1961). Both these groups derived their transfer coefficients over a snow surface whereas the other investigators were working over grass or water surfaces. Details of the various investigators' work may be obtained by consulting the references given in APPENDIX C.

In summary the melt calculated using the evaporative transfer coefficients found in the literature was always in exess of that observed. In the introduction to CHAPTER IV it was pointed out that the values of the evaporative transfer coefficients represent the only uncertainties in this energy balance. Thus as the instrumentation has been shown to be adequate it appears that the values of these coefficients found in the literature do not suit the meteorological conditions encountered at Wilson Creek.

Derivation of Evaporative Heat Transfer Coefficient

As the Transfer coefficients reported in the literature were not suitable, it was necessary to determine coefficients that were applicable under the meteorological conditions encountered during this study. This was done using an iterative approach.

The first step was to assume that "A" equalled zero thus leaving only "B" to be evaluated. Once a value for "B" was assumed, Q_e was readily calculated from equation (4) and Q_h from $Q_h = RQ_e$. Then the melt was found from equations (9) and (10). If the accumulated melt for the period April 12 07.00 - April 14 12.00 did not agree with the results of the snow survey (a loss at 3.89 in. water), the value of "B" was adjusted. After several iterations the value of the transfer coefficient "B" was found to be 0.184 calories/(cm^2 · mile · mb). That is:

$$Q_e = (0.000 + 0.184\ V)\ (E_a - E_s)\ \text{calories}/(\text{cm}^2 \cdot 12\ \text{hr}) \qquad \text{------------- (13)}$$

It was assumed in this study that if a crust formed at the snow surface during the night of the 11th (the night before significant melting occurred) that the heat deficit it represented had to be supplied next morning.

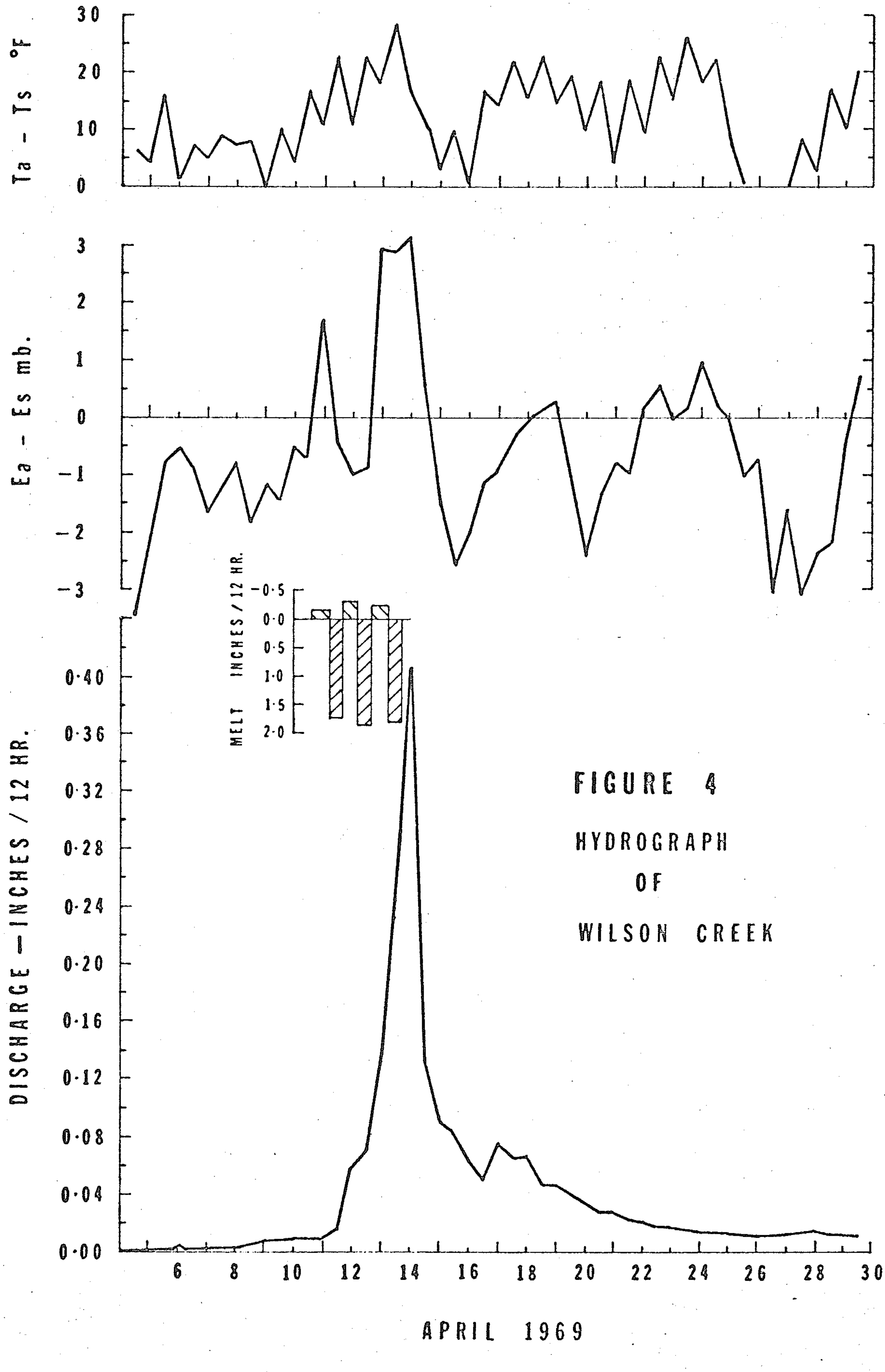
The difference in the results of the energy balance observed by using the experimentally determined value of B = 0.184 as opposed to using the transfer coefficients found in the literature is clearly shown by the mass curves of $Q_e + Q_h$ in FIGURE 7. As was expected the experimental curve falls below that of Barry's.

Summary

In this section it has been shown that if the experimentally determined evaporative heat transfer coefficient was used; that is, if

$$Q_e = (0.00 + 0.184\ V) \cdot (E_a - E_s) \text{ calories}/(\text{cm}^2 \cdot \text{mb} \cdot 12 \text{ hr.})$$

the energy balance gave a predicted melt similar to the melt obtained from the snow surveys. If the transfer coefficients found in the literature are used the resulting melt is excessive.



Ta - Ts °F
Ea - Es mb.
MELT INCHES / 12 HR.
DISCHARGE — INCHES / 12 HR.
FIGURE 4
HYDROGRAPH
OF
WILSON CREEK
APRIL 1969

TABLE 1

EVAPORATIVE TRANSFER COEFFICIENTS
"A" AND "B" FOR MASS TRANSFER EQUATIONS[a]

NO.	INVESTIGATOR	A	B	MELT April 12-14 in.
1	"FERGUSON"	0.000	1.191	5.31
2	GOLD & WILLIAMS	0.000	7.652	13.54
3	WMO (a)	0.000	1.186	5.30
4	WMO (b)	3.898	0.838	5.48
5	ROHWER	6.273	0.705	5.69
6	PENMAN 1956	2.744	0.881	5.35
7	GANGOPADHYAYA	5.376	1.308	6.32
8	LAKE HEFNER	0.000	1.226	5.35
9	LAKE MEAD	0.000	1.167	5.28
10	MEYER	11.200	1.408	7.38
11	U.S.C.E.	0.000	2.244	6.65
12	BARRY	0.000	0.582	4.47
13	LAMOREUX[b]	8.854	1.324	6.77
14	MORTON	7.988	1.331	6.76

[a]General Form:

$$Q_e = (A + B \cdot V_{10}) \cdot (E_a - E_s) \text{ CAL./(CM.}^2 \cdot \text{12HR.)}$$

[b]Form used by LAMOREUX:

$$Q_e = (A + B \cdot V_{10}) \cdot (E_a - E_s)^{0.88} \text{ CAL./(CM.} \cdot \text{12HR.)}$$

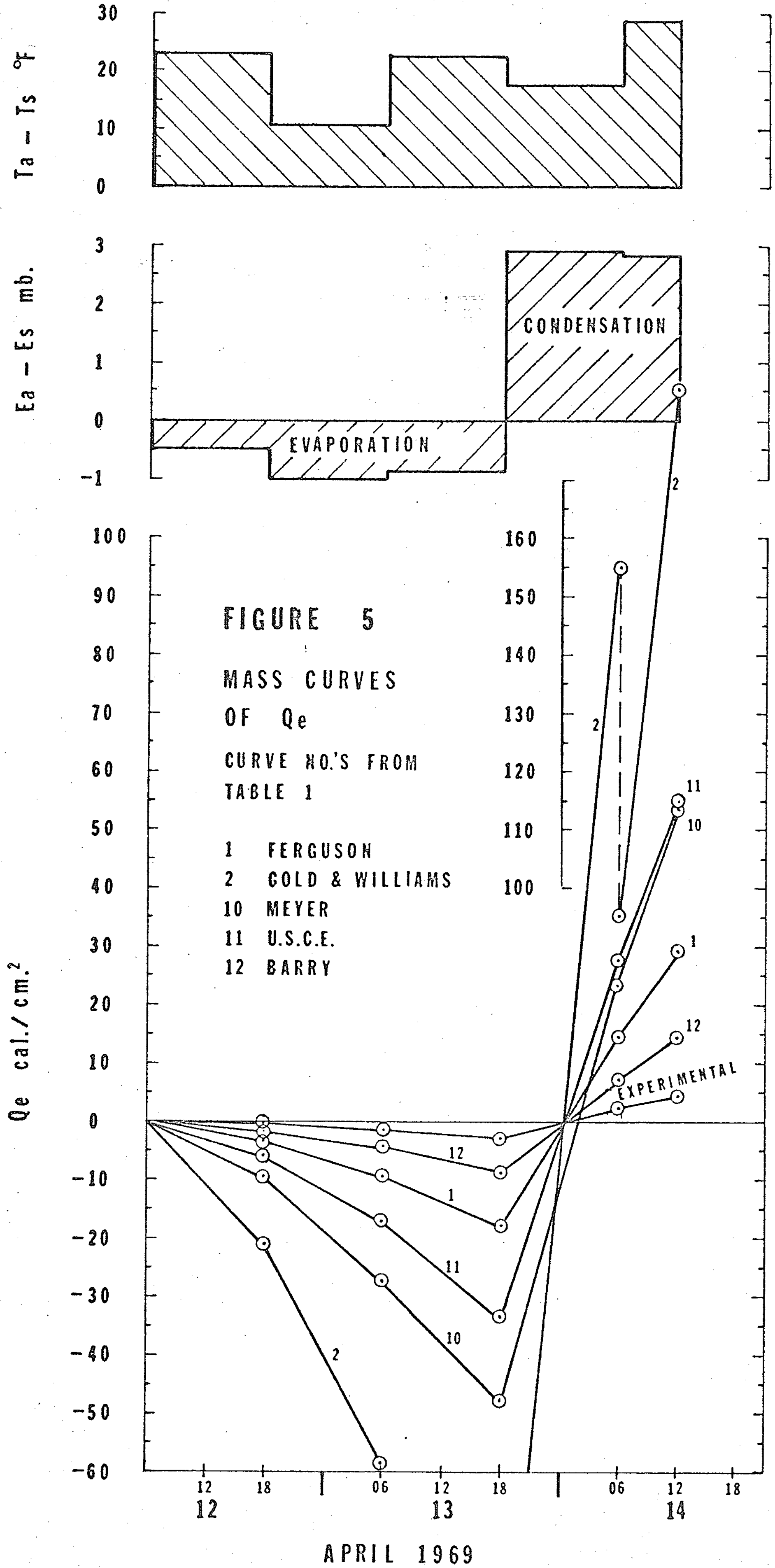

Ta - Ts °F
30
20
10
0
Ea - Es mb.
3
2
1
0
-1
CONDENSATION
EVAPORATION
Qe cal./cm.²
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
160
150
140
130
120
110
100
MASS CURVES
OF Qe
CURVE NO.'S FROM
TABLE 1
1 FERGUSON
2 GOLD & WILLIAMS
10 MEYER
11 U.S.C.E.
12 BARRY
EXPERIMENTAL
12
18
06
12
18
06
12
18
12
13
14
APRIL 1969

FIGURE 5

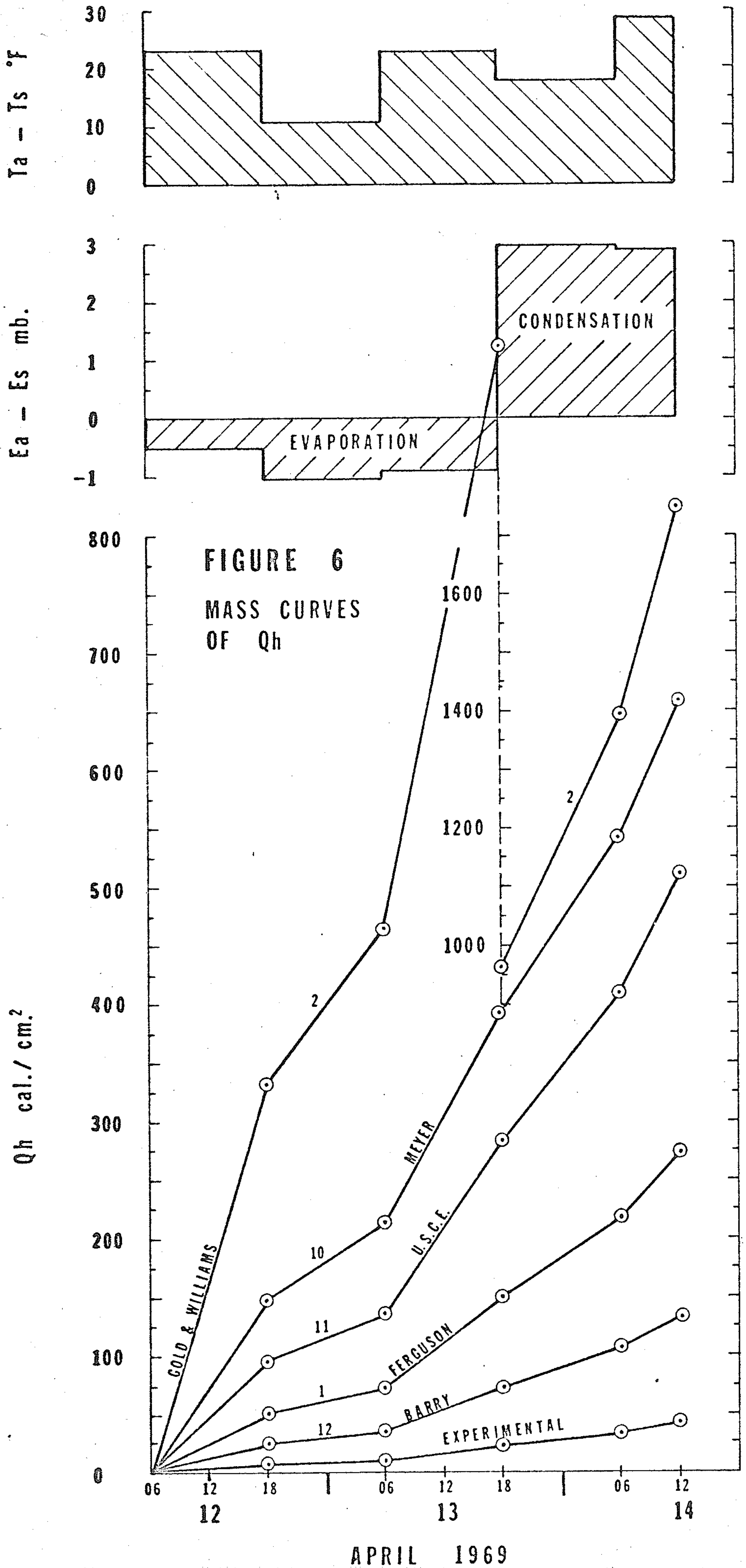
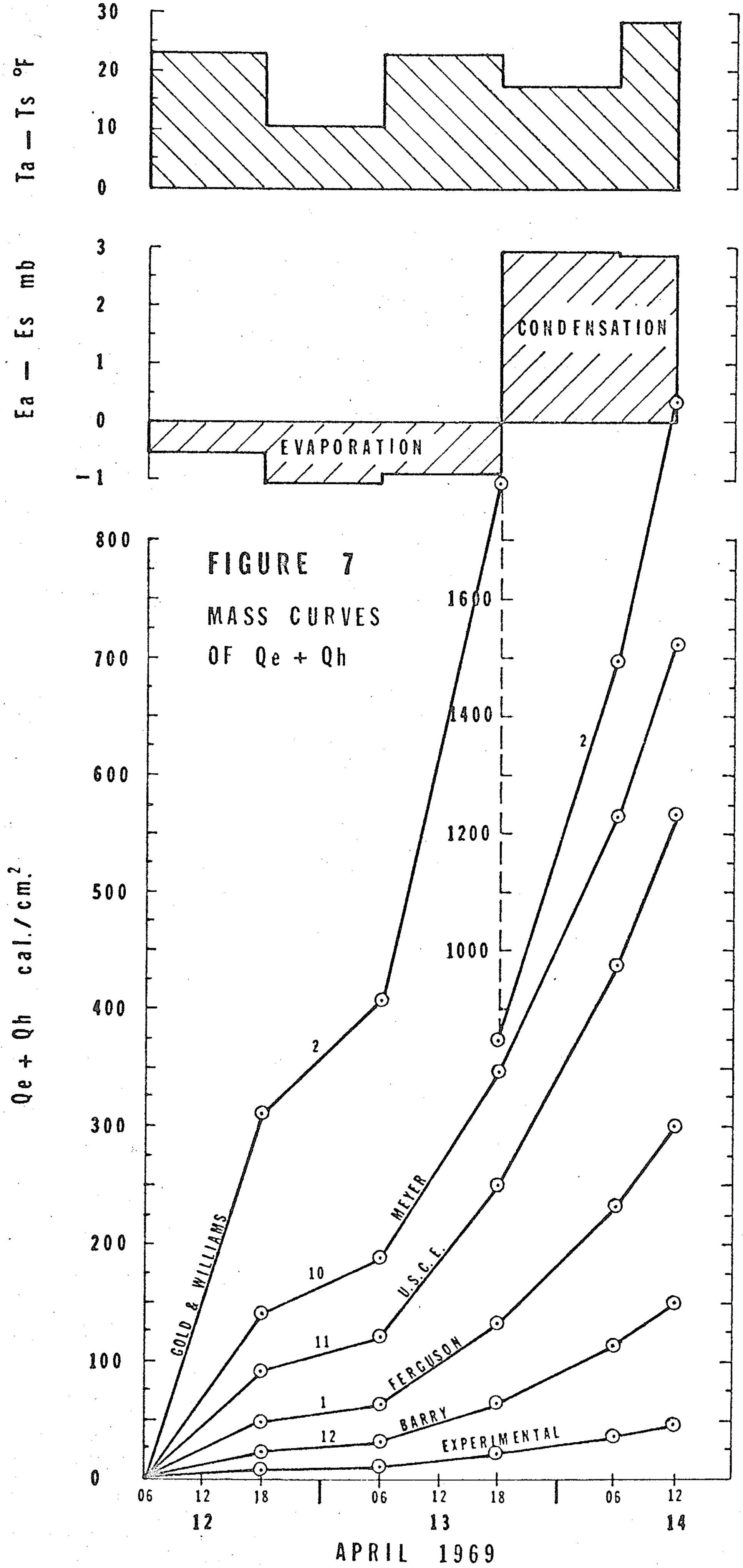


FIGURE 6

MASS CURVES OF Qh


Ta — Ts °F
Ea — Es mb
CONDENSATION
EVAPORATION
FIGURE 7
MASS CURVES
OF Qe + Qh
Qe + Qh cal./cm.^{2}
GOLD & WILLIAMS
MEYER
U.S.C.E.
FERGUSON
BARRY
EXPERIMENTAL
APRIL 1969

CHAPTER V

DISCUSSION OF RESULTS

Comments on the "Derived" Transfer Coefficient

The most striking point brought out by the above calculations is illustrated by the "experimental" mass curve of $Q_e + Q_h$ in FIGURE 7. The fact that this mass curve is so close to the origin indicates that the snowmelt is due mainly to the radiation component of the energy balance. In fact the accumulated $Q_e + Q_h$ is only six (6) percent of the accumulated Q_r.

This approximate equality between Q_m^1 and Q_r is not in agreement with the results of Gold & Williams (1961). However, Munn (1966, p. 142) reproduced a graph (see FIGURE 8) of the "Daily Components of the energy balance on the Blue Glacier, in the state of Washington" in which it is seen that Q_r and Q_m^1 are approximately equal and that Q_r is much greater than $Q_e + Q_h$. FIGURE 9 is reproduction of a graph presented by Ambach & Hoinkes (1963). Ambach & Hoinkes (1963) reported that 68 percent of the heat causing melting was supplied by net radiation and 32 percent by net convection ($Q_e + Q_h$) and that these figures compared very well with those on the Blue Glacier.

One disappointing result of this study was that neither the derived evaporation transfer coefficient nor those found in the literature enabled the energy balance to distinguish between periods of actual runoff producing melt and periods in which the melt contributed only to the "ripening" of the snow pack. This is illustrated in TABLE 2 which shows the melt obtained for each period from April 8 - 12 using:

$$Q_e = (0.000 + 0.184\ V) \cdot (E_a - E_s).$$

The importance of these small evaporative and sensible heat components of the energy balance might be questioned. Yet, it is interesting to note in FIGURE 10 how the mass curve of $Q_e + Q_h$ rose at the same time as the curve of accumulated melt and with changing meteorological conditions.

During the energy balance computations it was assumed that all negative Q_m^1 went towards freezing liquid water in the snow pack. Using this assumption the following results were obtained:

Night of April	$-Q_m^1$	Q_m^1 on following day	$-Q_m^1/Q_m^1$ %
11	-29.6	345.9	8.6
12	-61.8	371.0	16.7
13	-47.2	331.6	14.2

Section 8-04.05 of "Snow Hydrology" (1956) states that the nighttime energy deficit is approximately 15 percent of the daytime energy input in the open. Thus it appears that our assumption is acceptable.

From the snow survey results there were 0.95 inches of water left on the watershed at noon on April 14th. Using the derived evaporative transfer coefficient in the energy balance it was calculated that another 0.86 inches melted during the afternoon of the 14th. Assuming that this represented the end of the snowmelt period, the mass curve of snowmelt was plotted in FIGURE 11 in order to compare the volume of melt with the volume of runoff. From FIGURE 11 and from the hydrograph of Wilson Creek in FIGURE 4 it is seen that the runoff peaked approximately 6 hours after the end of snowmelt on the 14th. At the time of the peak the runoff volume was 17% of the melt volume. By 18.00 hours on April 18 the runoff-melt ratio had increased to 0.31 and by April 24 to 0.39.

Comparison of the "Derived" Transfer Coefficient with Barry's

Barry's evaporative transfer coefficient was the closest to the derived coefficient. Thus this experiment may be an indication of support for Barry's belief that even in fully rough flow the viscous skin friction in the laminar sublayer cannot be neglected "since it is to this part that mass (and heat) transfer correspond". (Barry 1967)

Comparison of the "Derived" Transfer Coefficient with Gold & Williams'

The difference between the value of the evaporative transfer coefficient derived at Wilson Creek and by Gold and Williams is very interesting for the methods used are believed to be basically the same. As previously described the calculations on Wilson Creek were performed by working with individual terms of the energy balance; whereas Gold & Williams factored the energy balance equation, worked with various groupings of physical data and later multiplied by appropriate factors. Gold and Williams obtained their sums of $V \cdot (E_a - E_s)$ and $V \cdot (T_a - T_s)$ by graphical integration which may theoretically be more correct than using twelve hour averages of the individual quantities.

Although the sites of the two experiments were different; as Gold and Williams conducted their experiments on a flat, open field and Wilson Creek is a very open forest, the wind speeds were approximately equal, as shown in TABLE 3. TABLE 3 also shows that the temperatures experienced on Willson Creek were considerably higher than those at Ottawa. The average vapour pressures must have also been higher at Wilson Creek for over the period considered there was not condensation while at Ottawa there was considerable evaporation. The integration of these differences is clearly seen in the following indices:

	Wilson Creek	Gold & Williams	
Average $V_{2m} \cdot (E_a - E_s)$	89	-1498	mb · miles/day
Average $V_{2m} \cdot (T_a - T_s)$	2380	151	^{o}F · miles/day

Gold and Williams recognized that under weather conditions where the air was moist and had a temperature consistently above 32^{o}F the evaporative component in the energy budget would tend to be suppressed or even reversed.

as was the case at Wilson Creek. Perhaps the results of Gold and Williams' study are more applicable to early spring melting periods than to later periods during which there are influxes of warm, relatively moist air.

Summary

From the studies on Wilson Creek it appears that the heat required for snowmelt is principally supplied by the radiation component of the energy balance with evaporative and sensible heat transfer being of only minor importance. The results of other studies reported in the literature show that there are discrepancies in the importance of the evaporative component that cannot be easily explained but simply point towards more research into the physics of evaporation. Both Gold & Williams and Barry have tried to relate their transfer coefficients to a drag coefficient but at present such a relationship is not clearly understood.

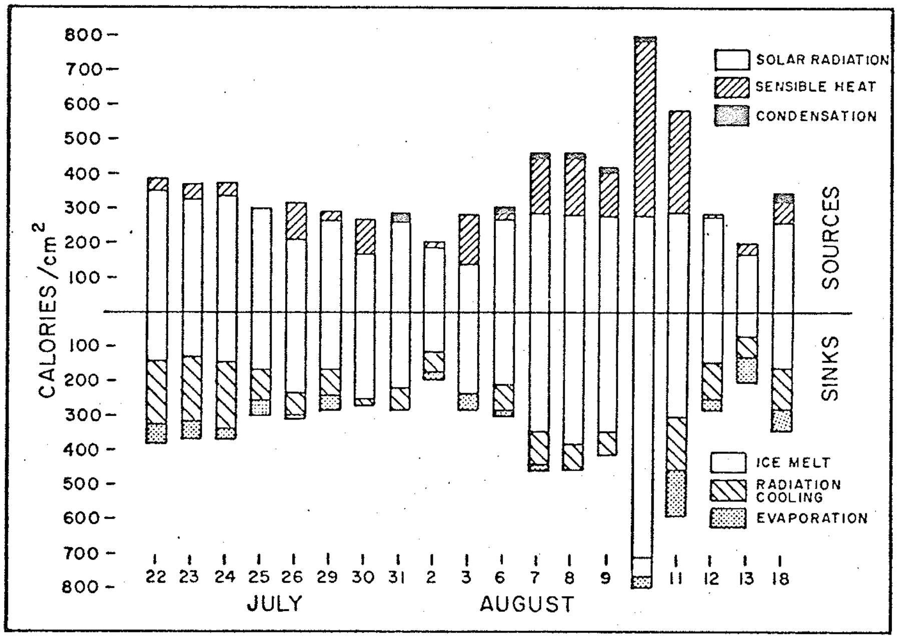


FIGURE 8 – DAILY COMPONENTS OF THE ENERGY BALANCE ON THE BLUE GLACIER IN THE STATE OF WASHINGTON

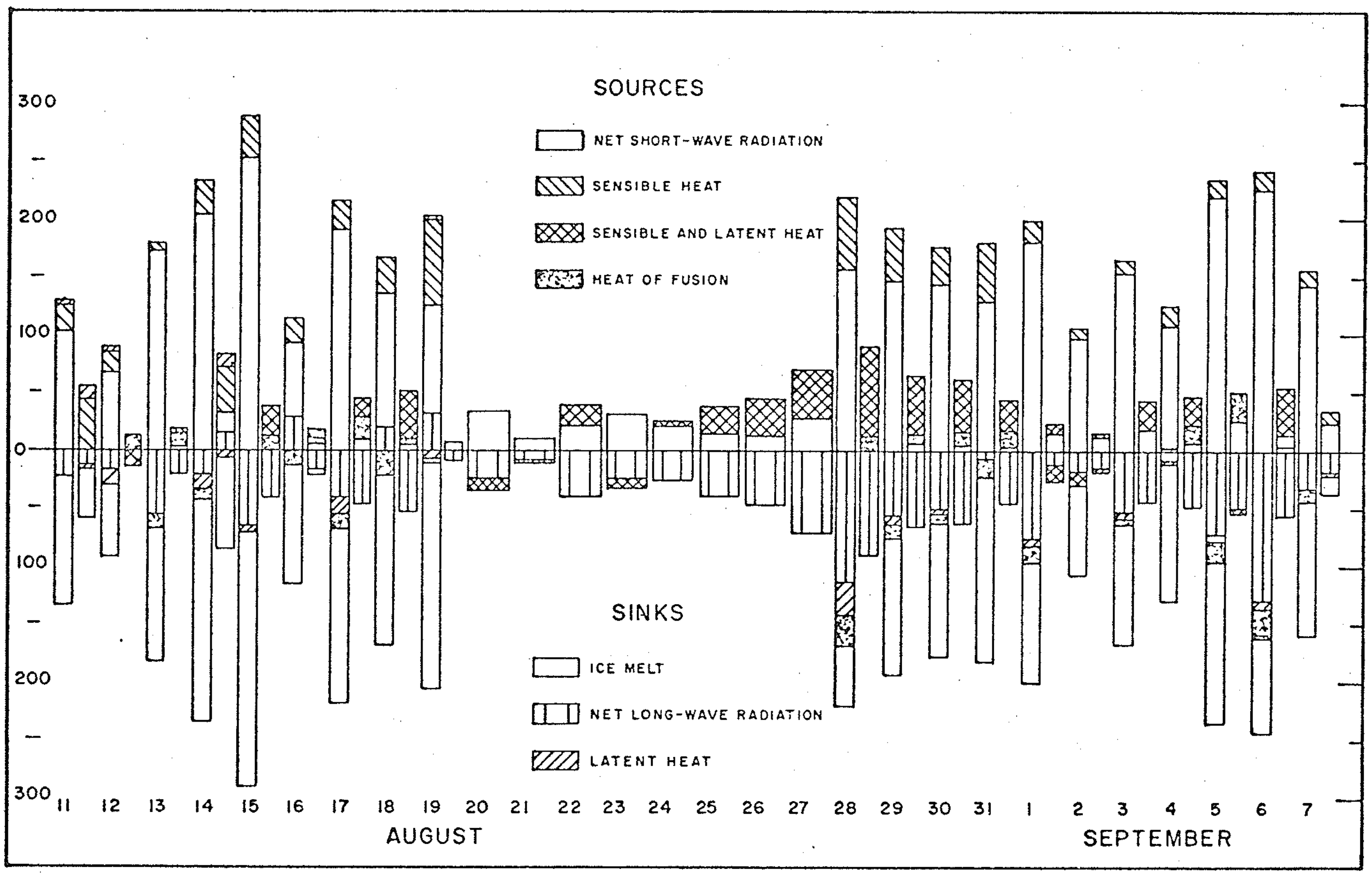


FIGURE 9 – HEAT BALANCE AT SNOW SURFACE · KESSELWANDFERNER 3240 m · AUG.—SEPT. 1958

TIME INTERVALS FOR TWO ABLATION PERIODS USUALLY 08-18 HRS. AND 18-08 HRS. FOR ACCUMULATION PERIOD 09-09 HRS.

TABLE 2

SNOWMELT AT WILSON CREEK*

IN./12 HR.

DAY	TIME	MELT
9	19-06	-0.13
	07-18	1.66
10	19-06	-0.35
	07-18	1.80
11	19-06	-0.28
	07-18	1.84
12	19-06	-0.15
TOTAL		4.41

* Obtained Using Equations 9 & 10 with $Q_e = (0.000 + 0.184 \cdot V_{10}) \cdot (E_a - E_s)$ Cal./(CM.^{2} · 12HR.)

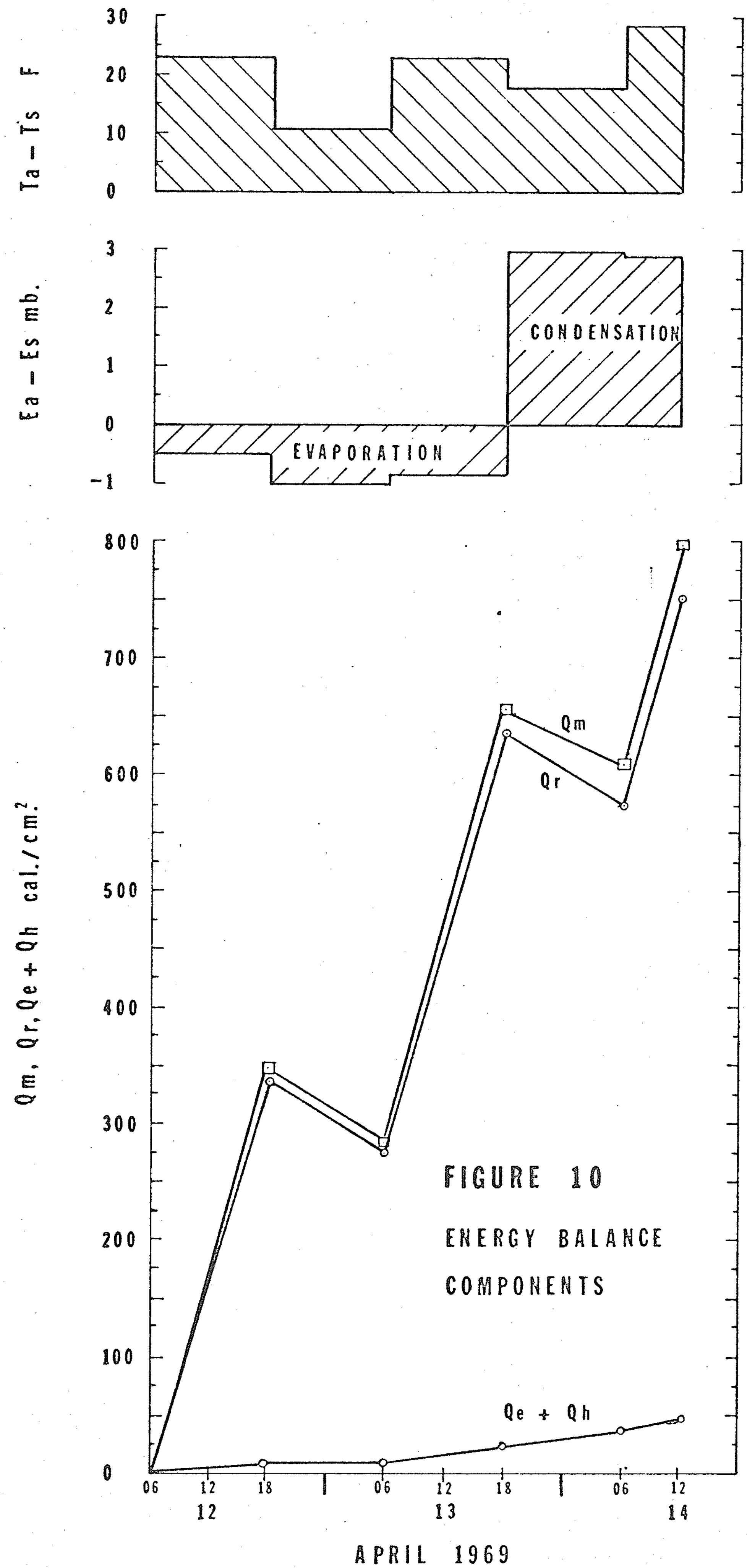


FIGURE 10

ENERGY BALANCE COMPONENTS

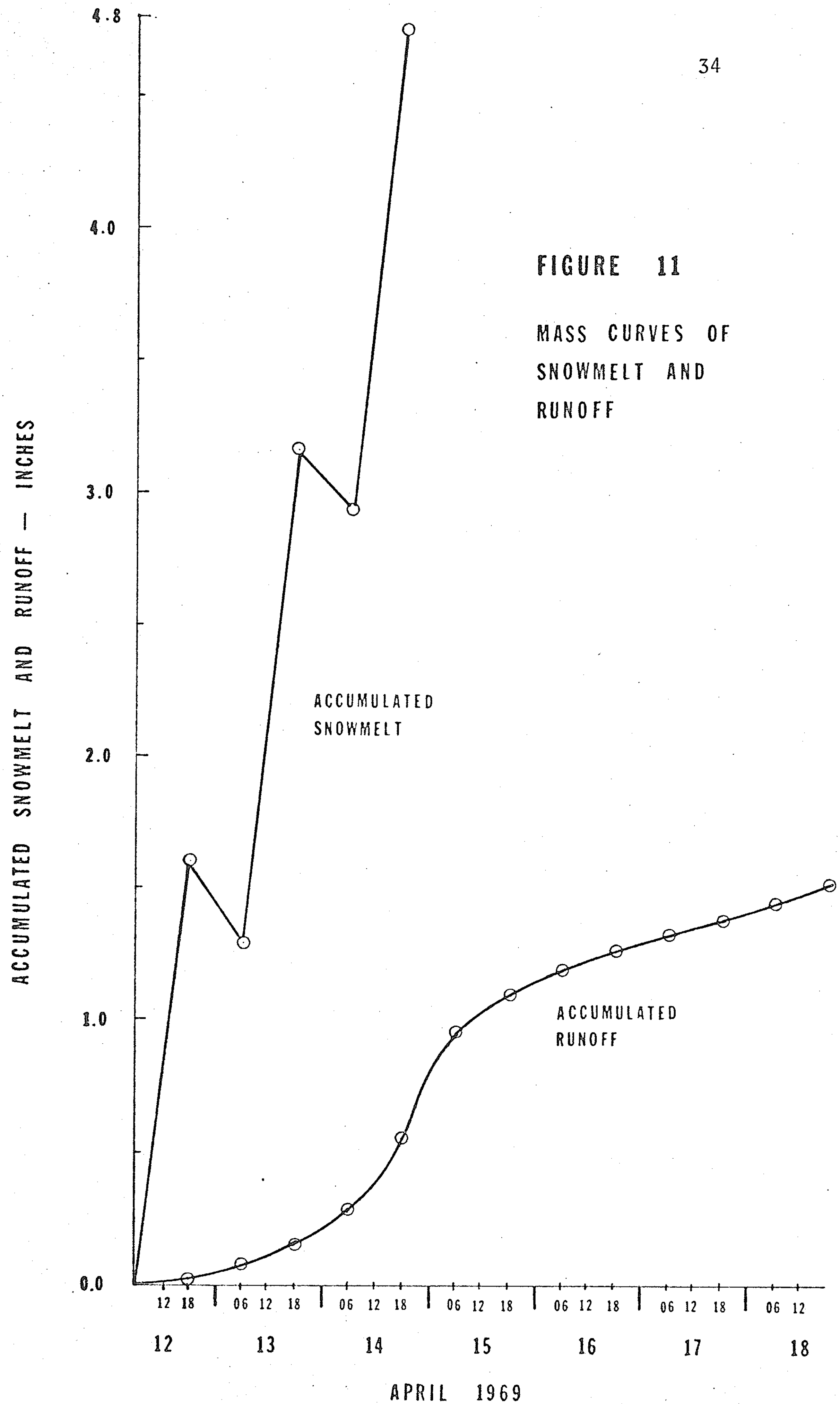


FIGURE 11

MASS CURVES OF SNOWMELT AND RUNOFF

TABLE 3

COMPARISON OF METEOROLOGICAL CONDITIONS DURING MELTING PERIOD OTTAWA 1959 VS WILSON CREEK 1969

METEOROLOGICAL PARAMETER		OTTAWA 1959	WILSON CREEK 1969
T_a	Air Temp.	33.5 °F	52.2 °F
$T_a - T_s$		1.5 °F	20.2 °F
$E_a - E_s$	Vapour Pressure Deficit	-1.48mb. (evaporation)	+0.59mb. (condensation)
V_{2m}	Wind Speed	6.31m.p.h.	5.06m.p.h.
$V \cdot (E_a - E_s)$		-1498 $\frac{\text{mb.-miles}}{\text{Day}}$	89.4 $\frac{\text{mb.-miles}}{\text{Day}}$
$V \cdot (T_a - T_s)$		151 $\frac{\text{°F-miles}}{\text{Day}}$	2380 $\frac{\text{°F-miles}}{\text{Day}}$
Q_r	Net Radiation	165 $\frac{\text{Cal.}}{\text{cm.}^2\text{-Day}}$	334 $\frac{\text{Cal.}}{\text{cm.}^2\text{-Day}}$
Q_m	Snowmelt	57.1 $\frac{\text{Cal.}}{\text{cm.}^2\text{-Day}}$	343 $\frac{\text{Cal.}}{\text{cm.}^2\text{-Day}}$
Q_e	Evaporative Heat Transfer	- 164 $\frac{\text{Cal.}}{\text{cm.}^2\text{-Day}}$	2.0 $\frac{\text{Cal.}}{\text{cm.}^2\text{-Day}}$
Q_h	Sensible Heat Transfer	56.1 $\frac{\text{Cal.}}{\text{cm.}^2\text{-Day}}$	18.7 $\frac{\text{Cal.}}{\text{cm.}^2\text{-Day}}$

CHAPTER VI

SEMI-EMPIRICAL METHODS

Three semi-empirical methods of calculating snowmelt were tested using the data from Wilson Creek. The three equations are presented below along with some observations on the test results. A detailed explanation of the terms in the equations and a fuller description of the test results is given in APPENDIX D.

A. Degree-Day Method

$$\text{Melt} = (\text{Degree-Day Factor}) \cdot (T_a - 32) \quad (14)$$

B. Multiple Linear Regression Equation (Coefficients determined in New Brunswick

$$\text{Melt} = 0.534 + 0.00407\,RL + 0.00309\,V\,(T_a - 36) + 0.0343V(RH) + 0.000772\,R_s\,(1 - A) + 0.007P_r\,(T - 32) \quad (15)$$

C. U.S.C.E. Equation

$$\text{Melt} = K^1\,(0.00508)(1 - A)R_s + 0.029\,N\,(T_c - T_s) + ((0.0212)(T_a - T_s) - 0.84)\,(1 - N) + K\,(0.00629)(Z_a\,Z_b)^{-1/6}\,((T_a - T_s)\,P/P_o + 8.59\,(E_a - E_s))\,V_b \quad (16)$$

Using the measured snowmelt and air temperatures a degree-day factor of 0.08 inches/degree-day was derived. This is well within the standard range of degree-day factors. The U.S.C.E. equation for snowmelt predicted a melt greatly in excess of that determined by the snow surveys, while the multiple regression equation proposed by Pysklywec, Davar, and Bray underestimated the melt considerably. The melt quantities associated with the various indices; such as, melt from the radiation exchange; were found in the case of the U.S.C.E. equation to be of the same order of magnitude as the corresponding parts of the energy balance equation, but this was not found to be so in the case of the regression equation.

CHAPTER VII

CONCLUSIONS

This study began with an examination of the terms in the energy budget equation that produced a simplified form of the equation suitable for use in this study:

$$Q_m^1 = Q_r + Q_h + Q_e$$
$$= Q_r + Q_e\ (R + 1)$$

It was then apparent that as Q_r was measured and as Q_h was related to Q_e it was only necessary to calculate Q_e to be able to calculate Q_m^1 and thus the amount of melt.

Using values of the evaporative heat transfer coefficients "A" and "B" found in the literature, Q_e was calculated, and the amount of melt predicted. In all cases this predicted melt was in excess of the melt determined from the snow surveys.

In order to obtain values of the transfer coefficients that were applicable under the meteorological conditions encountered at Wilson Creek an iterative approach was used. Assuming "A" to be zero (0) and knowning the total accumulated melt during a given period, various values of the transfer coefficient "B" were assumed until both sides of the energy balance equation were equal. "B" was thus found to be 0.18 calories/(cm^2 · mile · mb). That is:

$$Q_e = (0.000 + 0.18\ V_{10}) \cdot (E_a - E_s) \text{ calories/(cm}^2 \cdot 12\text{ hr)}$$

With such a small value for the transfer coefficient it is apparent that Q_e was only a minor term in the energy budget, and that at Wilson Creek the energy for snowmelt was supplied almost entirely by net radiation transfer.

Even with the use of the derived transfer coefficient it was impossible for the energy balance to distinguish between periods of runoff - producing melt and those in which the melt contributed only to the ripening of the snow pack. This was also found to be true of the three semi-empirical approaches tested; the degree-day, the U.S.C.E. snowmelt equation, and a multiple regression equation.

The predicted melts from the U.S.C.E. equation and from the regression equation considerably over- and underestimated, respectively, the melt determined from the snow surveys. However, by working the degree-day method backwards a degree-day factor of 0.08 inches/degree-day was obtained; which is well within the standard range.

From comparisons with the results of research on evaporative heat transfer coefficients over a snow surface by Gold and Williams and by Barry it is clear that the discrepancies encountered cannot be explained without some intensive research. One direction for this research would be to examine the transfer of heat, mass, and momentum in the laminar sublayer and its relationship to drag coefficients as suggested by Barry (1967).

Until this research is done the energy budget approach to snowmelt cannot be used with confidence except in conjunction with regional index basins at which the evaporative transfer coefficients may be checked and melt starting dates determined.

This study has shown that an evaporative heat transfer coefficient of 0.18 calories/($cm^2 \cdot$ mile $\cdot$ mb) is suitable for use in Western Manitoba under warm temperatures late in the melting season.

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APPENDIX A

SAMPLE ENERGY BALANCE COMPUTATIONS

For the Period April 13, 1969 07:00-18:00

Given: Q_r = 360.4 calories/cm^2/12 hr.

V_{10} = 8.33 m.p.h.

$E_a - E_s$ = -0.88 mb.

$T_a - T_s$ = 22.8°F

From Equation 14:

$$Q_e = 0.184 \cdot V \cdot (E_a - E_s) \text{ cal./cm}^2\text{/12 hr.}$$

$$= (0.184)(8.33)(-0.88)$$

$$Q_e = -1.34 \text{ cal./cm}^2\text{/12 hr.}$$

From Equation 6:

$$Q_h = R \cdot Q_e$$

From Equation 12:

$$R = 0.342 \cdot (T_a - T_s)/(E_a - E_s)$$

$$= 0.342 \cdot (22.8)/(-0.88)$$

$$R = -8.861$$

Therefore:

$$Q_h = -8.861\ (-1.34)$$

$$Q_h = 12.0 \text{ cal./cm}^2\text{/12 hr.}$$

From Equation 11:

$$Q_m^1 = Q_r + Q_e + Q_h$$

$$= 360.4 - 1.3 + 12.0$$

$$Q_m^1 = 371.1 \text{ cal./cm}^2\text{/12 hr.}$$

From Equation 12a:

$$\text{Melt} = Q_m^1/202.4 \ (0.98) \text{ inches}$$

$$= 371.1/202.4 \ (0.98)$$

$$\text{Melt} = 1.87 \text{ inches}$$

∴ For the daytime period 07:00-18:00 on April 13, 1969 the snowmelt equaled 1.87 inches.

APPENDIX B

TABLE OF REPRESENTATIVE EQUATIONS

REPRESENTATIVE EVAPORATION EQUATIONS		EQUATIONS REPRESENTED	
NO.	INVESTIGATOR	NO.	INVESTIGATOR
1	"FERGUSON"	3 4 5 6 8 9	WMO (a) WMO (b) ROHWER PENMAN 1956 LAKE HEFNER LAKE MEAD
2	GOLD & WILLIAMS		
10	MEYER		
11	U.S.C.E.	7 13 14	GANGOPADHYAYA LAMOREUX MORTON
12	BARRY		

APPENDIX C

TABLE SHOWING SOURCES FROM WHICH INFORMATION FOR TABLE 1 WAS OBTAINED

NO.	INVESTIGATOR	SOURCE
1	"FERGUSON"	"A Preliminary Estimate of the Ice-Season Energy Balance for the Niagara River." Bulletin of the Internation Assoc. of Scientific Hydrology (I.A.S.H.), III (Sept. 1968), p. 49.
2	Gold & Williams	"Energy Balance During the Snow Melt Period at an Ottawa Site." I.A.S.H. Pub. No. 54, pp. 289-294. (Reprinted by NRC as NRC 6283).
3	WMO (a)	Ferguson's paper - p. 47
4	WMO (b)	Ferguson's paper - p. 47
5	Rohwer	Ferguson's paper - p. 47
6	Penman 1956	"Estimating Evaporation." Trans. Amer. Geoph. U., 37 (Feb. 1956), pp. 43-50.
7	Gangopadhyaya	"Evaporation - Its Measurement and Estimation." I.A.S.H. Pub. No. 68, II, p. 520.
8	Lake Hefner	Water-Loss Investigations: Lake Hefner Studies, Technical Report - Geol. Survey Prof. Paper 269. Washington, D.C., 1954 p. 65.
9	Lake Mead	Water-Loss Investigations: Lake Mead Studies - Geol. Survey Prof. Paper 298, Washington, D.C., 1958, p. 34.
10	Meyer	"Computing Run-off from Rainfall and Other Physical Data." Trans. ASCE, 79 (1929), pp. 1056-1224.

NO.	INVESTIGATOR	SOURCE
11	U.S.C.E.	"Snow Hydrology". Summary Report Snow Invest. North Pacific Div., Corps of Eng., Portland, Oregon, 1956.
12	Barry	"The Use of Radioactive Tracer Gases to Study the Rate of Exchange of Water Vapour Between Air and Natural Surfaces". Isotope Techniques in the Hydrologic Cycle - Amer. Geoph. U. - National Res. Council - Geoph. Monograph Series, No. 11 (1967), pp 69-76.
13	Lamoreux	"Modern Evaporation Formulae Adapted to Computer Use." Monthly Weather Review, Jan. 1962, pp 26-28.
14	Morton	"Potential Evaporation and River Basin Evaporation". J. Hydraul. Div. ASCE, 91, HYC (Nov. 1965), pp 69 & 74.

APPENDIX D

SEMI-EMPIRICAL METHODS FOR ESTIMATING SNOWMELT

Degree-Day Method

The simplest and oldest method of calculating snowmelt is the degree-day method in which air temperature is used as an index for all the factors affecting snowmelt. Snowmelt is very simply calculated from:

$$\text{Melt} = DDF\ (T_a - T_b) \quad \text{-----------------------------} \quad (17)$$

where:

T_a = Average daily air temperature (^oF)

T_b = Base Temperature (assumed here to be 32^oF)

DD = $(T_a - T_b)$ = Degree Days

DDF = Degree-Day Factor (inches/DD)

Melt in inches/day.

If temperature averages are for 12 hours, one works with degree half-days. From the computations shown in TABLE 4 a degree half-day factor of 0.038 (or a degree day factor of 0.076) was obtained. Using this value the melt in each period was calculated as shown in TABLE 5. Linsly, Kohler, and Paulhus (1949, p. 429) give the usual range of dry-bulb degree-day factors as 0.05 to 0.15 in/degree-day. Clark (1955) found the values of the degree-day factor for the Red River basin to range from 0.02 to 0.06 in/degree-day.

Multiple Linear Regression Equation
(New Brunswick Coefficients)

Pysklywec, Davar, and Bray (1968) have presented a multiple linear regression equation using the basic meteorological indices presented in CHAPTER 6 of "Snow Hydrology" but with the regression coefficients derived from a local index plot. Their equation is:

$$\text{Melt} = 0.534 + 0.00407\, R_L + 0.00309\, V\, (T_a - 36) + 0.0343\, V\, (RH) + 0.000772\, R_S\, (1 - A) + 0.007\, P_r\, (T_a - 32) \quad \text{------------ (18)}$$

where:

Melt is in inches/day

A = albedo (decimal fraction)

P_r = rainfall (in/day) = 0.0

R_L = net longwave radiation (langleys/day)

R_S = incident shortwave radiation (langleys/day)

RH = relative humidity at 4.5 foot level (decimal fraction)

T_a = mean daily air temperature at 4.5 foot level (^oF)

V = wind velocity at 33 foot level (miles per hour).

R_S (1 - A) may be replaced by (Q_r - R_L) where Q_r is the net all-wave radiation. Estimates of R_L were obtained using the formula presented in "Snow Hydrology" (1956, p. 160):

$$R_L = 1440\,(0.757\,\sigma\, T^4 - 0.459)\,(1 - KN) \quad \text{------ (19)}$$

where:

R_L = net longwave radiation (langleys/day)

σ = Stefan-Boltzmann constant

= 8.26×10^{-11} langleys/min/(deg K)^4

N = Portion of sky covered by clouds (decimal fraction)

K = cloud quality function based on cloud height and type.

In this study estimates of (1 - KN) were taken as the value of the ratio of observed shortwave radiation(QSOL) to maximum possible (or cloudless day) insolation (QCS). The cloudless day insolation was obtained by Mateer (1955). Thus equation (19) may be written:

$$R_L = 1440\ (0.757\ \ T^4 - 0.459)\ (QSOL/QCS) \text{ ------- } (20)$$

The results of using this regression equation to obtain the daily melt quantities is shown in TABLE 6. The computations were done on a daily basis as that is the way the regression coefficients had been derived, and it was thought it would make for a fairer comparison. The melt quantities obtained using the "derived" evaporative transfer coefficient are also shown for comparison. They were put on a daily basis by combining the daytime melt with one-half the melt of the preceding nighttime period and one-half that of the following nighttime period.

The total amount of melt computed by this method is considerably below the melt determined from the snow surveys. The most interesting point about the use of this regression equation is that the magnitude of the melt quantities associated with various indicies bears no relation to the magnitude of the actual quantity, as illustrated in TABLE 7.

U.S.C.E. Equation

The U. S. Army Corps of Engineers have presented an equation for snowmelt during rain-free periods in an open area which takes into account all the components of the energy balance: the absorbed shortwave radiation, the net longwave radiation from clouds, from the atmosphere and snow surface; the sensible heat transfer; and the latent heat transfer from evaporation and condensation. Combining the equations on pages 176 and 253 of "Snow Hydrology" we obtain:

$$\begin{aligned} \text{Melt} = {} & K^1 (0.00508)(1 - A) R_S + 0.029\, N (T_c - T_s) \\ & + ((0.0212)(T_a - T_s) - 0.84)(1 - N) \\ & + K (0.00629)(Z_a Z_b)^{-1/6} ((T_a - T_s) P/P_o \\ & + 8.59 (E_a - E_s)) V_b \quad \text{------------------} \quad (21) \end{aligned}$$

where;

Melt is in inches/day

A = albedo (decimal fraction)

R_S = incident shortwave radiation (langleys/day)

N = estimated cloud cover (decimal fraction)

T_c = cloud base temperature (^oF)

T_s = temperature of snow surface (^oF)

Z_a = height of air temperature measurement (feet)

Z_b = height of wind velocity measurement (feet)

P = air pressure at station elevation (mb)

P_o = air pressure at sea level (mb)

E_a = air vapour pressure (mb)

E_s = saturation vapour pressure at the temperature of the snow surface (mb)

K^1 = "factor to correct R_s for average slope angle and orientation of snow area" (Johnson & Boyer (1959))

K = "An average corrective factor for the degree of exposure of the snow area to wind" (Johnson & Boyer (1959)).

For Wilson Creek

Z_a = 4.5 ft.

Z_b = 32.81 ft. (10m.)

P/P_o = 0.9

K^1 = 1.0

K = 0.8

R_s (1 - A) was replaced by (Q_r - R_L) with estimates of R_L obtained as for the multiple regression method.

The cloud base temperature was obtained using a lapse rate of 3.0°F per 1000 ft as suggested on p. 247 of "Snow Hydrology". The cloud base during the active melting period was believed to be roughly at 5000 ft and this figure was assumed to be constant throughout the period.

The value of N the estimated cloud cover was obtained as follows:

During the discussion of equation (20) it was suggested that:

$(1 - KN) = QSOL/QCS$

From equation 5-14 p. 160 of "Snow Hydrology"

$K = 1-0.024 Z$

where:

Z = cloud base height in thousands of feet

Therefore:

N = (1 - QSOL/QCS) / (1-0.024 (5000)).

The results of using the U.SC.E. equation for snowmelt are shown in TABLE 6; where it is seen that this method considerably overestimated the actual melt. As might be expected from the form of the equation, the melt quantitites due to the various component parts (radiation, sensible heat etc.) of this equation are of the same order of magnitude as for the energy budget. TABLE 7 illustrates this point.

Summary

A degree-day factor of 0.08 inches/degree-day was derived from the measured snowmelt which is well within the standard range of degree-day factors. The U.S.C.E. equation for snowmelt was found to predict a melt greatly in excess of that determined by the snow surveys, while the multiple regression equation proposed by Pysklywec, Davar, and Bray underestimated the melt considerably. The melt quantities associated with the various indicies; such as, melt from radiation exchange; were found in the case of the U.S.C.E. equation to be of the same order of magnitude as the corresponding parts of the energy balance equation, but this was not found to be so in the case of the regression equation.

TABLE 4

CALCULATION OF DEGREE HALF-DAY FACTOR

DATE	TIME	Ta - 32 (Degree Half-Day)
April		
12	07-18	23.0
13	19-06	10.8
	07-18	22.8
14	19-06	17.8
	07-18	28.6
Total Degree Half-Days		103.0

$$\text{Degree Half-Day Factor} = \frac{\text{Total Melt}}{\text{Total Degree Half-Days}}$$

$$= \frac{3.89 \text{ in.}}{103}$$

Degree Half-Day Factor = 0.038 in./Degree Half-Day

TABLE 5

COMPARISON OF SNOWMELT COMPUTED

BY TWO METHODS:

DEGREE-DAY* AND ENERGY BALANCE

DAY	TIME	MELT - INCHES DEGREE-DAY	MELT - INCHES ENERGY BALANCE
12	07-18	0.87	1.60
13	19-06	0.41	-0.31
	07-18	0.87	1.87
14	19-06	0.68	-0.23
	07-12	1.09	0.96
TOTAL		3.92	3.89

* Degree Half-Day Factor = 0.038 in./½ Deg.-Day

TABLE 6

COMPARISON OF SNOWMELT COMPUTED BY THREE METHODS: A REGRESSION EQUATION, U.S.C.E. EQUATION, AND AN ENERGY BALANCE

DAY	TIME	SNOWMELT - INCHES		
		REGRESSION[a]	U.S.C.E.[b]	ENERGY BALANCE[c]
12	01-24	0.84	1.64	1.51
13	01-24	1.00	1.77	1.60
14	01-24	1.40	2.00	1.66
TOTAL		3.24	5.41	4.77

[a] MULTIPLE LINEAR REGRESSION EQUATION - NO. 15

[b] UNITED STATES CORPS OF ENGINEERS SNOWMELT EQUATION - NO. 16

[c] ENERGY BALANCE EQUATIONS - NO:s 9 & 10

TABLE 7

PORTION OF SNOWMELT ON APRIL 13, 1969 ATTRIBUTED TO VARIOUS COMPONENTS OF THE ENERGY BALANCE BY THREE DIFFERENT METHODS:

ENERGY BALANCE COMPONENTS	SNOWMELT - INCHES		
	REGRESSION EQUATION	U.S.C.E. EQUATION	ENERGY BALANCE
SHORT-WAVE RADIATION	0.28	1.87	2.73
LONG-WAVE RADIATION	-0.29	-0.38	-1.23
NET RADIATION	-0.01	1.49	1.50
EVAPORATIVE HEAT TRANSFER	0.13	0.00	0.02
SENSIBLE HEAT TRANSFER	0.35	0.28	0.05
REGRESSION CONSTANT	0.53	----	----
TOTAL	1.00	1.77	1.57

APPENDIX E

METEOROLOGICAL DATA

WILSON CREEK WATERSHED
1969

DATE	TIME	CARD NO.	EAES MB.	TATS F	BOWEN RATIO	VTEN MPH	QNET	QSOL	QCS	RH
MARCH										
26	19-06	51	-0.46	0.0	0.0	999.99	999.9	999.9	999.9	0.858
	07-18	52	-1.12	0.0	0.0	999.99	999.9	999.9	999.9	0.743
27	19-06	53	-0.83	0.0	0.0	5.00	999.9	999.9	999.9	0.802
	07-18	54	-0.47	0.0	0.0	11.91	999.9	999.9	999.9	0.708
28	19-06	55	-0.34	0.0	0.0	13.33	999.9	999.9	999.9	0.548
	07-18	56	-0.66	0.0	0.0	11.67	999.9	999.9	999.9	0.321
29	19-06	57	-0.34	0.0	0.0	6.08	999.9	999.9	999.9	0.567
	07-18	58	-0.92	0.0	0.0	6.83	999.9	999.9	999.9	0.318
30	19-06	59	-0.65	0.0	0.0	7.33	999.9	999.9	999.9	0.488
	07-18	60	-1.29	0.0	0.0	7.50	999.9	999.9	999.9	0.260
31	19-06	61	-0.67	0.0	0.0	11.08	999.9	999.9	999.9	0.611
	07-18	62	-0.75	0.0	0.0	8.83	999.9	999.9	999.9	0.762
APRIL										
1	19-06	63	-0.41	0.0	0.0	7.17	999.9	999.9	999.9	0.861
	07-18	64	-0.72	0.0	0.0	7.67	999.9	999.9	999.9	0.754
2	19-06	65	-0.75	0.0	0.0	6.25	999.9	999.9	999.9	0.642
	07-18	66	-1.37	0.0	0.0	13.00	999.9	999.9	999.9	0.704
3	19-06	67	-0.56	0.0	0.0	6.75	-27.6	999.9	999.9	0.862
	07-18	68	-0.63	0.0	0.0	9.08	66.6	999.9	999.9	0.852
4	19-06	69	-0.69	0.0	0.0	6.25	-3.6	999.9	999.9	0.861
	07-18	70	-2.62	3.6	-0.470	8.83	165.2	999.9	999.9	0.495
5	19-06	71	-1.21	0.0	0.0	4.25	-64.8	999.9	999.9	0.764
	07-18	72	-3.39	6.4	-0.646	13.75	210.6	999.9	999.9	0.345
6	19-06	73	-2.24	4.4	-0.672	14.67	-58.2	999.9	999.9	0.531
	07-18	74	-0.74	16.1	-7.441	7.08	222.2	999.9	999.9	0.470
7	19-06	75	-0.46	1.3	-0.966	10.50	-26.3	999.9	999.9	0.878
	07-18	76	-0.87	7.6	-2.988	12.83	244.3	999.9	999.9	0.634
8	19-06	77	-1.65	4.6	-0.953	10.75	-53.3	999.9	999.9	0.608
	07-18	78	-1.14	8.8	-2.640	5.00	194.2	341.6	568.0	0.574
9	19-06	79	-0.77	7.4	-3.287	7.08	-27.8	0.0	0.0	0.652
	07-18	80	-1.84	8.1	-1.506	10.25	327.3	546.4	573.0	0.507
10	19-06	81	-1.14	0.0	0.0	5.08	-68.8	0.0	0.0	0.802
	07-18	82	-1.47	10.5	-2.443	5.08	355.6	534.6	578.0	0.502
11	19-06	83	-0.52	4.0	-2.631	6.17	-57.0	0.0	0.0	0.780
	07-18	84	-0.72	17.1	-8.122	7.83	357.9	510.4	583.0	0.454
12	19-06	85	1.74	10.5	2.064	7.50	-37.0	0.0	0.0	0.850
	07-18	86	-0.50	23.0	-15.732	5.50	338.4	506.4	588.0	0.380
13	19-06	87	-1.02	10.8	-3.621	4.75	-64.1	0.0	0.0	0.545
	07-18	88	-0.88	22.8	-8.861	8.33	360.4	541.3	594.0	0.357
14	19-06	89	2.93	17.8	2.078	9.33	-62.7	0.0	0.0	0.742
	07-18	90	2.88	28.6	3.396	11.25	335.0	515.1	598.0	0.498
15	19-06	91	3.18	16.7	1.796	8.25	-31.1	0.0	0.0	0.795
	07-18	92	0.55	11.8	7.337	6.25	101.5	160.4	604.0	0.686
16	19-06	93	-1.46	3.1	-0.726	8.25	-75.4	999.9	999.9	0.672
	07-18	94	-2.61	9.9	-1.297	8.67	330.4	999.9	999.9	0.387
17	19-06	95	-2.01	0.9	-0.153	5.67	-62.7	999.9	999.9	0.647
	07-18	96	-1.17	16.8	-4.911	11.42	230.4	999.9	999.9	0.421
18	19-06	97	-0.94	14.4	-5.239	14.92	-28.8	999.9	999.9	0.482
	07-18	98	-0.41	22.1	-18.435	16.42	233.9	999.9	999.9	0.399
19	19-06	99	-0.01	15.0	-513.000	11.17	-64.1	999.9	999.9	0.556
	07-18	100	0.17	22.8	45.868	15.67	215.2	999.9	999.9	0.429
20	19-06	101	0.28	14.6	17.833	10.58	-62.0	999.9	999.9	0.592
	07-18	102	-1.01	19.6	-6.637	15.67	280.7	999.9	999.9	0.392
21	19-06	103	-2.47	9.5	-1.315	10.00	-91.8	999.9	999.9	0.409
	07-18	104	-1.37	18.8	-4.693	12.92	297.8	999.9	999.9	0.375
22	19-06	105	-0.78	3.7	-1.622	5.25	-66.2	999.9	999.9	0.752
	07-18	106	-0.98	18.8	-6.561	6.92	312.9	999.9	999.9	0.406
23	19-06	107	0.17	9.8	19.715	9.67	-69.6	999.9	999.9	0.698
	07-18	108	0.60	22.8	12.996	11.08	335.1	999.9	999.9	0.458
24	19-06	109	-0.09	15.0	-57.000	11.25	-77.0	999.9	999.9	0.549
	07-18	110	0.08	25.9	110.722	13.33	323.7	999.9	999.9	0.378
25	19-06	111	0.98	18.2	6.351	9.75	-43.4	999.9	999.9	0.573
	07-18	112	0.20	22.2	37.962	13.42	137.6	999.9	999.9	0.440
26	19-06	113	0.0	7.3	999.999	16.08	-20.2	999.9	999.9	0.748
	07-18	114	-1.03	0.0	0.0	18.67	38.4	999.9	999.9	0.796
27	19-06	115	-0.71	0.0	0.0	13.00	-55.2	999.9	999.9	0.840
	07-18	116	-3.09	0.0	0.0	9.75	303.4	999.9	999.9	0.468
28	19-06	117	-1.56	0.0	0.0	3.83	-72.0	999.9	999.9	0.648
	07-18	118	-3.09	8.8	-0.974	5.58	325.6	999.9	999.9	0.349
29	19-06	119	-1.84	2.5	-0.465	7.67	-71.4	999.9	999.9	0.632
	07-18	120	-1.70	17.2	-3.460	9.33	336.4	999.9	999.9	0.370
30	19-06	121	-0.45	10.2	-7.752	8.17	-51.8	999.9	999.9	0.620
	07-18	122	0.76	20.4	9.180	12.58	257.2	999.9	999.9	0.512

EAES - VAPOUR PRESSURE DEFICEIT (AIR - SURFACE)

999.9 - MISSING DATA

TATS - TEMPERATURE DIFFERENCE (AIR - SURFACE)

BOWEN RATIO = 0.342 * TATS / EAES

VTEN - WIND SPEED AT 10 METERS

QNET - NET RADIATION (LANGLEYS / 12 HR.)

QSOL - OBSERVED SHORTWAVE RADIATION (LANGLEYS / 12 HR.)

QCS - MAXIMUM POSSIBLE INSOLATION (MATEER,1955)

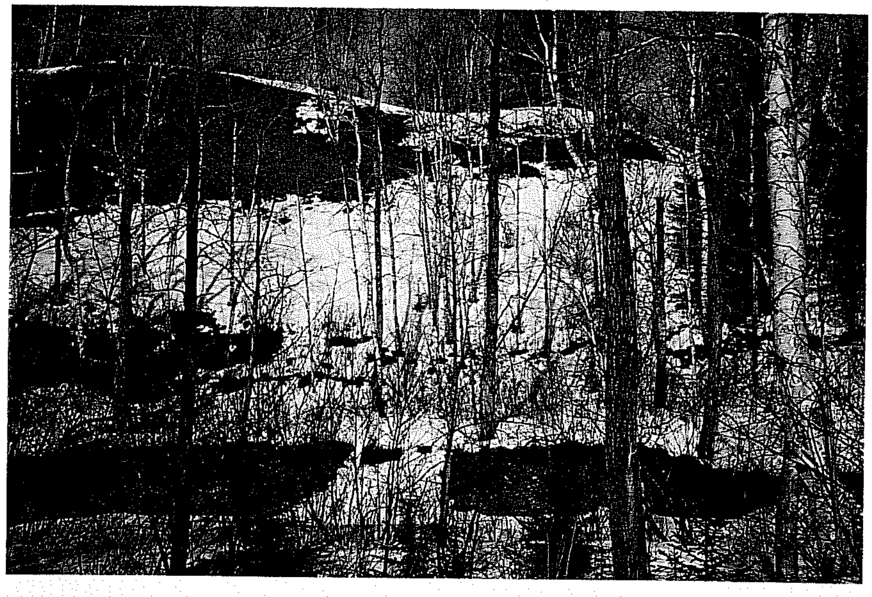
RH - RELATIVE HUMIDITY

APPENDIX F

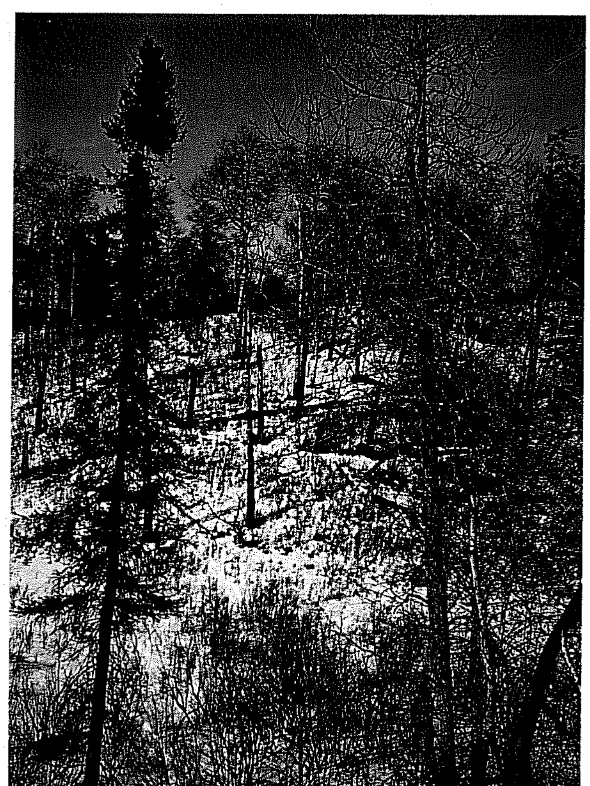
MISCELLANEOUS PHOTOGRAPHS

PHOTOGRAPH NO. 1 - ON JET TRAIL AT EL. 1520 LOOKING EAST ACROSS PRAIRIE - EL. 1200 AND SHOWING A MT. ROSE SNOW SAMPLER. APRIL 4, 1969

PHOTOGRAPH NO. 2 - FROM ANIMAL EXCLOSURE NO. 3. LOOKING ACROSS A LOWER REACH OF THE VALLEY OF BALD HILL CREEK. APRIL 4, 1969



PHOTOGRAPH NO. 3 - SOUTH-FACING SHALE BANK ALONG BALD HILL CREEK. APRIL 4, 1969



PHOTOGRAPH NO. 4

SOUTH-FACTING VALLEY SIDE ON THE UPPER REACHES OF PACKHORSE CREEK.

SNOW CONDITIONS:

DEPTH - 16.9 IN.
DENSITY - 0.32
APRIL 5, 1969

PHOTOGRAPH NO. 5 - EXTENT OF SNOW COVER AT PRAIRIE LEVEL: AVERAGE DEPTH = 8.5 IN., AVERAGE DENSITY = 0.30 - APRIL 5, 1969

PHOTOGRAPH NO. 6

NORTH-FACING VALLEY SIDE ON THE UPPER REACHES OF PACKHORSE CREEK.

SNOW CONDITIONS:

DEPTH - 25.6 IN.
DENSITY - 0.21
APRIL 5, 1969

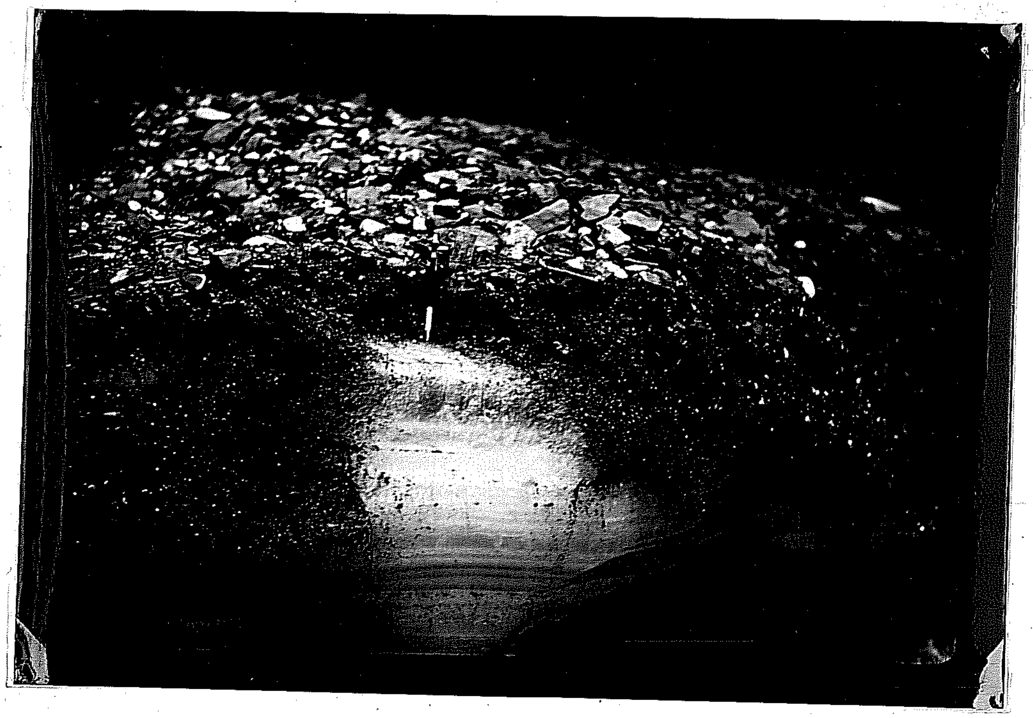
PHOTOGRAPH NO. 7 - BALD HILL RESERVOIR ON APRIL 30, 1970. WATER LEVEL IS 8.2 FT. OVER AN UNCONTROLLED CULVERT.

PHOTOGRAPH NO. 8

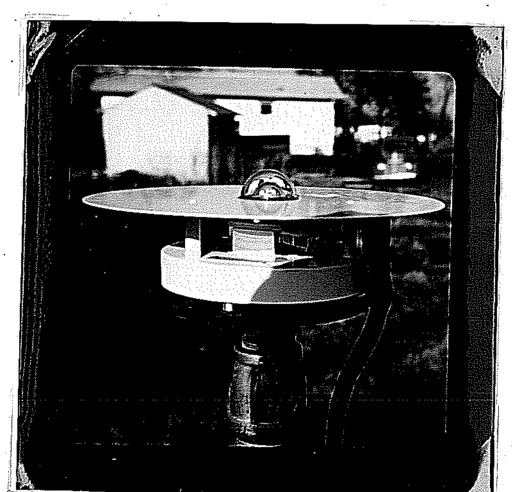
BALD HILL CREEK
AT JET TRAIL CROSSING

DISCHARGE = 12 CFS

MAY 1, 1969



PHOTOGRAPH NO. 9 - IN MANY PLACES THE SNOWMELT RUNOFF FLOWED OVER THE WINTER ICE COVER, THIS SHALE DEPOSIT WAS FOUND IN LOWER REACHES OF PACKHORSE CREEK ON MAY 1, 1969



PHOTOGRAPH NO. 10
NET PYRRADIOMETER
CSIRO

PHOTOGRAPH NO. 11
PYRANOMETER
KIPP & ZONEN