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THE THERMAL CHARACTERISTICS AND RELATED  
HYDROLOGY OF A PENNINE STREAM

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(St. John's College)

Thesis presented for the degree Doctor of Philosophy



### Abstract

An experimental catchment of  $1 \text{ km}^2$  was established at Lanehead in Upper Weardale to study the effects of atmospheric conditions upon stream water temperature. Discharge from the catchment was measured by a prefabricated wooden flat vee weir which was installed during the summer of 1968. Precipitation was measured at two sites in the catchment; standard and ground level totaliser gauges, together with a Dines recorder gauge were installed at each site. Air, stream and ground water temperatures were recorded with thermographs at various sites within the catchment.

Because the volume of discharge would have a modifying effect upon the relationship between the stream water temperature and the atmospheric conditions the rainfall/runoff relations in the catchment were studied. During the summer period this relationship varied according to the antecedent soil moisture condition. In the winter, when the precipitation was in the form of snow the release of discharge was controlled by other factors such as air temperature, humidity and solar radiation. The release of snow melt as discharge had a dominating effect upon the temperature of the stream water.

The thermal characteristics of the stream water were found to vary in a three dimensional sense of time and space. The water temperature at any point in the stream varied within the context of the diurnal air temperature cycle, the magnitude of this fluctuation differed with distance from the stream source, and finally the scale of both of these varied with the differing overall atmospheric environment which occurred from season to season. The stream channel exerted a strong influence upon the water temperature by virtue of the fact that it modified the influence of factors such as air temperature and solar radiation.

## ACKNOWLEDGEMENTS

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First and foremost, I would like to acknowledge with gratitude the assistance and encouragement given by my supervisor Dr. K. Smith, without whom this research project would hardly have been started let alone completed.

Secondly, I would like to thank Professor W. B. Fisher, my Professor and Principal, for the concern and interest he has shown in my studies at all stages.

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## INTRODUCTION

This thesis attempts to investigate the relationship between stream water temperature and surrounding air temperature and the extent to which this relationship is influenced by other hydrological factors such as the thermal capacity of the stream, volumes of discharge and snowmelt. To do this an experimental catchment of about 1 km<sup>2</sup> was established between 470-610m OD at Lanehead in County Durham. The period January - September 1968 was spent selecting and installing a stream gauging structure, precipitation recorders and air and water temperature recorders that would operate satisfactorily in an upland region. The results presented are based upon data collected during the two water years 1968/69 and 1969/70.

Little has been published about the controls over stream water temperature despite its importance as an aspect of water quality with important implications upon the distribution of aquatic life, the effectiveness of pollutants in the stream water and consequently upon any meaningful analysis of the minimum acceptable flow. The range of water temperature variation has a direct affect upon the distribution of aquatic life, but its main effects are indirect since the demand by fish for example, for oxygen increases with the temperature of the water. The critical factor is not the amount but the percentage of dissolved oxygen, and since solubility of oxygen decreases with rise in temperature from 14 ppm at 0°C to 0ppm at 100°C, water temperature and available oxygen are closely related. (Hynes 1960). Many substances such as cyanides,



oresols and ammonia become more toxic as the oxygen content falls and thus indirectly changes in water temperature affect the toxicity of a polluted stream, and consequently considerations of water temperature must also affect the level of acceptable minimum flow for a river.

Thus it can be seen that water temperature variation is an important aspect of water quality. This project attempts to relate the variations in stream water temperature to the relatively easily and universally recorded parameter of air temperature. This relationship is modified by other hydrological factors such as the volume and the nature of the discharge.

Section I deals with the instrumentation of the catchment for precipitation, air and water temperature and discharge. In order to select a minimum number of sites for the recording of precipitation a pilot scheme of eight gauges was established in the catchment. From this study two sites were selected which would give a representative value for the catchment. Many of the problems of recording precipitation are increased because of the altitude of the catchment. With an increase in altitude the gauges become more exposed to windy conditions and the difficulties caused by freezing air become greater both because the air temperature conditions would be more extreme and also longer in duration. Protection against the wind and freezing air conditions has therefore had to be provided for the gauges. The non-recording gauges have been protected as far as possible from the wind in order to obtain an accurate measure of rainfall, but the recording gauges, the most vulnerable to freezing air conditions, were installed only

to give a record of the time of occurrence of rainfall.

Air and water temperature records presented problems of location rather than difficulties in recording. They were recorded in close proximity so that the relationship between the two could be studied, and both of these were sited near the weir so that the water temperature could be related to the changes in the volume of discharge. For part of the study period a continuous record of ground water temperature was taken but this recorder was later moved to record the temperature of the stream water at source.

In order to obtain a continuous record of stream discharge a gauging structure had to be constructed. The choice of structure was controlled partly by the steepness of the catchment and the amount of bed load material moving downstream, partly by the shallow nature of the banks and also by the difficulties of access to the site. The installation of these instruments was carried out between January and September 1968.

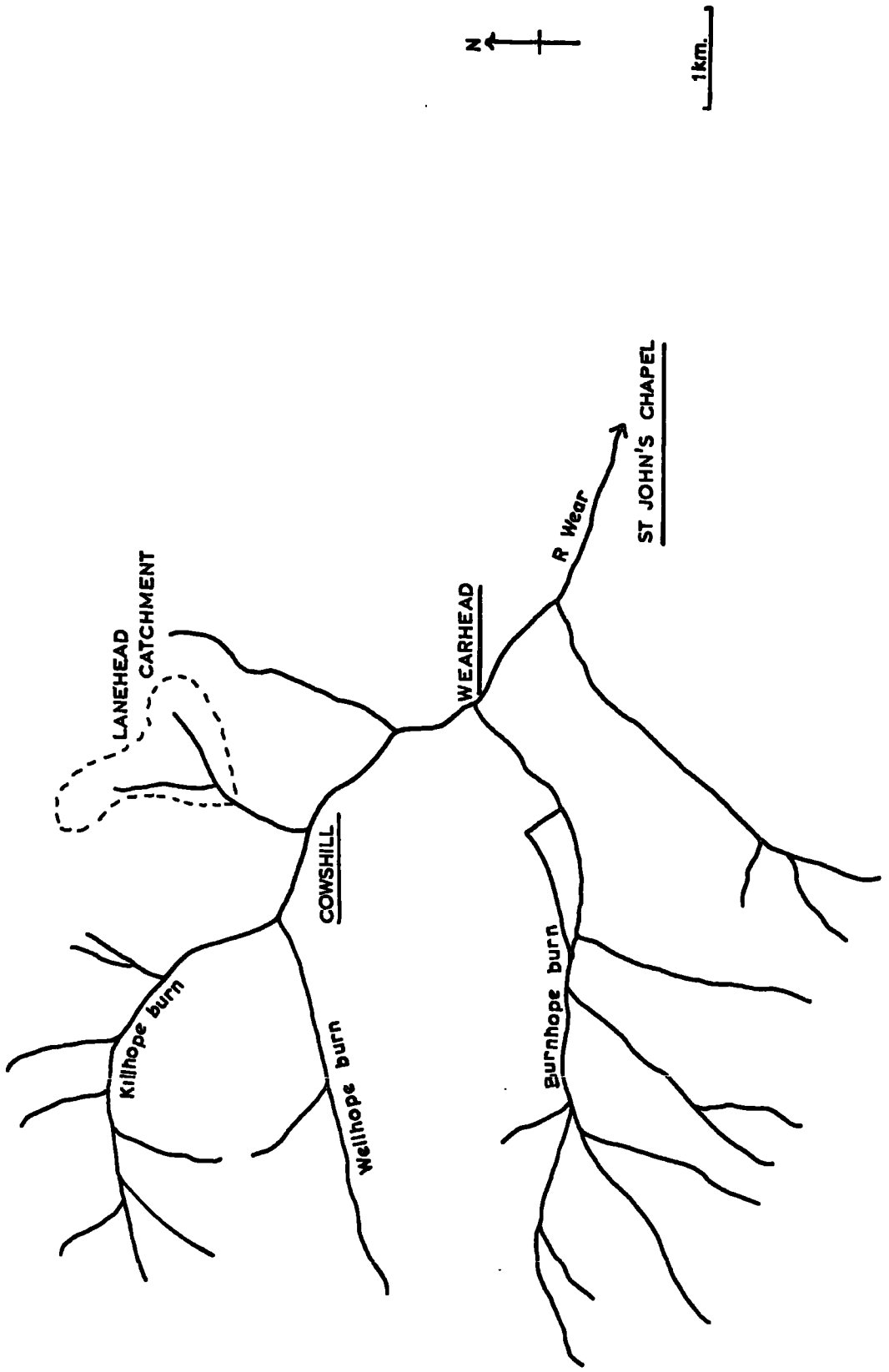
In Section II the thermal characteristics of the stream are analysed. Because the volume of discharge in the stream has a modifying effect upon the relationship between the atmospheric environment and the stream water, the nature of the runoff from the catchment has been studied. During the summer period the runoff is controlled by the nature and the occurrence of rainfall, and in Chapter 5, the relationship between rainfall and runoff is related to the conditions of the catchment soil. The specific difficulties of obtaining rainfall and runoff records in an upland catchment are discussed. The snowmelt floods have been

treated separately from the direct rainfall/runoff floods in Chapter 6 because the conditions that give rise to them are very different, and snowmelt has special implications for water temperature. Periods of snowmelt have been isolated, and these floods related to the rainfall and temperature conditions prevailing.

In Chapter 7 the thermal characteristics of the stream water are described. Since the water temperature varies with distance along the stream as well as through the day and throughout the year several avenues of study were followed. Water temperature was studied in relation to the air temperature and the volume of discharge at the weir site. This also acted as the basic reference to which the other studies could be related. Variations in water temperature along the stream course were measured by a series of temperature measuring sequences. These were taken throughout 24 hour periods on at least one occasion each month so that the results obtained would indicate changes occurring at all times of day and give a representative cover over the whole year. The effects exerted by the stream channel itself were studied. The two streams in the catchment were very different in physical channel characteristics and therefore the differing response of the water temperature in each stream to the same climatic conditions would indicate the differences exerted by the channel itself.

#### Catchment Characteristics

The Lanehead catchment is a headwater tributary of the River Wear in County Durham (Fig.1). Above the village



**FIG 1 THE LANEHEAD CATCHMENT IN UPPER WEARDALE**

of Wearhead the River Wear is formed from three main catchments, Killhope Burn, Wellhope Burn and Burnhope Burn together with many smaller catchments draining the watershed from the north and the south. The Lanehead catchment is a north tributary draining an area of approximately 1 km.<sup>2</sup> between 470m - 610m O.D. on the watershed with the River East Allen in Tynedale. This particular catchment was selected because of its accessibility for data collection. A main road runs through the catchment from which most of the instrument sites could be approached relatively easily during adverse weather conditions and the Geography Department Field Centre at the old Lanehead school 1 km. away provided accommodation for longer periods of field work in the catchment.

The catchment comprises two streams, the western tributary draining N-S (A) and the eastern tributary draining NE-SW (B). The sub-catchments of these streams differ greatly in physical terms such as relief, area, orientation and channel form, but also the sub-catchments coincide with the major vegetation division within the main catchment. For these reasons the analysis and description of the catchment has been made in terms of the two sub-catchments forming the Lanehead experimental catchment.

The vegetation of the area is "Heather moorland" (definition as used by Pearsall in 'Mountains and Moorlands'). Much of the area is dominated by blanket peat supporting calluna heath; in the east of the catchment, where the peat cover has degenerated, there is a grass cover, mainly juncus squarrosus and j. effusus. The difference in

vegetation between the east and west of the catchment coincides with the sub-catchments of the two streams and in this context the vegetation is analysed in more detail below.

The geology of the catchment is composed of a series within the carboniferous group (Fig.2). The southern part of the catchment is part of the Yoredale series, a sequence of limestone, shale and sandstone. In the north of the catchment, above the Great Limestone, there is a succession of shales and sandstones containing only very thin bands of limestone. The topography reflects the geology of the catchment, the more resistant Four Fathom and Great Limestone bands together with the Firestone Sill stand out as benches around the catchment. These bands cause waterfalls or rapids where they are crossed by the stream channels. The Four Fathom and Great Limestones act as aquifers feeding ground water to the surface streams.

Precipitation over the catchment is normally greater than 1600 mm per annum, and during the winter period most of this falls in the form of snow. Continuous records of precipitation have been made for the two water years 1968/69 and 1969/70. The results are discussed in Chapter 2, but they tend to be incomplete as a result of the difficulties of measuring snowfall and rainfall in freezing winter conditions.

The shape of a drainage basin will have an effect upon the characteristics of the stream discharge since it governs the speed at which water is supplied to the main stream and the rate at which it proceeds to the outlet of the basin. Long narrow basins tend to attenuate flood

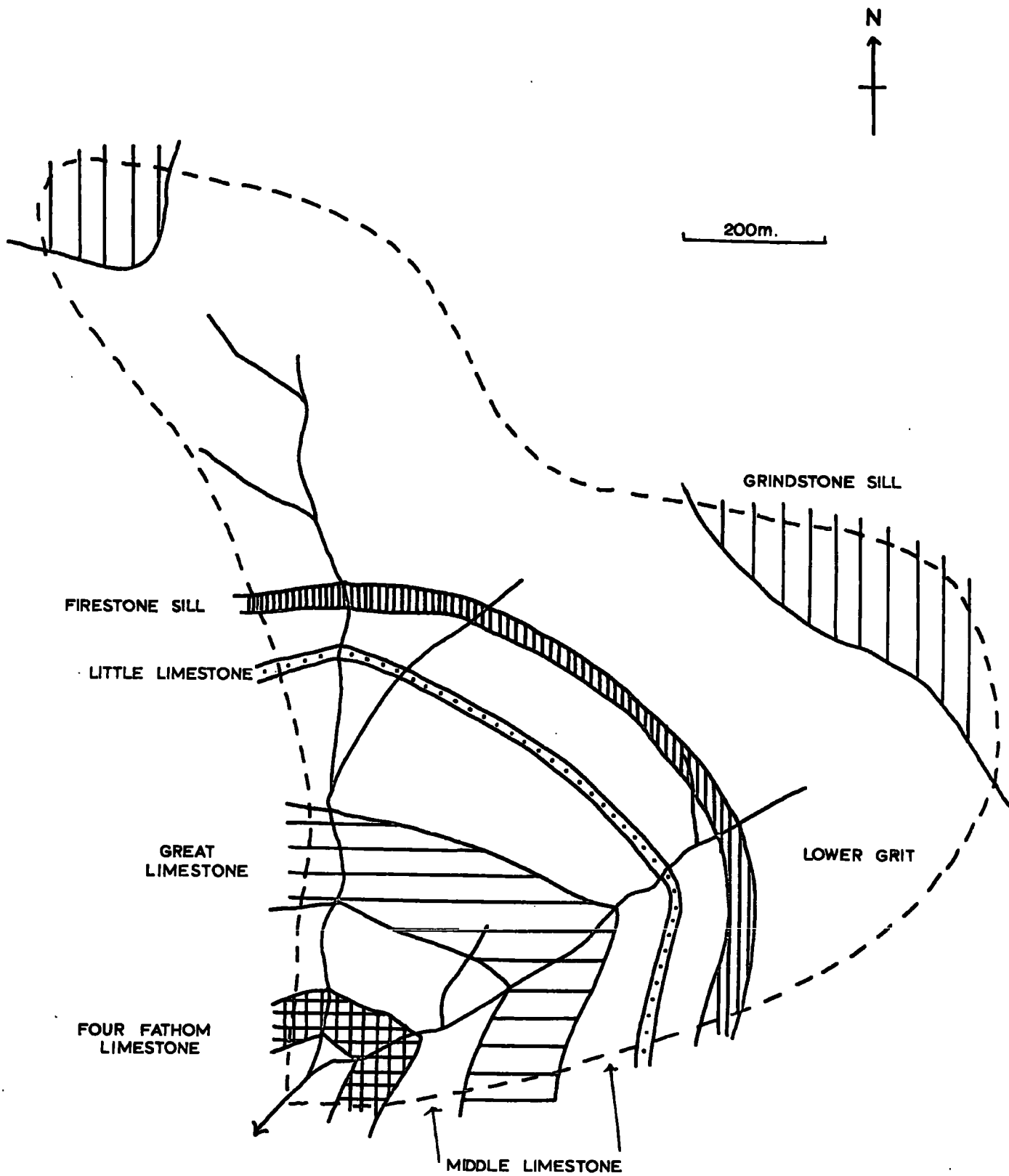


FIG 2

LANEHEAD CATCHMENT:  
— GEOLOGY

discharge since the contribution of discharge from the progressively distant parts of the catchment pass the outlet from the catchment gradually. On the other hand, with pear shaped basins the contributions from the various parts of the catchment tend to collect at the outlet to the catchment at the same time, producing a much more sudden peak. The precise quantitative representation of a basin shape is difficult, although several schemes have been suggested. Horton (1932) used the ratio:

$$\frac{\text{basin area}}{(\text{basin length})^2}$$

while Schumm (1956) used the ratio:

$$\frac{\text{diameter of a circle equal in area to the catchment}}{\text{maximum basin length}}$$

and Miller (1953) used the ratio:

$$\frac{\text{basin area}}{\text{area of circle having same length perimeter as the basin}}$$

Snyder (1938) approached this problem in a much more direct way on the assumption that the effective shape of the catchment could be expressed by drawing isopleths of travel time of the water above the catchment outlet. If the area between isopleths is then plotted against time the resulting curve would give an expression of the shape of the catchment. The main drawback to this is that it does not give a value that can be used for direct comparison with other catchments.

It is clear that tributary A has a relatively long narrow catchment when compared with catchment B; and the main catchment shape is a compromise between the two. The pattern of the discharge leaving the catchment is the

product of the combined effects of the two sub-catchments rather than a pattern that would necessarily result from the shape of the main catchment. In other words, the pattern of discharge at the weir will be the result of the pattern from each of the two sub-catchments superimposed. Sub-catchment B is marginally larger than A, the areas being  $0.551 \text{ km}^2$  and  $0.49 \text{ km}^2$  respectively. Since the total catchment is  $1.05 \text{ km}^2$ , catchment A represents 46.4% and catchment B 53.6% of the total catchment area.

Though similar in area the sub-catchments are very different in their physical nature. Catchment A has an altitude range of 150m. compared with 120m. in B. In Fig.3 the altitude frequency graphs for the two catchments are compared. Much of the greater part of catchment A is at a high altitude, above 570m., on the flat peat lands at the head of the catchment, while at the lower altitudes the catchment is very narrow. Catchment B shows no such peculiarities. A large proportion of the catchment is at 550-570m., and the area of the catchment at the lower altitudes gradually becomes smaller as the catchment becomes narrower. A possible hydrological consequence of this is that catchment A will tend to receive a slightly greater proportion of its precipitation as snow and that the snow will lie for a longer period of time.

Vegetation is an important factor controlling the nature of the drainage from an area. At Lanehead the vegetation of the catchment falls into two main categories which approximately coincide with the two sub-catchments (Fig.4). This divide is partly due to the degeneration of the peat cover, but the clear divide between the two types

A Catchment B

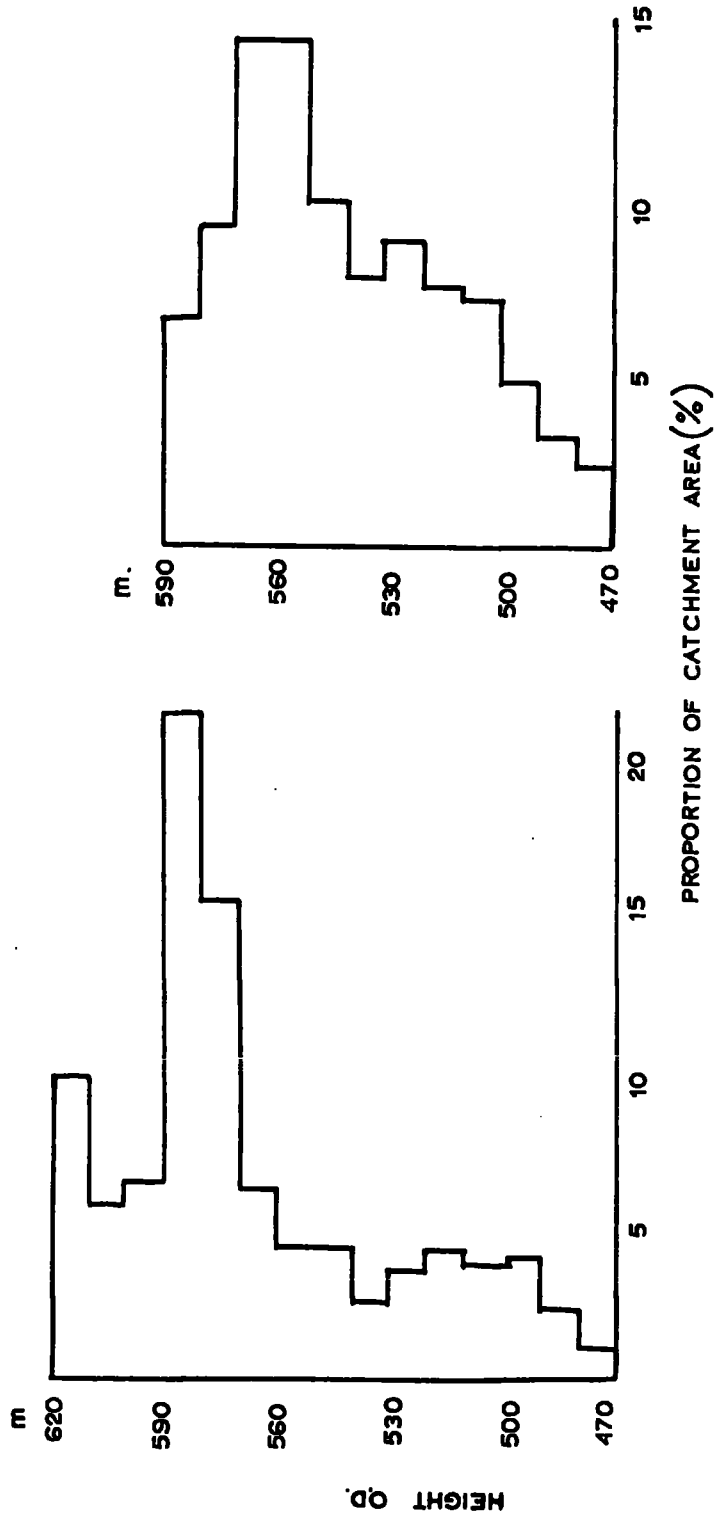


FIG 3 ALTITUDE FREQUENCY GRAPHS

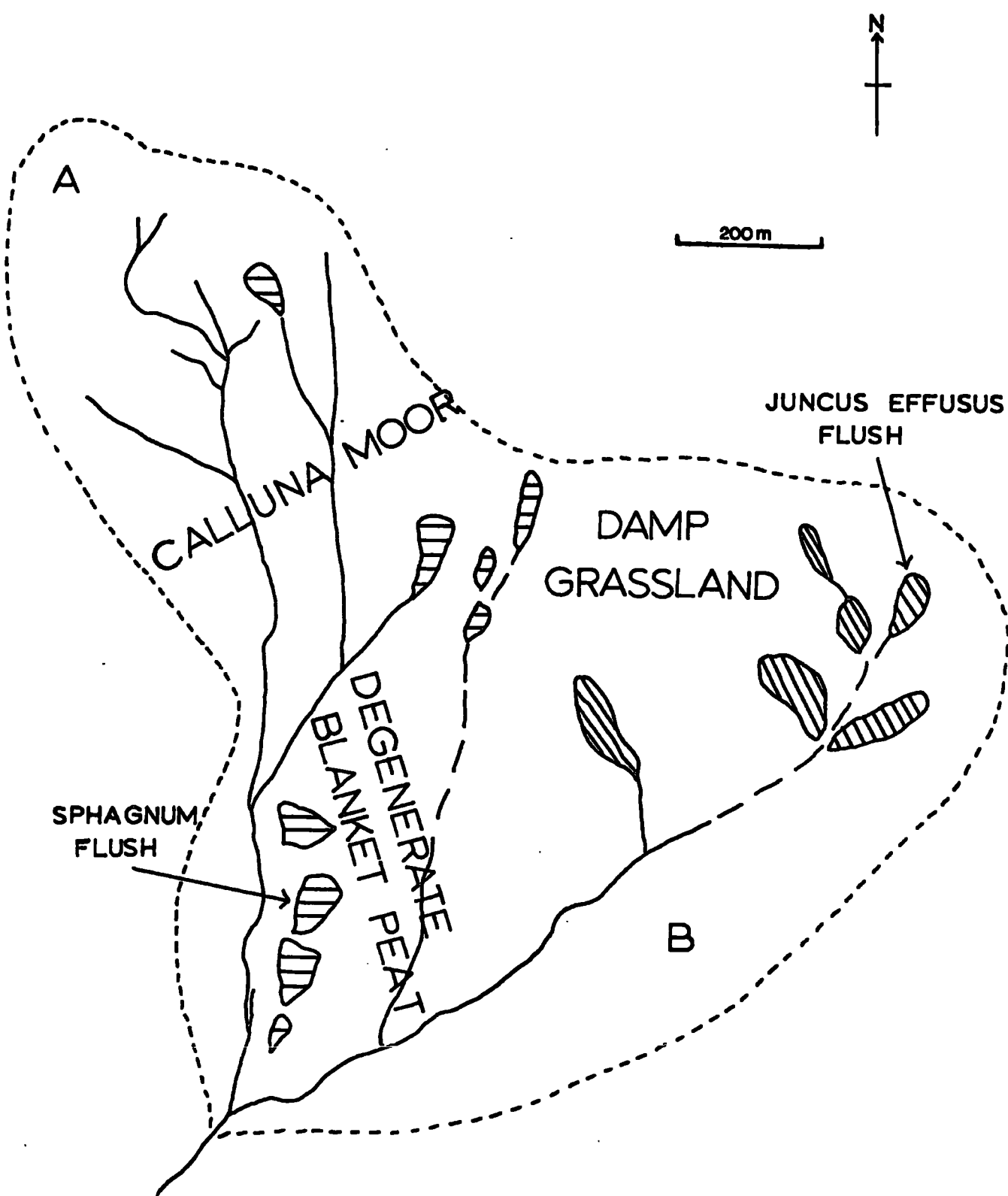


Fig 4  
 LANEHEAD CATCHMENT — VEGETATION

is exaggerated by land usage. The western part of the catchment, though grazed, is maintained as a grouse moor, whereas the eastern part is used exclusively for sheep pasture and hence the stone wall which runs down the middle of the catchment acts as a fairly distinct division between these two groups.

In co-operation with Dr. P. Bridgewater of the Department of Botany the vegetation of the catchment has been classified and mapped as five groups of habitats.

I. Damp Grassland. The eastern part of the catchment is a poor grassland area; in the eastern extreme it is dominated by Nardus stricta but to the west the Juncus squarrosus becomes more dominant. This is an area of degenerated peat, and all that remains is a relatively well drained peaty podsol soil. Near the water courses, or in the small, isolated areas of poor drainage, the vegetation cover is dominated by other species (Group IV).

II. Degenerate Blanket Peat. An area of degenerating blanket peat dominated by Scirpus caespitosus and with Calluna vulgaris and Erica tetralix on the drier ground. This group occupies the lower part of sub-catchment A.

III. Calluna Moor. This part of catchment A is an area of thick blanket peat supporting a vegetation dominated by Calluna vulgaris and it forms part of the Heidemoor (Heather moor). The presence of the Calluna indicates an area of rapid drainage, and this has been further improved by a number of artificial ditches cut in the early 1950's. The progression from the Heidemoor at the top of the catchment to the degenerated blanket peat in the south is a gradual one, but the boundary coincides approximately with the

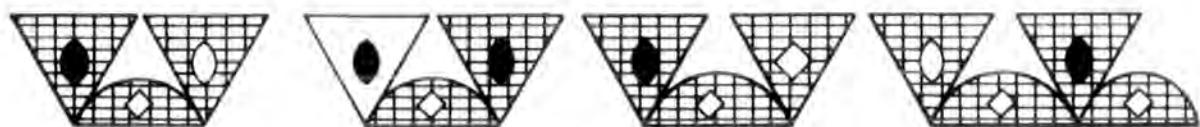
change of slope in the catchment which occurs at the out-crop of the Firestone sill. The wetter parts of the catchment, either along the water courses or in small isolated patches of poor drainage, support a different vegetation.

IV. Juncus Effusus flush. In catchment B the water courses are lined with vegetation dominated by water loving plants, Juncus effusus and characterised by Sphagnum cuspidatum and Equisetum fluviatile. This type of vegetation also occurs where the water course is just below the ground surface; the pattern of these courses can be seen in Fig.4. It occurs near the running water of the streams rather than in stagnant pools.

V. Sphagnum flushes. Sphagnum dominated flushes. These areas are very small in size, of very poor drainage and occur in catchment A particularly near the watershed in the Heidemoor zone. They are dominated by species of sphagnum, notably S. subsecundum and S. recurvum.

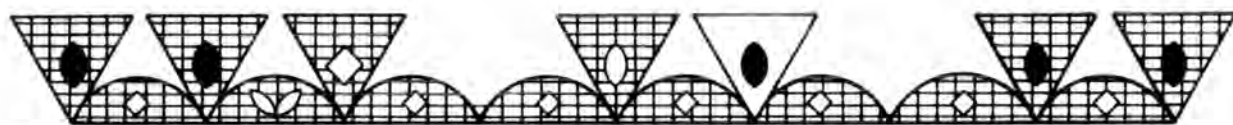
The five habitats have been presented visually using the scheme developed by Danserau 1951 (Fig.5). The main species in each habitat have been represented schematically on the basis of the five physical characteristics; life, form, size, function, leaf shape and texture. The value of this method is that it enables the different habitats to be differentiated without the species themselves having to be identified. (The species found in the catchment are listed in Appendix III).

The pattern and nature of the drainage channels in the two sub-catchments are very different, partly as a result of the different gradients of the catchment, and



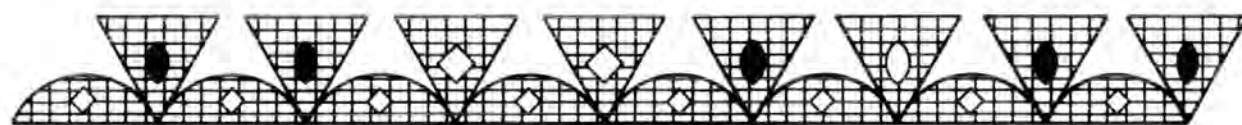
Hmegxp, ml(m)eazi, Hmegzp, Hmdgxp, Hleazp

### 1 DAMP GRASSLAND



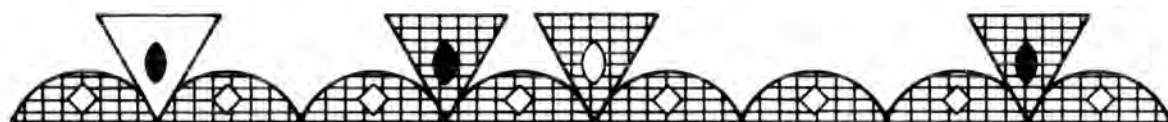
Hmegxp, mleazc, mlevzi, Hleazp, Hmegzp, Hmdgxp

### 2 DEGENERATE BLANKET PEAT



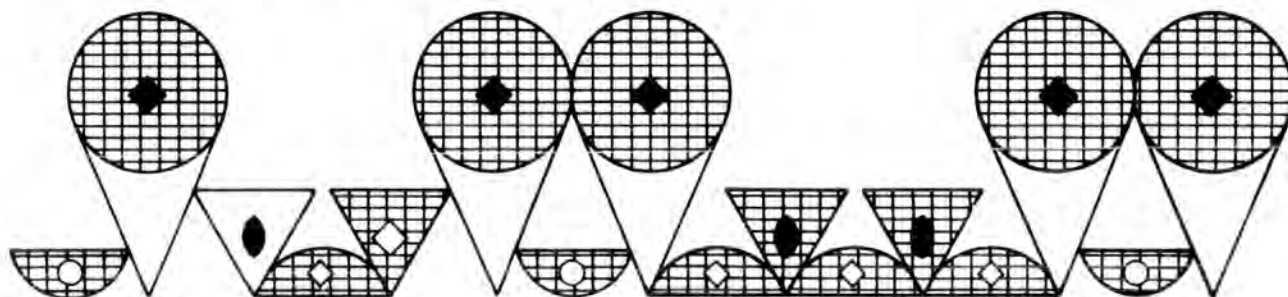
ml(m)eazc, Hmegxp, Hleazp, Hmegzp

### 3 JUNCUS EFFUSUS FLUSH



ml(m)eazc, Hmdgxp, Hmegxp, Hmegzp

### 4 SPHAGNUM FLUSH



sleqkp, fleaxc(i), Hmdgxp, ml(m)eazp, Hmeazi, Hmegxp

### 5 CALLUNA MOOR








THE FIVE VEGETATION GROUPS IN THE  
CATCHMENT

KEY OVERLEAF

FIG 5

# FIG 5 SIX CATEGORIES OF CRITERIA USED IN VEGETATION DESCRIPTION (MODIFIED AFTER DANSEREAU (1957))





## 1 LIFE FORM

- T  trees
- F  shrubs
- H  herbs
- M  bryoids
- E  epiphytes
- L  lianas
- S  lichens







## 2 SIZE

- t - tall ( T = minimum 25m  
F = 2-8m  
H = minimum 2m)
- m - medium ( T = 10-25m  
F, H = 0.5-2m  
M, S = min. 10cm)
- l - low ( T = 8-10m  
F, H = maximum 50cm  
M, S = maximum 10cm)





## 3 FUNCTION

- d  deciduous
- s  semi-deciduous
- e  evergreen
- j  evergreen leafless

## 4 LEAF SHAPE & SIZE

- n  needle or spine
- g  graminoid
- a  medium or small
- h  broad
- v  compound
- q  thalloid

## 5 LEAF TEXTURE

- f  filmy
- z  membranous
- x  sclerophyll
- k  succulent or fungoid

## 6 COVERAGE

- b barren or sparse
- i discontinuous
- p tufts
- c continuous cover

partly as a result of the varying soil and vegetation types. In both of these catchments surface flow is the main source of drainage and consequently the nature of the channel influences the nature of the discharge from the catchment. The main stream in catchment A rises on the blanket peat near the watershed. Like the tributaries that join it, the main stream channel is cut into the peat, and in places the channel is linked with small flat sandstone boulders (c.10 cm. in diameter). In its middle reaches, the main channel is steep, floored with small boulders and gravels, and often deeply incised into unstable peaty/podsol banks, which are frequently undercut during high flows. In its lower reaches, such as the section 300 m. above the weir, the banks and the stream channel are much more stable and clearly defined. Where the stream crosses the outcrop of the Four Fathom Limestone there is a series of waterfalls. During very low flows the stream flows for short reaches through the channel gravels. The only other stream channel of significant size in this part of the catchment drains the area near the eastern edge of the sub-catchment and originates in a number of flushes. Significantly it is this stream rather than the main stream which dries up during a drought although the flushes themselves retain water for a long period. During periods of high flow the water passes over rather than through, the flushes.

Stream B rises in the peaty/podsol soil in the upper part of the catchment. - The headwaters seep through *Nardus* grass flushes with few clearly defined stretches of channel. The first appearance of a recognisable main channel occurs at 540 m. OD. From here downstream the channel is well

defined with very stable banks throughout its length. Where it crosses the more resistant strata such as the Four Fathom and Great Limestones, and the Firestone sill, small waterfalls occur. The Little Limestone does not form a marked feature in the long profile of the stream although where it is crossed by the stream, the channel is of bedrock and without gravels. Between the outcrops of Four Fathom and Great Limestone the stream is deeply incised, partly since it follows the line of a structural fault, and partly because this part of the channel has been eroded by lead mining activities. Two other smaller streams drain this sub-catchment near the watershed. On the watershed several channels are cut in the peat, but away from this flatter area at the top of the catchment the stream channel is less clearly defined and the water drains through an area of *Nardus* grass. This drainage system joins stream B just below the outcrop of the Firestone sill. The second tributary drains the lower part of the catchment by a series of sub surface channels. The line of these channels is very often marked on the surface by lines of water-loving vegetation, and, in places, by active sphagnum flushes. The stream forms a surface drainage channel for about 50 m. above its confluence with stream B just above the outcrop of the Four Fathom Limestone.

The average gradient of the two streams are very similar, A being 1:10.5 and B 1:11, but the long profiles are quite different. (Fig.6). At its source on the deep blanket peat stream A has a relatively shallow gradient of about 1:25. The stream meanders through a wide channel cut into the peat, and in part erodes through to the shale

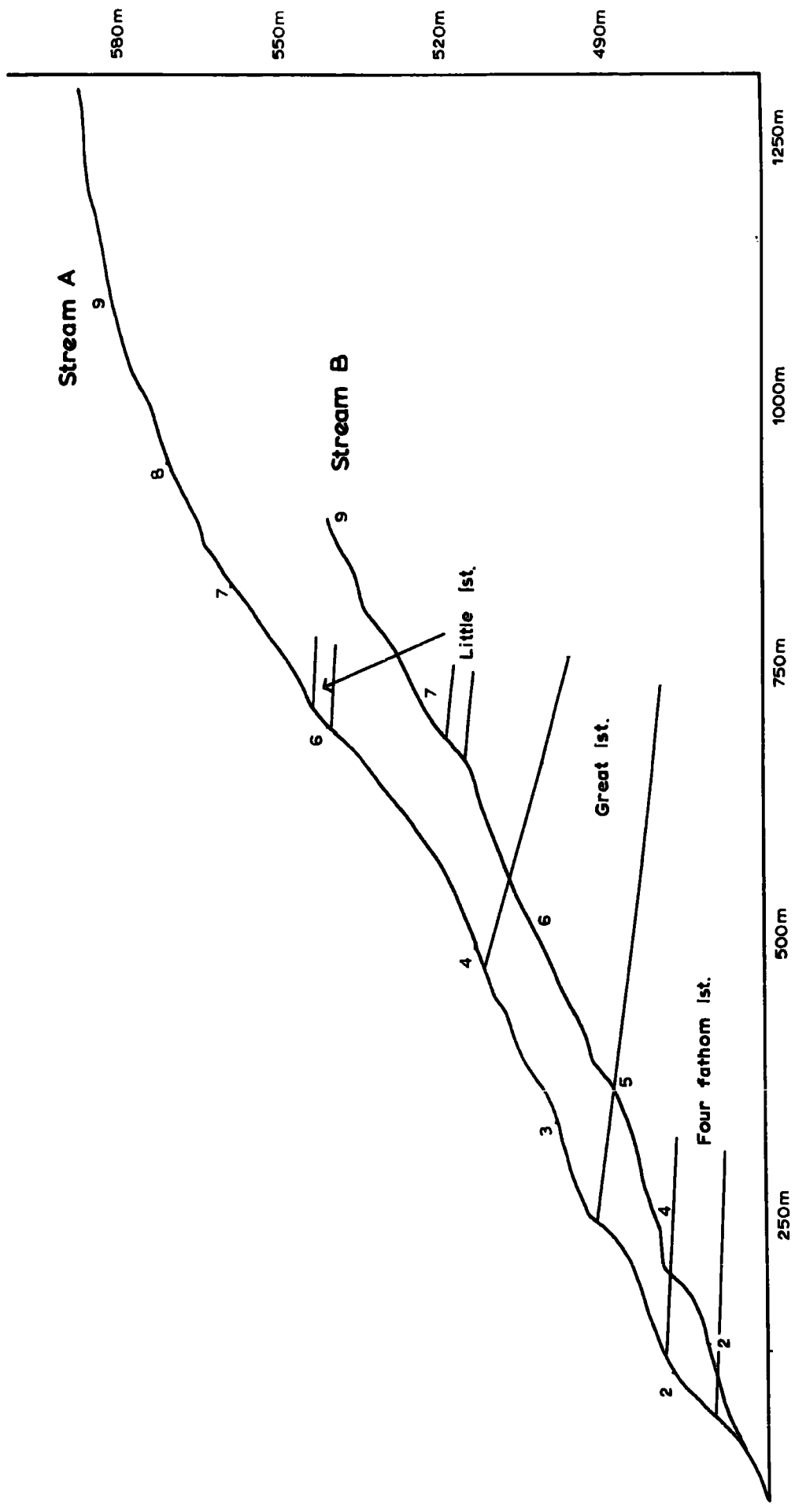


FIG 6 LONG PROFILES OF THE TWO STREAMS

and sandstone bedrock. When the stream crosses the Firestone sill on to strata belonging to the Yoredale series, the gradient becomes much steeper, about 1:6, with a series of short stretches with even steeper gradients where the channel crosses the Little Limestone at 540m OD. It becomes much shallower above the upper limit of the Great Limestone outcrop at 510m OD. Where the stream crosses the more resistant rocks waterfalls occur, but where the rock is less resistant the channel meanders on a layer of gravels, which are often 0.25-0.5m deep. The most striking features of this profile are the rapids and falls at the base of the Great Limestone (490m OD) where there is a permanent spring, and over the Four Fathom Limestone (475m OD) where the stream has a local gradient of 1:2.5.

In contrast, stream B has a more uniform profile with only minor reaches of markedly increased gradient coinciding with outcrops of the more resistant bedrock, the Four Fathom Limestone at 475m OD, the base of the Great Limestone at 490m OD and the Firestone sill at 520m OD. The outcrop of Little Limestone has very little influence upon the gradient of this stream.

PART I

INSTRUMENTATION OF THE CATCHMENT

## CHAPTER 2

### THE MEASUREMENT OF PRECIPITATION

A great deal of attention has been paid to the problems of precipitation and discharge measurement because the aim was not merely to provide the framework for this study, but to furnish the essential instrumentation for an experimental catchment with much wider utility. Nevertheless the study of precipitation in the catchment was also of direct relevance in this specific study for two reasons. Through its effect upon the volume of discharge, precipitation has an indirect control over the thermal characteristics of the stream water. Secondly, relatively little information is available in the United Kingdom about the problems of instrumenting for precipitation in an exposed upland catchment.

#### The rainfall measurement problem

The principle of precipitation measurement is that a rain gauge will measure the amount of water reaching the surface of the earth nearby. This principle assumes that the gauge will collect the amount of precipitation that would have fallen on the ground had the gauge not been there. However, this situation has not yet been achieved, for the very presence of the standard rain gauge with its rim one foot above ground level, produces a local environment of turbulent airflow which is very different from that which existed before its installation. The standard gauge consists of a funnel set in a cylinder

of exactly 5" diameter, which directs the rain into a collecting bottle. The funnel is 4" below the rim to minimise the amount of rain lost by splashing from the sides of the funnel. The gauge is installed so that the rim is horizontal and exactly 12" above the surrounding ground in order to reduce the insplash of rain from this surface.

The deficient collection of rain by the gauge is a greater problem, the local eddies of increasing wind speed around the gauge cause rain, particularly light drizzle, to be carried clear of the gauge. Robinson and Rodda (1969) experimenting with rain gauges in wind tunnels have shown that the acceleration of the air flow across the orifice of the gauge can be as much as 132% of the wind speed in the tunnel (Fig.7). Collinge (1963) has shown that gauges at different heights above the ground, and therefore exposed progressively to greater wind speeds, have collected less rain:-

<u>Gauge</u>	<u>Catch</u> (ins.)	<u>Deficiency</u>	
		(ins.)	(%)
Ground level	78.5		
1' gauge	72.4	6.2	7.8
10' gauge	68.9	10.0	12.0
30' gauge	71.0	7.6	9.6

(from Collinge 1963)

Bornstein (1884) correlated the difference between the catch of a protected and of an unprotected gauge against wind speed:-

Wind speeds as percentages  
of the wind tunnel air flow

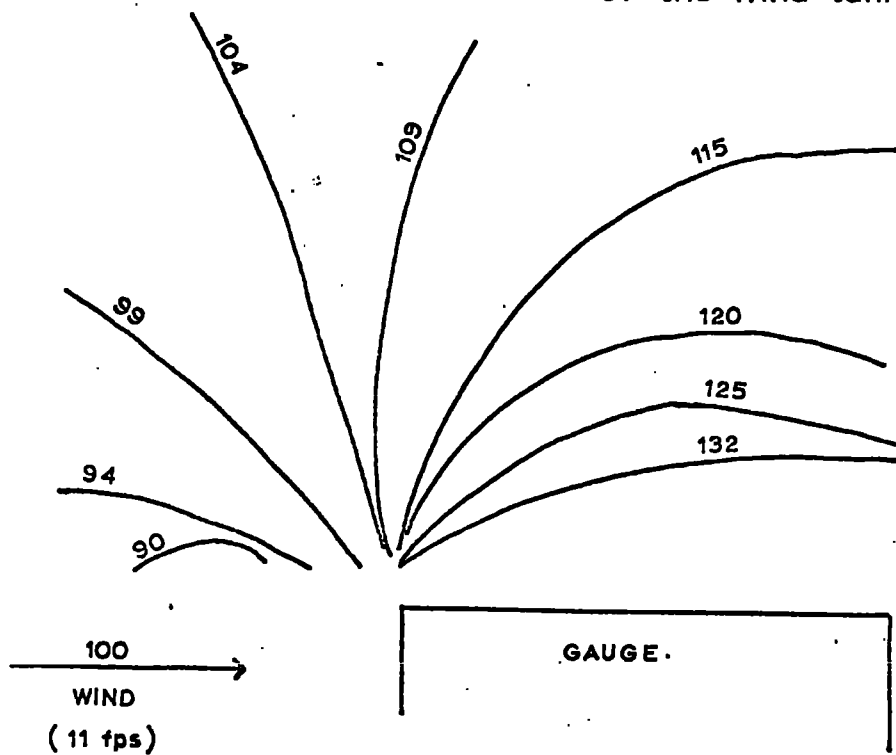


FIG 7 THE WINDFIELD ABOVE A STANDARD GAUGE

after RODDA 1969

<u>Windspeed:</u> (Beaufort scale)	<u>unprotected</u> <u>protected</u> (%)
0-2	92
3-4	87
5-6	69

(from Bornstein 1884)

These differences were significantly higher for periods of fine rain or drizzle:-

<u>Windspeed</u> (mph)	No. of days	<u>Heavy Rain</u> Deficiency	No. of days	<u>Light Rain</u> Deficiency
0-1			4	23%
1-3	17	6%	8	25%
4-7	13	13%	6	18%
8-12	7	14%	6	46%
13-18	6	17%	2	52%

(from Bornstein 1884)

The main problem of gauge installation is to create a situation in which the actual presence of the gauge does not produce a non-uniform and turbulent flow of air over the gauge. It is also important that this should remain the primary consideration, rather than as is often the case, that the success of the gauge is viewed in terms of the increased catch above that of an adjacent gauge not similarly located.

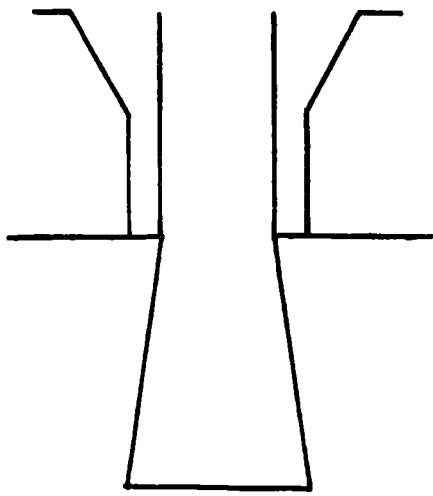
Attempts to overcome the problems of exposure have been many and varied, but basically they can be grouped into three categories:- changing the size of the gauge; changing its shape; and removing the gauge from the flow of air altogether. The purpose of reducing the size of the gauge is that, the smaller the gauge, the less its dis-

turbing affect upon the airflow. However, if a gauge has an orifice of less than 4" diameter, the amount of water retained by, or evaporated from, the funnel of the gauge is relatively large compared with the volume of rain collected.

Experiments with aerodynamically shaped gauges have been carried out in an attempt to produce a shaped gauge that will give the minimum resistance to airflow. Of the many shields produced, the Nipher is regarded as the most successful (Fig.8a). The air is diverted down and away from the top and the sides of the gauge, so that these eddies do not affect the direct flow of air across the top of the gauge. The increase in catch which undoubtedly results from the use of a Nipher shield could well result from rain splashing from the top of the shield. In the United Kingdom, gauges in exposed areas are often protected by a turf wall (Fig.8c). The height of the wall is 12", and the top of the wall is in the same horizontal plane as the rim of the gauge. This method is costly in effort for both construction and maintenance, and although perhaps providing some protection from the sweep of the winds, a poorly maintained structure may actually increase turbulence in the airflow.

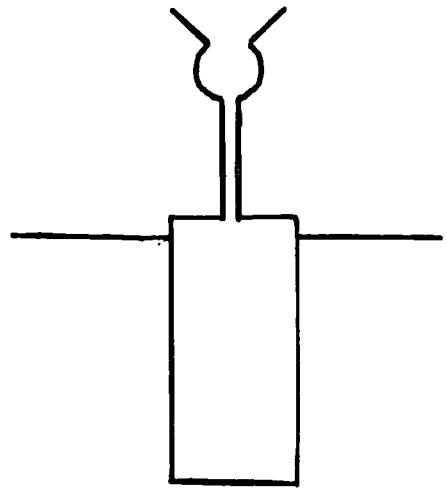
In Belgium, Poncelet (1959) experimented with the shape of the gauge itself. After testing various shapes in a wind tunnel he came to the conclusion that a gauge shaped like a wine glass (Fig.8b) would offer the least resistance to the flow of air, and thus cause the minimal air turbulence.

By far the most successful attempts to minimise exposure problems have been made by placing the gauges at

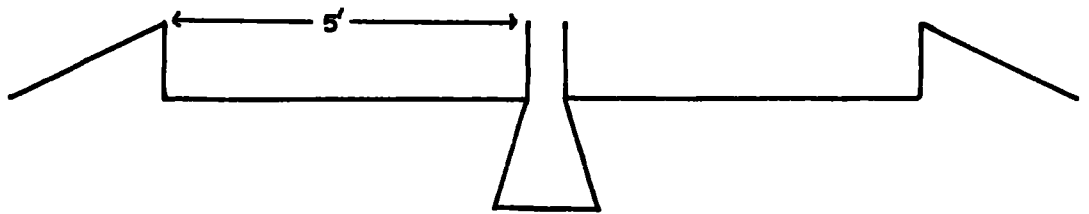


**A NIPHER SHIELD**

12"



**B PONCELET GAUGE  
(after PONCELET 1959)**



**C TURF WALL**

**FIG 8 PROTECTED RAIN GAUGES**

ground level, and thus completely removing it from the flow of air. Under these conditions though, the gauge is susceptible to rain splashing, or flowing in from the surrounding ground. Ashmore (1934) has demonstrated that considerable splashing will occur from a rainstorm of 10 mm/hr.:-

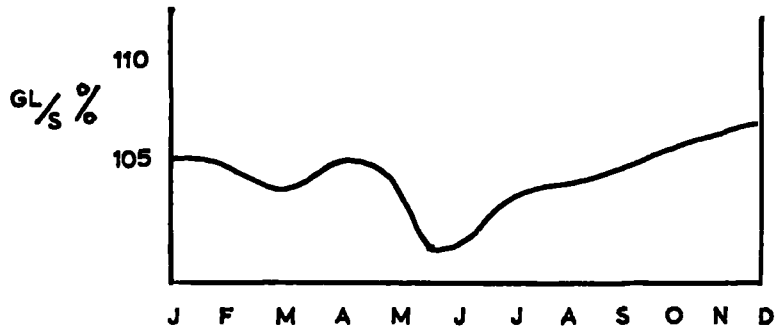
<u>Surface</u>	<u>Height of splash (mm)</u>
Poor lawn	210
Gravel	280
Lawn	290
Water	350
Bare soil	410
Ice	625

The first successful ground level gauge was used by Koschmeider (1934). The gauge was set in a pit approximately 30 cm. deep so that the top of the gauge was level with the surrounding ground, but the earth in the immediate vicinity of the gauge was 30 cm. below the rim of the gauge, and thus minimised splash. To reduce the disturbance to the airflow caused by the pit, the depression was covered with wire netting. Other anti-splash surfaces have now replaced the wire netting - plastic grids or angled slats so designed to deflect splash away from the gauge. The effectiveness of these anti-splash surfaces can be tested by the use of a compound gauge (Bleasdale 1958, 1959). The compound gauge is composed of nine rain gauges set in a square. If no splash is occurring from the surrounding surface, then all the gauges should collect the same amount of rain. If however, the surrounding surface does not prevent splash, then the central gauge can be expected to collect the least amount of rain since it is farthest from the surface, while the corner gauges will collect the most.

Although it is dangerous to equate increased catch with increased efficiency until it is known if some of the increase results from insplashing, it is impossible to ignore the many experiments that have shown significant differences between the catch of a standard one foot gauge and an adjacent gauge set at ground level. Rodda (1967) making a comparison between the catch of two such gauges over the period September 1961 - August 1966, has shown that the ground level gauge consistently collected more (Fig.9a). Koschmeider's (1934) experiments indicated that the discrepancy between his gauges increased with increasing windspeeds (Fig.9b). Winter and Stanhill (1959) conducting a similar experiment found that the discrepancies were least during the summer period when windspeeds were less and the raindrop size larger.

Although a gauge installed at ground level and surrounded by an anti-splash surface appears to give a much more accurate reading of precipitation than the standard gauge, nevertheless over long periods of study the standard gauge can be regarded as a good estimate of the amount of precipitation. The standard gauge also has the very distinct advantage of being much more easily installed, and of providing a measure directly comparable with the vast majority of rainfall records in this country. However these advantages are not those required in an experimental catchment where the emphasis is upon short term records of maximum accuracy. Rodda (1967) estimates that the difference between the standard and ground level gauges at the Wallingford site to be about 6%, and if differences of this degree are obtained in relatively

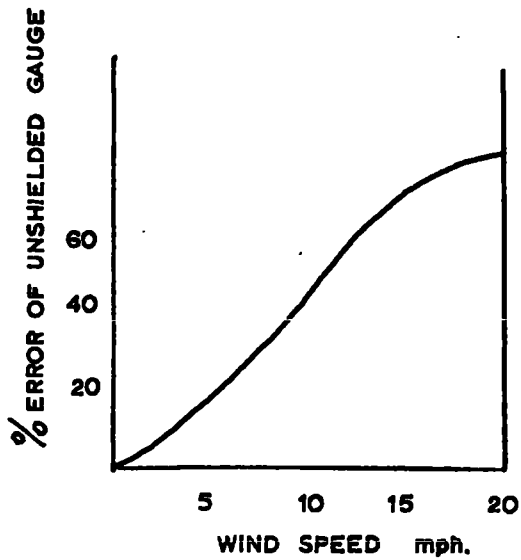
A



A COMPARISON BETWEEN THE CATCH OF A STANDARD AND A GROUND LEVEL GAUGE

RODDA 1967

B



THE RELATIONSHIP BETWEEN GAUGE ERROR AND WINDSPEED

KOSCHMEIDER 1934

sheltered lowland sites, then the magnitude of the problem is likely to be much greater in a windswept upland area such as the Northern Pennines.

In order to gain some idea of this problem, a ground level gauge was installed in the Lanehead catchment. The gauge was set in a pit one foot deep and three feet square, so that the height of the rim was level with the surrounding ground. The pit was covered with wire netting in order to prevent turbulence to the airflow being caused by the depression, and yet at the same time not giving a surface from which rain splash could occur (Fig 10). The gauge was installed adjacent to a standard gauge so that the catch of each could be compared. Periods during which snow was known to have fallen have been ignored from the analysis since snow, being very light and more susceptible to wind conditions around the orifice of the standard gauge, would tend to exaggerate the difference that occurred. Weekly readings were taken from these gauges between 28th February and 5th June 1968 (Table I).

On only two occasions was the catch of the ground level gauge less than that of the standard gauge, and on both of these occasions the discrepancy was 0.1 mm (within observer error). The total catch of the ground level gauge exceeded that of the standard by 24.4%, and the mean deviation was 16.3%. Differences in catch of this magnitude would occur 'by chance' less than once in a thousand even when the high value difference (54%) observed for the period 15th - 20th March is ignored.

Where precipitation measurements are employed for design and research purposes, as in experimental and

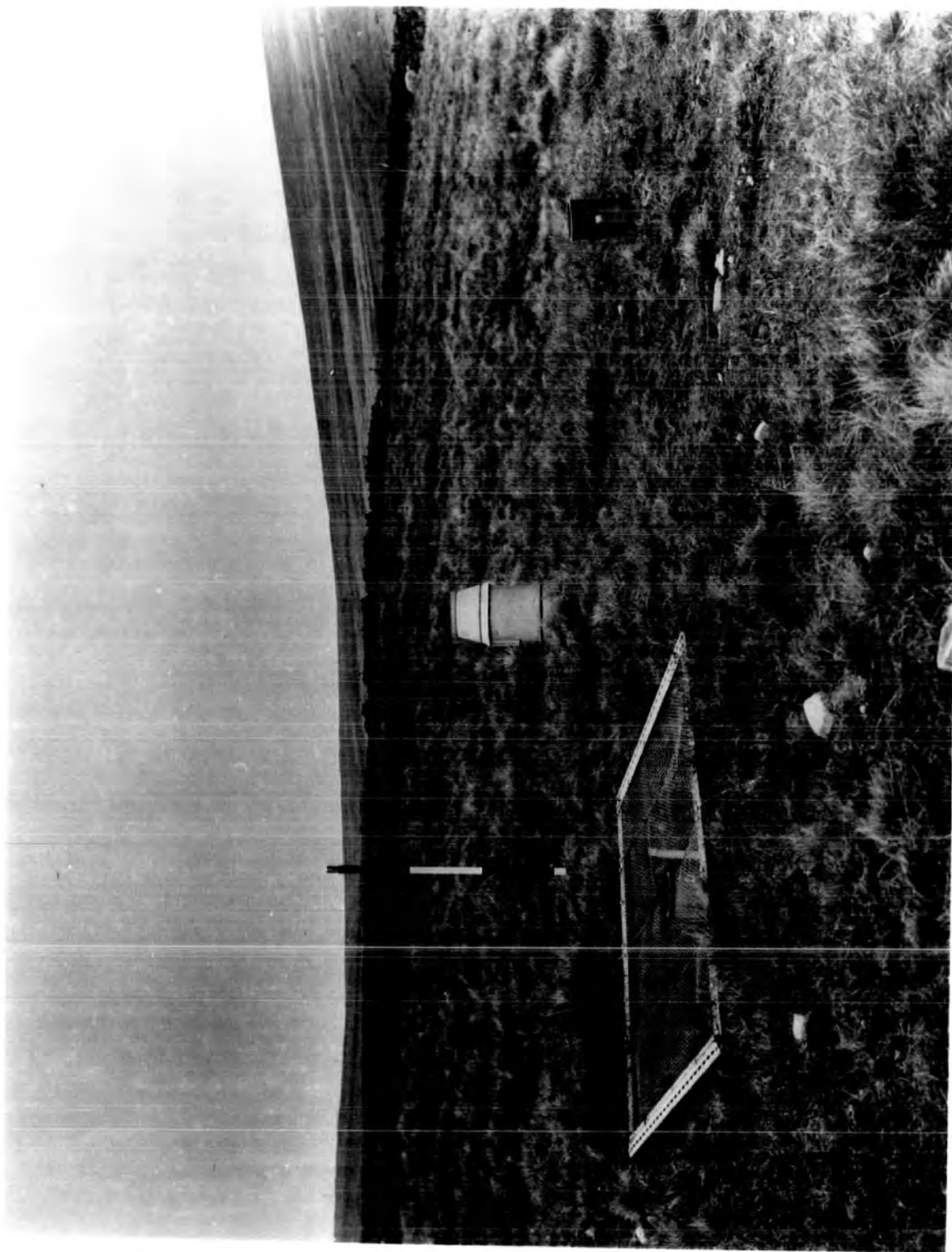


FIG 10 GROUND LEVEL GAUGE AT SITE 2

TABLE I

Period	Gauges		GL/S %
	Standard (mm)	Ground Level (mm)	
28 Feb - 6 Mar	0.6	0.5	83.3
6 Mar - 13 Mar	8.5	11.0	129.4
13 Mar - 14 Mar	0.8	1.0	125.0
15 Mar	3.5	3.5+	100.0+
15 Mar - 29 Mar	51.1	79.1	154.8
20 Apr - 26 Apr	3.4	4.5	132.4
26 Apr - 3 May	15.4	16.2	105.2
3 May - 8 May	18.3	20.9	114.2
8 May - 15 May	35.3	37.9	107.9
15 May - 22 May	11.5	11.4	99.1
22 May - 30 May	3.8	4.0	105.3
30 May - 5 June	1.8	1.9	105.6
	154.0	192.0	124.61

representative basins, there is a need to obtain as accurate a value as possible. In the Lanehead catchment, the discrepancy between the catch of these two gauges of at least 15%, constitutes a potential additional surface runoff of 124 gallons per minute or a continuous flow of 0.3 cusecs. throughout the year. The mean discharge for the catchment is about 1.5 cusecs. During the summer period, the rainfall readings obtained in this catchment can be expected to be accurate  $\pm 10\%$ , but during the winter, when much of the precipitation falls as snow, inaccuracies will be much greater.

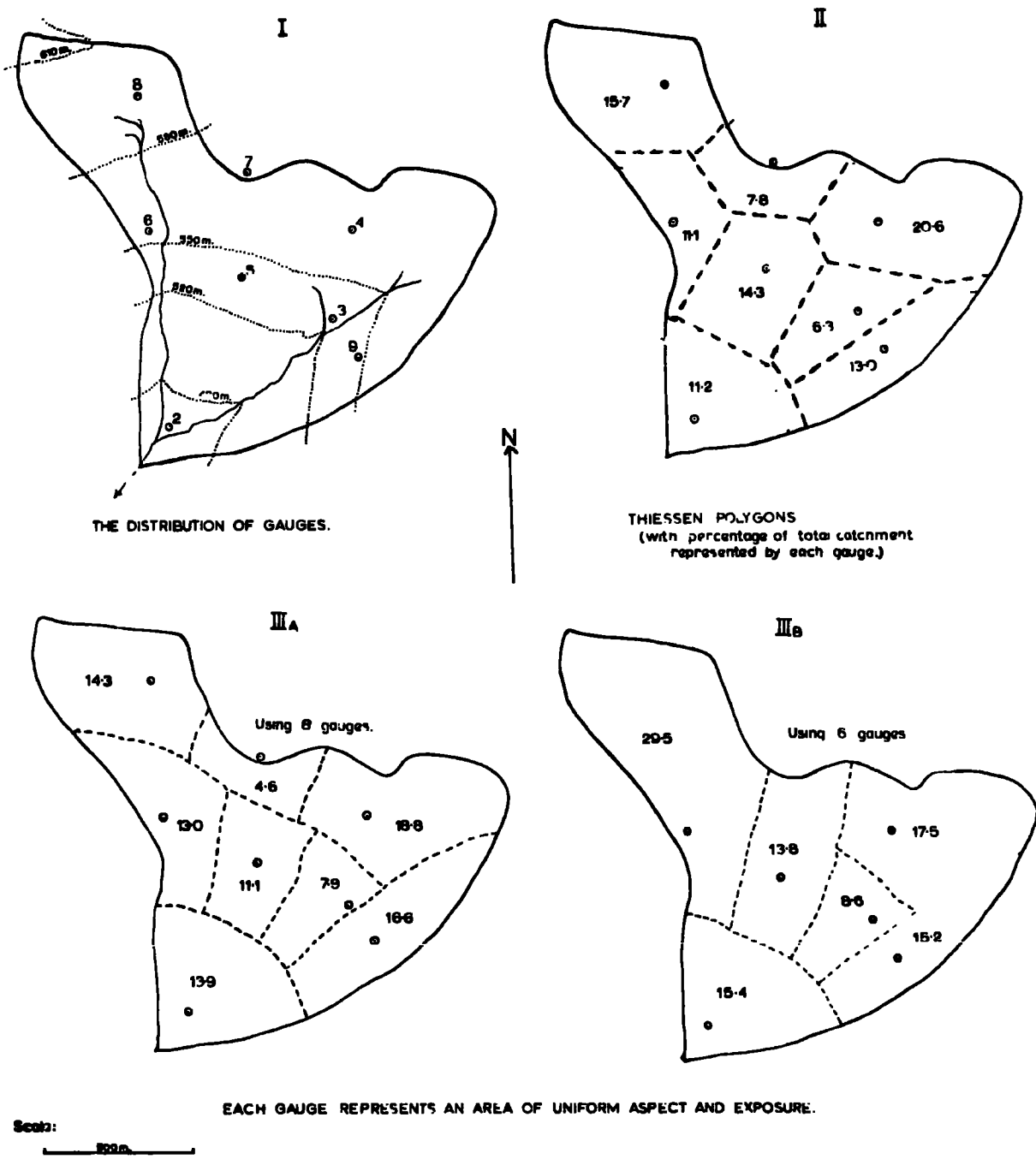
Pilot study to select two recording sites for main study  
(January - June 1968)

The purpose of measuring precipitation in a hydrological study of a catchment area is to calculate the amount of water deposited over the area. It is a measure of the input of energy, and in the same way the calculation of discharge is a measure of the output of energy. The catch of one rain gauge, even within a catchment as small as  $1 \text{ km}^2$ , does not necessarily mean that this amount of rain has fallen uniformly over the whole area.

Point measurements of precipitation, however accurate and reliable they may be, are of little value until they can be applied areally to the catchment. The greater the concentration of gauges within the catchment, the more reliable will be the resultant distribution and mean value of areal rainfall. However, a compromise must be reached between the increased reliability resulting from a large number of gauges and the practical considerations arising from the necessity of maintaining them.

From January to June 1968, eight rain gauges were distributed throughout the Lanehead catchment. This represents a gauging density of eight gauges per  $\text{km}^2$  compared with the United Kingdom average of one gauge per  $38 \text{ km}^2$ . The distribution was planned to give an even cover over the area, and also each gauge was to be representative of an area of uniform aspect, exposure and height (Fig.11). The gauges were installed with the rim one foot above the ground surface in accordance with the Meteorological Office practice.

Site 2 was the lowest gauge in the catchment (472m. OD).



**FIG 11**  
METHODS OF DETERMINING AVERAGE PRECIPITATION OVER THE CATCHMENT.

The site was on the interfluve between the two main streams. This gauge was regarded as representative of the lower part of the catchment (below the 510m contour) which had generally a shallow slope and a south west exposure. A ground level gauge was installed at this site (Fig.10), and its catch was compared with the catch of the standard gauge set in the conventional way. The results are presented below (Table I).

The middle zone of the catchment, 510 - 560m. OD., was sampled by the four gauges at sites 6, 5, 3 and 9. Site 6, at 546m. OD. was in the western part of the catchment, in an area of southern exposure. Here an attempt was made to protect the gauge by placing it in a position surrounded by heather one foot deep. Site 5, at 540m. OD., near the centre of the catchment was conventionally sited on short grass and with no form of protection. The exposure was south, similar to site 6. Gauge 3, 527m. OD., was sited on an interfluve, but unlike site 2, was a sheltered location, surrounded on all sides except south west by higher ground. No other protection was given to the gauge. Site 9 at 540m. OD., was selected to sample the north west facing slope in the eastern part of the catchment. In order to give some protection to the gauge, in what would otherwise have been a very exposed site, the gauge was placed in a natural hollow. The disadvantage with this site was that it soon became buried in periods of snow fall.

The upper part of the catchment, above 560m., was gauged at sites 8, 7 and 4. Gauges 8 and 7 sampled the flat surface, while gauge 4 was representative of the much

steeper, south west facing slope in the eastern part of the catchment. Gauge 8 at 588m.OD., was the highest site in the catchment, and like site 6, it was placed amongst deep heather for protection. This gauge, sited at the break of slope between the erosion surface and the steeper slope leading up to Stangend Ridge on the watershed, was intended to represent this higher, southward facing area of the catchment. Gauge 7 at 568m. OD., was on the watershed and hence very exposed; no protection was given to this gauge. Site 4, 565m. OD., was deemed to be representative of the eastern section of the catchment where the slope is relatively steep and exposed to the south west.

Four methods were used to compute the mean value from the eight point measurements obtained.

#### 1. Arithmetic Mean

This was the simplest method of all, and involved merely taking the mean reading for all the gauges in the area. This method can give a perfectly reliable figure if the area is small, flat and the gauges evenly distributed. It may also give very good results in less favourable conditions if the siting of the gauges has been carried out with a view to the orographic influences. Above all it will give a completely objective mean value.

#### 2. Areas of uniform aspect and height

This method gave weight to the areal distribution of the gauges, and the affects of topography (Fig.11, IIIa and IIIb). It assumed that areas of similar aspect and exposure have comparable amounts of rainfall. The catchment was divided up into regions of uniform relief,

aspect and general exposure to the environment, and each region was sampled with a gauge. The area represented by each gauge was calculated as a percentage of the total area, and the weighted mean for the area was calculated by multiplying the catch of each gauge by the percentage of the total area that it represented. The installation of the gauges within the Lanehead catchment was made with this method of analysis in mind.

One of the main objections to the weighted area method is that where a gauge representing a large proportion of the area has an extreme value, it exerts a strong pull upon the resulting mean value. In order to safeguard against this, method II was carried out twice, once with all the gauges used (Method IIIa) and once with the two most unreliable stations, (i.e. those which gave a large number of readings greater than  $\pm 15\%$  arithmetic mean) sites 7 and 9 ignored (Method IIIb). The discrepancy between these two methods was small, and apart from one 17% difference, the variation was between -7% and +1% (Table III). The pull exerted by isolated extreme values from individual gauges would appear, from this study, to be minimal.

### 3. Thiessen polygons

This method, described by Thiessen (1911) again gives weight to the areal distribution of the gauges. The catch of each gauge was taken to be representative of the area nearer to that gauge than to any other (Fig.11, II). In this way there was an allowance for an uneven distribution of gauges. A Thiessen network was constructed by drawing the perpendicular bisectors to the lines connecting the

gauges. Each gauge was then left in the middle of a polygon, which varied in size according to the spacing of the gauges. The proportion of the total area represented by each polygon was calculated, and the catch of each gauge weighted as in the second method.

#### 4. Isohyetal Method

The isohyetal method assumed that any difference in catch between two neighbouring gauges, represented a gradual increase (or decrease) in precipitation along the line between the two sites. Isopleths were constructed over the area joining points of equal rainfall, and the area between each isopleth measured. The average rainfall over the area was calculated as the product of the rainfall in each zone and the area covered. Potentially this method should provide the most accurate procedure since it enabled many details of relief and aspect to be taken into consideration; but on the other hand it was also the most subjective and effort demanding method.

The catch of each gauge in the Lanehead catchment was compared with the mean value determined for the catchment; the aim being to find out which site collected a measure of rainfall most nearly equal to that of the catchment mean. Table III shows the catch of each gauge for the various study periods, together with the mean values obtained by the various methods of areal rainfall determination.

In Table II the performance of each gauge is compared with the mean values of precipitation for the catchment determined by methods 1, 2a, 2b and 3. The performance of

AREAL DISTRIBUTION OF RAINFALL IN THE LAWREHEAD CATCHMENT

Gauges

2                    3                    4                    5                    6                    7                    8                    9

Method 1. Arithmetical Mean

% Mean

5	++ -	++++	----	++	----	++	----	++	----	++	----	++	----	++	----	++	----	++	----
5-10	++	----	----	+	----	+	----	+	----	+	----	+	----	+	----	+	----	+	----
10-15	-	++	----	+	----	+	----	+	----	+	----	+	----	+	----	+	----	+	----
15-20	+	----	----	+	----	+	----	+	----	+	----	+	----	+	----	+	----	+	----
over 20	+	----	----	-	----	-	----	-	----	-	----	-	----	-	----	-	----	-	----

Method 2a.

5	++	----	----	+	----	+	----	+	----	+	----	+	----	+	----	+	----	+	----
5-10	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+
10-15	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
15-20	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
over 20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Method 2b.

5	++	----	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-10	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+
10-15	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
15-20	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
over 20	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++

Method 3.

5	+	----	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-10	++	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+
10-15	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
15-20	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
over 20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

0 = + 2%

- = low value.

TABLE III

Gauges (catch in mm.)		Mean value for the catchment derived by each method									
2	3	4	5	6	7	8	9	1	2a	2b	3
4.1	15.2	4.3	4.4	4.7	5.7			4.7			
31.1	38.5	28.0	37.5	34.0	41.5			34.9			
2.0	2.5	2.1	2.4	3.2	2.5			2.4			
13.4	21.4	13.8	15.0	21.2	22.3	28.8	22.2	19.8	19.4	18.0	19.3
1.4	1.7	1.2	1.2	1.3	1.0	1.5	1.6	1.4	1.4	1.4	1.3
28.6	25.1	19.4	31.6	25.5	23.3			24.1			
0.6	1.6		1.8		4.0			2.0			
8.5	9.8	7.0	7.5		11.4	12.1		9.4			
0.8	1.1	0.7	0.9		0.8	1.3	0.7	0.9			
51.1	69.0	44.8			77.2			60.5			
3.4	5.0	4.1	4.1	3.9	4.5	9.4	4.7	4.9	5.0	4.1	5.0
15.4	15.8	17.0	15.8	16.0	14.1	16.9	16.2	15.9	16.1	16.1	16.1
18.3	16.9	16.9	16.2	15.2	13.9	20.2	19.5	17.1	17.6	16.9	17.4
35.3	39.3	35.3	35.2	37.1	38.1	40.0	36.5	37.1	36.9	36.3	36.9
11.5	10.5	10.1	10.5	12.2	8.6	10.8	10.4	10.9	10.7	11.0	10.5
3.8	4.0	4.0	4.6	4.2	4.0	4.0	4.3	4.1	4.1	4.2	4.1
1.8	1.5	1.2	1.6	1.5	1.0	1.8	1.5	1.5	1.5	1.5	1.5

TABLE III RAINFALL VALUES COLLECTED BY THE GAUGE NETWORK IN THE LAKEHEAD CATCHMENT

each site, whether it gave high or low readings and the conclusions drawn from this, could only be made by comparison between the arithmetic mean and the actual amount of the gauge catch. The average values derived by the other methods have been weighted according to the area represented, and therefore were not comparable. Furthermore, the most suitable sampling sites were not necessarily those that most closely represented the arithmetic mean value, but those that most closely represented the mean value which was thought to be the most realistic approximation for the whole area. The best site was the one that was usually the closest in all the various methods of analysis. Site 2. This site gave consistently low measures since it was the lowest site in the basin, and there was an expected increase in rainfall with altitude. Furthermore, the actual site being on an interfluve was more likely to be over exposed to wind. The performance of this site was much better when viewed in terms of the weighted area representation than when it was compared with the arithmetic mean.

Site 3. When viewed in terms of the arithmetic mean this site appeared to be very reliable, 50% of the observations being  $\pm 5\%$  mean. Overall, the site tended to give high values, suggesting that the position was relatively sheltered. If this site was viewed in terms of the area it represented c 7.7% of the catchment, the performance was even better; 60% of the observations were  $\pm 5\%$ .

Site 4. This site gave consistently low measurements, which were undoubtedly a result of its very exposed position.

This was further emphasised by the fact that for 30% of the observations the gauge recorded -20% mean. On the other hand when compared with the area weighted mean values 40% of the observations were  $\pm 5\%$  mean. This was because the area represented by this gauge was c.20% of the catchment area, and therefore exerted a strong influence upon the mean value obtained by these methods.

Site 5. This gauge, though giving slightly low readings, was for 50% of the observations  $\pm 5\%$  mean, and for 65% of the observations  $\pm 10\%$  mean. Since this gauge was near the centre of the catchment, and not unduly exposed, this was to be expected. When compared with the area weighted mean values the reliability of the gauge remained high, though still giving a slightly low reading.

Site 6. This siting gave results very similar to those at site 5., as its position in the area would suggest. The attempt to give the gauge protection from exposure by setting it in heather appeared to have been successful since it gave measures equally spread on either side of the mean for all analyses.

Site 7. The results from this gauge were remarkable in that they were evenly spread on each side of the mean when one would expect consistently low readings on account of its extremely exposed position. However, since the gauge was near the top of the catchment it collected more than the average during calm weather. The reliability of the site was poor; for 50% of the observations it was reading greater than  $\pm 15\%$  of the mean.

Sites 8 and 9. These two gauges consistently gave higher than average values, partly because of their position in

the upper part of the catchment and partly because attempts were made to protect them from wind exposure (by placing gauge 8 amongst heather and gauge 9 in a natural hollow). These sites frequently deviated from the mean by as much as  $\pm 15\%$ .

As a result of this study two sites were chosen to give representative measures of the precipitation falling on the catchment. The two most reliable sites were 5 and 6, but 6 was unacceptable for longer period gauging since it was remote with very difficult access during the winter period. A compromise position was selected between the two sites (Site A). For the second station (Site B) the third most reliable gauge, 3, was chosen; this had the additional advantage that it was on the other side of the catchment from the first site.

#### Instruments for recording precipitation

A brief mention has already been made to one of the problems of measuring precipitation falling in the form of snow. The lightness of the snow flakes made them far more susceptible to the eddies around the gauge, and therefore a much greater proportion of the fall was driven from the gauge resulting in an inaccurate measure. Furthermore, the snow would often be redistributed by later winds and a certain amount of the snow would be blown into the gauges and thus measured as additional precipitation. The problem of expressing snowfall in terms of areal distribution was even more difficult than that of rainfall since the snow drifted and caused an irregular and uneven distribution; only with a very high

density of measuring sites can an attempt be made.

When the standard gauge is buried by a depth of snow greater than 12", the catch of the gauge can be regarded as a very approximate measure of the depth of snow, in terms of its water equivalent that was lying above the gauge. For a depth of snow of less than 12", only the amount of snow trapped in the funnel can be measured. The ground level gauge was less satisfactory under snow conditions, for very often it became flooded, and far from giving a measure of the snow melt immediately above the gauge, it acted as a drain for the snow melt from the surrounding surface. Snow measurements made with equipment specifically designed to measure rainfall are unsatisfactory, but only in areas of very frequent snowfall can the use of expensive, specific snow measuring equipment be justified.

The distribution of rainfall in time is as important in a catchment study as its distribution in space, and the standard rain gauge can only give the observer the total fall of precipitation since the last reading. The purpose of the rainfall recorder is to measure the time, duration and amount of each period of precipitation, and also by computation from these data, the intensity of the falls. In the case of snowfall, it is not the time of the fall itself, but the time of the snow melt which is important.

In the United Kingdom, two basic types of recorder are in operation: the tipping bucket recorder and the self-emptying float recorder.

1. The tipping bucket recorder.

The principle of this recorder is that a bucket - divided into two compartments - is so arranged that when one compartment has received a certain amount of rain it tips and empties itself and brings the second compartment into a position to receive the precipitation. When this second compartment is full the process is reversed, and the first bucket is tipped back into service again. Each tip of the bucket, which usually represents a catch of 0.01", is recorded either mechanically or electrically on a recording drum. There are a number of objections to this recorder.

Firstly, a fall of rain of less than the capacity of the compartment will not be recorded at the time of occurrence, but will be included in the next period of rainfall, and in the meantime evaporation may well occur from this body of water.

Secondly, the bucket is designed to tip exactly at the moment that it contains a weight of water equal to 0.01". This calibration can be made for only one intensity of rainfall at any one time, and therefore if the rainfall intensity is greater than that for which the recorder is calibrated, the inertia of the falling water will cause the bucket to tip prematurely, while for a lesser intensity rainstorm the bucket will tip later.

Thirdly, since this gauge will only register when a certain amount of rain has fallen, it does not give a truly continuous record of rainfall but rather just a record of the time at which the rainfall total reached certain amounts.

Moreover, it is not a good recorder for misty rain.

Fourthly, any rain falling while the mechanism is tipping will not be recorded, and the greater the intensity of the storm the greater this loss will be.

Against these objections however, the recorder has the advantage of having a very simple mechanism that is unlikely to be damaged in freezing conditions.

## 2. Self-emptying float recorders.

The float gauge collects the precipitation in a chamber, and the volume of water collected is registered by the height of the float inside the chamber. The height of the float is transmitted by the float rod and registered by the pen on a moving chart. The natural siphon recorder empties itself when the float chamber has become sufficiently full to exclude air from the siphoning pipe. On the other hand when the Dines tilting siphon recorder chamber is full it tilts forward and causes a siphoning action to begin. When the chamber is empty it tips back to its original position where it is locked until the chamber is full once again (Fig.12). The Dines tilting siphon recorder is the usual standard recorder gauge in the United Kingdom.

These recorders have several disadvantages. Firstly, they are very vulnerable to freezing conditions, since the mechanism is above the ground and consequently gets no protection from the soil. As the rain is stored in an enclosed chamber, either the chamber or the float may become ruptured if the water freezes.

Secondly, unless the siphon mechanism is regularly



FIG 12 DINES RECORDER GAUGE WITH EXTENDED CHART

maintained it tends to become unreliable. The Dines recorder is better in this respect since the siphoning action is caused by a positive tilting action, but it is possible with the natural siphon for water to seep away down the pipe without creating a siphon action.

Thirdly, rain falling while the gauge is siphoning will not be recorded, but this is likely to be<sup>a</sup> minimal amount in every 5 mm. of rainfall.

Normally a daily chart is fitted to those recorders giving a chart travel of c.0.45 in/hr.; but since this requires daily visits it is of little value in a remote area. The Meteorological Office uses strip chart mechanisms to give a very much more extended chart travel of c.6 in/hr. The Road Research Laboratory, being more concerned with the problems of rain recording in remote areas where frequent visits are impractical, has also developed a strip chart mechanism that will operate for one month without attention but still give a coverage of 1 in/hr. (Fig.12).

Most of the problems of the self-emptying rain recorder are directly or indirectly attributable to the siphoning mechanism. The Road Research Laboratory has designed a recorder to overcome many of these problems - the T.S.L. Recorder (Tape recording, Storage, Long duration), and this gauge has been described in the Road Research Laboratory Report, RRL, LR.207. The principle of operation is simple, rain is fed into a float chamber with a capacity of 250 mm., which is sufficiently large to contain at least one month's rainfall without having to be emptied. The height of the float is registered, via

a transducer, on a data logger at predetermined intervals, usually every two or four minutes. This recorder is set low in the ground so that the insulation from the soil will prevent the rain in the float chamber from freezing.

During extremely cold periods anti-freeze can be added which, since the gauge will not empty itself, will remain effective until the gauge is next attended.

One of the disadvantages common to most of the other recorders, not suffered by the T.S.L., is that of size. In order to collect sufficient rain to activate the recording mechanism the gauges have to be much larger, and since they also have to house the mechanism they must be much bulkier than the standard gauge; consequently they are much more exposed to wind conditions. The T.S.L., having the logger housed at a distance from the gauge, can be made to the same specifications as the standard gauge. The precipitation collected by the gauge is recorded on magnetic tape which can be translated to give both a paper tape for direct use in a computer, and a print out of the record. Though the use of magnetic tape avoids the laborious manual preparation of data for computerisation, it has the definite disadvantage that no immediate visual trace of rainfall is available, and recorder faults will remain undetected until the tapes have been translated, which could mean a loss of records for at least as long as one month.

Technical information about both the gauge and the logger, together with preliminary laboratory tests, are given in the Road Research Laboratory Report, No. RRL. LR207. (Prudhoe and Rutledge, 1969).

Instrumentation at the two selected sites October 1968 - September 1970

The problem of instrumenting the Lanehead catchment for precipitation recording was examined with two main considerations in mind. Firstly, there was the physical difficulty of obtaining samples of the rainfall with maximum accuracy in an upland area where all sites were exposed to strong winds and all could be expected to give inaccurate measures. Secondly, since the accuracy of the precipitation data would improve as the number of gauges increased, the standard of accuracy desired had to be weighed against the increased investment in time required to attend to the larger number of gauges.

At each station weekly measurements of precipitation were taken from a standard gauge and from a ground level gauge. Undoubtedly the ground level gauge gave a more accurate measure of the fall than the standard gauge, but the latter was important since it produced a 'standard' which could be compared with nearby Meteorological Office maintained gauges; furthermore, this gauge was occasionally the only measure available when the ground level gauge was covered with snow. A continuous record of rainfall at each station was made by a Dines tilting siphon recorder. These were fitted with a clockwork strip chart mechanism with an open scale of 6 in/hr. The Dines recorders had several advantages over the other types of recorders; they could be fitted with an extended strip chart, the tipping mechanism gave an accurate tip every 5 mm. when other recorders tended to be less reliable, and light rain could be recorded and clearly identified on the open scale.

At Site A a T.S.L. recorder was installed. This recorder had not been fully field tested, and its reliability, accuracy and value in a project like this was unknown. The logger was housed in a metal bunker set in the ground to maintain a constant temperature, and was set to record every four minutes.

The problem of precipitation measurement in the catchment and an appraisal of the performance of the various gauges is dealt with in Chapter 5, together with the more specific problems of rainfall measurements in an upland catchment.

## CHAPTER 3

### THE MEASUREMENT OF AIR AND

### WATER TEMPERATURES

Despite its important implications, stream water temperature fluctuations have attracted surprisingly few studies. The control exerted by river temperatures upon aquatic life has long been recognised by ecologists, but the importance of the thermal regime of a river in a much wider setting has not inspired much investigation. The hydrological study of water temperatures, as distinct from the biological or ecological study, has, however, a very wide range of applications. A direct application would be the effectiveness of a river for industrial cooling purposes, while indirectly the thermal characteristics of a river affect its susceptibility to pollution, and consequently purification problems. (Herschey 1965).

The majority of studies have been made by biologists, concerned with water temperature as a factor influencing the distribution of aquatic life. (Macan 1958, Edington 1966). In these studies the emphasis has been upon the detailed investigations of the temperature distribution within a stream, and the controlling influences of the extreme temperature conditions. Attempts have been made to explain the distribution of certain species, such as the flatworm (Crenobia alpina), in terms of the temperature within a stream. On the otherhand it is well known that certain species of fish and plants cannot survive in

water temperatures which exceed certain critical values. The concept of temperature extremes, and the terms 'heat death' and 'cold death' are relative, and may refer to very different temperatures, depending upon the species. Long before these fatal values are reached the breeding habits of the species is often seriously impaired (Wood 1968).

Pioneer studies of water temperature related to hydrological and climatological factors have been carried out by Eckel (1951) in Austria. The river temperature represents a balance between the input and output of heat energy. The temperature is affected by the direct radiation, ambient air temperatures, the temperature of water draining from the soil and the temperature of the ground water. The water at any point is also obviously affected by the conditions existing farther upstream. Where the value of heat supplied to the stream is greater than the water temperature it will absorb heat and become warmer; where the supply of heat is less than that of the stream, the temperature will fall.

The response of a stream to any source of heat will be conditioned by certain intrinsic factors; for example, the larger the volume of water the slower will be any response to radiation or air temperature conditions, and the smaller will be the effect of the ground water contributions; secondly, the initial temperature of the stream may well exert strong control over the effectiveness of a given heat exchange.

The general instrumentation, including the choice

of instruments and the specific siting of the instruments, must be planned with regard to the problems to which it is to be applied. In the Lanehead catchment temperature data were required for several main avenues of research; to study the effect of freezing conditions on the discharge from the catchment, and the influence of changing air temperatures upon the water temperature. In order to do this three parameters had to be measured, air temperature, water temperature and ground water temperature.

Temperature measurements can be made by three basic methods. Firstly by recording the differential expansion of a liquid, usually mercury or ethyl alcohol, with respect to its container. The most usual thermometer of this type is the mercury-in-glass thermometer. A tube with a fine bore is attached to the main bulb or mercury reservoir. The change in the volume of the mercury, in relation to the glass container, resulting from a change in temperature is shown by the change in the position of the column of mercury in the tube, which is graduated to give a direct temperature reading. Secondly, temperature can be measured by a bimetallic strip thermometer. The bimetallic strip is a laminated strip of two metals having different coefficients of linear expansion. Changes in the temperature of the strip, causing the two metals to expand or contract by different amounts, will cause the curvature of the strip to alter. If one end of the strip is fixed then the movement of the free end can be measured and the movement calibrated to give a direct temperature reading. Thirdly, temperatures can be measured electrically either by the measurement of the electrical resistance

of a metal, or in a thermocouple of two different metals. A measurement of the electrical resistance in a metal, the resistance of which varies in a known manner with temperature changes, can be converted to a temperature reading. In a thermocouple two different metals are joined together to make a continuous circuit. If one metal has a different temperature from the other, then a current is set up in the circuit, and the greater the temperature difference the greater the current induced. If one of these junctions is maintained at a reference temperature while the other adopts the temperature it is required to measure, the current induced will give a measure of the difference between the reference and the variable temperatures, and from this the temperature can be converted to the required temperature scale.

Thermographs, thermometers designed to give a continuous record of temperature changes, function in a similar way to the ordinary thermometers. The mercury-in-steel thermograph operates on the same principle as the mercury-in-glass thermometer, the expansion or contraction of the mercury in the temperature sensitive probe is transmitted along capillary tubing. The movement of the mercury in the tube is transferred as an angular rotation on to a spindle which operates a pen tracing on a revolving drum. This thermograph has the advantage that the recording mechanism can, within limits, be remote from the temperature sensitive probe, thus making it a very suitable instrument for recording water temperatures.

The bimetallic thermograph differs from the equivalent

thermometer only in respect of the recording mechanism. The thermometer usually registers the temperature by means of a pointer against a scale whereas in the thermograph the pointer is replaced by a pen which draws a trace on a revolving drum. Unlike other thermographs it is not possible to record at a distance from the sensitive element, and it is therefore only suitable for measuring air temperatures. On the other hand the lag of this recorder is less than that of a mercury-in-glass thermometer.

The electrical thermometers can be changed into thermographs simply by changing the direct reading galvanometer into a recording galvanometer. This type of thermograph has several advantages; the recorder can be housed at quite a considerable distance from the sensitive element, even over long distances virtually no recording lag occurs and the sensitive element, while being very responsive to temperature changes, has a very low sensitivity to radiation. Against this however it has the two often overwhelming disadvantages of being very expensive and requiring main voltage electricity.

#### Temperature Instrumentation in the Lanehead Catchment

In Fig.13, the position of the various temperature recorders in the catchment is illustrated.

#### Air Temperature

The problems involved in measuring the temperature of the air are very similar to those encountered in obtaining valid precipitation data, in that, not only must

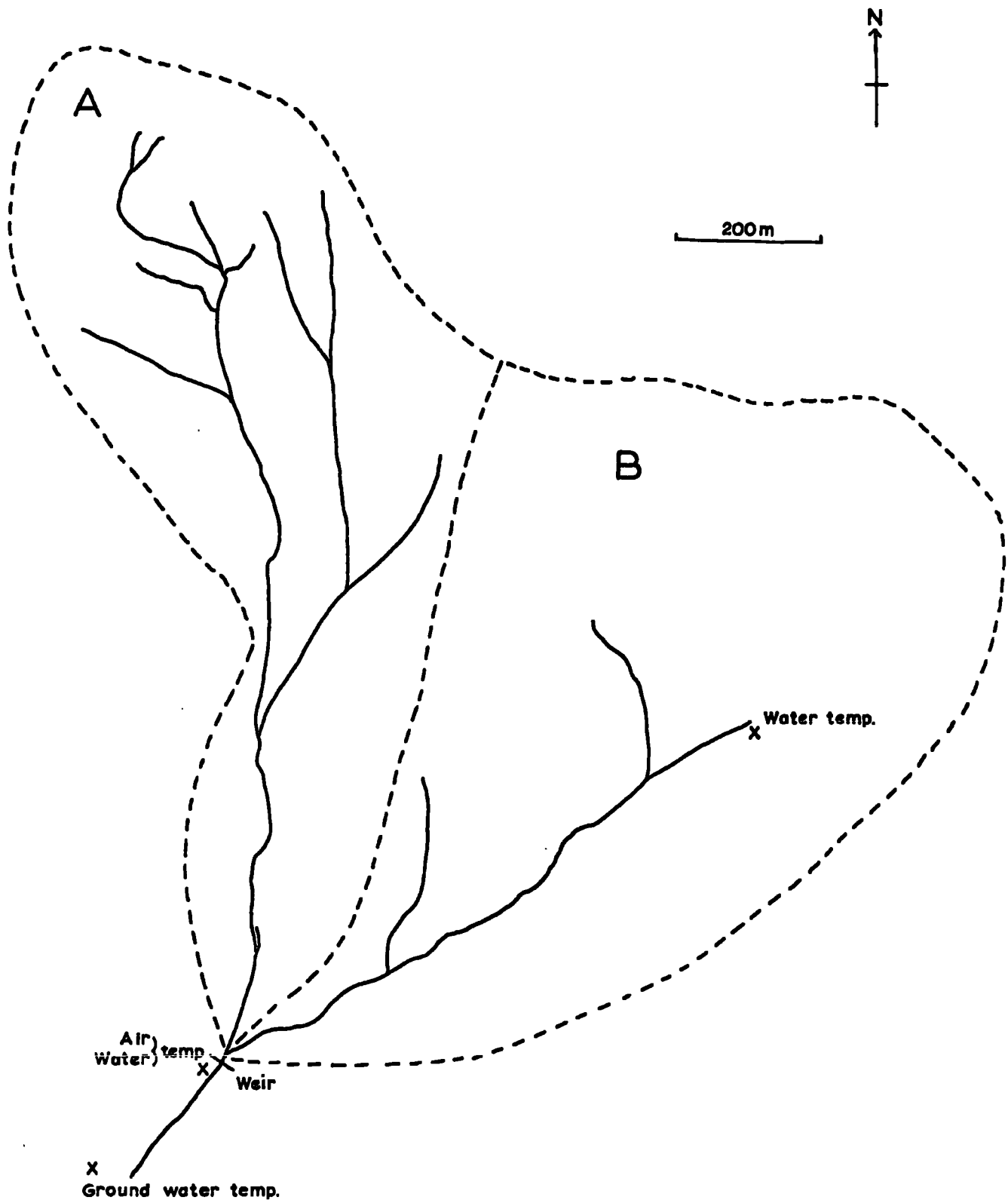


FIG 13

CONTINUOUS RECORDING TEMPERATURE  
GAUGE SITES

the validity of the point measurement be carefully analysed, but the areal application of such measurements must be carried out with a certain amount of caution. The aim of this instrumentation was to fulfill two main objectives. Firstly, to sample the temperature over the whole catchment in order to determine when the discharge from the catchment was being influenced by different temperature environments, for example when the catchment was in freezing conditions. Secondly, to measure the fluctuations of air temperatures in comparison with the fluctuations of water temperature. The first of these two objectives did not impose any restrictions upon the location of the measuring site provided that it was remembered that the reading did not necessarily represent an absolute temperature value for the whole catchment. On the other hand the second objective did impose a restriction, since in order to measure the relationship between the stream temperature and the air temperature it was necessary to measure these two in close proximity.

Any attempt to measure air temperature is accompanied by the problem of shielding the sensor from radiation. Radiation from the sun, clouds or the ground can pass through the air without appreciably affecting its temperature but any thermometer element exposed in free air will absorb radiation to a considerable extent and therefore its temperature may differ from that of the air. Even where the sensor is shielded from direct radiation the air flowing over the shield is likely to be warmed, and although the problem of radiation may be reduced it

is probably not eliminated. The Meteorological Office specifications for an ideal shield are as follows:

1. The screen should be a 'uniform temperature enclosure'.
  2. The temperature of the inner walls should be the same as that of the external air which is to be measured.
  3. The thermometer sensor should be completely surrounded by the shield.
  4. The shield should be impervious to radiation.
- (H.M.S.O. Handbook of Meteorological instruments).

Although conditions 3 and 4 are easily satisfied, 1 and 2 are virtually impossible to achieve, and therefore it is very important to have a standard type of shield so that all air temperature measurements are subjected to the same degree of error and are therefore comparable. The standard shield in the U.K. is the Stevenson Screen. These screens are painted white to reflect the maximum amount of radiation. The walls are constructed of louvers to allow the maximum circulation of air, and are double thickness so that, although the outside wall might become heated to a high temperature by absorbing radiation, the layer of air between the walls will reduce the amount of heat that is conducted to the inner wall and to the enclosure. Good circulation of air is essential, not only to keep a constant change of air between the double walls, but also to ensure that a change of air temperature is rapidly experienced inside the enclosure.

A Casella bimetallic thermograph was installed in

the catchment, housed in a standard Stevenson screen, adjacent to the site chosen for water temperature measurement (Fig.14a). The instrument was accurate to  $\pm 0.5^{\circ}\text{C}$  and could be read to  $\pm 0.1^{\circ}\text{C}$  (Maker's pamphlet) yet the sensitivity of the instrument was not so great that very rapidly fluctuating temperatures would give a blurred trace. The thermograph was checked weekly against a National Physical Laboratory certificated mercury-in-glass thermometer, accurate to  $\pm 0.05^{\circ}\text{C}$ .

In December 1969 this thermograph was replaced with a Negretti and Zambra recorder because it had a larger chart scale and would give a more accurate trace, but more important because it had distinct advantages for snow conditions. During blizzards the screen invariably became filled with snow and the more robust housing of the Negretti recorder prevented this from fouling the recording mechanism and secondly, since the bimetallic strip was in a coil it was less susceptible to snow lying on it and thereby affecting the recording. (The Casella recorder had a flat strip 8 cms. long and 2 cms. wide, which would support a significant weight of snow and made the strip unresponsive to changes in air temperature).

While this location was eminently suitable for obtaining air temperature measurements that could be related to the water temperature conditions it was by no means certain that the temperature reading would be typical of the catchment as a whole. In order to estimate the approximate relationship between the site temperature reading and the mean value for the catchment

A



AIR TEMPERATURE  
RECORDER

B



SOURCE WATER  
SITE

C



GROUND WATER  
SITE

FIG 14

a thermograph was placed in a higher part of the catchment so that the temperature at the two sites could be compared. However this site in the upper catchment had to be abandoned after a few weeks, since its location was very exposed and during periods of snowfall the screen became filled with drifting snow, and during periods of rain the thermograph became saturated with water, causing clock failure and recording errors in both cases.

### Water Temperature

The suitability of a measuring instrument depends upon the aims of the study. The Lanehead catchment required instrumentation to record the general trends in the fluctuations of water temperature. Since the response of stream temperature to a source of heat will obviously depend in part upon the volume of the stream the choice of location for the temperature probe will ideally be at a point where discharge measurements are being made. This restriction upon the choice of measuring sites emphasises the problem of 'sampling error'. The temperature of the stream is likely to respond mainly to the influence of direct radiation and to the air temperature. Where a stream is deep and where pools of still water occur, the effect of radiation is likely to be great, whereas a steep, shallow, fast flowing stream is likely to be influenced more by the temperature of the air. The siting of the sensor element should be <sup>a</sup>balance between these two. Since water

temperature varies along a stream, its temperature characteristics cannot be represented by a one-point measurement although the general condition can be deduced particularly where sample temperature sequences have been made along the course of the stream.

The water temperature of the Lanehead catchment was measured by a Negretti and Zambra mercury-in-steel thermograph at the gauging site. The instrument was guaranteed accurate  $\pm 0.5^{\circ}\text{C}$ , but could be read to  $\pm 0.1^{\circ}\text{C}$ ; chart travel was 2 ins. per day (Negretti-Zambra instrument pamphlet). The recorder was housed in the weir's instrument hut and the thermometer element placed in continuously moving water upstream of the weir. A steel rod was driven into the bed of the stream and to this the sensor element of the thermograph was attached in such a way that it was pointing with the current at a depth of 8 cms. below the surface of the stream at its lowest level of discharge. The sensor unit exposed in the water is subjected to similar radiation errors as one exposed in the air, but in the case of water temperature records, there is no standard shield. At this site the sensor was sheathed in a white plastic tube, 20 cms. long with an internal diameter of 3 cms., to shield the sensor from direct radiation. The shield was perforated with small holes to prevent the stagnation of water around the probe, and, since the sheathed probe was sited in flowing water, this ensured that the movement of water past the probe was sufficiently rapid to reduce the possibility of any heating of the shield significantly affecting the temperature measurement. The use of such a shield was

considered to be particularly important for water temperature measurements, since the probe would be exposed to varying degrees of exposure to radiation consequent upon the fluctuating water stage.

Although the water immediately upstream of the weir had been deliberately over deepened, it was thought that the proximity of the weir would ensure that no stagnation of the water could occur around the temperature probe. However during the periods of very high water temperatures during the summer of 1969 when the discharge of the stream was very low, it was found that the temperature in the stilling pool could be as much as  $1^{\circ}\text{C}$  higher than the stream water above and below the weir. In August 1969, the thermograph was moved 40m. upstream so that it was above the maximum extent of the stilling pool. The sensor probe was secured to a steel rod which was driven into the stream bed, but at this site it was necessary to place the element in such a position that it was always in a flow of continuously moving water. During low flows the stream had to be partially dammed in order to direct the flow of water into a relatively well defined channel over the probe, while in periods of high flow the probe had to be cleared regularly of bed material deposited over it.

The mean annual temperature for air and stream water at this site for the two water years 1968/69 and 1969/70 support the doubts about the first site.

	<u>Air Temperature</u>	<u>Water Temperature</u>
1968/69	5.7°C	6.9°C
1969/70	6.25°C	6.9°C

While the mean air temperature for 1969/70 was 0.5°C warmer than the previous year there is no difference in mean water temperature. Furthermore, despite the higher mean monthly air temperatures for the summer of 1969/70, the water temperatures were colder than those during the corresponding period of the year 1968/69.

	Mean air temperature (°C)		Mean water temperature (°C)	
	1968/69	1969/70	1968/69	1969/70
June	9.8	13.2	12.2	14.3
July	12.7	12.2	14.23	12.3
August	12.73	13.5	14.45	13.8
September	10.4	12.0	11.1	10.9

#### Ground Water temperature

Apart from drilling specific boreholes, the occurrence of suitable sites for measuring ground water temperature is very restricted, but there was no real problem of areal representation since variations of ground water temperature would be small. At Lanehead ground water flowing from a disused lead-mine adit could be conveniently instrumented, and although the site was not strictly within the limits of the experimental catchment it was draining from the same limestone formation that was supplying most of the base flow for the catchment (Fig.14c). The ground water temperature was recorded with a Negretti and Zambra mercury-in-steel thermograph of the same type as that used for measuring the

stream water temperature. Not only was the sensor shielded, as at the stream water site, but it was located in the tunnel of the adit in order that the effects of air temperature upon the ground water at the point of measurement would be minimal.

#### Source water temperature

Since the ground water temperature did not vary from 7°C for the twelve month period October 1968 - November 1969, the recorder was re-sited more usefully in the headwaters of tributary B at the point where the stream adopted a recognisable main channel (Fig.14b). The thermograph probe was housed in a plastic shield and sited in a continuous flow of water, in the same way as at the weir site. At this site the probe had constantly to be cleaned of peat debris which collected around it. Data from this site were compared with that collected at the weir site, and these together provided the framework into which more detailed studies of the water temperature down the stream, could be placed.

## CHAPTER 4

### THE MEASUREMENT OF STREAM DISCHARGE

Discharge measurements are concerned with the volume of water passing a certain point in a drainage basin system during a particular period of time. This volume will be the product of the cross sectional area of the stream and the rate at which the stream is flowing. If these two parameters can be measured then discharge can be calculated:

$$Q = A \times V$$

The cross section is defined as the section normal to the direction of flow bounded by the free surface and the wetted perimeter of the stream. The wetted perimeter of the stream can be determined by accurate survey, though this will be subject to alteration with the movement of bed material. The cross sectional area of the stream can be obtained from the wetted perimeter section merely by a measure of the height or stage of the stream. This measurement can most easily be obtained for periodic observations from a staff gauge - a graduated datum scale set in the stream from which the level of the stream can be read; or, where continuous readings are required, the height can be registered on a moving chart by means of a float mechanism. Several other methods exist but basically all methods are a measure of the height of the water above a fixed datum level.

The second parameter, stream velocity, is more difficult to calculate, partly because this varies over

the width and depth of the stream and partly because it is difficult to obtain a continuous record. The simplest form of measurement is the use of a float such as cork or wood which can be timed over a measured distance. This is far from a totally satisfactory method of measuring velocity because, at best, the float will travel at the speed of the fastest water at the surface, and, at the worst, it will become trapped either by an obstruction or in pools of dead water. The use of a dye or chemical tracer overcomes these problems, but it has the two disadvantages that the injected solution tends to diffuse and therefore becomes difficult to detect over long distances, and secondly, when a non visible tracer is used, results cannot be obtained until a laboratory analysis has taken place.

The current meter provides a more sophisticated method of measurement. A small propellor which is kept at right angles to the flow of the stream by means of tail fins, and which is ballasted to keep its position satisfactory in the stream, is immersed at a certain point in the stream. The flow of water past the propeller causes it to rotate, and the speed of rotation can be converted into stream velocity.

If one of these parameters, cross sectional area or velocity, can be stabilised, then the measurement of discharge can be related to the other parameter. The cross sectional area of the stream can be only partially stabilised since it will depend upon a measurement of stage; but if the rate of flow can be regularised, or at least related to the measurement of stage, then the dis-

charge can be computed from the one measurement of stage. When an obstruction is placed across a stream so that the flow upstream of the obstruction is independent of the flow downstream, the flow of water over the obstruction will be related to the height of the fall, the acceleration due to gravity and the nature of the obstruction:

$$v^2 = 2.g.h.$$

Both a weir and a flume can act as such an obstruction to create modular flow conditions but by different means and therefore with different attributes. Both structures provide a standardised and known cross section, and both cause the water to fall from the upstream level to the downstream level under gravity. The weir separates these two levels by a vertical fall. The flume causes the separation, not by a total fall, but by widening the channel below a formed contraction of the sides so that the water accelerates to a super critical velocity. The effect of the super critical flow is exactly the same as the fall over the weir since no gravity waves can travel upstream against the super critical currents, and therefore the downstream water body can have no affect upon the water body above the flume.

The theoretical calibration of the gauging structure becomes a product of the acceleration due to gravity, the head of water over the structure and the form of the structure.

Discharge	Gravity	x	Head	x	Form
Q	= 2/3	2g	$h^{3/2}$	b	Rect. thin plate
Q	= 8/15	2g	$h^{5/2}$	$\tan \frac{\theta}{2}$	V-notch
Q	= 2/3	$\frac{2}{3}g$	$h^{3/2}$	b	Trapezoidal flume
Q	= 4/5	g	$h^{5/2}$	n	Flat vee weir

(From British Standards Institution 3680 (1965) Measurement of liquid flow in open channels).

Many variations of these two types of gauging structure exist which differ only in the shape and nature of the control section. A vee shaped crest or flume throat gives a more sensitive measure of low flows but is less suitable for higher discharges as it requires a greater range of head measurement than a wider rectangular control section. The choice of structure depends upon the conditions that exist at the gauging site and upon the purpose for which the structure is required. A vee shaped structure is valuable where the emphasis is upon low flow accuracy, but a rectangular shape is more suitable where a wide range of measurement is demanded.

To a greater or lesser extent all hydrological instrumentation problems become more severe in upland catchments, either as a result of the remoteness or as a result of the physical conditions which demand specialised means of instrumentation. Normally the discharge over a weir or flume can be determined from a measurement of the head of water over the structure, but when conditions in the approach section are different from those that existed when the structure was calibrated, then the stage/discharge relationship may become meaningless. Harrison and Owen (1967) have shown

that inaccuracies resulting in this way are related to high values of Froude number, and since the Froude value is related to velocity:

$$F = \frac{\text{Velocity}}{\text{gravity} \times \text{depth}}$$

then these gauging problems become more acute as the stream becomes steeper. Errors arise from the presence of standing waves, or changes in the bed level as a result of sediment movement, in the approach section.

An error in head measurement will occur if a standing wave, or a trough associated with it, becomes stationary at the point where the measurement is made. Although the errors from this are negligible where the Froude value is less than 0.4, it can cause an error of 7% when the Froude value is 0.6. An error of this nature should not go unnoticed, since the presence of the standing wave can be seen, but if the approach section channel is shaped to give relatively deep approach conditions this type of error can be prevented.

When a gauging structure is installed in a river carrying a large sediment load, several problems arise from the movement or accumulation of bed material upstream of the structure. The stage/discharge curve for a gauging structure is determined for a fixed bed level, but such a static condition cannot exist permanently. When the stream is obstructed it will endeavour to adjust itself by deposition or by scour until the depth and velocity (and therefore the Froude value) is the same as that existing before the obstruction was installed. If the discharge changes then values of velocity and depth

upstream of the obstruction will change until the values correspond to the conditions further upstream. Consequently there will be an adjustment of bed level until the appropriate value of Froude number is attained, and therefore the bed level will change with every fluctuation of discharge. Such changes in bed level can be minimised by paving the approach section so that at least scour is prevented, but very often it is necessary for the correct functioning of a weir that a certain minimum depth of water is maintained upstream (usually half the maximum head). When this condition is not fulfilled due to the accumulation of sediment, it is necessary to clear out the approach section otherwise the shallow water would produce a high value of Froude number and also super-critical flow in the approach.

The form of a gauging structure will be largely controlled by the purpose for which it is built. At Lanehead the primary aim was to measure low flows accurately to 0.1 cusecs; but at the same time it was hoped that the annual flood could be measured within an acceptable level of accuracy. A prediction of the ten year and 100 year flood was made from the catchment characteristics of slope, area and rainfall, using the empirical equations constructed by Nash and Shaw (1966):-

$$\begin{aligned}
 Q(T) &= \bar{Q} + k.6Q \\
 \bar{Q} &= 0.009 \times A^{0.85} \times R^{2.2} \\
 &= 0.009 \times 0.4062^{0.85} \times 60^{2.2} \\
 &= 34.2
 \end{aligned}$$

$$\begin{aligned}
 CV_Q &= 219 \times R^{-0.5} \\
 &= 219 \times 60^{-0.5} \\
 &= 28.3
 \end{aligned}$$

$$\begin{aligned}
 6Q &= (CV_Q/100) \times \bar{Q} \\
 &= (28.3/100) \times 34.2 \\
 &= 9.66
 \end{aligned}$$

For a return period of 100 years  $k = 3.14$ , and  
of 10 years  $k = 1.3$

$$\begin{aligned}
 \bar{Q}(100) &= \bar{Q} + k.6Q \\
 &= 34.2 + 3.14 \times 9.66 \\
 &= 64.5 \text{ cusecs}
 \end{aligned}$$

$$\begin{aligned}
 \bar{Q}(10) &= \bar{Q} + k.6Q \\
 &= 34.2 + 1.3 \times 9.66 \\
 &= 46.7 \text{ cusecs}
 \end{aligned}$$

$$\begin{aligned}
 \bar{Q} &= 0.074 \times A^{0.75} \times S \\
 &= 0.074 \times 0.4062^{0.75} \times 1050 \\
 &= 39.5 \text{ cusecs}
 \end{aligned}$$

$$\begin{aligned}
 CV_Q &= 178 \times S^{-0.25} \\
 &= 178 \times 1050^{-0.25} \\
 &= 31.27 \text{ cusecs}
 \end{aligned}$$

$$\begin{aligned}
 6Q &= (CV_Q/100) \times \bar{Q} \\
 &= (31.27/100) \times 39.5 \\
 &= 12.4 \text{ cusecs}
 \end{aligned}$$

For a return period of 100 years  $k = 3.14$ , and  
of 10 years  $k = 1.3$

$$\begin{aligned}
 \bar{Q}(100) &= \bar{Q} + k.6Q \\
 &= 39.5 + (3.14 \times 12.4) \\
 &= 78.4 \text{ cusecs}
 \end{aligned}$$

$$\begin{aligned}
\bar{Q}_{(10)} &= \bar{Q} + k.6Q \\
&= 39.5 + (1.3 \times 12.4) \\
&= 55.6 \text{ cusecs.}
\end{aligned}$$

The choice of gauging structure for the Lanehead catchment

The Lanehead catchment of 1 km<sup>2</sup>, with an average slope of 1:9.5 and a mean annual rainfall of 1600 mm. could be expected to have a flood of 78 cusecs. every 100 years, and a ten year flood of 55 cusecs. For the greater part of the year the flow would be less than 5 cusecs. (0.14 m<sup>3</sup>/s) with a dry flow of less than 0.5 cusecs. (0.014m<sup>3</sup>/s).

The site selected imposed two restrictions upon the choice of structure. The banks of the stream, though relatively high, would not contain a structure with an overall height greater than five feet without the need to build long cut-off walls across the valley (Fig.15a). Secondly, the steepness of the catchment posed the special problems already described above, in the design of the structure. The overall gradient of the stream meant that high values of Froude number, and associated high approach velocities in the stream, would be likely to make the flow super-critical. Furthermore, the stream was likely to carry a large sediment load which would tend to alter its bed level and thus modify the approach channel conditions.

Since the Froude number =  $\frac{\text{velocity}}{\text{gravity} \times \text{depth}}$  then, if the depth of the stream could be increased, the Froude number would be decreased. This could be achieved by creating a



A WEIR SITE BEFORE INSTALLATION



B WEIR FOUNDATIONS

stilling pool upstream of the gauging structure, and if this pool was made sufficiently large, it could trap sediment and prevent it reaching the approach to the gauging structure and minimise any alteration of the approach conditions. These two considerations dictated that the range of head should not exceed 0 - 3 ft. so that the remaining 2 ft. of the overall available height of 5 ft. could be used to pond up the water to create a stilling pool 30 ft. in length.

The final consideration was a purely practical one. Access to the site was difficult since the nearest road was 350 m. away, and although a Land Rover could be brought to within 150 m. of the site the final distance was down a slope of  $30^\circ$ . Thus all construction materials had to be carried manually to site, and obviously this consideration was very significant when deciding the type of structure to be built.

With these considerations in mind the choice of gauging structure was made from the following alternatives:

1. A trapezoidal critical depth flume.
2. A compound  $120^\circ$  V-notch weir.
3. A  $157^\circ$  V-notch weir.
4. A flat vee weir.

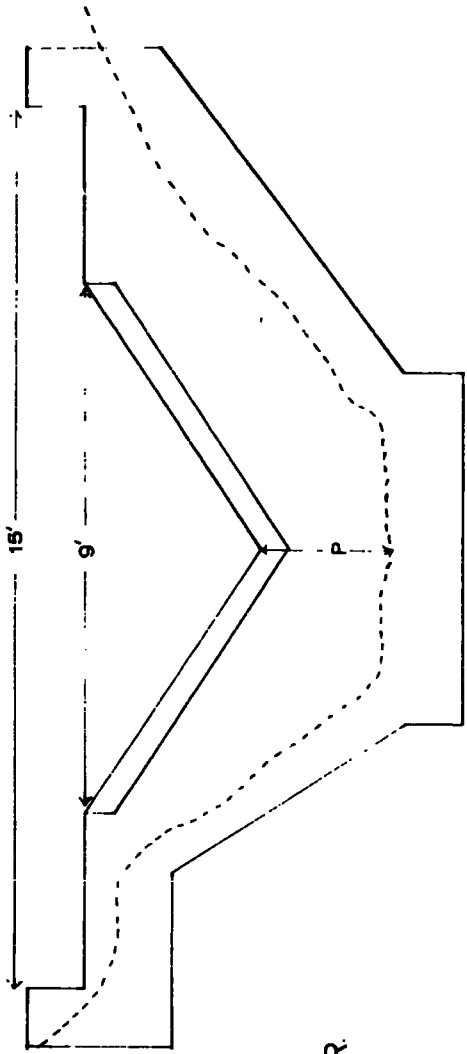
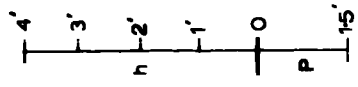
A great deal of emphasis has been given of late to the advantages of the flume method of stream gauging, and one advantage in particular recommended it in this specific problem; namely the fact that great efforts have been directed towards making such a structure in prefabricated form. The Water Research Association (1963) designed a

trapezoidal critical depth flume in  $\frac{3}{4}$ " marine plywood and the Lothians River Purification Board (Wright 1967) has produced a standardised glass fibre flume from the W.R.A. design. This flume would measure a discharge of 0.3 cusecs. at a head of 0.1 ft. but its maximum capacity was limited to 42 cusecs. at 3 ft. head. The flume could have been redesigned to cater for higher discharge, but unless a sacrifice of sensitivity at low flow as a result of widening the throat of the flume was tolerated, this could only be achieved by increasing the height of the flume to such an extent that it would not be within the 5 ft. limit imposed by the site. While it is normally regarded as one of the advantages of the flume that it is self-cleaning, in this particular situation this feature would have been a distinct disadvantage since a stilling pool could not be created without setting the already enlarged flume well above the level of the existing stream bed. Without the presence of the stilling pool the structure would be extremely vulnerable to inaccuracies as a result of high velocities through the throat section of the flume. Consequently it was necessary to think in terms of a weir, a gauging structure that would by its very nature create a stilling pool.

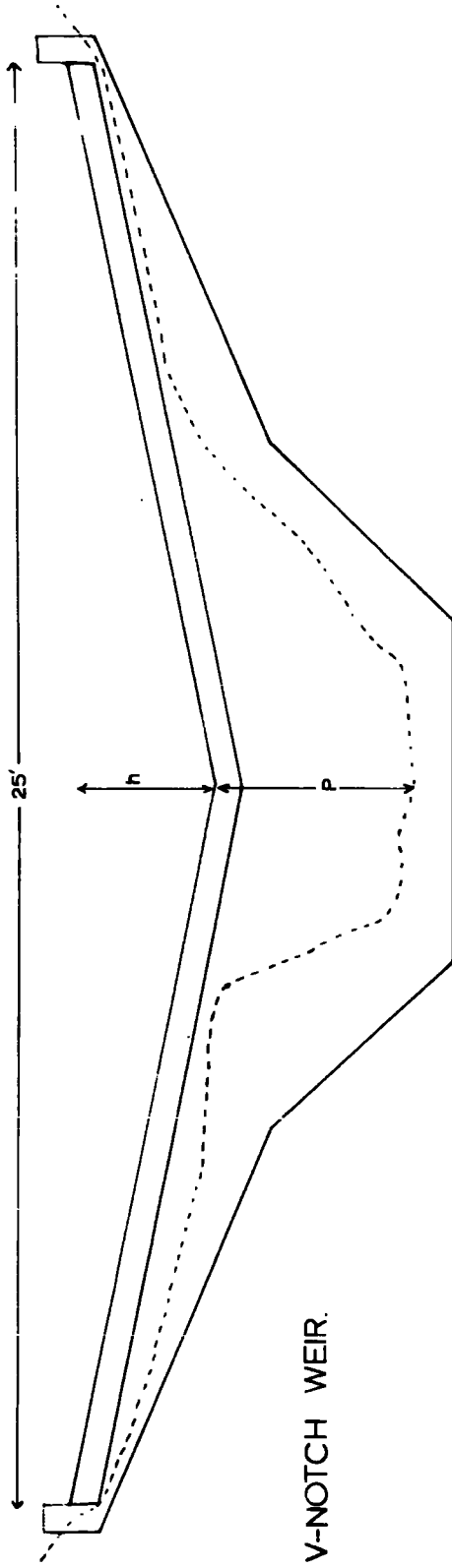
Although there is a great variety in weir types, with a resultant wide range of application, many of these types of structures were unsuitable for the Lanehead catchment. Neither a broad crested weir nor a rectangular thin plate weir were sufficiently sensitive at low flows since, in order not to fall below the minimum measurable head recommended by the British Standard

(3680), these structures were only capable of measuring flow to 0.1 cusecs. per foot of crest. In order to obtain greater sensitivity at low flows it was necessary to consider the use of a V-notch structure, or a compounded structure incorporating a V section.

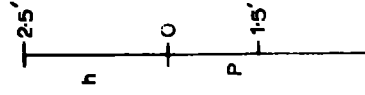
Of all the structures considered, a compounded weir appeared potentially to be the most sensitive at low flow, depending on the angle of the V-notch chosen. A  $120^{\circ}$  V-notch could measure down to 0.04 cusecs. at 0.1 ft. head, but the maximum flow measurable within the British Standard would be 10 cusecs. at 1.25 ft. head (Fig.16a). Since this head limitation had been imposed merely through lack of laboratory calibration with greater head values, it would no doubt have been acceptable to construct a V-notch with a head of 3 ft. containing a flow of 50 cusecs. Above this level the flow would be contained within a broad crested weir, containing a further 1 foot head, making an overall height of 4 feet and capacity of about 110 cusecs. Since  $\frac{\text{maximum head}}{\text{height of weir}}$  must be less than 2, the height of the weir crest would have to be 2 feet above the stream bed and the overall height of the structure would be 6 feet. This structure presented three major drawbacks. Firstly, there would have been a need for divide walls to separate the flow in the V-notch section from that over the broad crest, which would not only have added considerably to the cost of the structure since the walls would have had to be constructed for about three feet upstream of the crest, but they would also have acted as traps for trash. Secondly, there would have been a loss of accuracy when the discharge over the



COMPOUNDED 120°  
V-NOTCH WEIR.



157° V-NOTCH WEIR.



SCALE 0 feet 2

FIG 16 SUGGESTED DESIGNS FOR THE SHARP CRESTED WEIRS.

broad crest was less than the recommended measurable minimum. Thirdly, the computation of discharge at these higher stages would have been dependent upon field calibration, and, since floods in excess of 50 cusecs would be infrequent and of very short duration, the possibility of making satisfactory calibration would be remote.

Many of the problems associated with the compounded weir are a direct result of its being compounded. If a much shallower V section were to be constructed (e.g.  $157^\circ$ ) (Fig.16b), although it would be less sensitive at low flow - measuring 0.06 cusecs ( $0.0016\text{m}^3/\text{s}$ ), at 0.1 ft. head - a discharge of 125 cusecs ( $3.53\text{m}^3/\text{s}$ ) could be contained at 2.5 ft. head and the weir could be calibrated by the formula:

$$Q = 8/15 \times 2g \times C_e \times \tan \frac{\theta}{2} \times h^{5/2}$$

(British Standard Institution (3680))

throughout the whole range without the need for compounding.

The construction problems involved with both these weirs would have been very similar. Both would have required more than four cubic metres of concrete, since not only would they need relatively massive foundations, concrete aprons and stabilised banks downstream to prevent undercutting, but the compounded weir would have needed extra concrete for the construction of the divide walls. Ready mixed concrete could not be brought nearer than 350 m. to the site. Alternatively the sand and gravel could have been brought only to within 150 m. by Land Rover and thence carried manually, in addition to

being mixed manually at site. To build either of these structures in brick would have required at least 2,000 bricks together with the sand and cement needed for the foundations and the mortar. As a result of these enormous construction and access problems it was decided that a prefabricated structure offered considerable advantages.

Since the above structures were generally unsuitable, the eventual choice was a flat Vee weir, a new structure designed by the Hydraulics Research Station based upon the Crump Weir design (White 1966). The Crump weir, when designed in 1952, was an enormous advance upon the previous gauging structures. The weir had a triangular profile which, when incorporating a crest tapping point in addition to the normal piezometric tapping point enabled discharge in the non modular range to be measured, thus making the accurate measurement of high discharge possible with small afflux. It was thus no longer the first consideration of weir design that the structure should contain the flows within the modular range with the resultant lack of emphasis upon low flow measurement. By compounding, the Crump weir has proved to be a very successful structure on a wide range of rivers. However the Crump weir is not a suitable structure for very small streams, particularly where accuracy greater than 0.1 cusecs per foot width of stream is required. In order to provide accurate measurement at low flows compounding is necessary and this creates the two problems described below.

The Flat Vee weir was a modification of the Crump

weir designed to overcome these problems encountered in small streams. The triangular profile was retained so that the structure could operate in modular and non modular conditions, but accuracy at low flow was achieved by giving the normally horizontal crest a vee shape rather than by compounding. The sensitivity of the structure to measure discharges contained within the vee section would be dependent upon the slope of the arms of the vee.

#### The design and construction of the weir in the Lanehead catchment

Preliminary calculations showed that over a crest width of seven feet a discharge of 120 cusecs could be measured within a three foot head, and with a symmetrical crossfall of 1:10 a discharge of 0.1 cusecs could be gauged at 0.1 ft. head (Fig.17). The discharge could be calculated throughout the whole range by formula without initial field calibration. The design of the weir was also very suitable for the upland conditions and the steepness of the stream. The crest of the weir being 1.5 ft. above the bed of the stream, would create a stilling pool which would slow down the approach velocities and also act as a sediment trap. Since the crest had formed slopes both upstream and downstream, it would have a tendency to be self cleansing, thus requiring less attention than any other of the weir structures. Furthermore the formed approach section would reduce the risk of standing wave problems, whilst the overall height of the structure, 4.5 ft., was well within the height limit

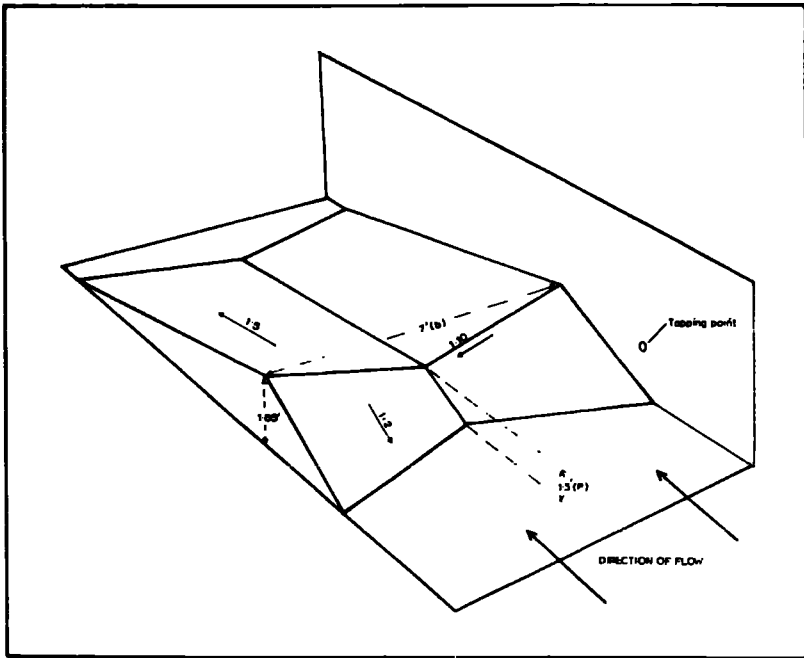


FIG 17 THE GEOMETRY OF THE FLAT VEE WEIR

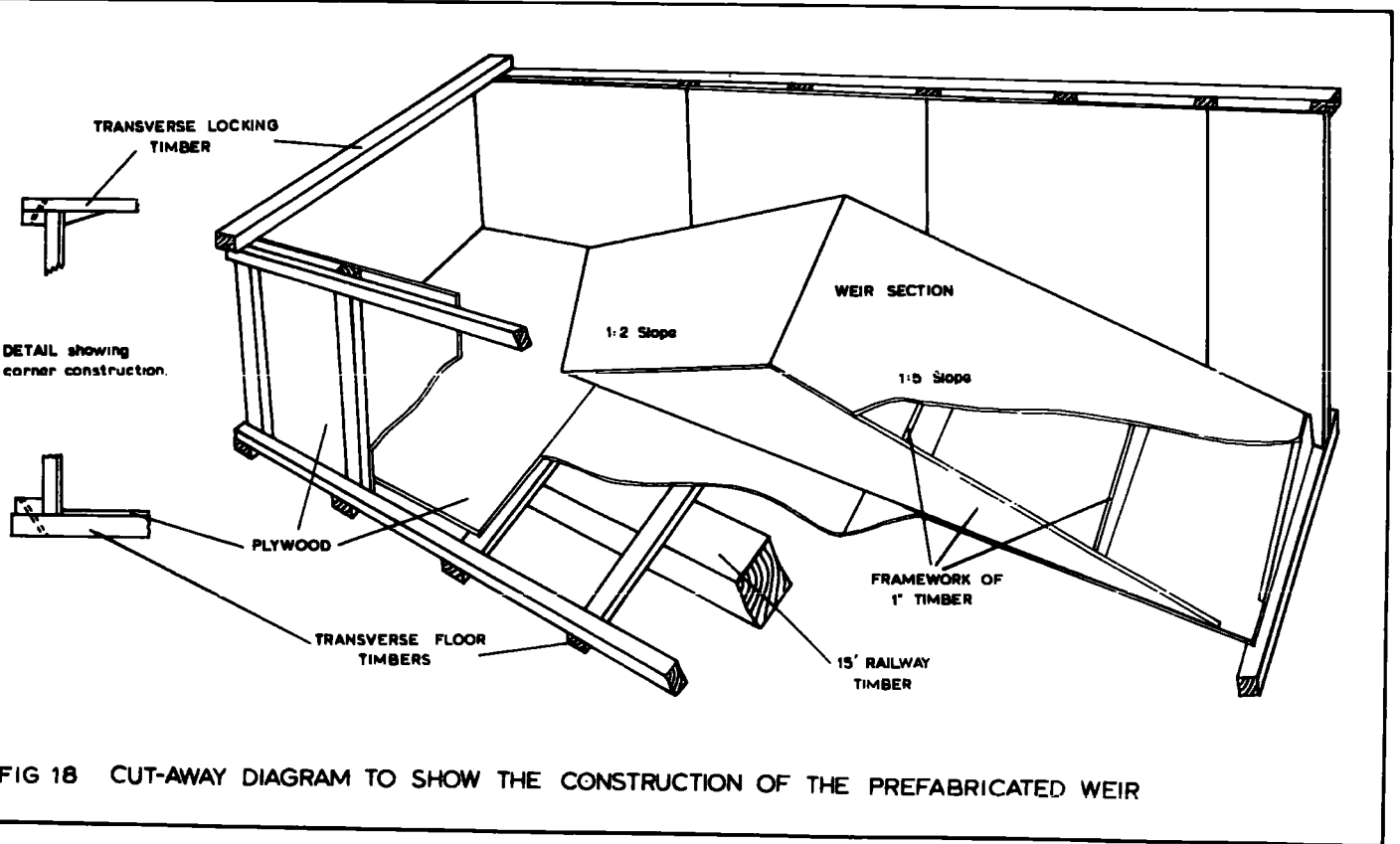


FIG 18 CUT-AWAY DIAGRAM TO SHOW THE CONSTRUCTION OF THE PREFABRICATED WEIR

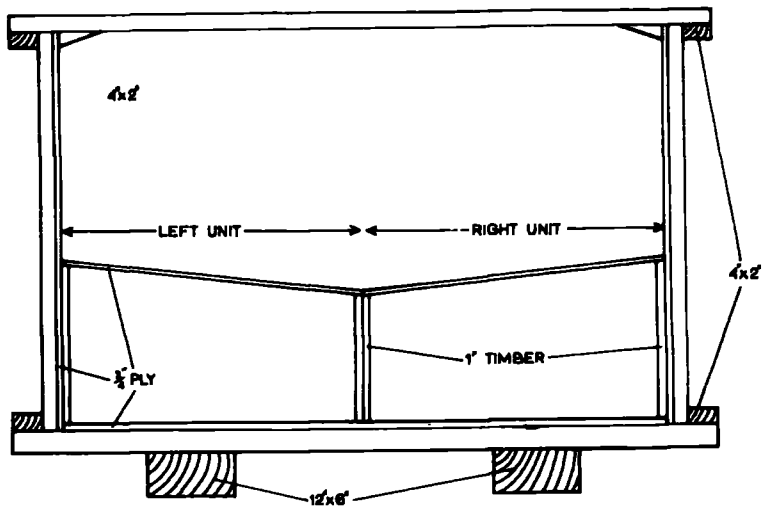
imposed by the river banks.

Like the flume, the flat vee weir can be built as a prefabricated structure in wood (Fig.18). Normally gauging structures are constructed in reinforced concrete. But this expense can only be justified when the station is expected to be in use over many years and for short term hydrological studies a less permanent structure is quite suitable. When a structure is prefabricated in such a way that it can be carried to site and assembled manually, it does not impose the same serious limitations upon the choice of site imposed where access for concrete supply vehicles is required. Because of the lightness of a prefabricated structure it could be laid upon timber foundations and thus still further reduce the amount of concrete needed at site. At Lanehead, 15 foot railway timbers were used as foundations (Fig.15b). The greater part of the construction work could be carried out in a workshop independent of environmental conditions and the amount of wasted skilled labour and time lost through bad weather was kept to a minimum. This proved to be an important consideration since September 1968, when construction work was in progress, was the wettest in Durham for 24 years. The preparation of site would be much easier and less vulnerable to sudden flood conditions if concreting was reduced - an important consideration where stream fluctuations are very rapid.

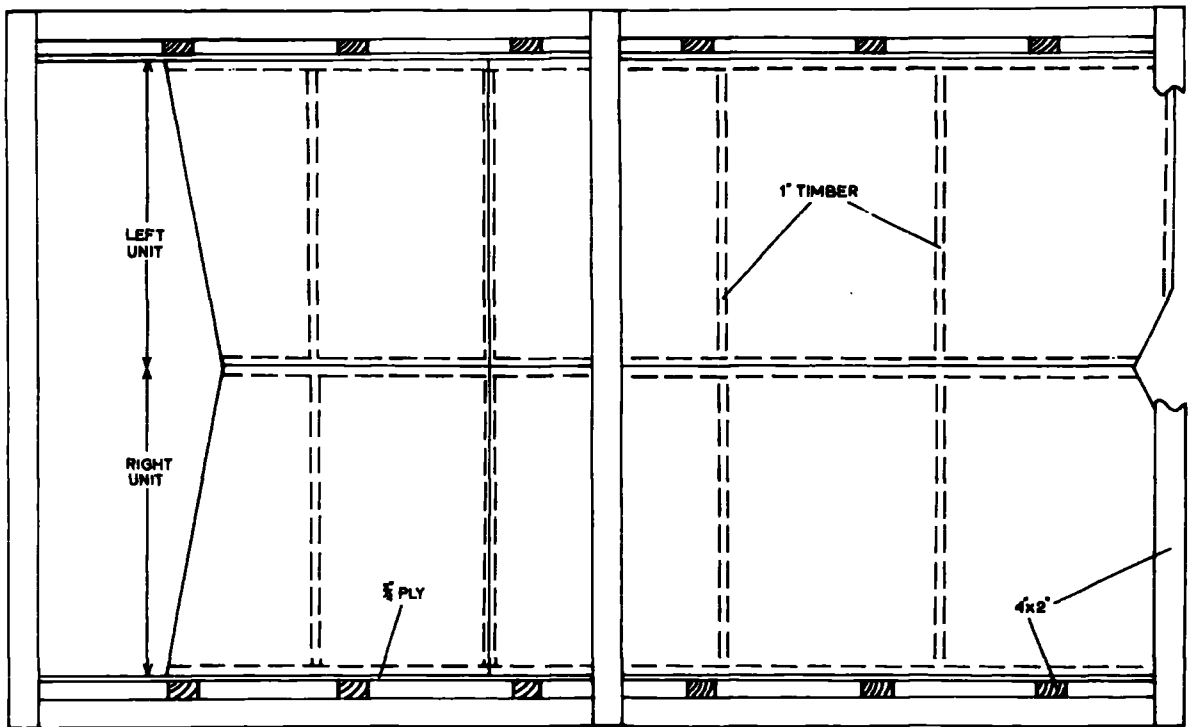
The materials and method of construction used were very similar to those used by the W.R.A. for their wooden flume at Hambledon Brook (1963). The weir, built in  $\frac{3}{4}$ " marine plywood of British Standard (1088) specifications,

was constructed on a framework of 4" x 3" and 4" x 2" timbers - all suitably rot proofed. The weir design falls into two parts, the formed rectangular channel and the weir block section. The rectangular channel was 13.5 ft. long, 7 ft. wide and 4.5 ft. high. The sides and floor were each constructed in three sections in order to facilitate handling (Fig.19). These sections were joined together at the site before the whole weir was assembled. The weir block section, comprising the critical approach and downstream slopes of 1:2 and 1:5 respectively and the 1:10 crossfall on the crest, was constructed in two units, each being supported on a framework of substantial timber. This section was divided longitudinally through the centre of the crest, thus each unit being a mirror image of the other. Once again the prefabrication was necessary only for the purpose of handling, and the two units of the weir block were bolted together before inclusion in the gauge assembly. Prefabrication was essential since each unit of the sides and floor required two persons to lift it, and each unit of the weir block required four persons.

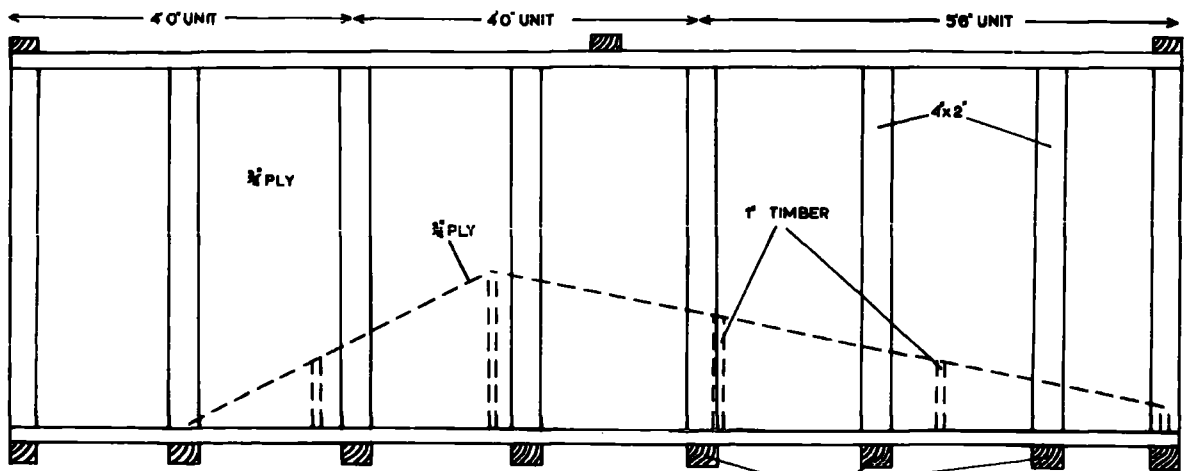
A great deal of site preparation had to be carried out prior to the assembly operation. A temporary dam of sand bags was constructed upstream of the site and the greater part of the stream flow conducted in a 4" diameter pipe over the working area. A trench was dug through the stream gravels into the underlying clay and a concrete cut-off wall one foot high laid in it to prevent water seeping underneath the weir. This cut-off wall was con-



SECTION



PLAN



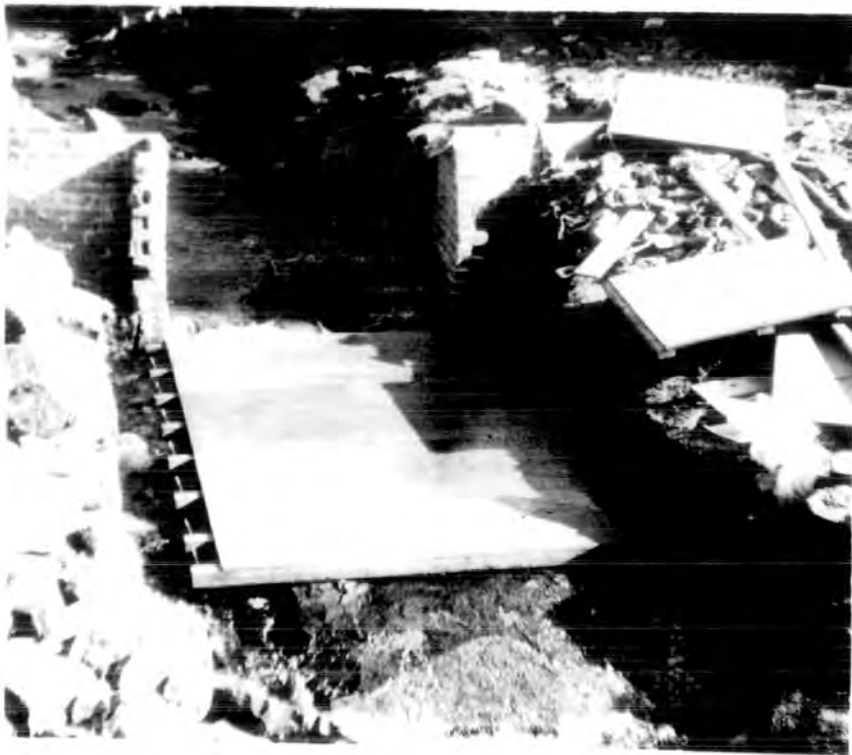
ELEVATION

Scale: 0 FEET 2

FIG 19 WORKING DRAWINGS OF THE WEIR

tinued as a brick wall to a height of 4.5 foot up the banks. Provision for a sluice gate was made low in the left hand wall so that the weir could be by-passed by the stream during installation and for any subsequent maintenance. Two 15 foot railway timbers were laid parallel, four foot apart, in the stream bed downstream of the cut-off wall as foundations for the weir. These were levelled to an accuracy of 0.1% and then cemented to increase their rigidity. A hole six foot deep and three foot in diameter was dug in the right hand bank, into which the float well, comprising two oil drums joined end to end, was set. Using railway sleepers as foundations, a small garden hut was erected over the float well to act as a housing for the instruments.

The installation of the weir was completed by myself and three persons in two days. The floor units were laid in sequence downstream and secured to the timber foundations by 6" coachbolts (Fig.20a). The successive units were joined to those already laid by being screwed into the overlapping timbers and an application of non setting rubber mastic compound was used on the joints to make them water tight. At the end of each transverse timber forming the framework for the floor, bolts angled at  $30^{\circ}$  to the vertical, were inserted (Fig.18) which would draw the sides of the weir tight against the floor when they were tightened. The left bank side units were joined together, using the same method of construction as the floor, and were placed as one piece resting on the transverse floor support timbers between the floor and the longitudinal timber



A FLOOR OF WEIR DURING INSTALLATION



B COMPLETED WEIR

placed on the angled bolts. The two units of the weir block were then bolted together and laid on the floor. Mastic rubber compound was smeared on all the edges of the weir block that were to make contact with the floor or sides. The weir block was then pushed home into the rebating cut into the side and screwed into the floor at both the upstream and downstream ends. The right hand channel side was then assembled and installed in the same way as the other and the two sides locked together by the three timbers across the top of the weir using the same system of angled bolts as had been used to lock the floor to the sides.

A concrete apron was then laid to seal the gap between the cut-off wall and the completed weir. The float well was then connected to the weir with an alkathene pipe of 1" internal diameter - this was expected to be large enough to transmit rapid changes in water level while preventing wind disturbances being transmitted. The tapping point was set flush with the side of the weir four feet upstream of the crest and 3" below the lowest point of the crest. Finally the sluice gate was put in place. This consisted of a piece of  $\frac{1}{4}$ " steel, backed with rubber, placed against a wooden frame set in the left hand wing wall and held in position by bolts attached to metal bars on the outside of the wall.

As a result of the access difficulties every attempt was made in the design of the weir to reduce the amount of materials that had to be carried to site, but nevertheless the amount required was quite considerable.

1. The prefabricated weir in 11 sections.
2. 10 ( $\frac{1}{2}$  cwt.) bags cement.
3. 300 house bricks.
4. 50 ( $\frac{1}{2}$  cwt.) sand bags.
5. 2 oil drums.
6. 2 railway timbers (15' x 1' x 0.5').
7. 6 railway sleepers.
8. Prefabricated hut in 6 sections.

In total eight complete man days were devoted to bringing the materials to the site prior to assembly.

Two water level recorders were installed.

(i) A Munro vertical drum recorder with a weekly clock and time scale 1 cm. = 4 hours. The actual water level change was reduced in the ratio 1:4 when drawn on the chart.

(ii) An Evershed recorder was installed in addition to the Munro since being an extended chart recorder with a time scale of 1" per hour, it enabled much more detailed study of specific hydrographs, but the fluctuations of water level were reduced in the ratio 1:6 when drawn on the chart.

In principle these two recorders operate in the same way. The height of the water in the float well, which is equal to the height of the water upstream of the weir, is recorded on a paper chart. All movements of the float are transmitted through gears to the wheel which is connected to the pen slider by means of a cable running over a pulley at each end of a polished pen slider support. The chart movement is driven by clockwork.

These recorders were zeroed in two ways. When the sluice gate was positioned the water became impounded behind the weir until a sufficient volume had accumulated for it to escape over the crest. At the moment that the water began to flow over the crest the recorders were set to zero. Secondly, when flow was contained within the vee section, the height of the water along the arm of the vee could be measured - every 0.1 ft. along the arms represents a vertical depth of 0.01 ft. The zero of the recorders was periodically checked in these ways in order to avoid a serious systematic error.

In January 1970 an Ott punch tape recorder was installed. Like the other recorders it operated on the basis of measuring the height of the water in the float well; the height of the water was punched every 15 minutes on paper tape. Apart from the immediate advantage that this provided in terms of being able to obtain results from the data more rapidly and with less effort than from the pen traces, the main purpose of this was to enable the catchment to be maintained in the future. This recorder was capable of operating for six months with very little attention and therefore with a minimum of labour the experimental catchment could be maintained after the period of this study.

Since the Ott recorder did not give an immediate visual record of the discharge it was necessary to acquire basic computer programming knowledge in order to benefit from the advantages that the recorder gave. Firstly a conversion programme had to be prepared that would trans-

late the recorder's Ferranti code as this was not directly available on the computer at Durham. These head measurements had then to be converted into values of discharge using a modification of the programme that had already been prepared to calibrate the weir structure. A graph routine was added in order to produce a visual record of the discharge. These graphs were significantly different from those obtained from the Munro recorder since these were based upon discharge data, not unconverted measurements of stage. The graph routine was based upon data recorded every  $\frac{1}{2}$  hour, and was accurate to  $\pm 0.125$  cusecs. Daily values of maximum, minimum and mean flow were prepared with the graph for each day. The value of the punch tape record is limited while there is no other data from the catchment being prepared for analysis by computer, but on the other hand its value will increase as more programmes are prepared to analyse the data.

The accuracy of this gauging structure has been checked against salt dilution results as described later in this chapter, but it is important to emphasise that 100% accuracy cannot be achieved without considerable expense and therefore the accuracy required of any structure is governed by the purpose for which it is built. Systematic errors may result from either the malfunctioning of the instruments or the observer making consistent misreadings, and random errors will occur due to physical conditions. Systematic errors will result where simplifications have been made to the original calibration formula or where the recording instrument has not been

correctly zeroed. Stream effects such as the accumulation of debris in the approach section or the drowning out of the structure or the occurrence of standing waves will also give systematic errors. Random errors may also occur due to physical conditions of irregular duration not allowed for the calibration, such as changes in the approach section associated with certain levels of discharge.

The same degree of accuracy would not necessarily be required for all gauging structures, nor would the same accuracy necessarily be required over the complete range of flow in the channel. For flood control projects accuracy at high flows would be necessary while for pollution problems high accuracy would be required at low flows but not at higher discharges. At Lanehead the emphasis was upon the measurement of small discharges and although the values have been given for higher flows from this catchment, the error involved might be  $\pm 10\%$ . To achieve accuracy at low flow is easier than for high flows. The vee shape of the crest for low flows meant that errors of head measurement produced a much smaller error than would be the case with a less sensitive structure. Furthermore, the errors incurred as a result of changing approach conditions and high approach velocities do not become significant until the discharge becomes relatively large. On the other hand, problems associated with surface tension and other fluid properties become most acute when the volume of flow is small in relation to the wetted perimeter of the stream, particularly when the head to be measured is less than 0.1 ft.

## The calibration of the weir

The calibration of the gauging structure, that is the calculation of the relationship between the measured head of water above the weir and the discharge through the weir, can be achieved by one of two methods. The stage/discharge relationship can be theoretically calculated from a prepared equation specifically designed to match the gauging structure concerned; or alternatively the volume of water passing through the gauge can be measured and recorded against the head of water. This second method is more suitable since it is in this way that the theoretical equations are checked and furthermore, no theoretical equation is entirely accurate except at the one site under the exact conditions in which it was prepared.

At Lanehead the flat vee weir was calibrated with the equation prepared by the Hydraulics Research Station (1967) in order to give an immediate indication of the approximate amount of discharge. Over the summer of 1969 a number of salt dilution tests were made and the discharge evaluated by this method has been presented in Fig.21 plotted against the volume expected from the theoretical equation.

Several causes may be partially responsible for the discrepancies that occur:

(i) Both the calibration equation and the salt dilution methods are only accurate to  $\pm 1\%$ .

(ii) The site conditions may be significantly different from those which existed when the discharge equation was prepared in laboratory test conditions.

(iii) The silting up of the stilling pool, which is vital to the proper functioning of the weir, may well cause the equation to be invalid.

(iv) Since great difficulty was experienced trying to compute the coefficient of velocity for the equation this was ignored in the stage/discharge curve (Appendix II). Although this will cause inaccuracies in the analysis, the discrepancies at low flow should be very small, and certainly smaller than the discrepancies obtained between the theoretical equation method, and the salt dilution method.

Consideration has already been given to the basic principles of calculating stream discharge by means of an artificial section of gauging structure which creates a measurable afflux or head. In theory, the discharge is the product of the force of gravity, the head of water and the shape of the gauging structure. The flat vee weir can be calibrated with the following two equations, the first referring to the conditions where flow is confined within the vee, and the second, for higher discharges.

$$Q = 4\sqrt{\frac{g \cdot n \cdot H}{5}} H^{5/2} \dots (1)$$

$$Q = 4 \frac{g \cdot n}{5} \left[ H^{5/2} - (H-b/2n)^{5/2} \right] \dots (2)$$

(from White 1966)

Such simplified formulae, if used to calculate discharge from measured head, completely ignore the effects of, for example, the viscosity and surface tension of the water, and therefore a correction factor, the coefficient of discharge, must be added. This is the

ratio of the measured discharge to the discharge calculated according to the theoretical considerations (British Standard 3680). Since this coefficient takes into account several variables it is wrong to think of it as having a single value for each structure. However, these variables can be regarded in two categories, those related to the shape and nature of the structure, and those that are affected by the fluctuations in head; the coefficient of structure,  $C_s$ ; and the coefficient of velocity,  $C_v$ .

The coefficient of structure ( $C_s$ ) takes into account such factors as the amount of contraction (the reduction in the effective size of the channel at the gauging structure compared with the size upstream) the surface roughness of the gauging structure and most important the fluid property effects of surface tension and viscosity. This coefficient therefore has a single value for each individual gauging structure, and is a dimensionless parameter independent of the units used. The coefficient is calculated by experimentation where the observed head is corrected to total  $H$  for inclusion in the above formulae by adding the velocity head. For rectangular thin plate weirs, this velocity head value is approximately 1 mm. but for vee notch weirs the value can increase to 2.8 mm. for a  $20^\circ$  v-notch with resulting coefficients in the range 0.65 - 0.585 (British Standard 3680 (1965)).

The coefficient ( $C_s$ ) can be evaluated by substituting various values of  $K_h$  (velocity head) in the theoretical formulae, thus for the flat vee weir:

$$C_s = \frac{5Q}{4n(H-K_h)^{xx2.5} - [(H - b/2n - K_h)^{xx2.5}] \sqrt{g}} \dots\dots (3)$$

Initially the Hydraulics Research Station assumed that the performance of the flat vee weir would be very similar to that of the two dimensional triangular profile of the Crump Weir, of which it is a modification; and substituted a  $K_h$  value of 0.0003 m. in equation 3 which had produced a constant coefficient of 0.626 (White 1966). For the Crump weir a  $K_h$  value of 0.0003 m. had produced a constant coefficient of 0.626 but when this  $K_h$  value was substituted in equation 3 no such constant coefficient was derived. Results for the flat vee weir were calculated for various values of  $K_h$  of which 0.0009 m. gave the best fit with a resultant coefficient of 0.619 which could be used as a constant for the structure. The difference between the  $K_h$  values for the Crump weir and the flat vee weir is probably caused by the converging flow (in plan) over the flat vee weir compared with the unidirectional flow over the Crump weir.

In order to calculate discharge directly from the gauged head and the dimensions of the weir it is necessary to introduce the coefficient of velocity. This coefficient will not have a single value for the structure since it is related to the flow geometry immediately upstream of the weir, which will vary with the afflux of discharge. For the flat vee weir the coefficient of velocity ( $C_v$ ) is dependent upon the two parameters:

(i) The ratio between the gauged head and the height of the lowest part of the weir crest above the stream bed ( $h/p$ ) and

(ii) The ratio between the gauged head and the

difference between the highest and lowest crest elevations ( $h_1/h^1$ ).

Since the height of the crest (P) and the amplitude of the vee section ( $h^1$ ) are fixed for any particular weir geometry then the otherwise independent variables and the coefficient of velocity become related to the measured head ( $h_1$ ). The coefficient of velocity can therefore be calculated from the following equations:

$$C_v = \frac{2 \times C_s^2 \times K^2}{25 (1+1/R)^2 \times (C_v^{2/5} - 1)} \quad (\text{within vee section})$$

$$C_v = \left[ \frac{1 + 2 \times C_s^2 \times C_v^2 \times k^2 [1 - (1-1/k)^{5/2}]}{25 (1+1/R)^2} \right] \times \left[ 1 - \left[ 1 - \frac{1}{K \left[ \frac{1 + 2 \times C_s^2 \times C_v^2 \times k^2 [1 - (1-1/k)^{5/2}]}{25 (1+1/R)^2} \right]^{5/2}} \right] \right]$$

Using these equations a rating table for the weir has been calculated by computer, and presented as an Appendix. The discharge from head measurements programme has been incorporated into a larger programme to translate the Ott recorder punch tape records of discharge values - this also is presented as an Appendix.

The weir calibration was checked by salt dilution tests since the current meter could not be used in small shallow streams. On the other hand, because the salt dilution tests require the rapid mixing of an injected solution in the stream the conditions at Lanehead favoured this method. The principle of salt dilution tests is that a chemical tracer is injected into the stream and

the volume of discharge calculated from the dilution that occurs to the injected chemical after it has thoroughly mixed with the stream water. The injection of the chemical tracer can be carried out by one of two methods, by a sudden injection or at a constant rate. If the samples are plotted against time the sudden injection method gives a peaked curve, whereas the constant rate method gives a plateau curve.

In the sudden injection or gulp method, a known volume of chemical tracer of known concentration is added to the stream as quickly as possible. At the sampling point the concentration of tracer in the water rises sharply to a peak and then slowly diminishes again. If a series of samples <sup>are</sup> taken at regular intervals of time and the chemical concentration plotted against time, a concentration/time curve is obtained. The volume of discharge can be calculated from:

$$(C_0 - C_1) \times V = Q \int_0^T (C_2 - C_1) \times d \times t.$$

(British Standard 3680 1965)

- Q rate of flow in cusecs
- q rate of injection
- C<sub>0</sub> chemical concentration of the injection
- C<sub>1</sub> background concentration
- C<sub>2</sub> sample concentration
- V volume of the injected solution

If the chemical tracer is injected at a constant rate several advantages are obtained, although it requires slightly more complex injection apparatus. The tracer chemical in known concentration is injected into the stream

at a constant rate. If the concentration of the water at the sampling point is plotted against time a plateau curve is obtained. The duration of the plateau is approximately the same as the period of injection, and the time required to achieve plateau conditions is the same as the time between the instance of sudden injection and the disappearance of the tail in the 'gulp' method.

The volume of discharge can be calculated from:

$$Q = \frac{(C_0 - C_2)}{(C_2 - C_1)} \times q \quad (\text{Collinge 1964})$$

but since  $C_2$  is so small compared with  $C_0$  it can be written

$$Q = \frac{C_0}{(C_2 - C_1)} \times q \quad (\text{Collinge 1964})$$

The constant rate injection method is preferable for three reasons:

(i) It is possible to measure a changing discharge because such a change will be seen in the shape of the plateau.

(ii) There is an economy of sampling since a longer interval between samples can exist without risk of missing the plateau level.

(iii) It is very much easier to assess the margin of error in all elements of the test - the rate of injection, the variations in tracer concentration measurements.

It is very important that the sampling point should be sufficiently far downstream from the point of injection for complete mixing to have occurred. If complete mixing has not occurred at the sampling point then any samples taken from a part of the stream with a high concentration of chemical tracer will produce too low a value of discharge whereas samples taken from a section

of the stream with a low concentration of chemical tracer will give too high a value of discharge. A measuring reach where turbulence is high as a result of bends, narrows and waterfalls, is very suitable for this type of gauging; and conversely channels that braid, or having pools or other zones of dead water should be avoided. In theory the longer the mixing length the better, but in practise it is necessary to sample where the mixing is nearly complete in order that a reasonable mixing length results.

To calculate the degree of mixing it is necessary to take a series of samples across the stream at the same time. Several methods of measuring the degree of mixing have been suggested, the best of which are Rimmar's and Schuster: (Collinge 1964).

$$M\% = \frac{\hat{C} - \bar{C}}{\bar{C}} \times 100 \quad \dots\dots \text{(Rimmar)}$$

$$M\% = 1 - \left( \frac{(N_1 - \bar{N}) + (N_2 - \bar{N}) + \dots + (N_x - \bar{N})}{x \times \bar{N}} \right) \times 100 \quad \dots\dots \text{(Schuster)}$$

O = maximum concentration at a section.

$\bar{C}$  = mean concentration at the same section.

Rimmar's method tends to lay too much emphasis on any extreme value found in the cross section, and for this reason Schuster's formulae is probably more reliable.

Several formulae have been suggested to calculate the mixing-length required before the test is begun.

$$L = \frac{100 \times b^2 \times v}{4D} \quad \dots\dots \text{(Hill)}$$

$$D = 2.5(Qv)^{0.5}$$

$$L = \frac{b^2}{h} \times (0.00286 \times C^2 + 0.0442 \times C) \dots\dots (\text{Rimmar})$$

h = depth of stream (ft.)

b = breadth of stream (ft.)

v = mean velocity of stream (ft./sec.)

D = dispersion coefficient.

Clayton (1963) experimented with these formulae with tests on the River Alwin and found them to be far from satisfactory.

Rimmar            2,500 ft.

Hill                150 ft.

Experiment        800 ft.

Consequently it is very important that field checks are made to ensure complete mixing immediately before any dilution test is carried out. A gulp injection of a strong dye such as flouresin can be used and the mixing evaluated by eye, but this can only be an approximation since it is impossible to evaluate accurately how uniform the concentration is. Alternatively, when NaCl. is being used a portable conductivity bridge can be employed to measure the concentration across the stream section.

To produce a constant rate of injection it is necessary to prevent a variation in the head over the point of injection. This can be achieved by various methods such as a constant head tank or a constant speed motorised pump, but both of these are extremely cumbersome. Without an excessive loss of accuracy, a much simpler piece of apparatus is the Marriotte vessel. Since the vessel is air tight except for an air inlet tube the head over the outlet valve is maintained constant and the rate

at which the air can enter through the inlet tube. This method does not give an absolutely constant rate of injection but the injection rate can be checked against a graduated scale on the side of the vessel and a 'rate of injection/time' curve can be constructed. Any inaccuracies which result from this are far outweighed by the relative simplicity and ease of handling of the apparatus.

The choice of chemical tracer used for a dilution test can be made from almost any substance which can be dissolved in and which remains stable in water. However, in practice several factors govern the choice of chemical tracers (Cole & Barsby 1964).

- (i) The background concentration should be low and as far as possible without any rapid fluctuations in concentration. It is not advisable to choose a chemical which is totally absent otherwise there will be a chance that the chemical might be absorbed by the environment or perhaps react with the natural water or any organic matter that it contains. A stream which contains a low background concentration of the chemical is likely to have reached equilibrium with the ions.
- (ii) The chemical, in the concentration to be used, must not be injurious to fish, plant or animal life.
- (iii) It is preferable that the concentration of the chemical should be able to be obtained relatively rapidly and accurately. The more

samples there are to be analysed the more important it is that the method of analysis is simple and rapid. Cole and Barsby (1964) have listed 16 chemical tracers that can be used, together with their properties, and have analysed their suitability for different gauging problems. The most commonly used chemicals tend to be sodium or potassium salts; but no chemical is universally applicable to all gauging problems, and the final choice is governed by the particular situation of the water being gauged and by the analytical techniques available.

In order to check the weir calibration a number of salt dilution tests were run and the results of these are shown in Fig.21. The test run of 4th June 1969 serves as an illustration of these tests. The mixing length required was ascertained by noting by eye the distance it took for a gulp injection of dye to become mixed with the stream water. Samples were taken to give a background reading of the concentration of NaCl in the water (7ppm.). A solution of salt water (NaCl) was injected from a Mariotte vessel into the stream at a constant rate of 3.2 litres/minute for five minutes. The rate of injection =  $\frac{\text{the volume of liquid injected}}{\text{time}} = \frac{16 \text{ litres}}{5 \text{ mins.}} = 3.2 \text{ litres/minute}$ . A sample of the injection solution was taken at the beginning and the end of injection, and found to be 28000 ppm.

Samples of stream water were then taken from the stream just above the stilling pool of the weir every 30 seconds.

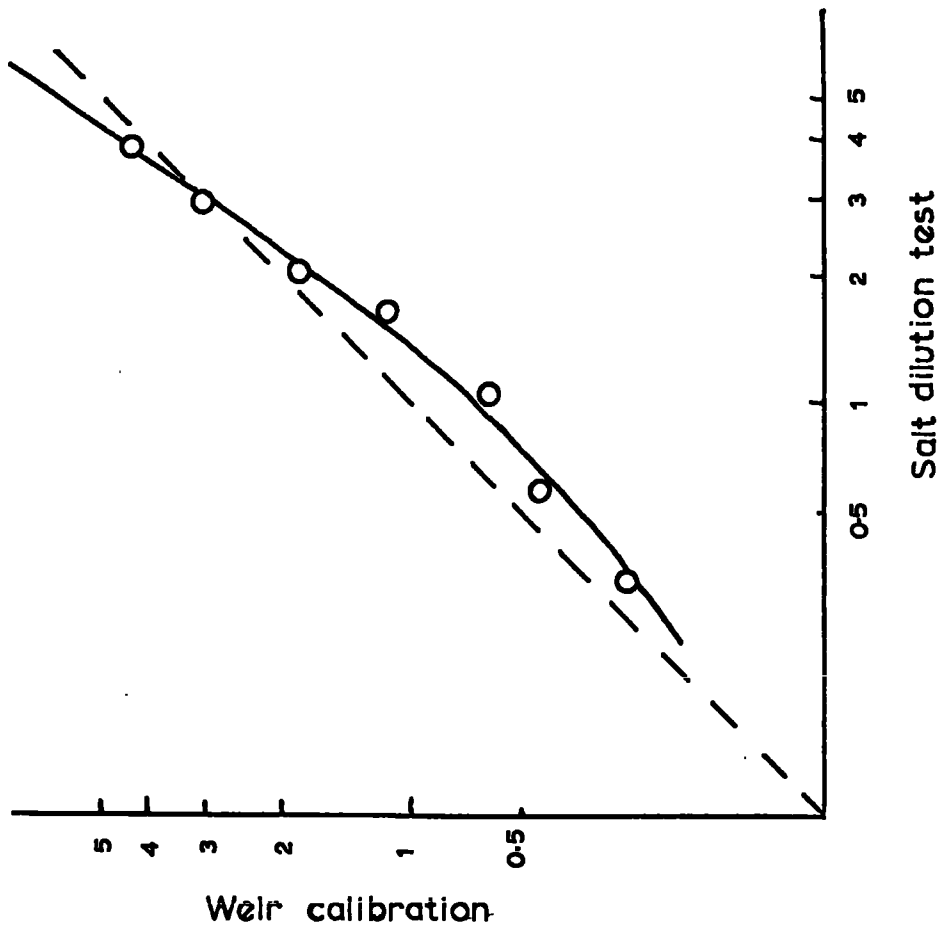


FIG 21 THE RELATIONSHIP BETWEEN THE CALCULATED DISCHARGE AND THE SALT DILUTION CHECK.

These samples were taken back to the laboratory for analysis by flame photometer. The principle of the flame photometer is that a hot flame will cause an excitation of a number of elements, one of which is sodium, to emit radiations. The intensity of this will depend upon the number of atoms excited and hence upon the concentration of the solution. By comparing the flame photometer readings of the samples with those of readings from solutions of known concentration, it was possible to calculate the concentration of salt in the samples. When the concentrations of salt in each sample were plotted against time a flat plateau curve was obtained (Fig.22). This plateau stage would be maintained as long as the injection continues. From the samples taken during the plateau stage (samples 14 - 18), it was possible to calculate the extent to which the concentration, injected solution had been diluted, and thereby the amount of water in the stream.

Thus: 
$$Q = \left[ \frac{\text{conc}}{C_1 - C_0} \right] q$$

where: Q = discharge.

Conc. = concentration of injected solution.

$C_1$  = concentration of sample.

$C_0$  = background concentration of salt in the stream.

q = rate of injection of concentrated solution (cusecs).

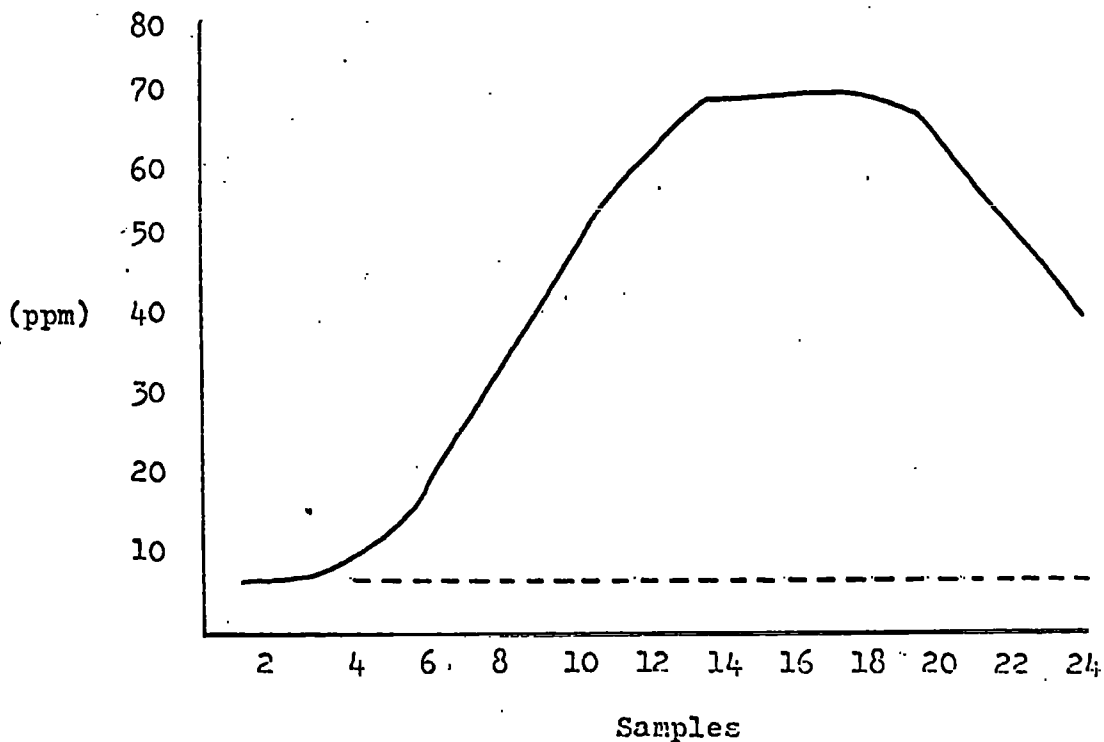
On 4th June 1969, the discharge calculated by the salt dilution test was:

$$\frac{2800}{(70 - 7)} \times 0.001882 = 0.8370 \text{ cusecs}$$

Fig 22

Salt dilution test on 4 June 1969

Background concentration of NaCl in the stream	7 ppm	Samples taken from the stream (ppm.)	1 7
			2 7
Injected solution ( 56 * 5000 ppm.)	28000 ppm		3 7
			4 9
			5 12
			6 19
Rate of injection ( 3.2 l/min.)	0.001882 cusecs.		7 28
			8 34
			9 42
			10 52
			11 58
			12 64
			13 69
			14 70
			15 70
			16 71
			17 71
			18 70
			19 68
			20 60
			21 55
			22 49
			23 42



The discharge from the weir calibration was 0.877 cusecs (104.8% of the salt dilution value).

In total 15 tests were made, but only seven were successful, in the others the peak was never sampled or the sampling interval was too long to define the peak accurately. There was a lack of tests during discharges higher than 5 cusecs since these were infrequent in occurrence, and short lived in duration, and the sampling interval would have had to be very short in order to get a good cover of dilution samples from the stream. From Fig.21 it can be seen that the weir gave an underestimate of the flow below 2 cusecs, and an overestimate for flows greater than 4 cusecs. For flows between 2 and 4 cusecs it was accurate  $\pm$  5%.

PART II

ANALYSIS OF THE DATA

## CHAPTER 5

### RAINFALL/RUNOFF RELATIONS IN THE CATCHMENTS

One of the main factors modifying the response of stream water temperature to the atmospheric environment is the volume of discharge itself. Consequently, the factors which control the volume of discharge have an indirect effect upon the temperature of the stream water. While discharge and precipitation are clearly related there are many other factors which modify the relationship. In this Chapter it will be demonstrated that the moisture condition of the soil modifies the rate at which water drains from the catchment, and, in the following Chapter, it will be shown that the snowmelt/discharge relationship is partly controlled by air temperature.

Because of the altitude and exposed nature of the catchment, together with the prolonged and severe winter conditions of the area, there were difficulties in obtaining reliable precipitation and discharge data. Therefore, preceding the analysis of the rainfall/runoff relations in the catchment, the practical difficulties of obtaining the data, and their limitations, are discussed.

#### Rainfall

The choice of the sites and the nature of the instrumentation for precipitation recording have been described in Chapter 2. The ground level gauges were set in small pits one foot deep and four feet square, surrounded by an anti-splash guard of wire netting lying flush with the adjacent ground (Fig.10). The wire netting had a

serious disadvantage during snowfall in that the snow clung to the netting and caused a snow surface to build up above the gauge. In September 1969 the wire grills were replaced by plastic grids to which the snow would not cling (Fig.23). At the same time drainage channels were dug from the pits in order to prevent the gauges being flooded. At Site B, where the gauges were sited on a small interfluve, it was feared that the drainage channel itself might funnel a flow of air under the anti-splash grid and cause turbulence to the air flow around the rain gauge, hence to reduce this effect the channel was covered over with stones and turf.

At some times during the winter period the rain collected in the gauges became frozen. To prevent shattering of the collecting vessel and the subsequent loss of reading, plastic bottles were used. Furthermore, when the rain collected in the gauge was frozen, it was difficult to measure the catch in the field and during these conditions the bottles in the gauges were exchanged with spare bottles, and the rainfall was measured in the laboratory later.

The areal representation of rainfall, and the problems of applying point measurements of rainfall to catchment areas, have been discussed in Chapter 2. From these studies it was decided that two rain gauge sites would give a representative measure of rainfall of acceptable accuracy for the whole catchment. However, on several occasions conditions were observed which would render the catch of the rain gauges unrepresentative, and these

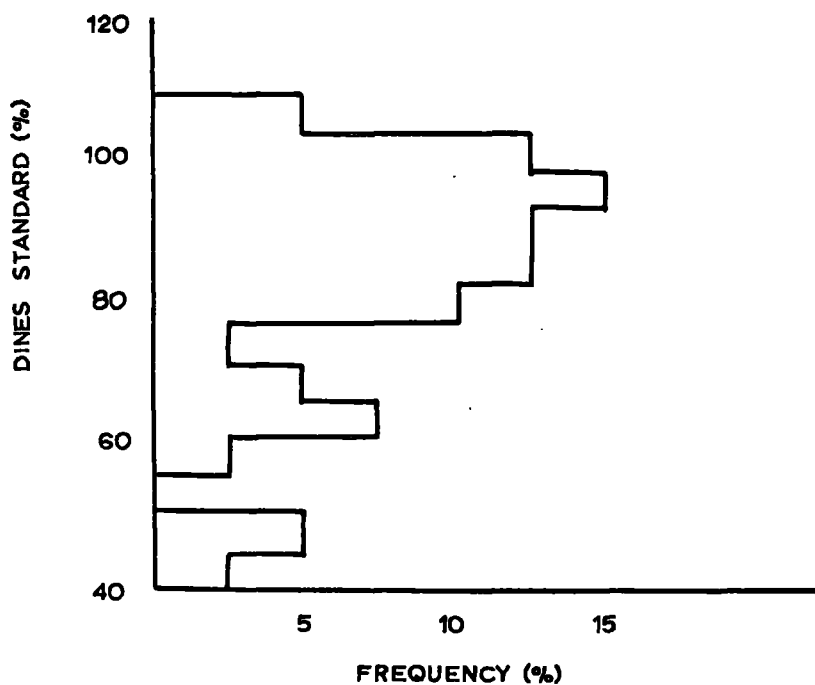


FIG 23 GROUND LEVEL GAUGE AT SITE B

were (a) periods during April and May when snowfall occurred at the top of the catchment while rainfall was occurring in the lower catchment, and (b) during periods of low cloud, when the upper catchment, often including the gauge sites, was enveloped in cloud while the lower catchment was receiving rainfall.

A continuous record of rainfall was maintained at each site by a Dines Tilting Siphon recorder fitted with an extended chart mechanism. Records from the recorders at Site A for the water year 1968/69 have been compared with the catch of the standard gauge in Fig.24. For all but two data periods for that year the standard gauge had a larger catch of rainfall. Usually the reading from the Dines recorder was approximately 85% of the catch in the standard gauge, but it varied quite considerably. However, the purpose of the Dines recorder was not to measure the absolute total of rainfall but to record the time, intensity and nature of the periods of rainfall which could then be related to the discharge from the catchment.

The incomplete nature of the Dines records for the year reflect in part the difficulties of maintaining any recording gauge in an upland environment, and in part the particular difficulties which these specific recorders presented. During freezing conditions the float chambers of the recorders became frozen, preventing further recording of rainfall until they thawed. Fortunately the float chambers were never ruptured by ice but the floats frequently were, and these had to be replaced before further recording could take place. During the summer



**FIG 24 THE CATCH OF THE DINES RECORDER AS A PERCENTAGE OF THE STANDARD GAUGE CATCH**

period different problems occurred which were more specifically associated with the clock and strip-chart mechanism. When damp, especially during periods of rainfall, the spool of the chart often became jammed and effectively acted as a brake upon the clock mechanism which then stopped. Several attempts were made to prevent this happening by removing a retainer spring on the chart spool mounting and also by allowing the spool platform to revolve. Although these modifications greatly improved the reliability of the recorders they were not completely successful and it might have been better to maintain one of the Dines recorders with a standard weekly clock (with a chart travel of 2.5 cm. per day) which would have had a more reliable clock mechanism.

The catch of rainfall at the two sites was quite consistent. When the performance of the standard gauges was compared (Fig.25) the variation was within  $\pm 10\%$  for 50% of the time. The ground-level gauges were less vulnerable to wind eddies around the gauge orifice. Accordingly the measurements showed less variation than those for the standard gauges, and were within  $\pm 5\%$  for 50% of the readings (Fig.26). The ground-level gauge was, therefore, a much more reliable record of the actual fall of precipitation over the catchment.

When the catch of the ground-level gauges was compared with the catch of the standard gauges, the ground-level gauges normally had a greater catch, as expected. However, despite the altitude and exposed nature of the catchment, the relationship between the two gauges was remarkably close. Between 25-30% of the readings taken

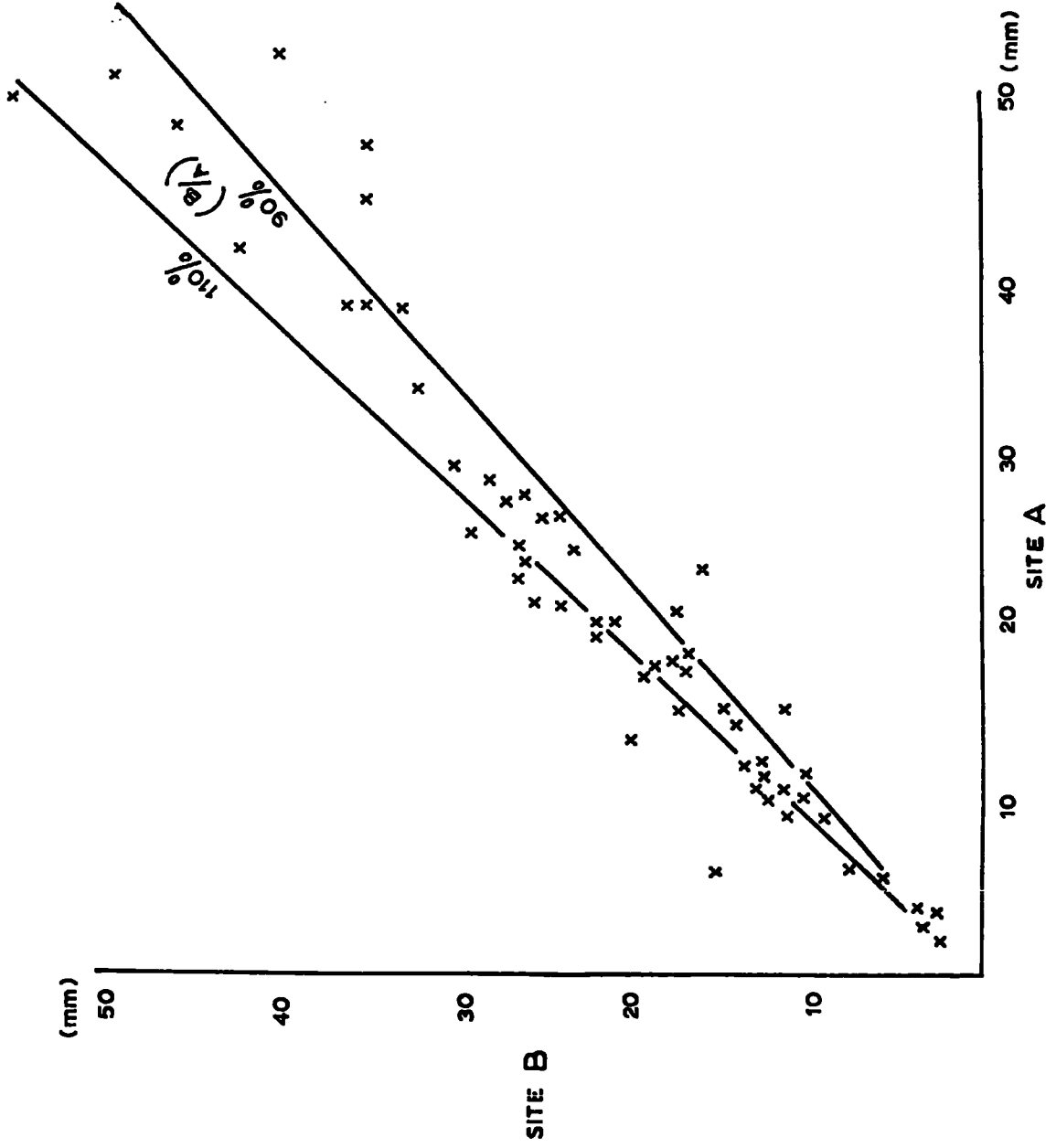


FIG 25

A COMPARISON BETWEEN THE CATCH OF THE TWO STANDARD GAUGES

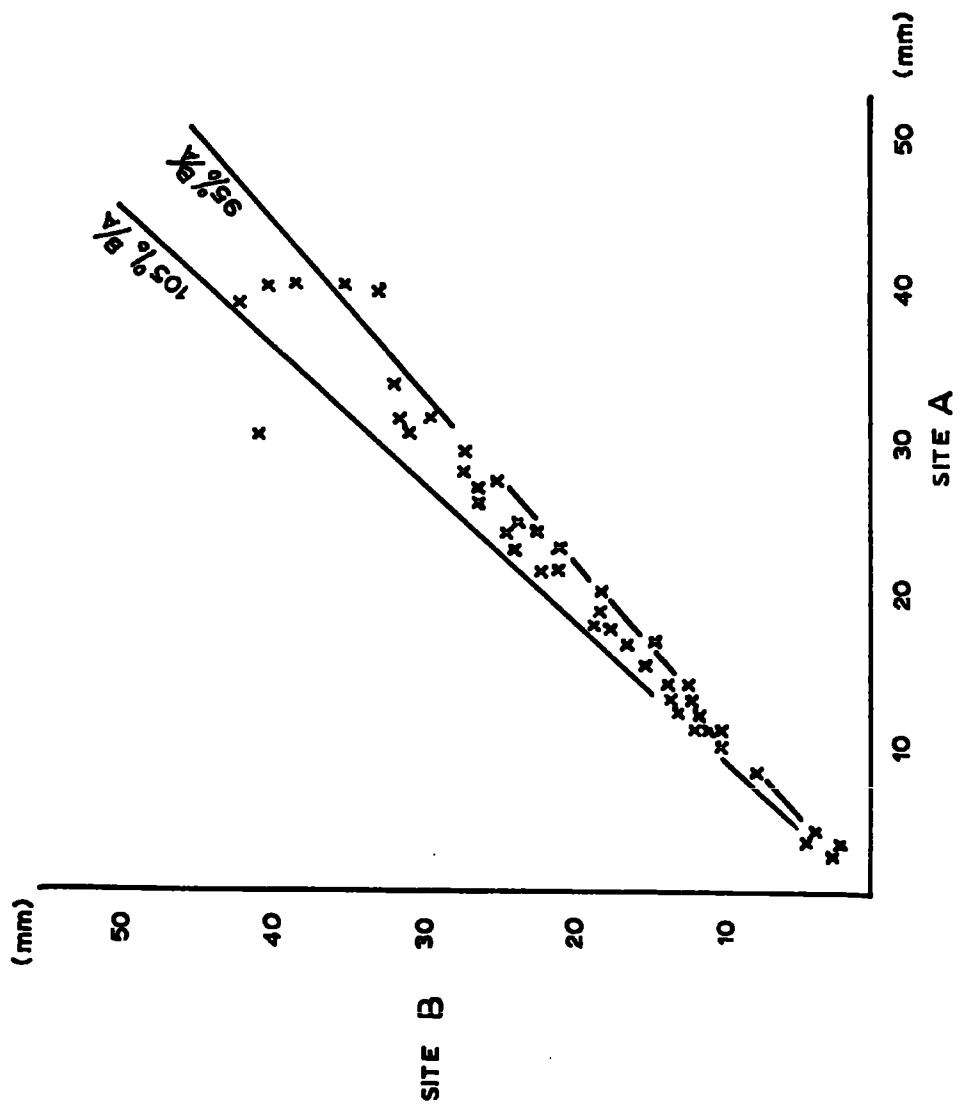


FIG 26 A COMPARISON BETWEEN THE CATCH OF THE TWO GROUND LEVEL GAUGES

were within 5% and approximately 50% of the readings had a discrepancy of less than 15% (Fig.27). The largest discrepancies occurred with the heavy falls of precipitation, particularly when this amounted to more than 30 mm. Site B, which was protected from the prevailing winds by higher ground, had fewer and smaller discrepancies (Fig.28).

A curious effect was noted at both sites when on a certain number of occasions the ground level gauge caught less than the standard gauge. At site A this accounted for 10% of the readings, while at site B it accounted for 20%. At site A these differences were not significant, since in most cases the catch of the ground-level gauge was greater than 95% of the standard and usually greater than 98% as is clearly shown in Fig.28. At site B, however, not only was there a greater number of occasions when the ground-level gauge catch was less than that of the standard gauge but the differences themselves were much larger. At first it was thought that these discrepancies were due to wind effects and micro-turbulence caused by the drainage channel which had been dug in September 1969 following the flooding of the gauge pit. However, the drainage channel was enclosed in November 1969 and, although there were no longer any consistent discrepancies, there were several reoccurrences. It seems possible that these discrepancies occurred largely during periods of predominantly south westerly winds, which were funnelled up the valley and then lifted up over the spur on which the gauge was sited. Such an upward movement could tend to carry the rainfall away from the gauges, since the ground level gauge and anti-splash grid were set horizont-

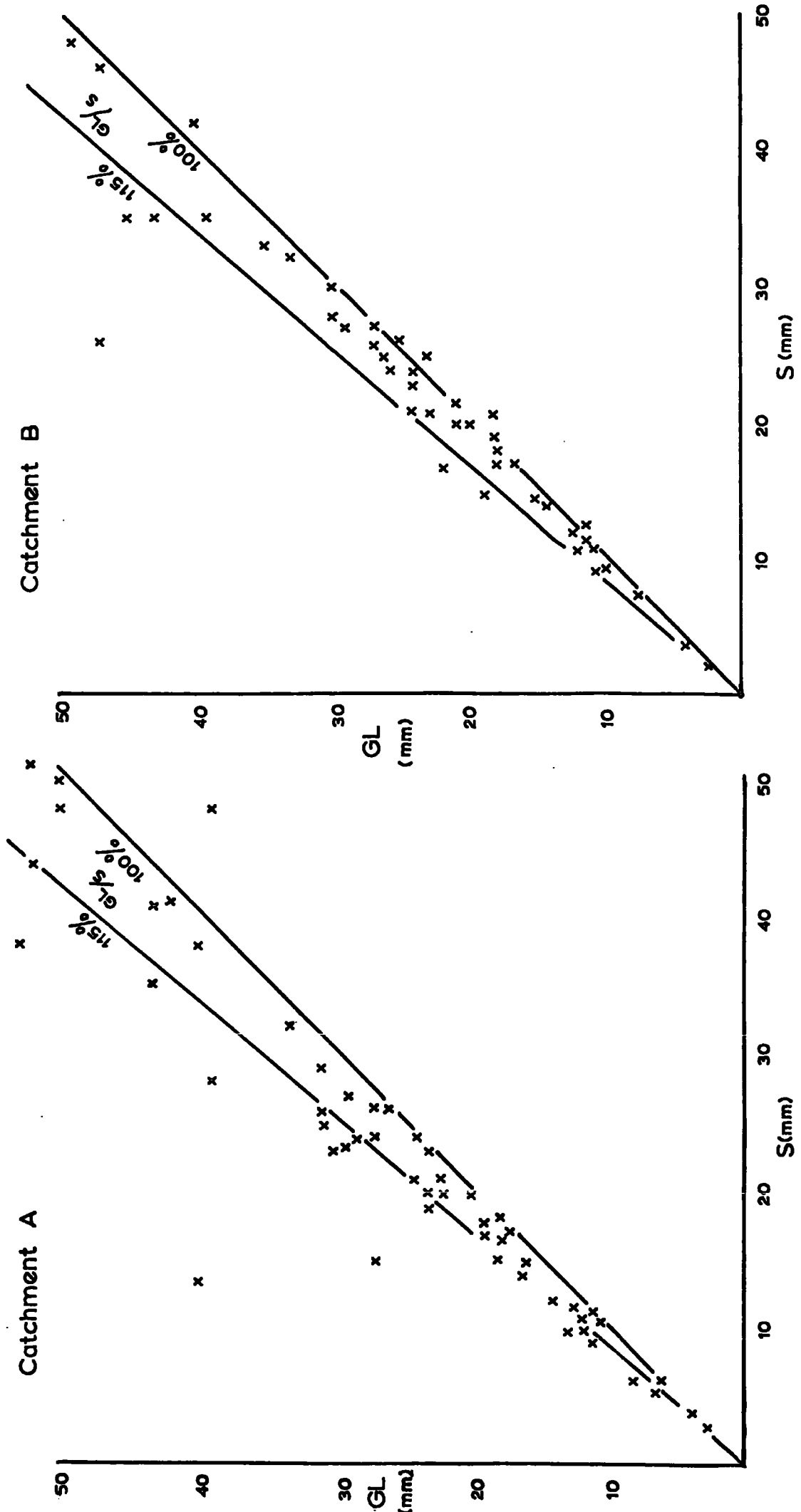


FIG 27 A COMPARISON BETWEEN THE STANDARD AND GROUND LEVEL GAUGES AT EACH SITE.

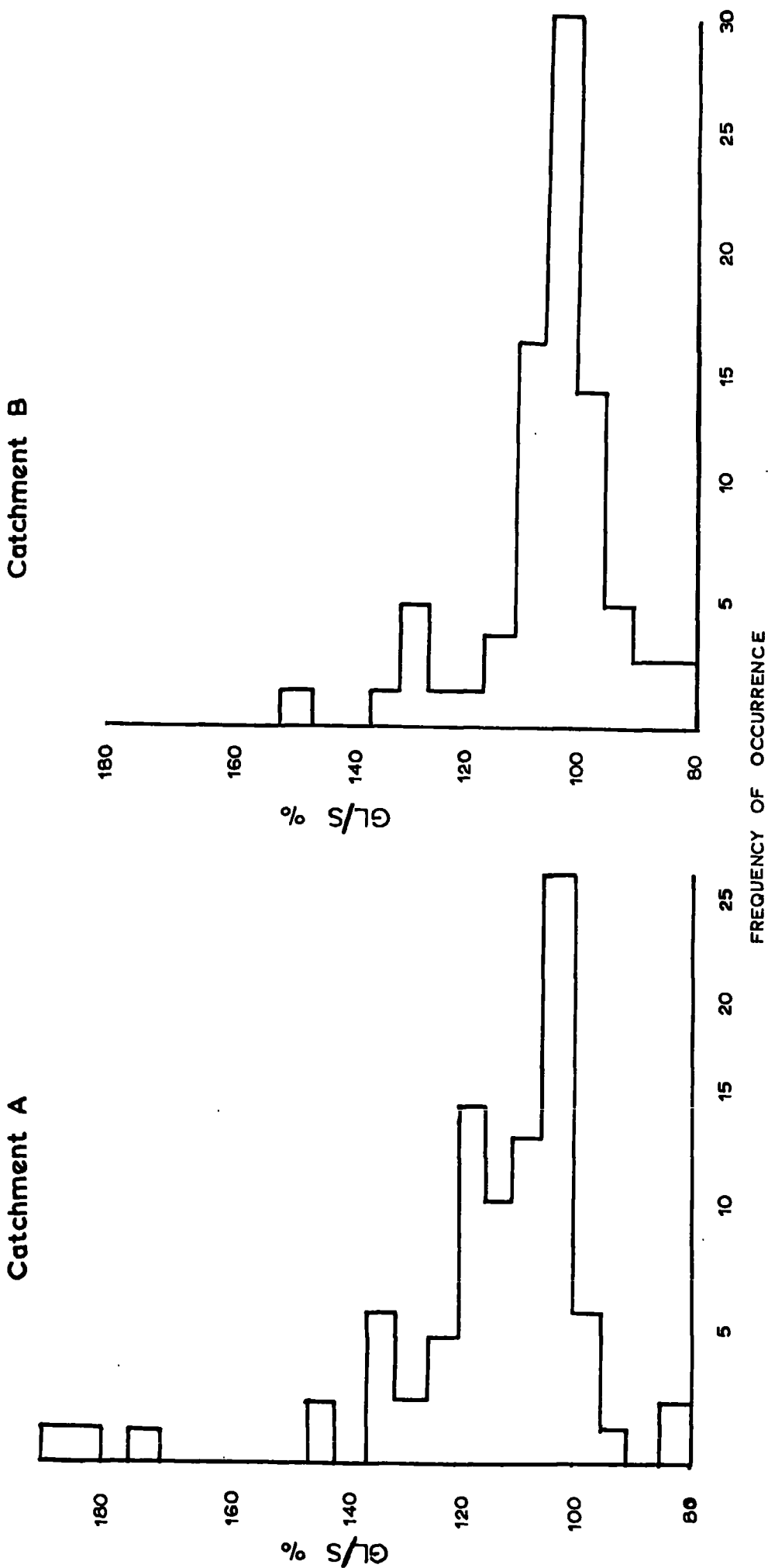


FIG 28 A COMPARISON BETWEEN THE CATCH OF THE STANDARD AND GROUND LEVEL GAUGES

ally rather than sloping with the ground surface. However, it is impossible to substantiate this theory in the absence of a continuous record of wind speed and direction.

Thus, it is suggested that the four gauges between them gave a satisfactory measure of the amount of rainfall over the catchment. The two recorder gauges were very vulnerable to winter conditions, but during the summer they recorded a trace for four out of every five storms.

### Runoff

The discharge measurements were inaccurate on a number of occasions due to the environmental conditions prevailing at this altitude. During the winter of 1968/69 the sides of the weir were not back-filled so that leaks could be more easily detected, but this meant that the pipe joining the weir structure with the float well was exposed to the air. The winter was fairly severe and consequently the inlet pipe became frozen with a resultant loss of records. During freezing conditions ice formed both above the stilling pool and on the downstream surface of the weir. Thus, with the crest of the weir heightened by the ice, the head measurement recorded was that of the depth of water and the layer of ice. When a thick layer of ice formed over the stilling pool the streamflow would tend to be forced below the ice under pressure and the flow of water over the weir would be at super-critical speeds. Although the head measurement would be greater than the height of the ice cover, due to the pressure of the water beneath the ice, the super-critical flow would invalidate the calculations of discharge from that head measurement.

The recording instruments had to be protected from frost. The hut itself was sealed at the base with several layers of turf to prevent a circulation of cold air over the water in the float well. The instruments were housed in weather-proof cases in the hut. No instrument problems were experienced with the Munro vertical drum recorder or with the Ott punch tape recorder, but the Evershed recorder was unreliable as a result of clock failures and faults on the transmission system between the float and the pen mechanism; the pen was a siphon-feed with a very fine capillary which frequently became choked.

A stretch of deep water upstream of the weir was vital to maintain a proper flow of water over the crest. If the pool became filled with debris the flow at high water became super-critical in the approach section. During the two years of study the stilling pool was completely dug out on five occasions:

8 June, 1969

21 September, 1969

22 March, 1970

17 May, 1970

20 September, 1970

The greatest movement of material in the stream was during flood conditions, and on occasions material had to be cleared away from the weir crest following a flood. After each excavation, the accuracy of the discharge measurements gradually diminished as the stilling pool filled again. It is, therefore, reasonable to assume that the records of high flow are slight under-estimates of the actual flow as any inaccuracies due to the filling

of the pool would be exaggerated at high flows. Apart from the loss of records during February and March 1969, due to the frozen pipe, a continuous record of discharge was obtained throughout the study period and is still being maintained (February 1973). It has been impossible to evaluate the accuracy of discharge measurements at the highest flows but, for the purpose of this study, accuracy in the range 0 - 5 cusecs. was more important than accuracy for the infrequent and short-lived floods.

## Rainfall/Runoff Relations

Broadly speaking hydrologists recognise two main sources of runoff to streams, indirect runoff and direct runoff. Indirect runoff is water which has infiltrated and percolated through the soil to become groundwater. Direct runoff is water which has reached the stream without being stored as groundwater and this includes precipitation that has fallen directly on to the stream, water which has flowed over the surface of the ground and water which has flowed through the upper subsurface layers. It is the relative importance of these several components of direct runoff that have been the subject of many investigations.

Horton (1933, 1945) suggested that storm flow resulted mainly from the contribution from overland flow. Storm runoff occurred when the rate of precipitation exceeded the rate of infiltration. He recognised that a certain amount of precipitation would fall directly on to the stream and thus contribute to a rise in stream volume irrespective of the infiltration rate of the soil, but this would be a very small amount in terms of total stream-flow volumes. Following a rainstorm there would be a movement of water through the subsoil to the stream channel and, although this might be a considerable volume, it would be contributed over a long period and would not contribute substantially to storm flow.

Other hydrologists, particularly those working on forested catchments, have postulated the mechanism of subsurface flow as the main source of storm runoff. Whipkey (1965) found that in a forest soil, which is

protected by litter and permeable to water infiltration, the water moves through the subsoil and not over the surface of the ground. Subsurface storm flow moves laterally through the soil towards the stream channel, the rate and volume of water movement depending on the rainfall rate and duration as well as the hydraulic properties of the soil. Whipkey (1965) noted that different rates of water movement through the soil occurred depending upon its 'wet' or 'dry' condition. These conditions were defined arbitrarily - the soil was classed as dry if more than four days had passed since the previous rainfall.

More recently, work by Dunne and Black (1970) has thrown doubt on the role of subsurface storm flow as the main source of storm runoff. They found that the importance of a hillslope as a producer of storm flow depended upon its ability to initiate overland flow, but unlike Horton, they found that this was limited to a small proportion of the catchment. Both Betson (1964) and Ragan (1967) concluded that only a small part of the watershed ever contributed flow to storm runoff, although Betson regarded these parts of the watershed as constant, while Ragan regarded them as changing. From these studies it would appear that the major proportion of storm runoff may well be produced as overland flow on small saturated areas, within the catchment, often close to the stream. The rest of the catchment acts as a reservoir during storms and maintains the areas that produce storm flow. During periods of storm runoff the whole of the saturated area acts as an extended stream system and therefore

precipitation falling on this saturated area becomes more important.

The so called partial area concept provides a feasible model for the study of runoff from the Lanehead catchment. During periods of storm runoff all the flushes within the catchment support overland flow while there is no evidence of this on the peat lands which represents a much greater proportion of the catchment. On the other hand, these flushes are not able necessarily to produce overland flow everytime there is precipitation. Indeed, it will be shown that following a period of 24 hours without precipitation, these flushes need to be 'reprimed' before they can support overland flow.

The precise system of runoff production is not relevant to this study at Lanehead and no attempt has been made to measure this process. However, since the volume of discharge in the stream channel will affect the response of the stream water temperature, clearly the factors which control runoff become indirect controls over stream water temperature.

For the purpose of this study it has only been necessary to relate the storm runoff occurrences with the conditions, particularly the precipitation, which promote them. However, not all storms did produce appreciable runoff and therefore only under the conditions generating runoff could precipitation be regarded as an indirect control over the thermal characteristics of the stream. In effect therefore, the rainfall/runoff relations have been studied in order to determine the conditions under which precipitation becomes an effective indirect control

over the stream water temperature.

The rainfall/runoff relations have been viewed generally by using mean monthly data and, more specifically, by the study of storm periods. From these preliminary investigations it will be shown that the antecedent catchment conditions affect the relationship between precipitation and the resulting discharge. A number of storm periods have been selected to demonstrate this.

The mean monthly discharge from the catchment during the two years 1968/69 and 1969/70 is shown in figure 29. The annual pattern for the two years is basically very similar showing a mean winter flow of 2 - 2.5 cusecs, and a mean summer flow of less than 0.5 cusecs. The variations between the years reflect the distribution of the precipitation. In 1968/69 much of the precipitation during February and March was snowfall and this did not appear as discharge until the main snowmelt in March. During the very mild winter of 1969/70 there was very little storage of water in the form of snow and consequently the discharge reflects the rainfall distribution more closely.

In both years the mean flow from the catchment for the drier summer months was less than 0.5 cusecs. During this period when the ground was dry and absorbent, and when the resources of ground water were very low, heavy falls of rain made only a small difference to the level of discharge. For example, in August 1970 a rainfall of 145 mm. produced a mean flow of only 0.9 cusecs while the equivalent fall of precipitation in November 1969 had

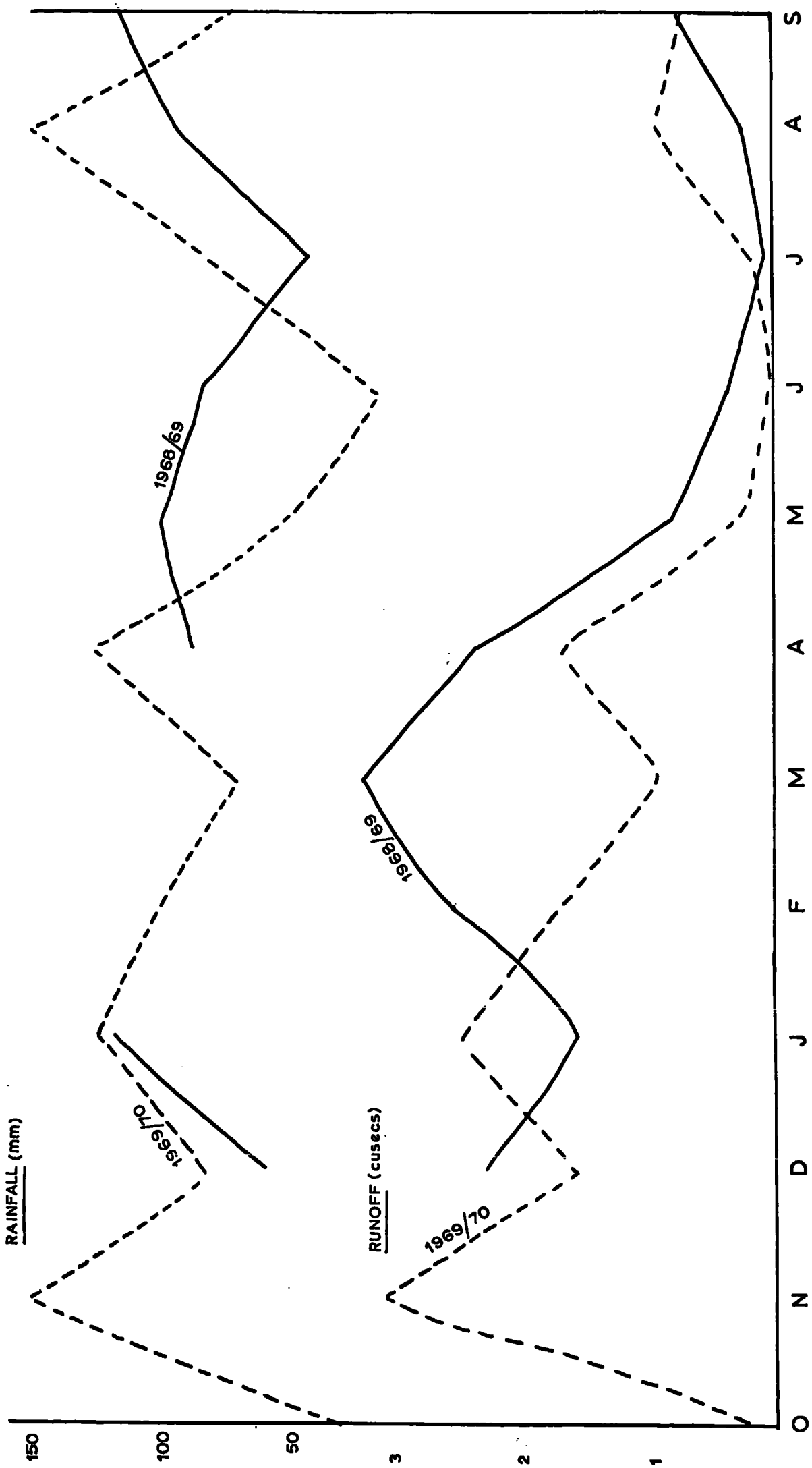


FIG 29 MEAN MONTHLY DISCHARGE RELATED TO RAINFALL

produced a mean flow of 3.0 cusecs.

The mean daily discharge for 1969/70 has been plotted on a semi-logarithmic scale in figure 30. The rapidity with which the stream responded to rainfall is demonstrated by the sudden rise in the mean flow from day to day, and the extent to which the catchment retarded the release of water was indicated by the much shallower recession curve which extended over several days. The recessions during the spring season were modified by the irregular nature of the release of water from the melting snow.

The rainfall/runoff relations during the winter period were influenced by various factors. Firstly, the release of water from the catchment was not always directly related to the fall of precipitation since much of it was stored as lying snow, the release of which was dependent upon other factors such as air temperature and solar radiation. Secondly, much of the precipitation fell as snow, and as explained above, the quality of the measurements was not comparable with that for the data collected during the summer. For these reasons the study of the relationship between rain storms and individual floods was limited to the summer period. Chapter 6 is devoted to the study of the snowmelt floods and to the winter conditions generally.

In figure 31, the rainfall periods have been related to the resulting mean flow. These six/seven day periods were not ideal for this type of analysis since they were not always hydrologically homogeneous, and the effects of three dry days at the beginning of the week might be modified by three wet days following; whilst the effect



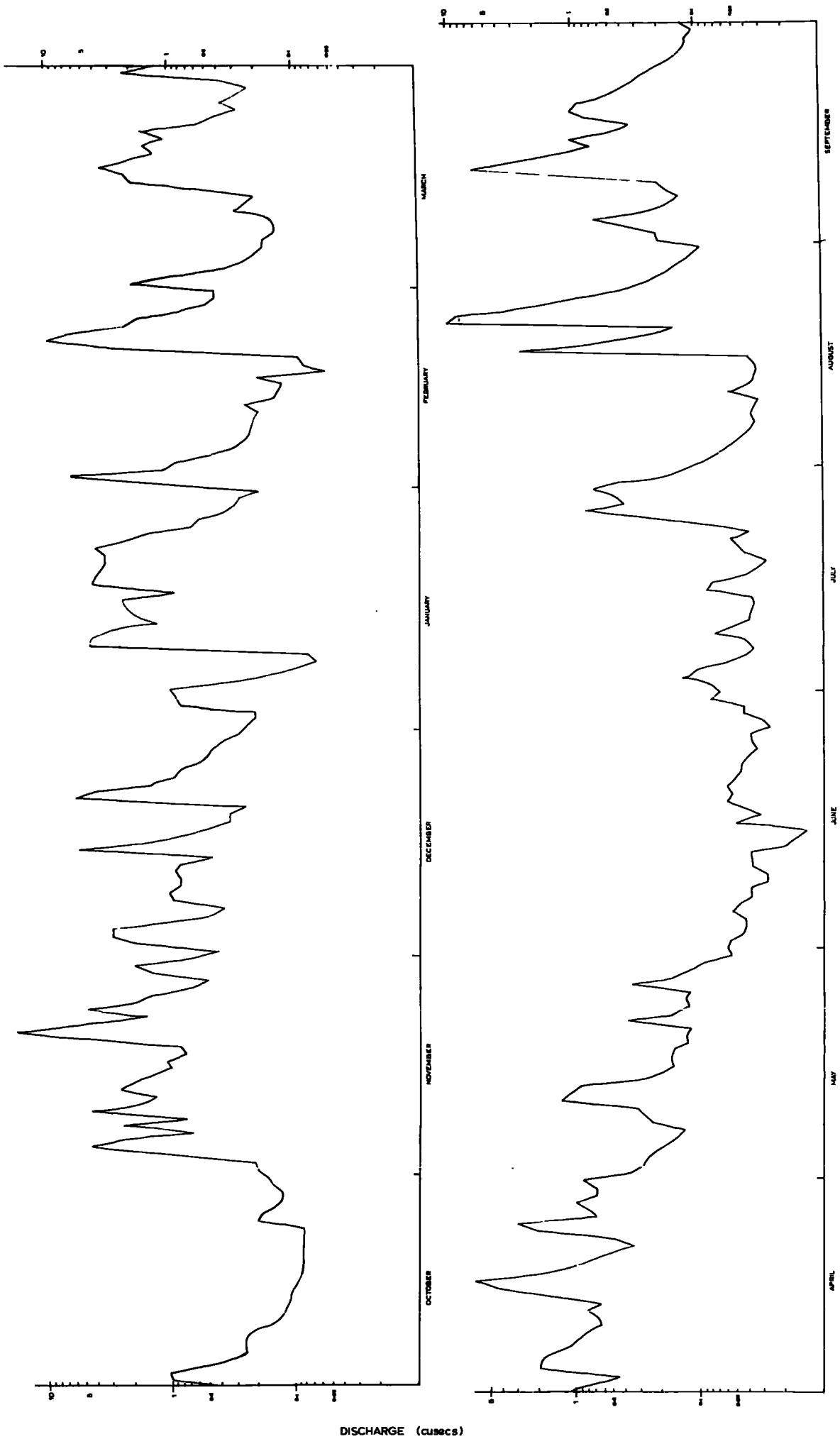
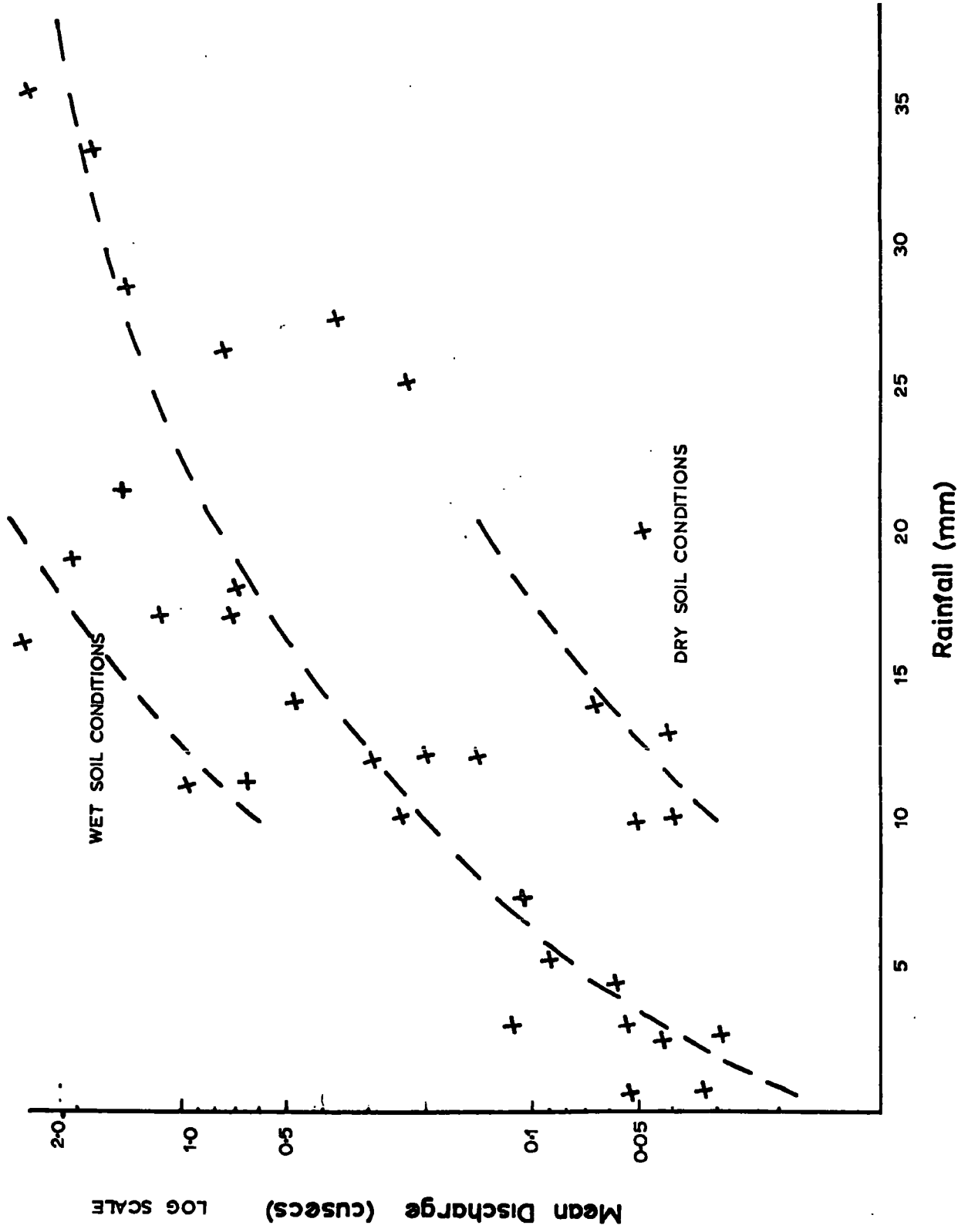


FIG 30 MEAN DAILY DISCHARGE 1969/70

FIG 31

RAINFALL/RUNOFF  
RELATIONS FOR  
WEEKLY VALUES

1970



of the wet days might well affect discharge in the following data period. It was possible however, to relate the mean discharge resulting from the weekly rainfall total for the majority of weeks as indicated.

The stream flow response to a given fall of precipitation varied according to the antecedent condition of the soil. If the rain followed a period of dry weather much of the rainfall was absorbed and very little appeared as flow over the ground surface. On the other hand, if the rainfall followed a period of wet weather there would be very little absorption by the soil and most of the fall would be carried out of the catchment very quickly.

When the rainfall/runoff relations for individual storms were examined it was seen that the hydrographs could be grouped into three categories; those resulting from dry catchment conditions, those resulting from wet catchment conditions and those resulting from several distinct rainstorms. The catchment was in a 'wet' condition if rain had fallen on the catchment within the 24 hours immediately preceding the storm; if no rain had fallen then the catchment was 'dry'.

The difference between the hydrographs resulting from 'wet' and 'dry' conditions was very clearly demonstrated on 21st and 22nd April, 1969 (Fig.32). The term rainfall hydrograph is used in this context to distinguish it from a hydrograph resulting from snowmelt. No precipitation had fallen in the catchment for five days before the beginning of the rainstorm at 1730 on 21st April (although the soil was probably dampened on the 17th April by the melting of a small amount of lying

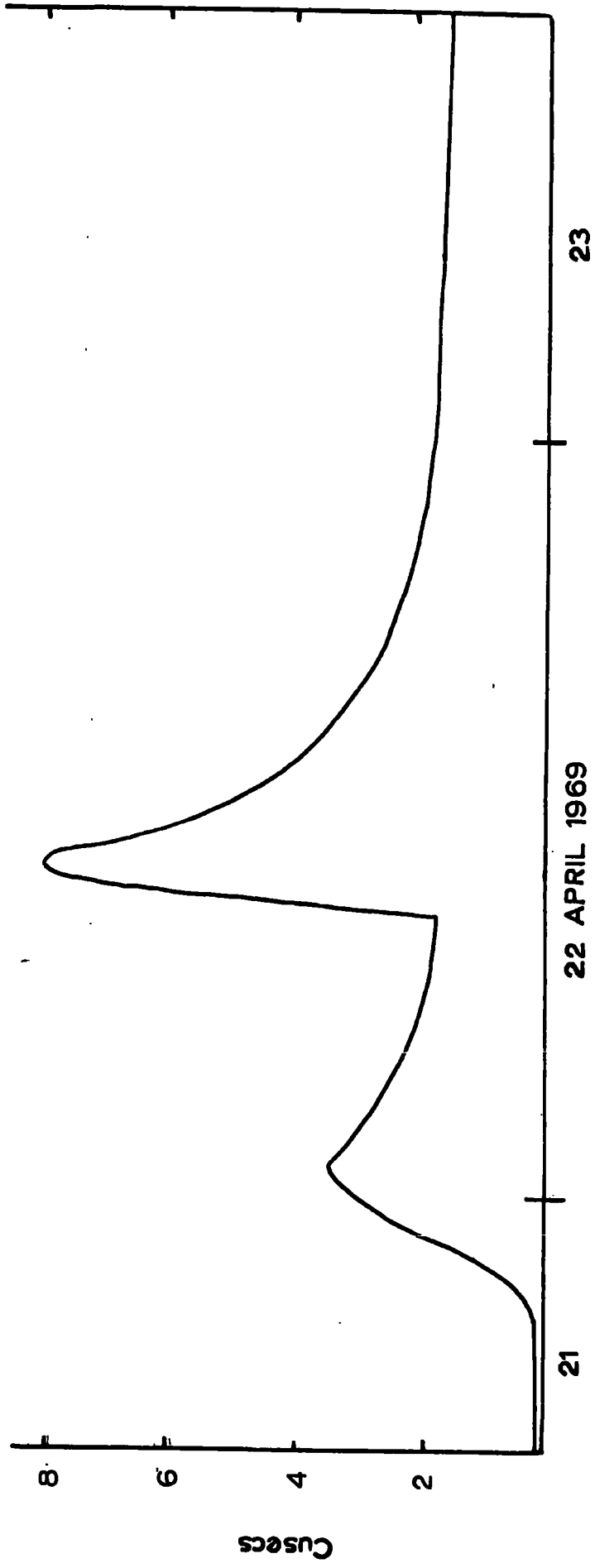
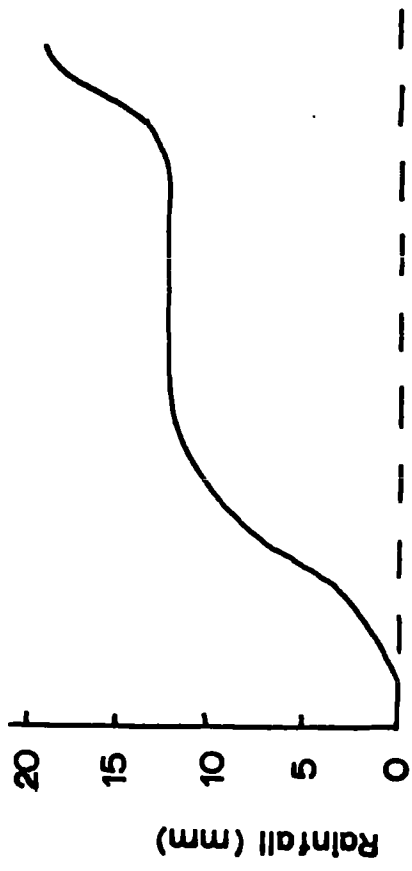


FIG 32 RAINFALL HYDROGRAPH

snow). The rainfall of 12 mm. fell at a uniform rate of 2 mm/hr. producing a flood of 3.4 cusecs. The discharge began to rise half an hour after the beginning of the rainstorm and increased in volume at the rate of 1 cusec/hour to its peak flow  $\frac{1}{2}$  hour after the rainstorm had ceased. After six hours a second storm of 7.5 mm., falling at the same intensity (2 mm/hour), produced a flood of 8 cusecs. As a result of this second, smaller rainstorm the flood level rose from 1.5 to 8 cusecs in  $1\frac{1}{4}$  hours - a rate of increase of 5.2 cusecs/hour.

A similar situation occurred in August 1969 (Fig.33). Following a period of four rainless days, a fall of 3 mm. at 0430 BST on 3rd August, 1969 produced a flood of 1.4 cusecs. The rain fell at a rate of 1.5 mm./hr. and the discharge increased at a rate of 0.7 cusecs/hour. The flood peak was reached one hour after the rainfall had stopped. A rainstorm of 7.5 mm. falling at an intensity of 3mm/hr. fell 10 hours later and produced a flood of 7 cusecs which reached its peak  $\frac{1}{2}$  hour after the rain had stopped. During the recession from this second flood a short but heavy storm of 3.8 mm. produced a minor pulse of flood water equivalent to an additional flow of about 2 cusecs. The following evening a very sudden and heavy storm of 18.75 mm. fell with an intensity of 9 mm/hr. to produce a flood of 27 cusecs. The discharge from the catchment rose from 0.5 cusecs  $\frac{1}{2}$  hour after the beginning of the storm to 27 cusecs in two hours. Once again the peak flow was reached  $\frac{1}{2}$  hour after the rain had ceased.

It is well known that the effectiveness of a rainstorm to produce a flood is increased if the soil is

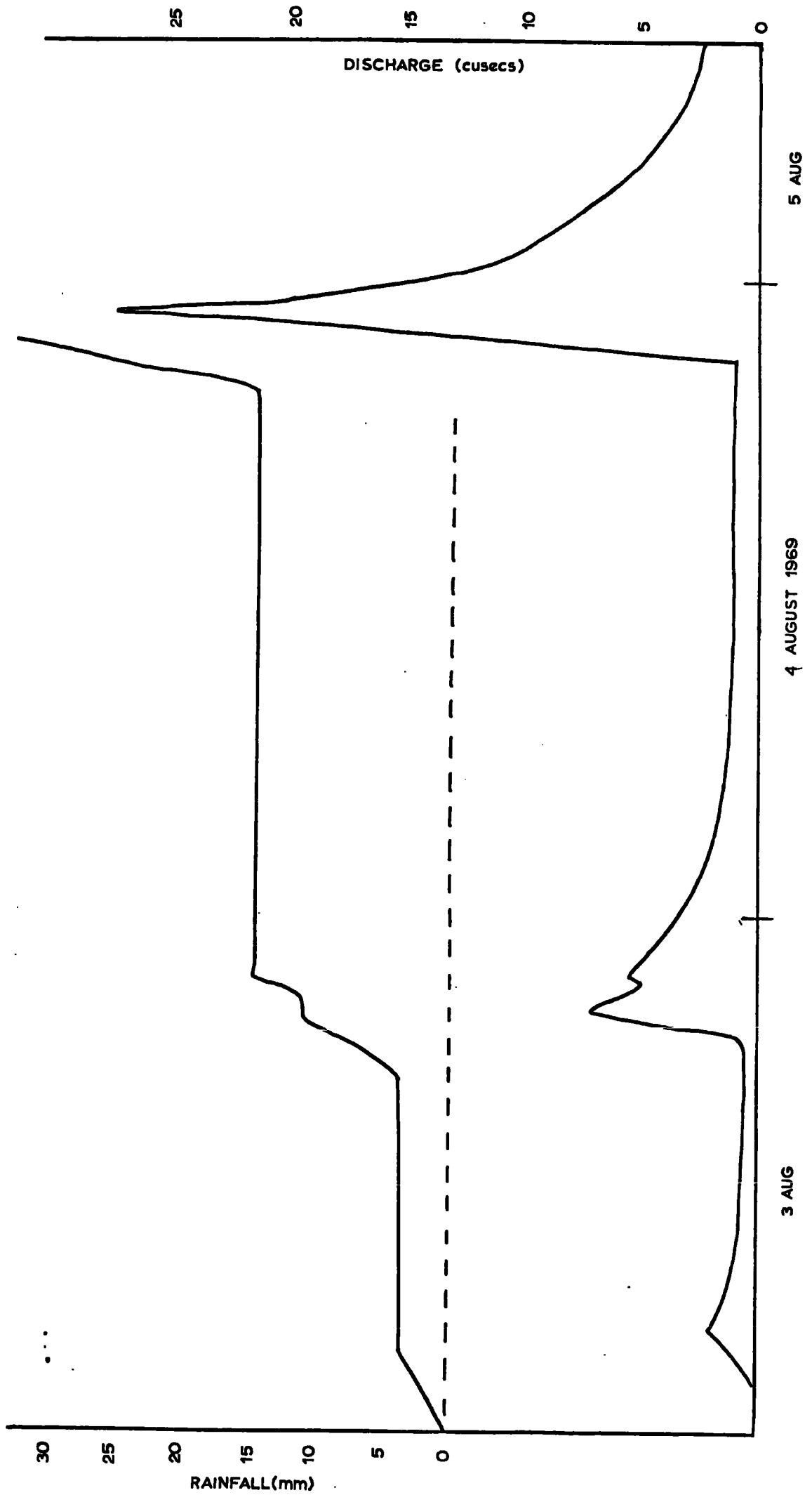


FIG 33 RAINFALL HYDROGRAPHS

already wet. This is clearly demonstrated in Fig.34, where the rainfall/runoff relations for 19 storms have been plotted. When the storms occurred after a period of at least 24 rainless hours the relationship between the maximum discharge and the rainfall was:

$$Q = 0.238 (P - 9.5) + 3.15$$

where P = rainfall in mm.

When the storms occurred after a recent period of rainfall the maximum flow per unit of rainfall was significantly greater.

$$Q = 1.744 (P - 8.3) + 8.6$$

In the following table an attempt has been made to compare the actual volume of runoff generated in the catchment compared with the total volume of rain falling in the area. The maximum expected volume would be the rate of discharge if all the rain had been drained from the catchment in one hour (see Fig.35A). The actual discharge data is calculated from the total flow for the catchment during a storm, presented as a volume of discharge during one hour. Clearly the wet catchment is generating a greater volume of discharge than the dry catchment, but the storm floods last for a shorter time.

Not only was there a difference in the size of the floods associated with wet soil conditions within the catchment compared with the floods which occurred after dry weather, but the nature of the hydrographs was also different. A number of flood hydrographs are shown in Fig.35B to demonstrate this. During the dry periods the rising limb of the hydrograph was less steep than during the wet periods. Frequently it was two hours, and on

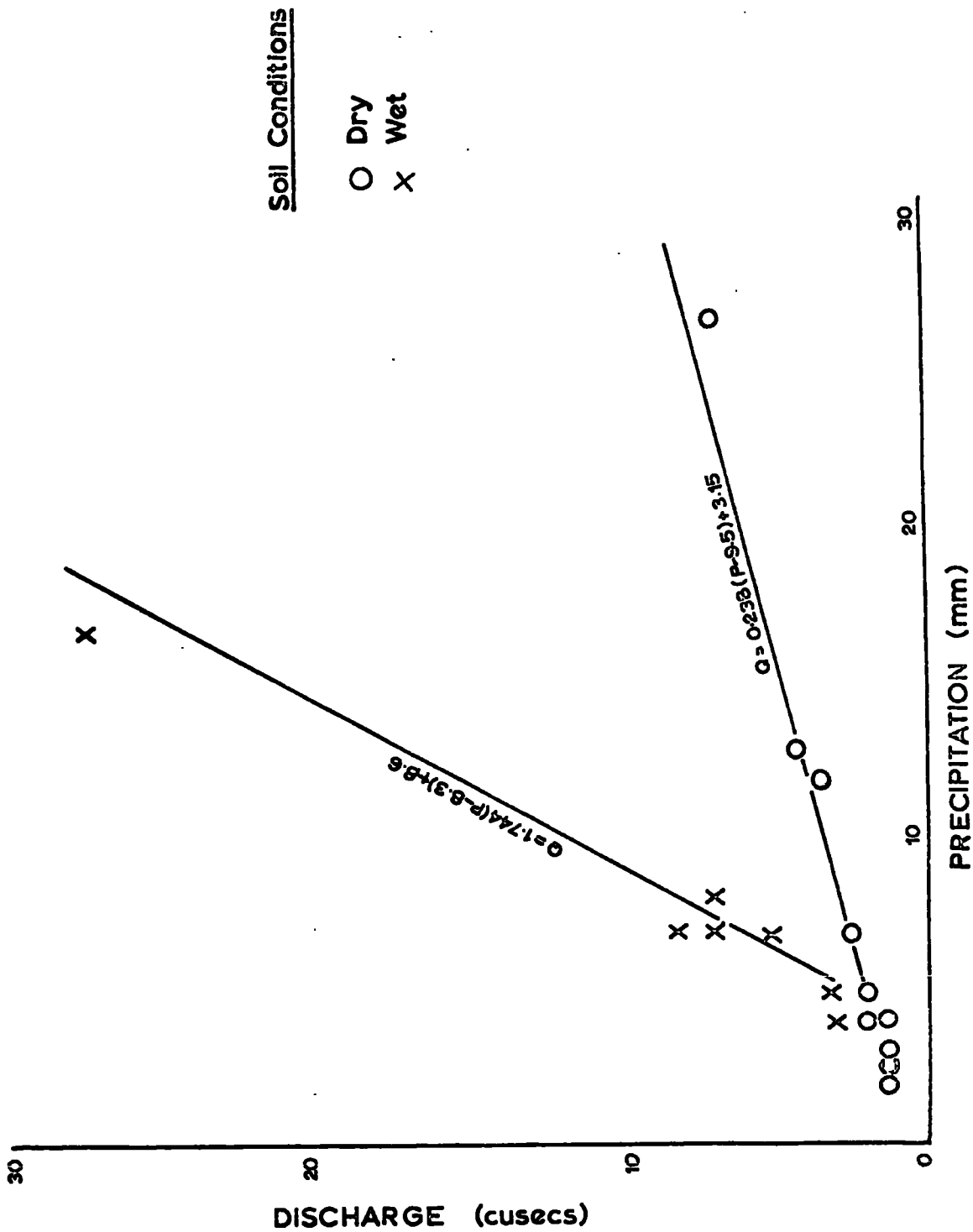


FIG 34 RAINFALL RUNOFF RELATIONS FOR 17 STORMS

FIG 35A WATER DEPTH OVER THE WHOLE CATCHMENT

EXPRESSED AS DISCHARGE

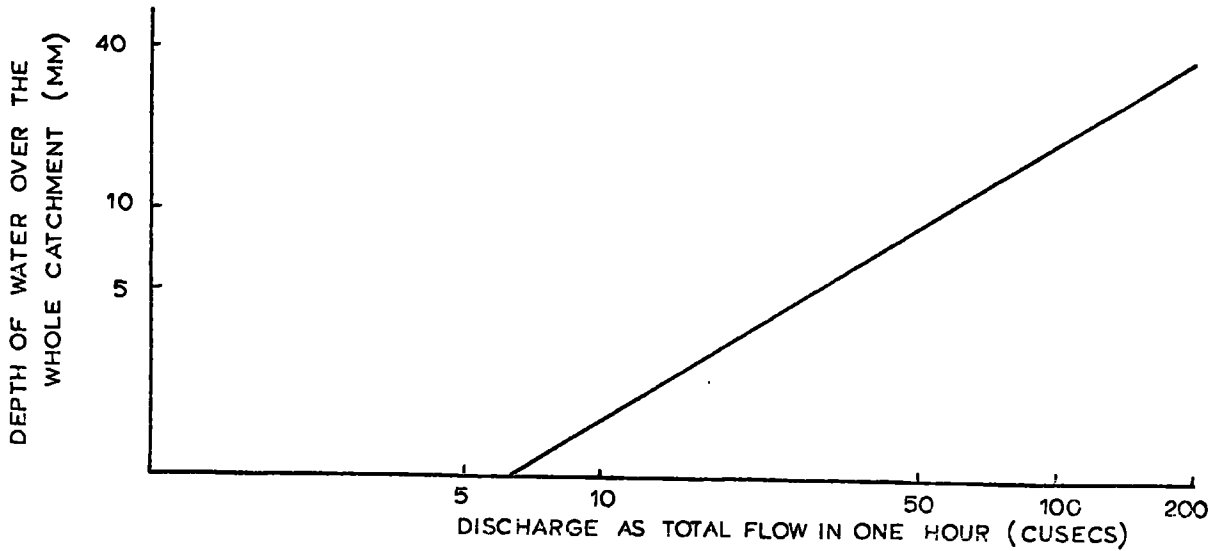
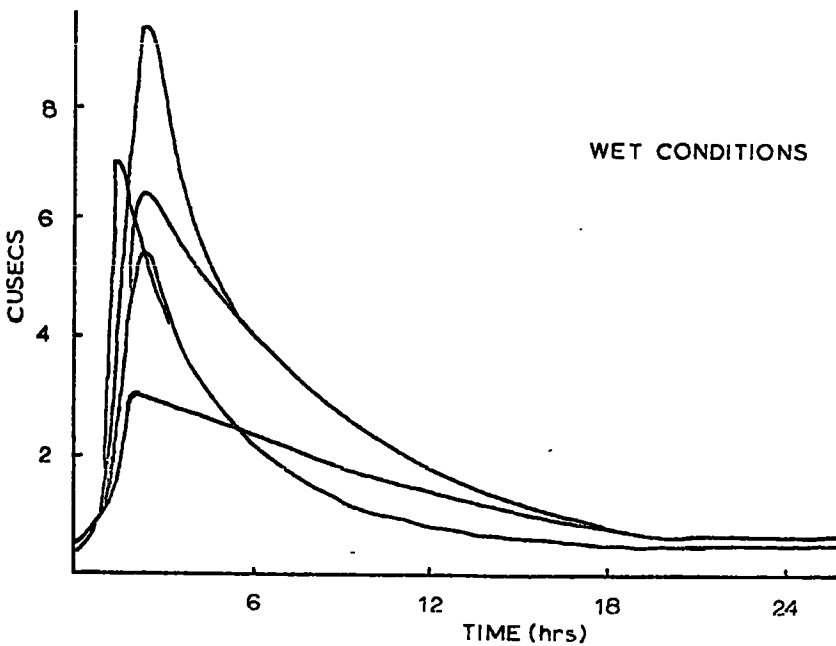
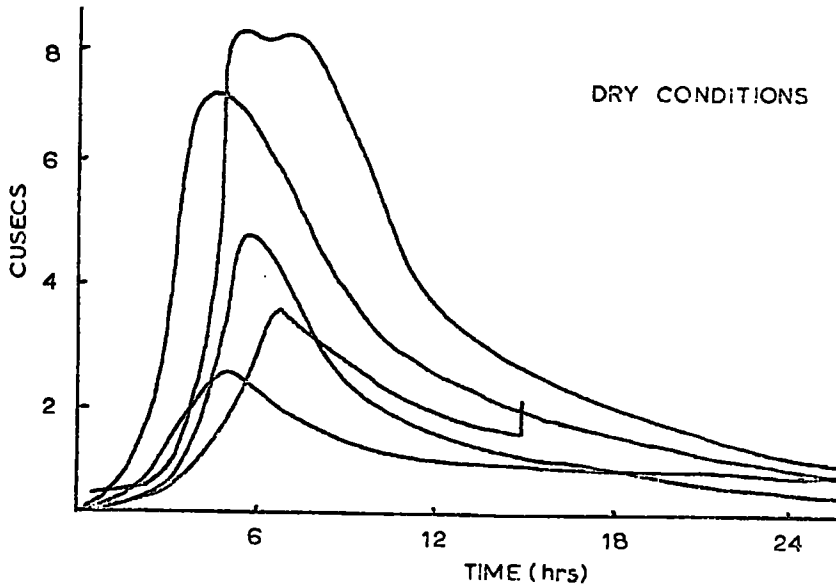


FIG 35B RAINFALL HYDROGRAPHS RESULTING FROM WET AND DRY CATCHMENT CONDITIONS



some occasions four hours before the volume of the stream had doubled its initial volume. The peak of the hydrograph was quite flat, and often the flow remained

Rainfall (mm.)	Maximum expected flow (cusecs in one hour)	Actual flow (cusecs in one hour)		Duration of flow (hrs.)	
		Dry Catchment	Wet Catchment	Dry Datchment	Wet Catchment
28	175	76		38	
18.75	115		106		29
13	80	53		35	
10	62		36		20
9	55		36		21
8.5	52	28		27	
7.5	45		32		16
			24		16
7	43	17		25	
4.5	27		23		26
4	25	17	18	29	17
3.6	22	10		13	
2.75	17	13		24	
1.4	9	7		18	

constant for an hour or so. During the wet conditions the hydrograph showed a very rapid response to rainfall. Depending in part upon the intensity of the rainfall, the stream could increase in volume from less than 1 cusec to 10 cusecs within an hour.

The rate of recession in both sets of hydrographs in Fig.35B is very similar, and is not related to the condition of the catchment surface, but more to the state of the groundwater resources. In general the rate of recession varied with the season of the year, in the winter it would fall to a base flow of about 1 cusec, while in the summer when the content of the aquifer was very low, the hydrograph receded to less than 0.25 cusecs.

If several rainstorms contributed to one flood a multiple hydrograph resulted. Such a compound flood occurred on 2/3 June and 18th August 1969. On both

occasions the flood period was preceded by at least 24 hours without rain. From Fig.36 it can be seen that the initial fall of rain produced a relatively slow rise in discharge as would be expected from a flood following a period of dry weather. Since the first storm dampened the soil the subsequent rainstorm produced a much steeper hydrograph, built upon the hydrograph of the earlier event. The higher the level of discharge at the beginning of subsequent storms the more rapid would be the response of the stream to the precipitation, since the flow would be moving faster through the catchment. Because of this much more rapid supply of water the rising limb of the hydrograph became very steep and the fall off was also rapid after the rainstorm had ceased.

On 2nd June 1969 the discharge increased in volume at a rate of 2 cusecs/hour between 2200 and 2400 BST. The rainstorm began at 1800 BST and 4 mm. of rain fell before any increase in discharge occurred. During this phase in the hydrograph the rainfall intensity was 2.5 mm/hr. The second rainstorm occurred at 0100 BST (3 June) and during this second storm, which lasted for two hours, a total fall of 6 mm. produced an increase in flow from 4 to 12.5 cusecs. The response of the stream flow to the rainstorm was immediate at 0100 BST. The third storm began at 0330 BST and produced an immediate response in the stream flow; a rainfall of 3 mm. produced a flood of 3 cusecs. A rainfall of 8.5 mm. was required to produce the first 4 cusecs of flow while only 3 mm. was required to increase the flow from 12.5 to 15.5 cusecs.

On the 18th September 1969 a rainstorm of 6 mm. between

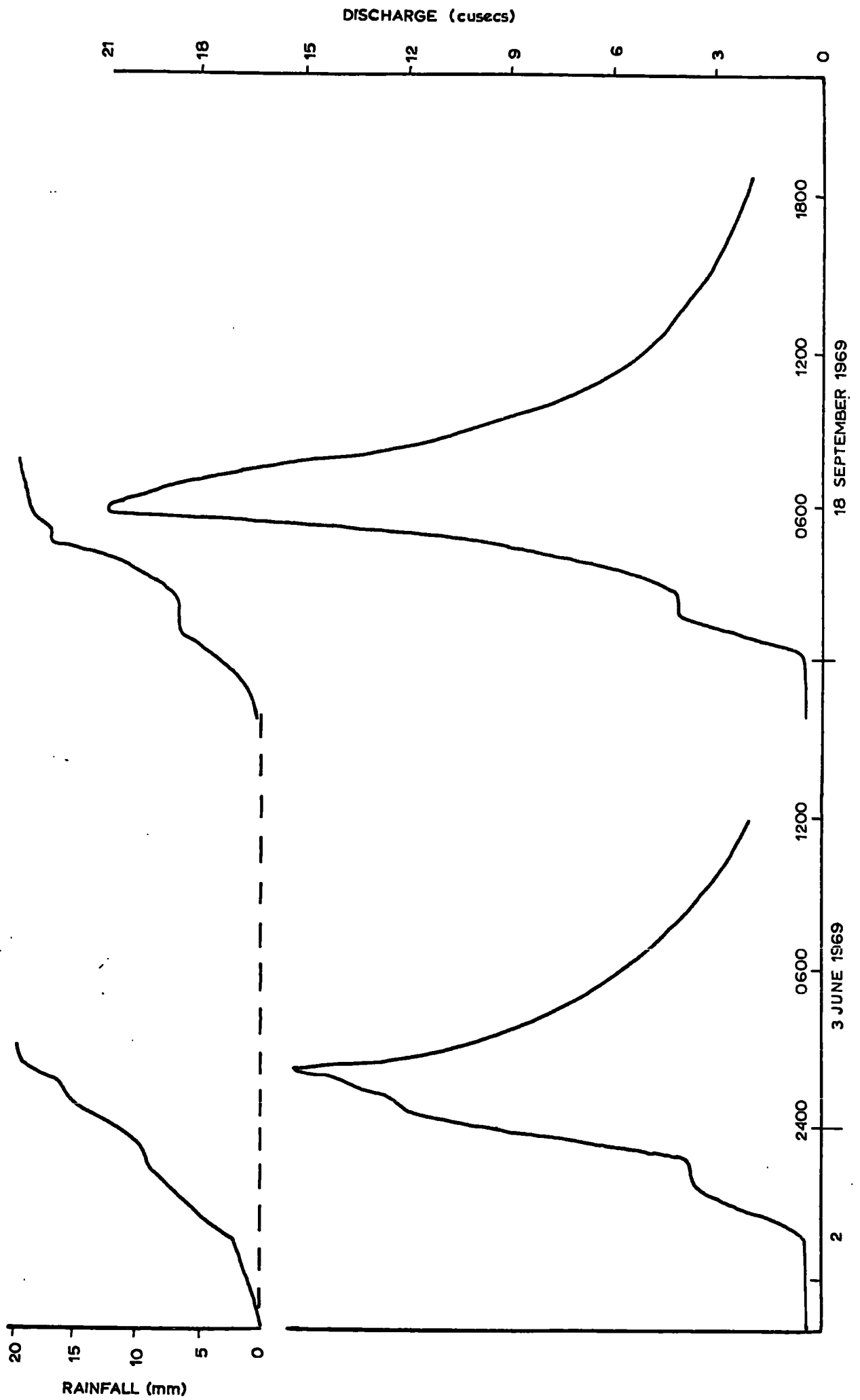


FIG 36 RAINFALL HYDROGRAPHS

0300 and 0600 BST produced a small flood of 4 cusecs. The response of the stream to the rainfall was slow. The stream did not begin to rise until  $2\frac{1}{2}$  hours after the first storm, and had ceased to rise within  $\frac{1}{2}$  hour of the end of the first storm. The second storm began at 0730 BST and lasted for  $3\frac{1}{2}$  hours with an intensity of 4 mm/hr. The discharge rose almost immediately and continued to increase in volume at the rate of 6 cusecs/hour for the duration of the storm. Although the main storm ceased at 1100 BST a certain amount of drizzle did continue to fall. The drizzle was not sufficient to maintain the level of the flood, but it was sufficient to distort the shape of the hydrograph. Normally the reduction in flow is most rapid in the initial stages immediately following the peak flow, and then more slowly later as the minor channels and then the larger ones begin to reduce their contribution. This was not the case on 18th August because the drizzle which continued after 1100 BST was sufficiently heavy to produce a noticeable effect upon the stream flow, and to prevent the rapid reduction in volume which would be expected after the peak flow at 1100 BST. The most rapid reduction in water level did not occur until 1300 BST when the drizzle finally ceased. From then onwards the shape of the hydrograph was similar to that on 3rd June 1969 (Fig.36).

The nature of the discharge from the catchment is a product of the nature of the precipitation and the state of the catchment. In very broad terms it can be seen from the mean monthly data that the discharge from the catchment reflected the occurrence of rainfall. However

the size and nature of a flood depended upon the condition of the catchment as well as upon the rainstorm. Rain, falling in a catchment which had been rainless for 24 hours, produced a small flood when compared with a similar amount of rain falling onto a wet soil, since much of the rain was absorbed by the soil. On the other hand floods from a dry catchment were longer lasting than those from a wet catchment.

The volume of discharge from the catchment depends upon the combined effects of both precipitation and catchment soil conditions. In this way a combination of factors has an indirect effect upon the thermal characteristics of the stream. This indirect control becomes much more direct where the precipitation involved is in the form of snow. Not only is the release of snow related to the atmospheric conditions, but the released water has a dominating influence upon the stream water temperature. This situation is discussed in the next chapter.

During periods of low flow, stream water moves through the catchment slowly and is, therefore, exposed to the atmospheric environment for much longer than it would be during higher flows. Furthermore, the surface area of the stream, the main point of contact between the stream water and the atmospheric environment, does not increase significantly with an increase in volume but remains relatively constant for a large range of discharge; therefore, the efficiency of the contact between these elements becomes progressively less as the volume of discharge increases.

In view of the modifying influence exerted by the

volume of discharge upon the relationship between the stream water temperature and the atmospheric environment, the factors affecting runoff conditions become indirect controls over the temperature of the stream water. It is to be expected that the closest relationship between water temperature and the atmospheric environment will occur for medium size discharges of 1 - 3 cusecs. For volumes less than this the influence of the groundwater will become increasingly dominating as its proportion in relation to the total discharge becomes greater. For discharges greater than 3 cusecs, the relationship between the water temperature and the atmospheric environment will become progressively less with the increase in discharge volume, due to the inevitably slower response of the larger volume of water.

The instrumentation for precipitation and discharge in the catchment was designed only to give an indication of the nature of the controls over the release of water from the catchment. There was no attempt either to instrument for, or to interpret, a complete water balance of the catchment.

## CHAPTER 6

### SNOWMELT DISCHARGE STUDIES

The rainfall/runoff relations described in Chapter 5 completely omit the winter conditions from late November to early May. This is partly because the data available were not as complete as those obtained in the summer, but mainly because the principles that held for the conditions of rainfall and direct runoff did not hold for the conditions of snowfall and subsequent snowmelt discharge. In Chapter 7 it will be seen that the temperature sequences involving periods of snowmelt discharge or frozen catchment conditions were different from those of other periods because the snowmelt itself obscured the effects exerted by the other influences on the stream water temperature.

Snowmelting is fundamentally a matter of thermodynamics involving the inter-action of many variables. In the Fraser Forest experiment (Garstka et al 1958) twenty factors causing snowmelt were isolated ranging from relative humidity, wind travel and solar radiation to dew point temperatures and degree-day temperatures. Both simple and multiple statistical correlation analyses were computed relating runoff to these factors, but the overall results indicated that the temperature factor is at least as good and in many ways better, than a combination of other factors.

This conclusion agrees with that of Wilson (1941) who demonstrated that the variables closely related to air temperature, namely air convection, turbulent exchange and

heat of vapourisation, caused the greatest heat transfer. Similarly Nishizawa (1969) used air temperature as the basis of his study of snowmelting in the Takinami river basin in Japan.

Solar radiation, atmospheric vapour pressure, air convection and air temperature are normally regarded as the important meteorological parameters causing snowmelt. Of these air temperature is regarded as the most significant for the degree-day has been widely used as a measure of a catchment's response to melt potential in America and Japan and other places (Johnson 1966). This response can be expressed in a simple relationship:

$$D = K(T-32)$$

Where D = average rate of snow melt over the basin in one day (ins/day)

T = average daily temperature °F

T-32 = daily number of degree days above freezing °F

K = a melt coefficient or degree/day factor

Clearly, snowmelt can be expected to influence the relationship between air temperature and water temperature if only in respect of the increased volume of water. But, in addition to this, by virtue of the temperature of the melt water, snowmelt will exert an even greater effect upon this relationship. Since air temperature appears to be one of the main controls over the release of melt water from a snow covered catchment it will have an indirect, as well as direct affect, upon the temperature of stream water during a period of snowmelt.

Snowmelt discharges, occurring during the winter as a result of warming atmospheric conditions rather than direct precipitation, display a combination of the hydro-

logic and the thermal characteristics of stream flow. Although only a small number of snowmelt floods have occurred during the two-year study period, some of these floods released several falls of precipitation which had been stored in the catchment as snow. Since precipitation in the form of snow may fall in the catchment at any time between November and April, snowmelt floods could account for a large proportion of the total annual discharge from the catchment.

During periods of snow lie heat energy either as air temperature or direct solar radiation may become a more direct influence upon the nature of the discharge from the catchment than precipitation. Smith (1971), working in the adjacent upper Tees, noted that the effect of winter freezing conditions could produce the periods of both maximum and minimum flow. Prolonged periods of sub-zero air temperatures could result in water being locked up as ice in the catchment to such an extent that the lowest recorded flows occurred during the winter rather than during the summer. This was not the case in the Lanehead catchment because, over the observation period, there was a base flow of approximately 0.5 cusecs during the winter compared with a flow of 0.1 cusecs during the summer. The winter base flow could not be affected by air temperature conditions until it emerged as surface flow and certainly during the two years 1968/69 and 1969/70 the air temperatures were never sufficiently low to lock up this supply in stream ice. Only streams with very little or no groundwater contribution would be likely to freeze-up completely in this country, except under the most extreme

atmospheric conditions. Also the accumulation of snow from several separate falls would often be released as one very large snow melt flood. Thus it could be that the air temperature rather than the immediate precipitation sometimes causes the maximum as well as the minimum flows from an upland catchment.

A diurnal fluctuation of air temperature above and below freezing point will tend to produce a series of diurnal snowmelts. The nature of these will depend upon the nature and amount of snow lying in the catchment and the amount of heat available for melting. Available heat is normally measured in terms of air temperature, but its effectiveness depends upon other factors such as the amount of solar radiation or the humidity of the air. A fall of precipitation during mild air temperature conditions would produce sufficient heat to cause a major release of water from a snow-covered catchment. Following, Wilson (1941) the amount of snowmelt resulting can be calculated by the following formula

$$D = \frac{P \cdot (T - 32)}{144}$$

where D depth of water melted from snow (ins)

P depth of rainfall (ins)

T temperature ( $^{\circ}$ F). (normally wet bulb)

This formula is used later to analyse a snowmelt hydrograph at Lanehead which was in part caused by a rainstorm.

#### Specimen snowmelt floods

Five periods of snowmelt flooding have been selected as case studies to illustrate various aspects of the

release of snowmelt as stream discharge. In 1968/69 there was one major release of snow from the catchment which lasted for several days at the end of March. Since the water was released in daily floods this situation clearly demonstrated that the factors which control the release of melt water were related to the diurnal cycle. In November 1969 there were two snowmelt floods which demonstrated that there was no direct relationship between air temperature and the release of snowmelt water. The flood of 21st December, 1969 demonstrates the ability of precipitation to initiate snowmelt discharge from the catchment. The final case study, 19-23rd February, 1970 is a three phase discharge illustrating the differences between floods caused by precipitation and those caused by other elements in the atmospheric environment.

(i) 29th March - 8th April, 1969

In 1969 the main snowmelt occurred between 29th March and 8th April. On this occasion the relationship between the fluctuations in air temperature and the release of water from the catchment was quite straightforward (Fig.37). Since the catchment had an altitude range of 140 m. the air temperature at the top of the catchment would be approximately  $1\frac{1}{2}^{\circ}\text{C}$  cooler than at the weir site due to the average lapse rate with altitude. Therefore it was necessary to regard the air temperature effective over the catchment as a whole, as  $1^{\circ}\text{C}$  colder than that actually recorded at the weir site. (All air temperature values plotted relate to the temperature at the weir site).

The first and largest single release of snowmelt occurred on 30th March. Following a period of several days

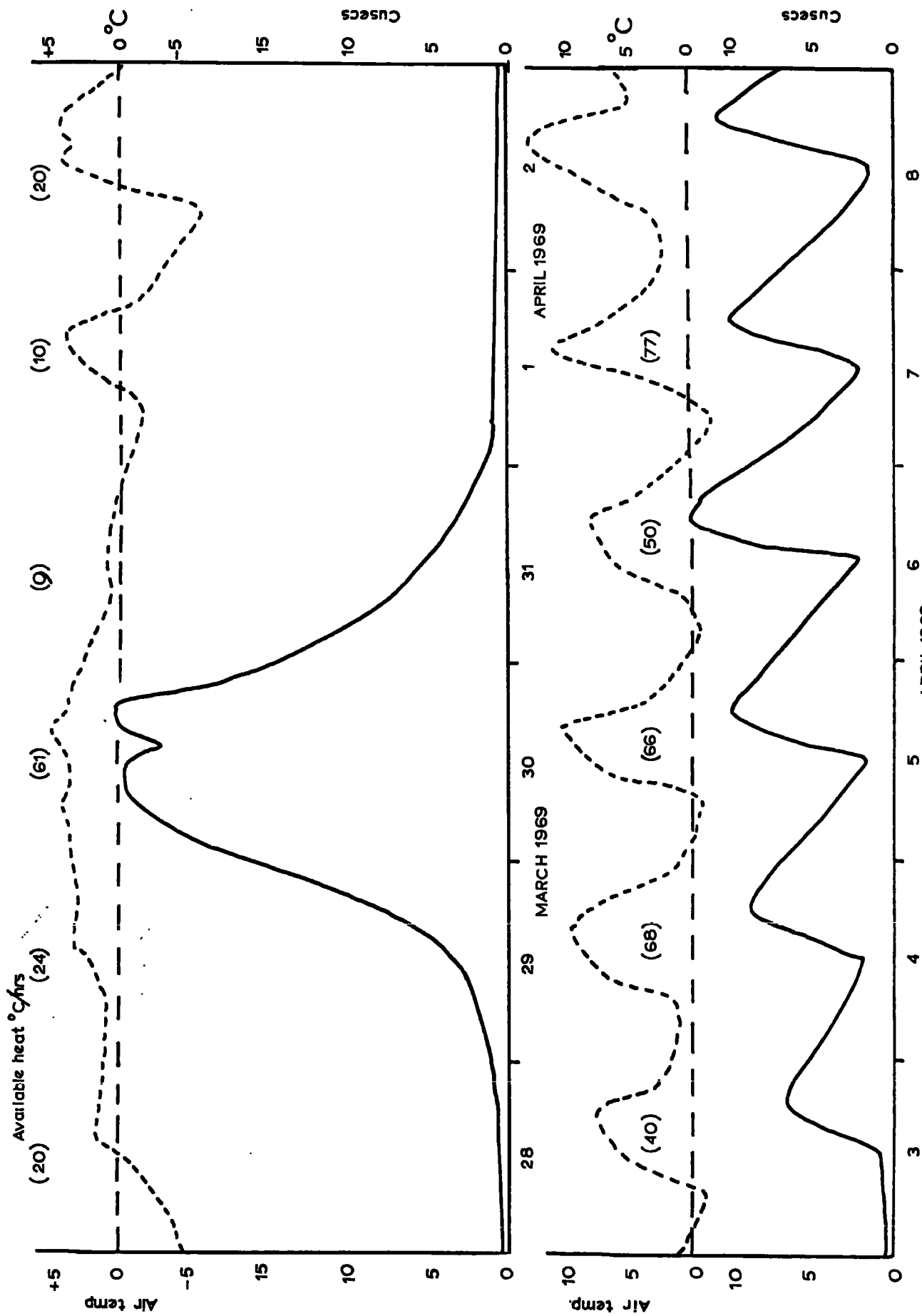


FIG 37 DIURNAL RELEASES OF SNOWMELT DISCHARGE

of sub-zero temperatures, at 1000 BST on 28th March the air temperature rose above freezing point where it continued for several days. The rise in the volume of discharge began to accelerate once the air temperature at the weir exceeded 1°C. The first flood had a double peak separated by six or seven hours. A similar pattern had been noted on other snowmelt floods on 18/19th November and 21st December, 1969. Although this double peak was characteristic of the first in any series of snowmelt floods, the subsequent floods did not have this. There was insufficient evidence to explain the cause of this but the following theory is suggested. Due to the different shape and altitude distribution of the two catchments, the snowmelt from each of them would reach the weir at different times. Catchment A was higher and would experience slightly colder mean air temperatures than catchment B and snowmelt water would therefore take longer to reach the weir site. The double peak, therefore, could represent the contribution of snowmelt from each catchment. The thaws on the subsequent days would not produce double peaks because the snow would be near a 'ripe' condition throughout the whole catchment and because there would be a certain amount of snowmelt in the process of moving down the catchment - its progress having been temporarily arrested by the night-time freeze up. The subsequent thaws were, in fact, continuations of the first flood which was interrupted at regular intervals by the diurnal fluctuations in air temperature.

The maximum temperature was not necessarily a sufficient indication of the amount of heat available to

melt the snow. Following the main flood on 30th March there was no further flood until 3rd April despite the fact that the air temperature rose above freezing point at the weir each day. For melting to occur there had to be a certain amount of available heat which could best be expressed in terms of cumulative degree/hours. Since the mean air temperature for the catchment as a whole was likely to be 1°C colder than the temperature recorded at the weir site, all cumulative temperature figures were expressed as degree/hours above 1°C. These values for each day are shown in Figure 37. Clearly snowmelt floods did not result from all periods of non freezing air temperatures but only when the cumulative air temperature exceeded 20°C degree/hours. Even when this value had been exceeded however, there was no direct relationship between the cumulative air temperature and the volume of the snowmelt flood.

In the following table, the available heat in degree/hours is shown against the volume of snowmelt generated. (See following page)

Clearly, the amount of snowmelt was not directly related to the available heat. The amount of heat required to turn snow into water is large compared with the amount needed to prevent water reverting to ice (Wilson, 1941) and, therefore, the amount of heat required to initiate a snowmelt is much greater than the amount required to maintain one. Hence, despite low temperatures on 31st March a flow of discharge was maintained while no increase in flow was initiated on 2nd April despite the

Dates (1969)	Max. air temp. (°C)	Available heat (°C/hrs.)	Discharge		Runoff generated	
			Max. (cusecs)	Mean (cusecs)	(cusec flow in one hour)	(rainfall equivalent mm.)
28 March	2	20	0.5	0.5	12	1.5
29	3	24	16	8.5	204	33
30	5	61	25	20.5	492	79
31	3	9	14	7.5	180	29
1 April	4	10	1.25	1.0	24	4
2	5	20	0.75	0.75	18	3
3	8	40	6.5	1.5	36	6
4	10	68	9	5.5	132	21
5	10	66	10	5.75	138	22
6	8	50	12	7	168	27
7	11	77	10	5.75	138	22

much warmer air temperatures. The extent and depth of the snow cover in the catchment is also likely to influence the quantity of melt water released as was noted by Smith (1971) in Teesdale.

From 3 - 8th April the snowmelt floods corresponded directly with the periods of non-freezing air temperatures. The flood hydrographs were very similar, the beginning of the flood occurred at 1200 BST and reached its peak at 2300/2400 BST. The peak flow rose from 6 cusecs on 3rd April to 12 cusecs on 6th April and then fell away to 10 cusecs on 8th April. In contrast the low flows for each day remained constant, by 1200 BST on each day the flow had fallen to 1.4 cusecs. This 'base flow' was obtained from ground and sub-surface sources and its supply was unaffected by variations in air temperature; the additional flow was controlled by the available heat.

Although the available heat in the form of air temperature was responsible for the series of snowmelt floods, it did not have a direct control upon the nature of the floods. The daily snowmelt flood hydrographs between 3rd and 8th April were very similar but resulted from very different patterns of diurnal air temperature fluctuations. Not only was there no apparent relationship between the volume of discharge and the available heat expressed in degree/hours as shown in the table above, but neither was there any relationship between the maximum air temperature and the snowmelt or the peak flow. The peak flow occurred regularly at 1800 BST but the time of the maximum air temperature varied between

1500 and 1800 BST.

Furthermore, since the amount of heat required to raise the temperature of a quantity of pure dry snow to the melting point is very small compared to the amount of heat required to convert the same snow entirely to water (Wilson 1941) the magnitude of the nocturnal sub-zero temperatures would not affect the release of water from the catchment except in so far as there can be no release of water during sub-zero temperatures. There would be no significant relationship between the nocturnal sub-zero temperatures and the time of the release of melt water the following day.

The beginnings of the snowmelt floods were not recorded at the weir until at least three hours after the whole catchment had been in non-freezing conditions, i.e. when the air temperature at the weir had exceeded  $1^{\circ}\text{C}$  for three hours. On 3rd April the flood was delayed, and did not occur until five hours after the appropriate rise in temperature, since the temperature remained only just above  $1^{\circ}\text{C}$  and the available heat to melt the snow did not reach  $20\text{ C degree/hours}$  for five hours. On 8th April the air temperature remained above freezing point at the weir throughout the night, but the temperature remained relatively low in the morning and the available heat did not exceed  $20\text{ C degree/hours}$  until 0900 BST. As a consequence the flood began earlier than normal at 1100 BST. On the other days the flood began exactly three hours after the air temperature at the weir exceeded  $1^{\circ}\text{C}$  and on all occasions the heat available had exceeded  $20\text{ C degree/hours}$  at the beginning of the flood. The snowmelt

flood could not occur within three hours of the beginning of the melting conditions since this was the average time of melt and travel for the snowmelt through the length of the catchment.

The air temperature did not act as a direct influence upon the process of snowmelt any more than it did upon the heating and cooling of the stream water temperature. It acted rather as a useful indicator of the effectiveness of the various factors of the atmospheric environment acting upon the snow cover. This was clearly seen during the recession of the snowmelt hydrographs. The recessions occurred at a constant rate as all the unfrozen water drained from the catchment until the flow was composed entirely from non-surface sources. The recession began, not when the catchment became frozen, but as soon as there was no longer any further melting of the snow cover. When there was insufficient heat available to increase or even to maintain the temperature of the air there was insufficient also to cause a melting of the snow cover. At the same time this lack of heat was not sufficiently severe to cause a complete freeze-up in the catchment, and therefore the recession represented the draining away of the snow that had already melted.

(ii) 18th November, 1969

During the 1969/70 winter there were four major snowmelt floods, each of short duration, and none displayed the effects of large diurnal fluctuations of temperature under anticyclonic conditions. The snowmelt flood beginning on 18th November 1969, followed a period of three days with sub-zero temperatures (and four

days since air temperature was warmer than  $1^{\circ}\text{C}$ ) (Fig.38a). Snow had fallen during this three day period and was lying in the catchment. At 0500 BST on 18th November the air temperature in the catchment rose to  $1^{\circ}\text{C}$ , and by 1200 BST the available heat had exceeded 20 C degree/hours. The flood began just before 1200 BST, and the volume increased rapidly at a rate of 3 cusecs per hour until it was at its peak flow of 33 cusecs at 2100 BST. The fall off in discharge after 2100 BST, although it corresponded with a fall in air temperature, could not be directly attributed to freezing conditions in the catchment since the air temperature did not fall below  $4^{\circ}\text{C}$ . The air temperature trace merely reflected a reduction in the amount of heat available to melt the snow and as a result of this, the snowmelt rate was slower and the volume of discharge fell.

(iii) 20th November, 1969

The air temperature may be used as an indicator of changes in the general atmospheric environment which affect the snowmelt, but that it cannot be regarded as the only major control over snowmelt was clearly illustrated by the conditions on 20th November 1969. Between 0900 and 1300 BST the air temperature rose from  $0^{\circ}\text{C}$  to  $3^{\circ}\text{C}$  and was accompanied by an increase in the volume of discharge released from the catchment. However the air temperature was in fact colder than it had been during the previous 18 hours when there had been a recession in the volume of discharge. The changing weather conditions such as solar radiation and humidity, which were reflected in the upward trend in air temperature between 0900 and 1300

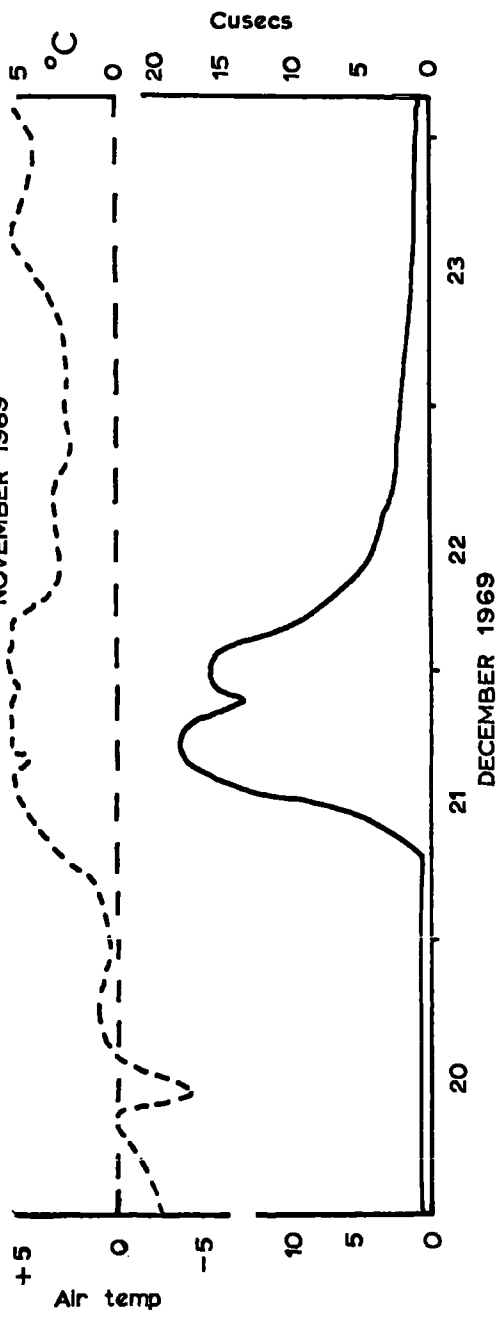
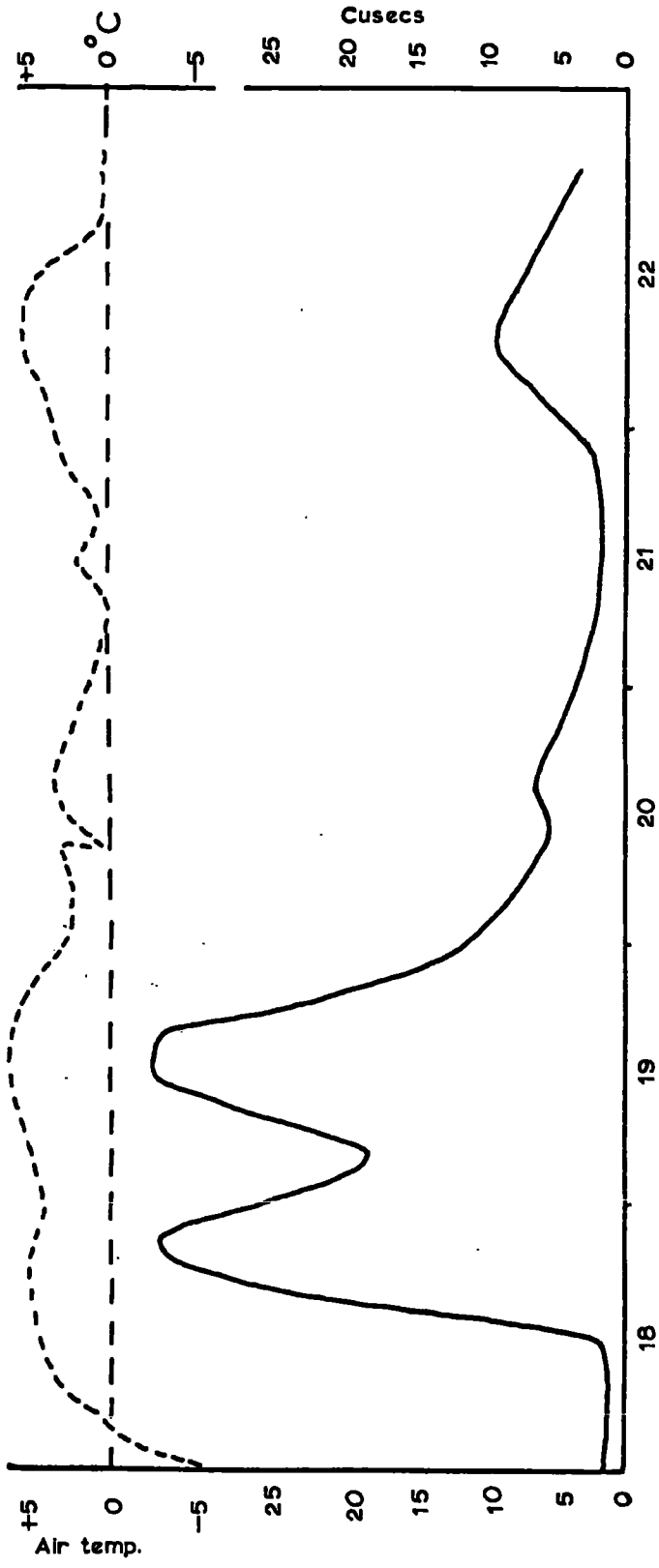


FIG 38 SNOWMELT FLOODS

BST on 20th November, also caused the increased release of melt water from the catchment. Conversely, the reverse was true for the period between 1200 BST on 19th November and 0900 BST on 20th November, when the falling air temperature indicated a deterioration in the conditions for snowmelt.

(iv) 21st December, 1969

Rainfall, in addition to its obvious direct contribution towards the discharge from a catchment, because of its heat input, may be an important factor in relation to the rate of snowmelt. The rise in air temperature on 21st December, 1969 was not sufficient in itself to produce a thaw, but the warm atmospheric conditions coupled with a fall of precipitation produced sufficient heat to cause a snowmelt (Fig.38b). At 1400 BST on 20th December the air temperature rose above 1°C at the weir. At the beginning of the flood, at 0830 BST on 21st December, the amount of available heat had risen only to 14 C degree/hours, which was insufficient to cause a snowmelt in itself. However this rise in temperature was accompanied by a rainfall of 5 mm., which from figure 34 would produce a discharge of 2 cusecs, but more important in this case was the fact that the sensible heat of the rain water also produced a certain snowmelt. From the following equation the amount of snowmelt can be calculated

$$D = \frac{P(T-32)}{144} \quad (\text{Wilson, W.T. 1941})$$

Where D = depth of water melted from snow (ins)

P = depth of rainfall (ins)

T = temperature (°F) (normally wet bulb)

On 21st December, the snowmelt resulting from the heat of the rain itself was equivalent to a depth of water of 0.6 mm. over the whole of the catchment. From figure 35a it can be seen that this would produce a flow of 3.5 cusecs for one hour. The significance of this was not only the snowmelt contributed by the rainstorm itself, but that it triggered off a release of melt water from the catchment which would not have resulted from the air temperature conditions alone.

The discharge from the catchment was maintained by the further melting of the snow due to the warm conditions indicated by the air temperature. From 1630 - 1730 BST on 21st December there was a rapid, though short lived, fall in air temperature which was reflected in a drop in the discharge as a result of the temporary restriction upon the rate of snowmelt. By midnight on 21/22nd December all the snow had been removed from the catchment, and therefore subsequent periods of warm air conditions, such as at 1400 - 1600 BST on 23rd December, could not produce further snowmelt floods.

(v) 19th-23rd February, 1970

Between 19th and 23rd February, 1970 three floods occurred (Fig.39). The first and third resulted from snowmelts linked with periods of warm air temperature, but the second flood, by far the largest of the three, was caused by mild air conditions coupled with rainfall. On 19th February a flood began at 1800 BST, for although the air temperature had been above 1°C for the whole of the day the available heat did not exceed 20 C degree/hours until that time. The release of the snowmelt was

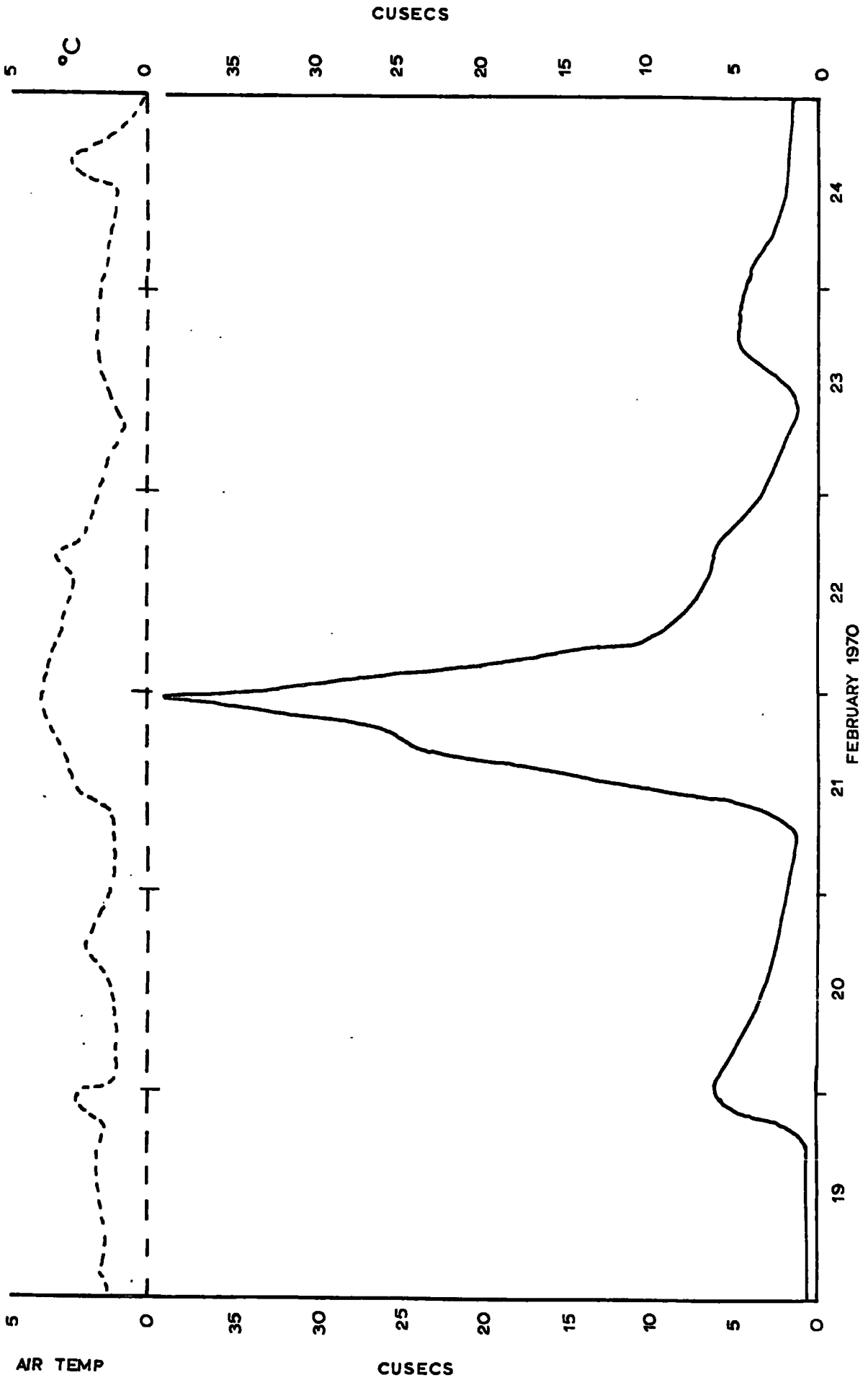


FIG 39 A COMBINED SNOWMELT AND RAINFALL FLOOD

slow at first, but increased to reach a peak flow of 6 cusecs at 0200 BST on 20th February as a result of a relatively rapid rise in air temperature to  $4^{\circ}\text{C}$  at 2200 BST on 19th February. The recession began four hours later at 0200 BST on 20th February, by which time the air temperature had fallen to  $1^{\circ}\text{C}$ . Similarly the flood on 23rd February followed about six hours after a minor rise in air temperature. No snowmelt occurred on 20th February since the amount of available heat did not exceed the required 20 C degree/hours until 0500 BST on 21st February. There were no floods associated with the warm air temperatures on 24th February as the snow cover had been removed.

The second snowmelt flood began at 0700 BST on 21st February following a period of 18 hours with air temperatures greater than  $1^{\circ}\text{C}$ . The flood occurred with a rapid rise in air temperature which reached  $6^{\circ}\text{C}$  at 2130 BST. The volume of discharge increased at a rate of 3 cusecs/hour to a flow of 26 cusecs at 2000 BST. At this time rain began to fall, and by 2030 BST 9 mm. had fallen in the catchment. From figure 34 in Chapter 5, it can be seen that such an amount of rain falling in an already wet catchment would be likely to produce a flood of about 10 cusecs. During this storm the flood discharge rose by 14 cusecs from 26 at 2100 to 40 cusecs at 2230 BST. Thus not only did the rainfall produce an additional 10 cusecs of discharge, but indirectly the sensible heat of the water produced an increase in the rate of snowmelt.

The amount of snowmelt produced by this heat can be

calculated

$$D = \frac{P(T-32)}{144} \quad (\text{Wilson, W.T. 1941})$$

Where D = depth of water melted from snow (ins)

P = depth of rainfall (ins)

T = temperature ( $^{\circ}$ F) (usually wet bulb)

The 9 mm. of rain would produce a snowmelt the volume of which would be equivalent to a depth of water 1 mm. deep over the whole catchment, which it can be seen from figure 35a would produce a flow of 6 cusecs for 1 hour. In fact this melt water travelled through the catchment in one and a half hours accounting for the peak flow of 40 cusecs. The recession limb of this storm hydrograph was distorted by a short period of snowmelt associated with the rise in air temperature at 1200 BST on 22nd February.

The flood hydrograph that occurred on 22nd February served to illustrate the very different nature of the hydrographs resulting from snowmelt compared with those resulting from rainfall. Instead of the rounded peak of the snowmelt hydrograph extending over a period of several hours which occurred on 19th and 23rd February, the rainstorm of 22nd February produced a much sharper peak lasting only a few minutes. The processes involved in producing a snowmelt flood were normally much more gradual than those of a rainstorm flood. The release of snow would be dependent upon the atmospheric environment providing a certain amount of heat to melt it, and this would normally be a lengthy process. Furthermore, the melting conditions, both the climatic factors and the

readiness of the snow to melt, would not be uniform over the whole catchment, and thus melt water would be released from different parts of the catchment at different rates and different times. Similarly the cessation of flow in a snowmelt/<sup>flood</sup>would be gradual as snowmelt ceased successively in different parts of the catchment.

The evidence suggests that snowmelt floods did not occur as a direct result of increases in air temperature although these two often happened coincidentally. In Chapter 7 it will be seen that the air temperature was not the only major control over the temperature of the stream water and, from the snowmelt floods described in this chapter, it is also clear that the air temperature did not directly cause any of the snowmelts. However in both cases the air temperature could be used as an indicator, reflecting other changes in the atmospheric environment, which caused the changes in the stream water temperature and the rate of snowmelt.

Snowmelt could not occur in the catchment while the air temperature was below freezing point, and in fact it was not until the air temperature at the weir site was greater than  $1^{\circ}\text{C}$  that the catchment as a whole became under non-freezing conditions. The melting of the snow required a great deal of heat; represented in this study in degree/hours. Snowmelt floods did not occur during every period of non-freezing conditions but only when there was sufficient heat; in the cases described above, in excess of  $20^{\circ}\text{C}$  degree/hours. The flood did not begin until about three hours after the advent of favourable

melting conditions as the melt water took this period of time to melt and to travel the length of the catchment.

The snowmelt floods occurred after periods of non-freezing conditions lasting at least three hours and contributing in excess of 20 C degree/hours of heat to melt the snow. Any additional heat did not produce either a faster or a greater flood since the time of travel controlled the speed of the supply and the amount of lying snow controlled the volume available for release.

## CHAPTER 7

### THERMAL CHARACTERISTICS OF THE STEAM WATER

The earliest studies of river water temperature under natural conditions were made in central Europe. During the last 15 years more research has been undertaken by hydrologists in Japan and the U.S.A. than elsewhere.

These early studies were concerned with observing water temperatures and gradually led to attempts to explain the temperature of the stream water as a response to a combination of meteorological and hydrological factors. Most studies attempted to represent changes in heat storage of streams in terms of the easily measured variables of air and water temperature. In Japan Miyaka and Takeuchi (1951) used long term air and water temperature data to indicate the seasonal relationship between the two, and Nishizawa (1967) produced a model of the heat balance process for several Japanese rivers.

A more comprehensive approach had been attempted in Europe. Eckel and Reuter (1949) used a number of the physical factors affecting the temperature of stream and lake water to determine the relative effects of these over the temperature of the water. Due to the complexity of these processes Eckel (1951) reverted to more empirical studies using data from several Austrian rivers. From these he showed that not only did the different rivers have differing temperature regimes from day to day and throughout the year, but that the relationship between air and water temperatures differed between stations along the same river. Schmitz (1954) conducted a similar study

on a 5 km. stretch of river in Germany. He compared water and air temperatures at ten stations over a 24 hour period, and found that whilst at all stations the water temperature trend resembled that of the air, the patterns became increasingly similar to the air with distance from the source as equilibrium between the water and air temperatures were progressively achieved.

Studies of stream water temperature in Britain have occurred only since 1958 and have been conducted largely by ecologists to meet their own specialised requirements with a tendency to study small streams rather than large rivers. Because streams have a smaller capacity for heat storage than rivers they are more responsive to changes in the atmospheric environment and to local vegetative, geological and hydrological factors. Edington (1965) was primarily interested in examining how the variations in temperature in the stream affected the distribution of temperature sensitive animals. Crisp and Le Cren (1970) attempted a more comprehensive analysis of the temperature of three small upland streams and produced, effectively, a classification of types of stream environment based upon the surroundings (vegetation and soil) the slope and flow of the stream and the altitude of the catchment.

The volume of discharge is the main hydrological factor affecting the water temperature of any river and consequently due to the progressive increase in volume downstream there is a different response between air and water temperatures with distance downstream. Frequently the water temperature changes result more from a mass

transfer of the water from upstream than from the influence of the local atmospheric environment. This is obviously the basic and initial element studied by the various investigators.

There is however a conflict in the results obtained by Edington (1966) Schmitz (1954) and Crisp and Le Cren (1970) for short stretches of stream (less than 4 km.) and those obtained for much longer stretches of river by Eckel (1951) Yakuma (1960) and Smith (1968). The studies of short streams are essentially studies of source waters. Both the temperature and daily range of temperature increase downstream and the maximum temperature becomes progressively later, but never later than 1800 hours, as the small volume of water becomes nearer to thermal equilibrium with the environment. At some point along the stream course the increasing heat capacity of the river ensures that the water becomes less responsive to air temperature changes and is influenced more by the mass transfer of the water from upstream. The actual point along the stream course where this change over occurs will differ from stream to stream and will vary along the same river through the year: exact location will be related to the volume and speed of flow of the stream since it is likely to be approximately related to the distance from the source that the stream water can travel during a 12 hour period. Once the stream water has reached its daily maximum temperature and then begun to cool its temperature is no longer the product of the ability of the atmospheric environment to raise the water from its temperature at source, but rather its inability

to maintain the temperature of the stream. The volume of flow and its speed of travel then become the most important modifiers of the temperature rather than the temperature of the source water as in the upper stages of the river. Clearly therefore, in studies of water temperature, a distinction should be made between those investigations in water upstream and those downstream of this change-over point.

Although several studies have been made of the relationship between air and river water temperature for many rivers, no systematic long term study has been made of this relationship in the head waters. Apart from the 24 hour study by Schmitz (1954) the only detailed investigations of streamwater temperature in source water streams have been carried out by biologists to study river ecology.

The Lanehead catchment study deals entirely with source water conditions. It attempts to isolate the factors which control the temperature of the stream water and to evaluate their relative effectiveness. From the research which has already been carried out, and briefly described above, it is clear that in the headwaters of a stream the following factors effect some control over the temperature of the stream water:

1. air temperature
2. volume of discharge
3. groundwater temperature
4. channel form
5. mass transfer of heat from water from upstream

#### air temperature

air temperature is a relatively easily measured parameter which can be used as an indicator of various elements of the atmospheric environment such as radiation, humidity and wind.

#### volume of discharge

the volume of discharge affects the thermal capacity of the stream and hence it controls the rate of response of the stream water to the influence of the other factors of the environment. At any one point in a stream channel speed of water movement tends to increase with volume of discharge. The volume also controls the period of time that the water is under various environmental influences, and since precipitation affects the volume of discharge it should be regarded as an indirect influence on stream temperature.

#### groundwater temperature

the effect that groundwater will have upon the stream water temperature will depend partly upon the proportion it contributes to the total flow and the extent to which its temperature differs from the stream water temperature.

#### channel form

the form of the channel modifies the effect that other factors have upon the stream water temperature rather than providing a direct control. Steep banks,

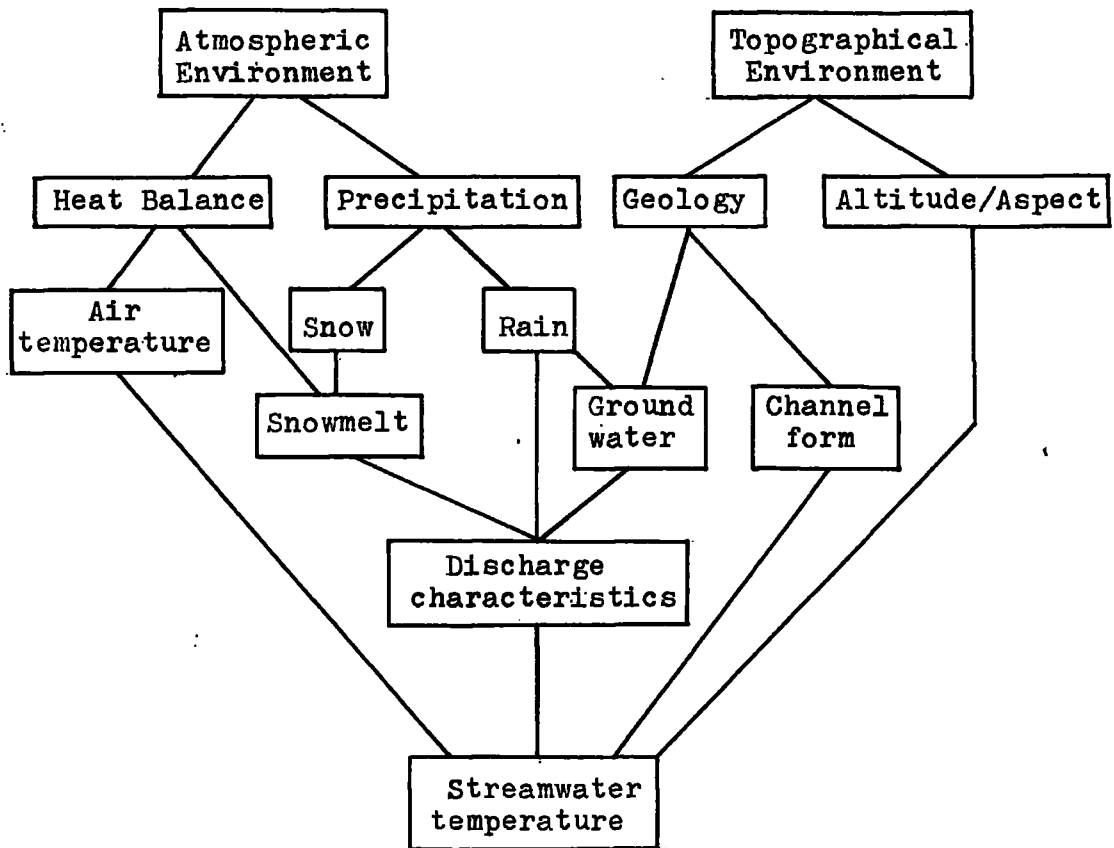
bankside vegetation and an underground watercourse section through limestone or through gravels, shade the stream from direct solar radiation and thus depress the range of water temperature.

mass transfer of heat from water from upstream.

the response of stream water to the atmospheric environment is modified by the original temperature of the water itself. The temperature of stream water at any point in a stream channel will be related to both the influences of the atmospheric environment and the temperature of the water being supplied from farther upstream.

## The Lanehead Catchment Study

The experimental catchment at Lanehead was established in order to study the nature of the changes in stream water temperature and the relationship with certain other aspects of the environment within the first kilometer stretch of upland stream. A theoretical scheme might be shown as follows:



### A diagrammatic model to show the factors influencing streamwater temperature

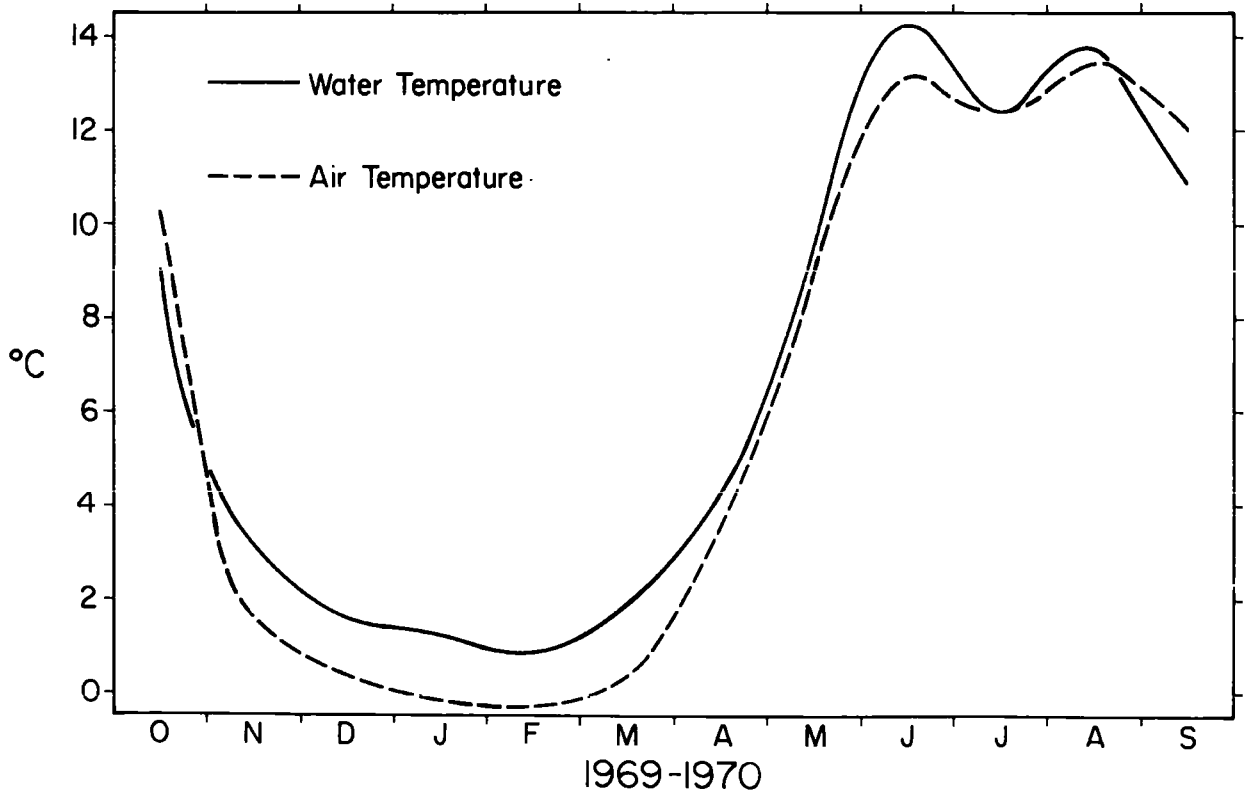
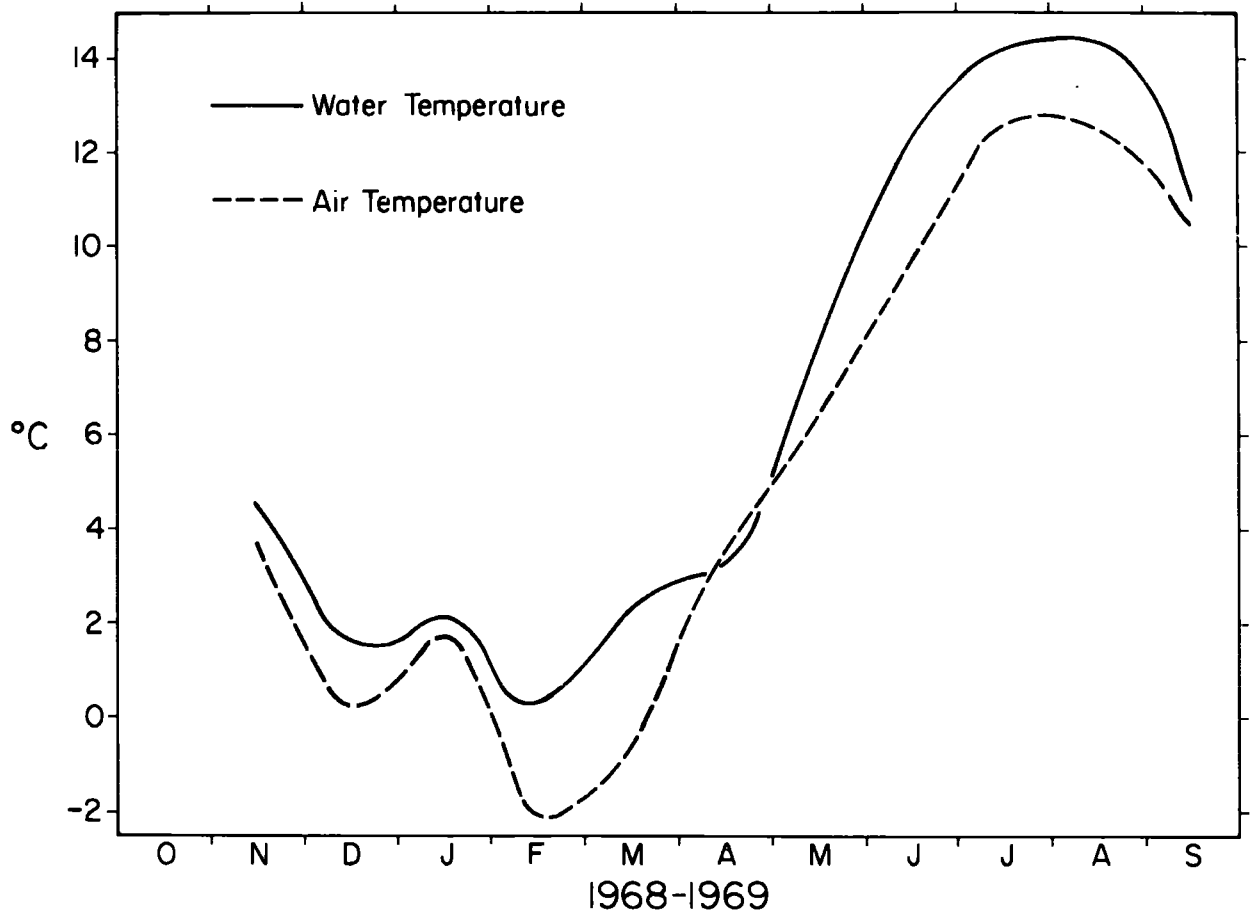
The emphasis of the study was upon the relatively long term measurement, over a period of two years, of some of those factors thought to affect the water temperature. This contrasts with most of the earlier studies outlined above which were based upon shorter-term data and directed towards specific problems.

The thermal characteristics of the stream were studied within the scope provided by the available continuous recording equipment which could be established in the catchment. Air and stream water temperatures were recorded at the weir site, ground water temperatures were measured in a disused lead mine adit and, for the final nine-month period, stream water temperature was recorded at the source of stream B.

The original instrumentation was designed to deal specifically with the relationship between the stream water temperature and the local air temperature. In figure 40 the mean monthly values of air and water temperature at the weir site have been plotted for the two water years 1968/69 and 1969/70. The mean air temperature was normally less than that of the stream water. The mean annual water temperature for both years was  $6.9^{\circ}\text{C}$  while the air temperature was lower at  $5.7^{\circ}\text{C}$  and  $6.3^{\circ}\text{C}$  respectively. During the periods of spring and autumn the air and water temperatures were most closely related. In the winter the mean water temperature was warmer by virtue of the fact that, unlike the air, it was impossible for it to become colder than  $0^{\circ}\text{C}$ . During the summer the mean daily temperature of the water was higher than the air, partly due to heat storage as the water released its heat more slowly than the air, but mainly due to the fact that it appeared to be more responsive to heating by direct solar radiation. The response of the water temperature to the various controlling factors was viewed in a three-dimensional sense of time and space:

- (i) There was a 24-hour diurnal fluctuation which could

FIG 40 MEAN MONTHLY AIR AND WATER TEMPERATURES  
(1968-1969 and 1969-1970)



be traced on most days throughout the year.

(ii) The response of the stream water to factors such as air temperature or direct solar radiation depended very much upon the distance from the source of the stream. The greater the distance from the stream source, the longer the period of time during which these influences were operating, and the greater the modifying effect resulting from the increased volume of discharge.

(iii) The observations were placed in the context of the annual cycle or seasons. Thus, the changes in water temperature were viewed in the context of the diurnal cycle, the changing conditions which occurred with distance from the stream source and finally the differing overall atmospheric environment which varied from season to season.

The ramifications would be complex even when the two variables of air and water temperature only were considered, but, in addition, attention had to be paid to the many other factors which were significant. These included the volume of discharge plus the nature of the stream channel and the duration of effective sunshine - that is, the period of time during which the sun can shine directly on the water, since certain stretches of the stream might from time to time be in the shadow of the banks. The effect of direct sunshine as a source of heat and the fact that it could<sup>not</sup> be applied uniformly to all parts of the catchment was clearly demonstrated after periods of snow cover, when the snow lying on the northerly facing slopes remained very much longer than that lying on the southerly facing slopes (Fig.41). A

FIG 41 THE EFFECT OF SUNSHINE ON SNOW MELT



further consideration was the temperature of the water reaching the sampling site. It was impossible really to understand the thermal regime at one point without reference to the conditions farther upstream. The effect of air temperature or any other environmental factors would be modified by the characteristics of the water being supplied. If the temperature of the stream was warmer upstream, then the effect of a given air temperature would be different from that if the water was colder upstream.

Several methods of analysis were tried in order to isolate some of these problems. Basically some conditions were fixed so that the relationship of the remaining variables could be compared.

(i) The instrumentation at the weir was the main project. This was designed to relate water temperature to air temperature and discharge conditions, and to provide a context into which other investigations which were of necessity shorter term, could be placed. In addition, it gave a complete, hour-by-hour record of these three parameters.

(ii) The variation of water temperature with distance from the stream source was studied by taking stream temperature measurements at regular distances down the water course.

(iii) Just as the relationship between the air and stream water temperatures at the weir site varied through a 24-hour period, it was likely that the relationship between the parts of the stream in a spatial sense, as between source and mouth, would also vary in any period

of 24 hours. To analyse this situation further, temperature sequences were taken along the stream course at regular intervals during a 24-hour period in each month.

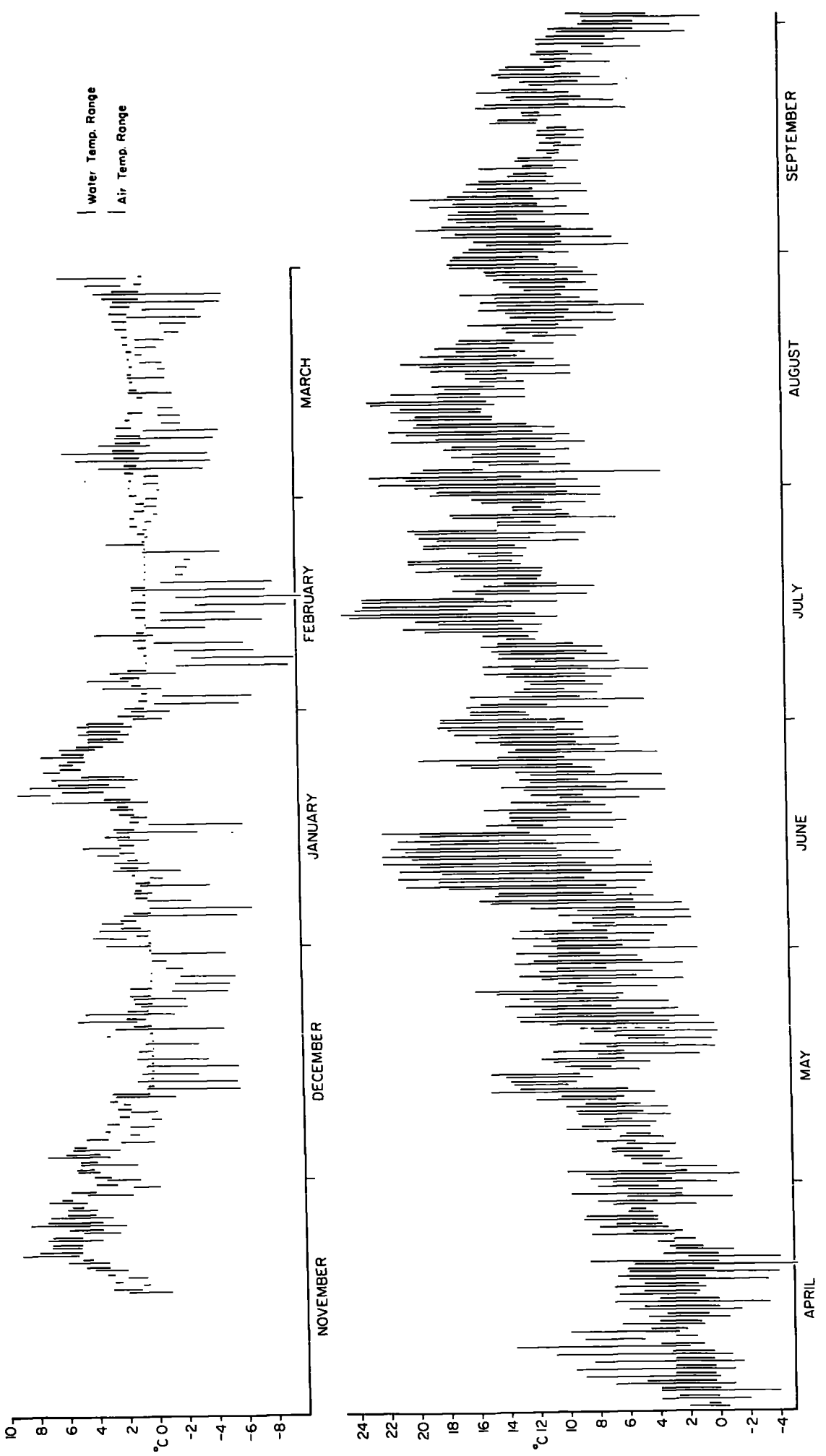
(iv) In order to evaluate the effect that the stream channel itself would exert upon the temperature of the water a comparison of the temperature sequences down two streams of differing characteristics during similar environmental conditions was made. The Lanehead catchment was particularly suitable for this study since the two tributaries were somewhat different in character.

#### I The relationship between air and stream water temperature at the weir site (Site 1)

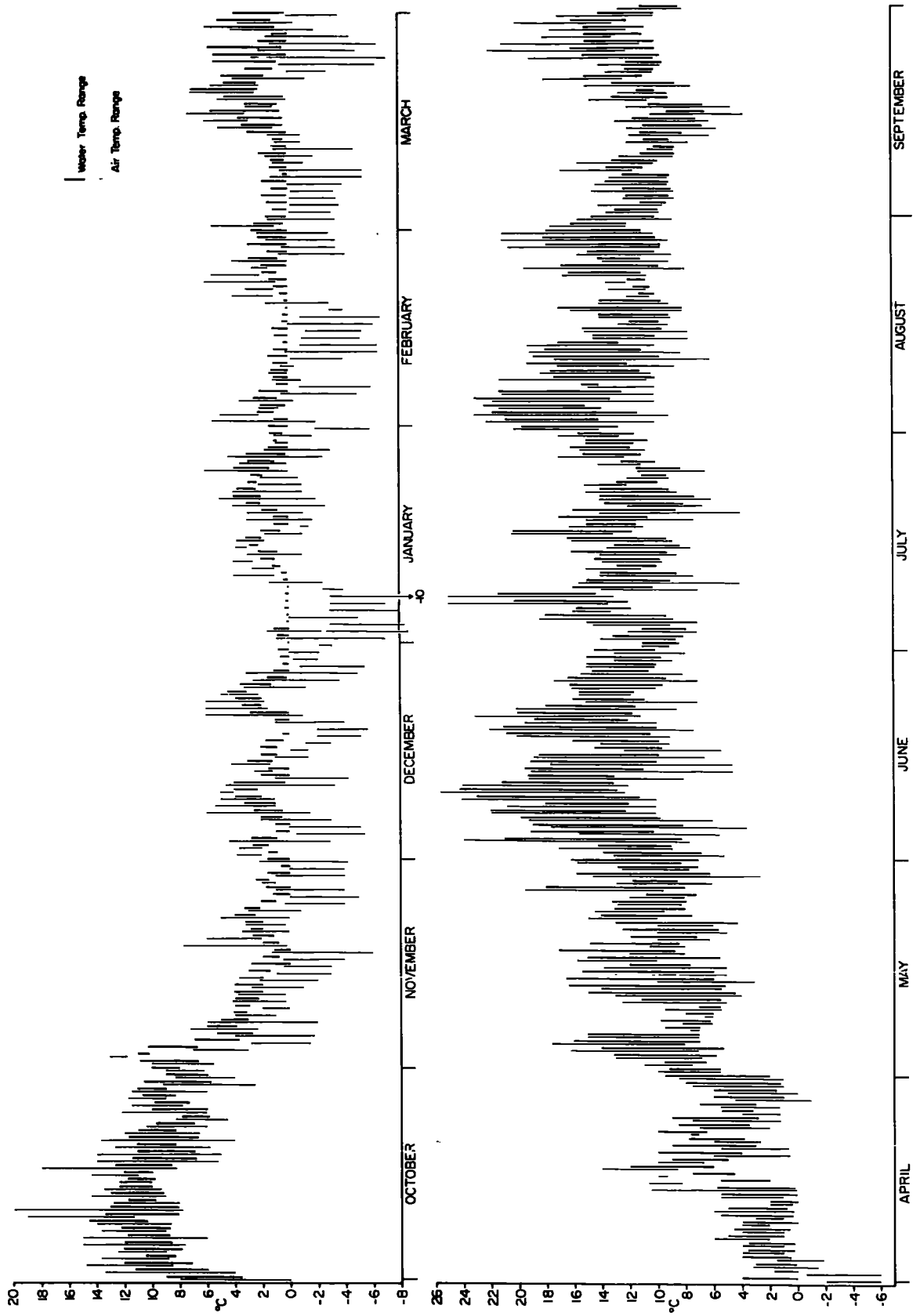
In figures 42 and 43 the daily ranges of air and water temperature have been plotted together. Like the graphs of mean air and water temperature data, these data show the close relationship between the air and water through the seasons. Since the heating of the stream water was affected by a 24-hour cycle within the annual context, it was important to study the data on a daily basis. During the spring season the stream water tended to become warmer each day and, during the autumn, this was reversed as a result of the progressive influence of the local atmospheric environment acting upon the waters each day.

Although there was a continuance of change, it was valuable to subdivide the year into seasons to provide a significant framework within which the thermal characteristics of the stream water could be studied. While it was important to regard each day as an entity in itself, it was possible to generalise within the seasons, either

**FIG 42**  
**DAILY RANGE OF AIR AND WATER TEMPERATURES 1968-1969**



**FIG 43**  
**DAILY RANGE OF AIR AND WATER TEMPERATURES 1969-1970**



because the influence which affect water temperature remained reasonably uniform during these periods, or because the response of the water was different from season to season. The delimitation of the seasons was based upon figures 42 and 43. Winter and summer represent the periods of relatively steady water temperatures, while spring and autumn represent the periods when the water temperatures were tending to become progressively warmer, or colder, each day. Where the day-to-day variations were smoothed out in mean data, as in figure 40, these divisions were clearly demonstrated. However, from the two years' data, it was impossible to do other than to define the periods during which certain trends occurred in general terms.

During the winter season from December to March the mean air temperature was approximately  $0^{\circ}\text{C}$ . Daily ranges of temperature were between  $+4^{\circ}\text{C}$  and  $-4^{\circ}\text{C}$ , while occasionally maximum temperatures exceeded  $6^{\circ}\text{C}$  and minimum temperatures fell below  $-8^{\circ}\text{C}$ . During non-freezing air conditions the water temperature quickly responded to air temperature changes. For example, on the 7th December 1969, a rise of air temperature from  $0^{\circ}\text{C}$  to  $6^{\circ}\text{C}$  at a rate of  $2^{\circ}\text{C}$  per hour caused a rise of water temperature of  $2.5^{\circ}\text{C}$  over the same seven hour period. In periods of freezing air conditions the water temperature very quickly fell to  $0^{\circ}\text{C}$  but, even under these conditions, it was quite usual for the water temperature to become heated to  $1^{\circ}\text{C}$ . From 12th February 1969 until noon on the 17th February the air temperature was below freezing point, and for a third of this period less than  $-5^{\circ}\text{C}$ ; nevertheless, at

1600 BST on the 13th, 14th, 15th and 17th February, the water temperature had risen to 1°C.

The spring season extended from late March to early June. Late March and early April was often characterized by the daily air temperature fluctuating around freezing point. During this period snowmelt conditions dominated and thus, despite high air temperatures during the day causing snow melt, the temperature of the water remained low due to melt water influences. This condition was clearly seen during the days 29th, 30th and 31st March 1969. Following a period of freezing air temperature conditions, during which stream water temperatures had varied between 0.1 and 1.5°C, a rise in air temperature on 29th March 1969 caused a snowmelt flood. Despite air temperature greater than 3°C for 48 hours the stream water remained at 0°C until the peak of the flood at noon on 30th March. Only when colder air temperatures caused an end to the snowmelt did the stream temperature rise above 0°C. Throughout this season the water temperature progressively increased. This was not the result of the conditions of the previous day being carried over and reflected in the water temperature but rather that the daily maxima became progressively greater. The mean air and water temperatures remained very similar, rising from 2°C at the beginning of April to 10°C at the end of May. During this time the daily maximum air temperatures were usually greater than the maximum water temperatures.

Throughout the summer season from June to August the mean temperature of the stream water at 13.5°C was at least 1°C warmer than the mean air temperature. Despite

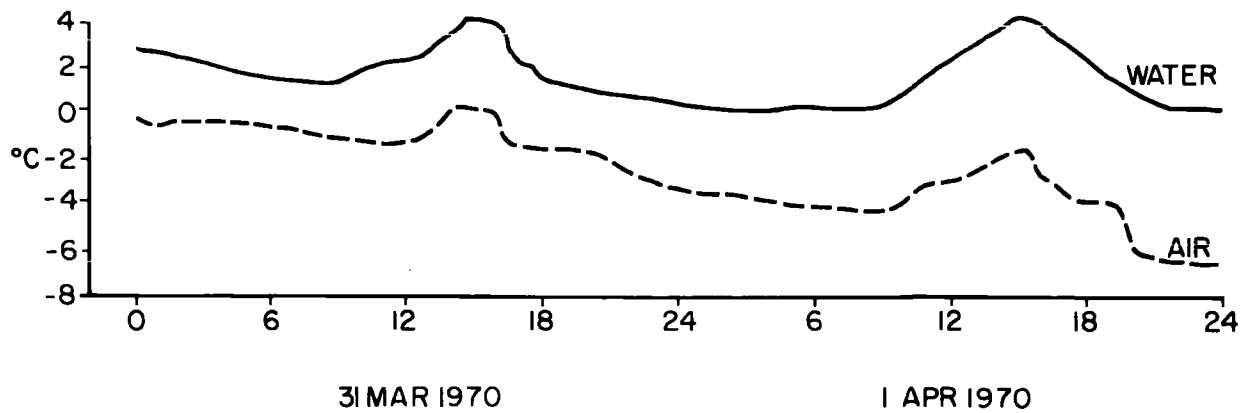
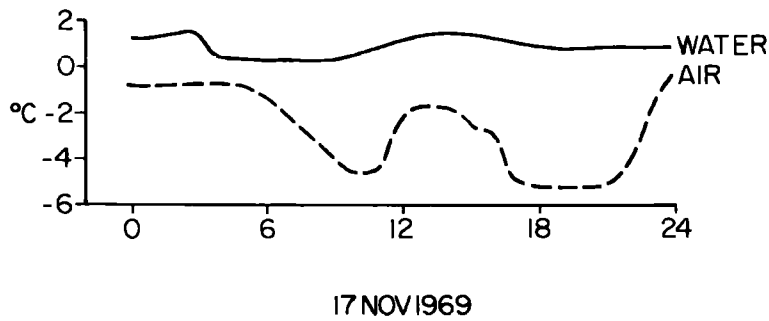
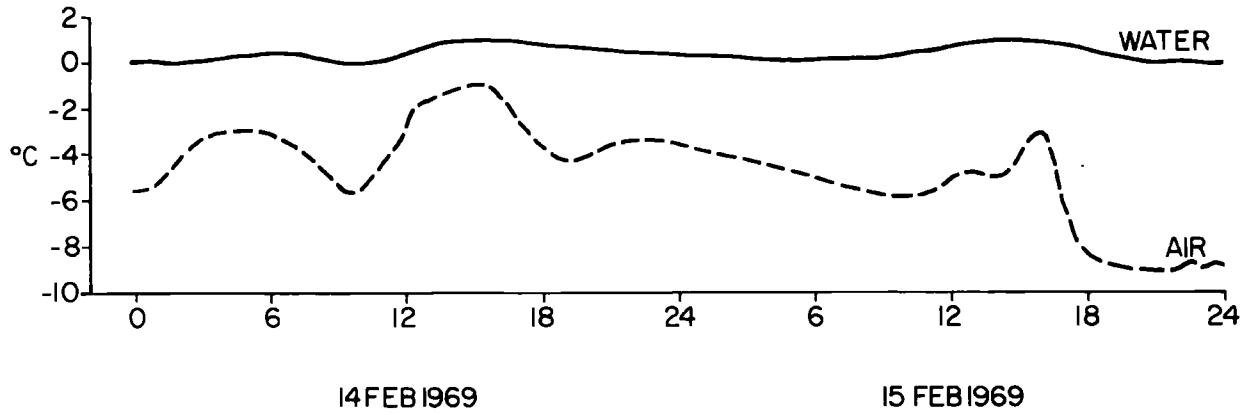
this, maximum air temperature was greater than maximum water temperature on two out of three days. Minimum air temperatures were invariably less than the minimum water temperatures on each day. In June the water temperature had an average diurnal fluctuation of  $10^{\circ}\text{C}$  compared with  $7^{\circ}\text{C}$  in August.

Autumn, from September to November, was the period of cooling conditions, the reverse of the spring season, though in fact the cooling process was faster than the spring warming process. From mid-March to mid-May the mean water temperature rose by approximately  $6.5^{\circ}\text{C}$  while from mid-September to mid-November the mean temperature fell approximately  $8^{\circ}\text{C}$ .

From the annual trends it was quite clear that the water temperature was not always dominated by a transference of heat to or from the air. For long periods of time during the winter the air temperature remained below freezing point throughout the day and yet the water temperature showed a diurnal fluctuation. In figure 44, three periods have been isolated to demonstrate this, though several others could be added. On the dates 14th/15th February 1969, on the 17th November 1969, and the 31st March/1st April 1970, there was a distinct diurnal fluctuation of water temperature, reflected it is true by the air temperature, while the air temperature was well below freezing point. This pattern can be explained in terms of relative heating. Obviously there could be no heating of the water due to a transference of heat from the air. The air temperature really acted as an indicator of other influences, and it appears that the

FIG 44

DIURNAL FLUCTUATIONS OF WATER TEMPERATURE  
DURING PERIODS OF SUB-ZERO AIR TEMPERATURE

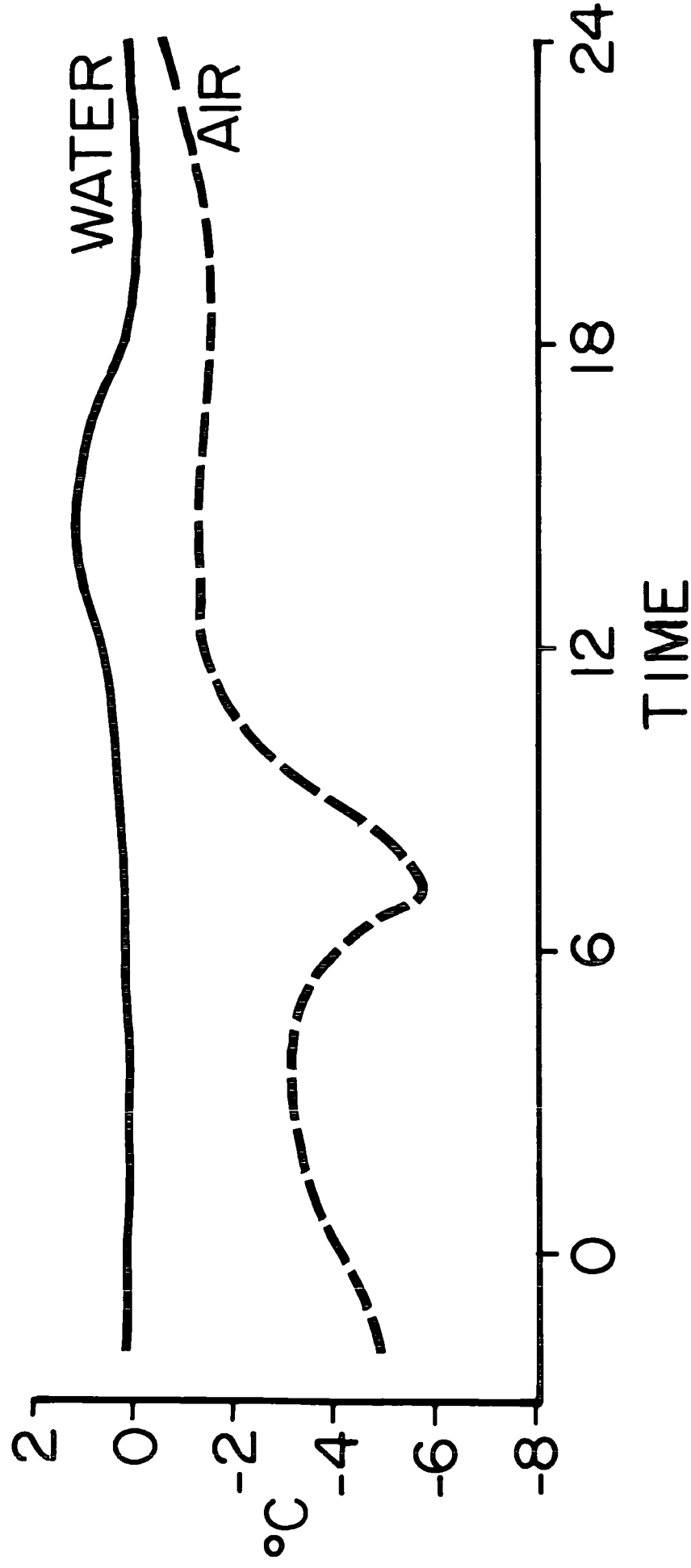


same source of heat which was warming the air, probably short wave radiation and sunshine, was heating the stream water more effectively, because of its ability to absorb radiation better than air.

Occasionally a situation arises, as on 6th February 1970 (Fig.45) when an increase in water temperature was not accompanied by a rise in air temperature. On that day, not only was the fluctuation of water temperature not reflected in the air temperature trend during the afternoon, but the marked rise in air temperature during the morning from  $-6^{\circ}\text{C}$  at 0700 BST to  $-2^{\circ}\text{C}$  at 1100 BST was not shown in the stream water temperature trace. No doubt under certain conditions it was possible that a sudden fall in air temperature could cause surface runoff to become locked up as ice and the stream, thus starved of this supply, would be reduced in volume. Consequently the stream would have an increasing proportion of discharge derived from relatively warm base flow, although this warming affect was likely to be confined to the immediate locality of the source of ground water. Under these circumstances it was possible that a rise in water temperature immediately downstream of a ground water source might accompany a fall in air temperature. On the other hand, the situation existing on 6th February 1970 would not justify this type of explanation since the air temperature did not fall rapidly, and there was no reduction in the discharge which remained constant at 0.5 cusecs. Since the fluctuation of water temperature did occur between 1200 BST and 1800 BST, the hours

FIG 45

DIURNAL FLUCTUATION OF STREAM WATER  
INDEPENDENT OF AIR TEMPERATURE CHANGE



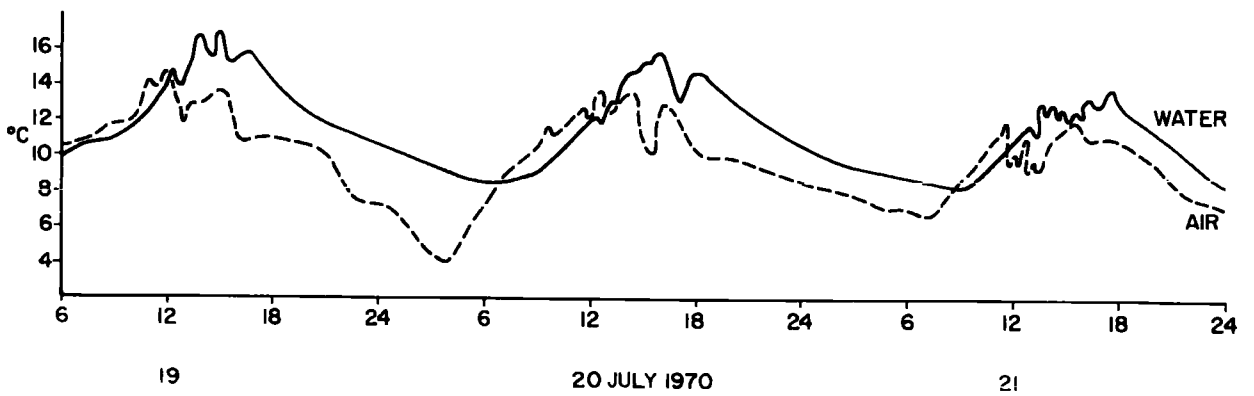
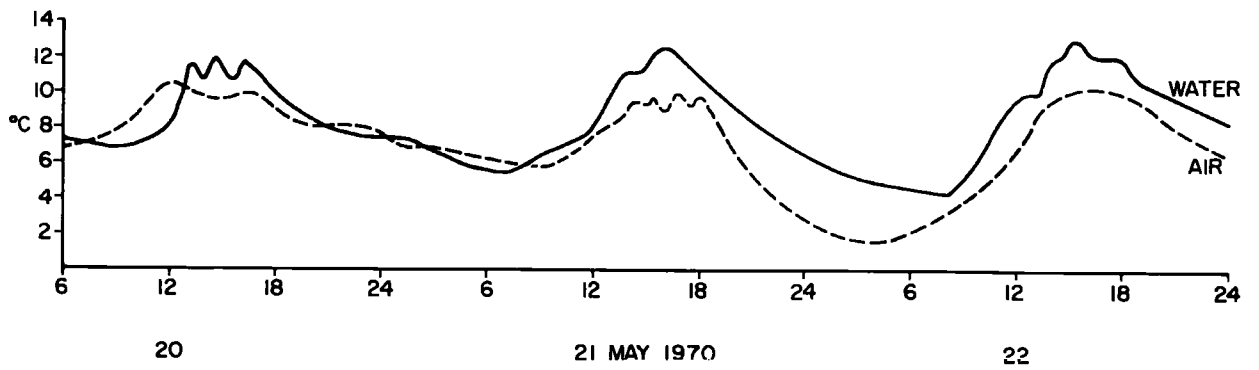
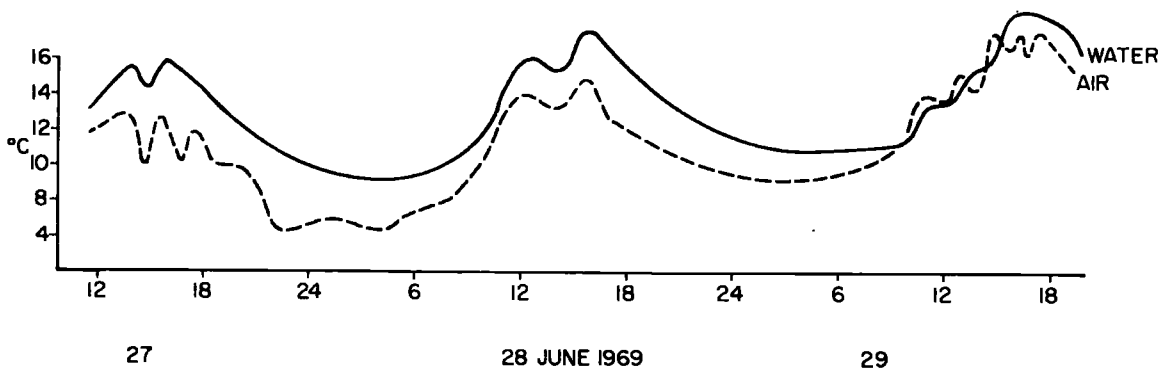
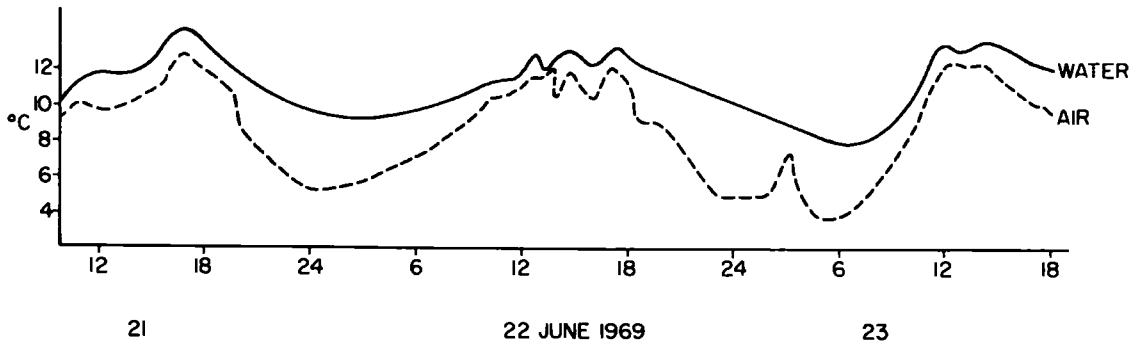
6 FEB 1970

of maximum potential solar radiation, it may be that the heating was due to direct solar radiation. Winter sunshine could well have had the effect of heating the stream water through radiant heat while having a negligible affect upon the turbulent air following the passage of a warm front across the area during that morning.

During the summer, there were many periods when the air temperature was lower than the water temperature, again indicating that the heating of the stream water was not necessarily the result of direct heat transfer from the air. Four periods, shown in figure 46, have been selected to illustrate this, although a study of the two yearly comparisons of air and water temperatures in figures 42 and 43 clearly indicates that this was not an infrequent situation. Furthermore, it was evident that this situation was not confined to the mid-summer period when maximum direct radiation occurred, but also occurred during the spring and autumn seasons.

The reverse situation, where stream water temperatures became colder while the air temperature became warmer, was more easily explained. During winter periods of snow-lie, an increase in air temperature beyond a certain threshold temperature, would produce a period of snowmelt. This discharge would then soon dominate the stream water temperature and reduce it to  $0^{\circ}\text{C}$ . These occurrences were easily identified by reference to the discharge charts, as for example on 29th-31st March 1970, which is illustrated in detail in figure 47.

**FIG 46** SELECTED PERIODS WHEN THE WATER TEMPERATURE IS WARMER THAN THE AIR TEMPERATURE



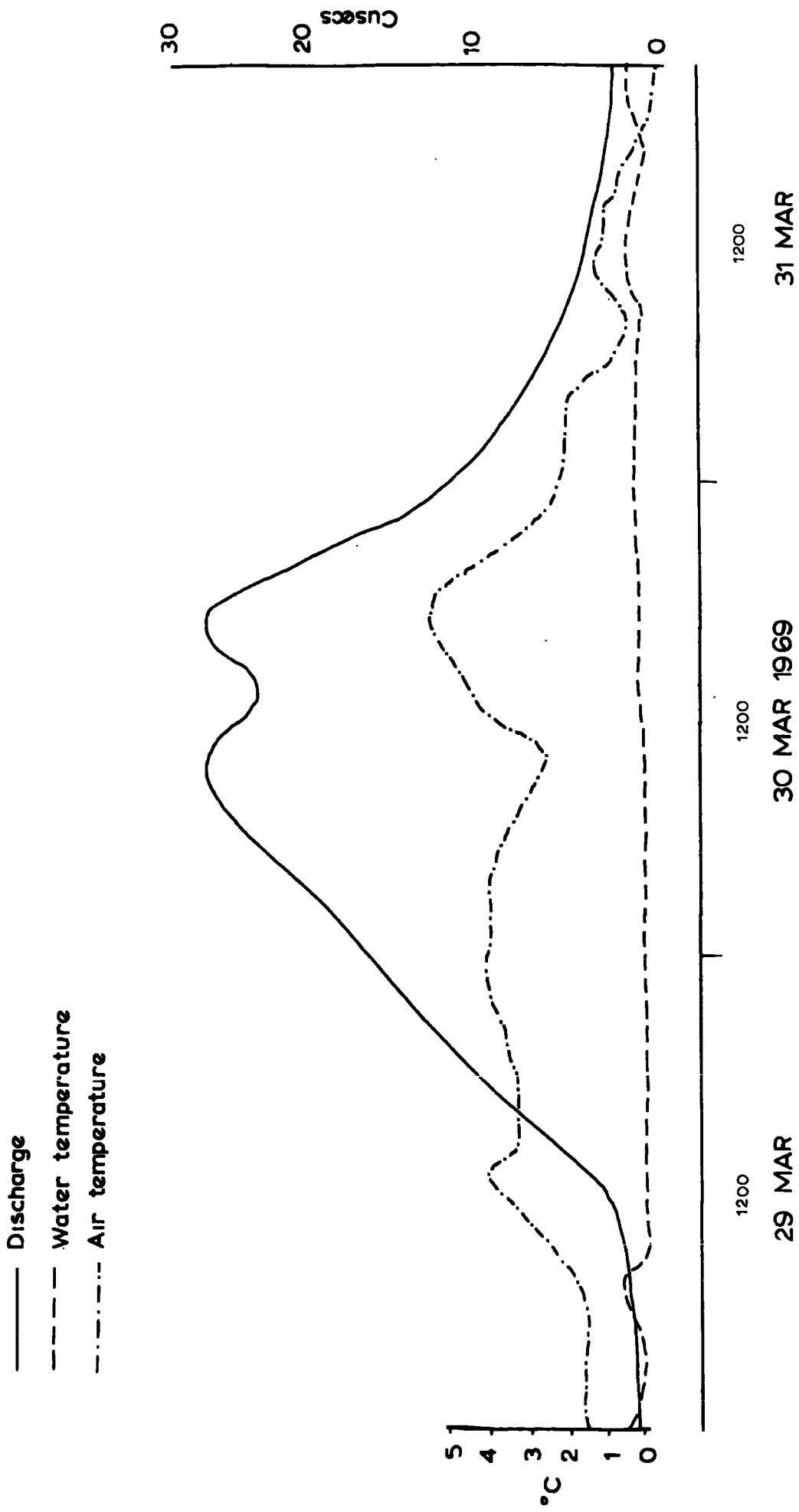


FIG 47 WATER TEMPERATURE RELATED TO A SNOW MELT FLOOD

Similarly, during the summer period, a very heavy rainfall producing a sudden increase in the volume of the stream could produce a cooling effect if the volume of discharge increased at a rate faster than that at which the water could be heated by the environment. Such a situation occurred on 10th May 1970 when a sudden rainstorm caused a flash flood (Fig.48). During the rise of the flood the water temperature, which had been warming like the air temperature, fell suddenly by 0.75°C. Once the flood had passed its peak flow the stream water temperature began to rise again despite the fact that the air temperature was falling by this time.

Although the mean daily temperature for water and air were very similar throughout the year, air temperature could not have been the source of heat for the water since it was frequently colder than the water temperature. Using the daily maximum and minimum temperature values, the air temperature and the stream water temperature at the weir site were compared for various levels of discharge. The resultant coefficients of correlation, together with an indication of the significance of each, are given in the following table:-

Correlations between air and water temperature at the weir site for various levels of discharge using daily maximum and daily minimum temperatures

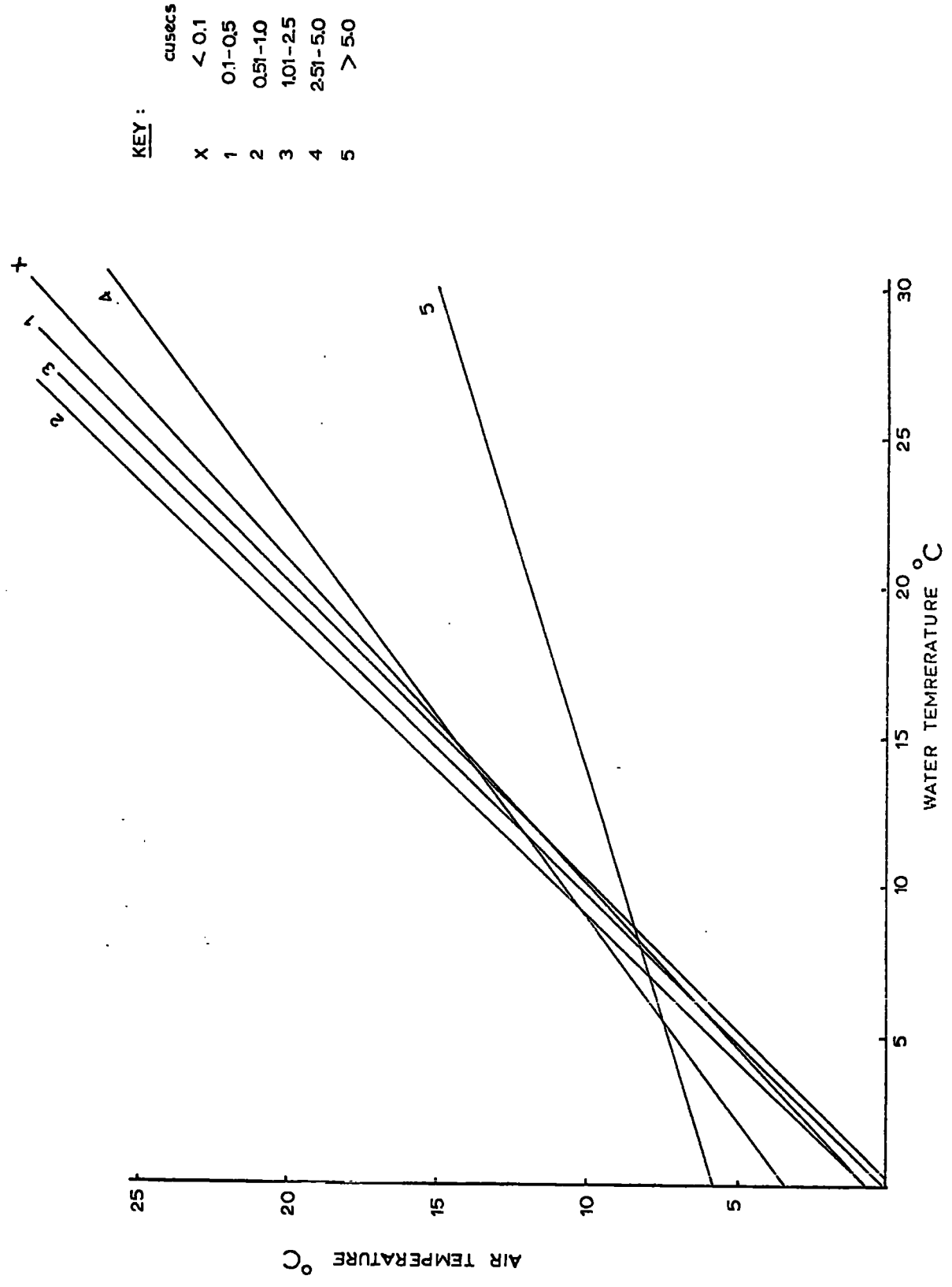
Discharge (cusecs)	Corr. coeff.	t	P
<u>Daily max.</u>			
0.1	0.911	17.022	1000
0.1 -0.5	0.944	31.343	1000
0.51-1.0	0.963	23.134	1000
1.01-2.5	0.948	21.072	1000
2.51-5.0	0.782	5.464	1000
5.0	0.292	1.180	
<u>Daily min.</u>			
0.1	0.700	7.528	1000
0.1 -0.5	0.953	34.495	1000
0.51-1.0	0.912	14.399	1000
1.01-2.5	0.888	13.673	1000
2.51-5.0	0.912	9.698	1000
5.0	0.436	1.876	10



It is clear that there is a very close relationship between the water temperature and the air temperature during flows of less than 2.5 cusecs. This cannot be because the air temperature is controlling the water temperature, but because they both reflect changes in the atmospheric environment; one of the most important single elements of which was solar radiation. While the relationship between the air and the water temperature was close for low flows it was significant that the closest relationship did not occur at the very lowest flows but when the discharge was between 0.5 and 1.0 cusecs (or 0.1 and 0.5 cusecs when the daily minimum temperatures were considered). Mean daily discharge was less than 0.1 cusecs for 20% of the year.

The regression lines drawn in figure 48A indicate that the greatest heating effect upon the water compared with the air occurred when the volume was between 0.5 and 1.0 cusecs. As the volume of flow increased the response of the water to heating from the atmospheric environment became slower. With smaller volumes the groundwater contribution assumed sufficiently large a proportion of the total flow to modify the effectiveness of the environment to warm the stream water. Since groundwater temperature is unaffected by the air temperature the stream water adopts a temperature unrelated to the air temperature. This feature became less with distance from the point of the groundwater contribution. For flows greater than 2.5 cusecs the relationship between the air and water temperatures became progressively less as discharge increased since there

FIG 48 A THE RELATIONSHIP BETWEEN AIR AND WATER TEMPERATURE AT THE WEIR FOR VARIOUS LEVELS OF DISCHARGE

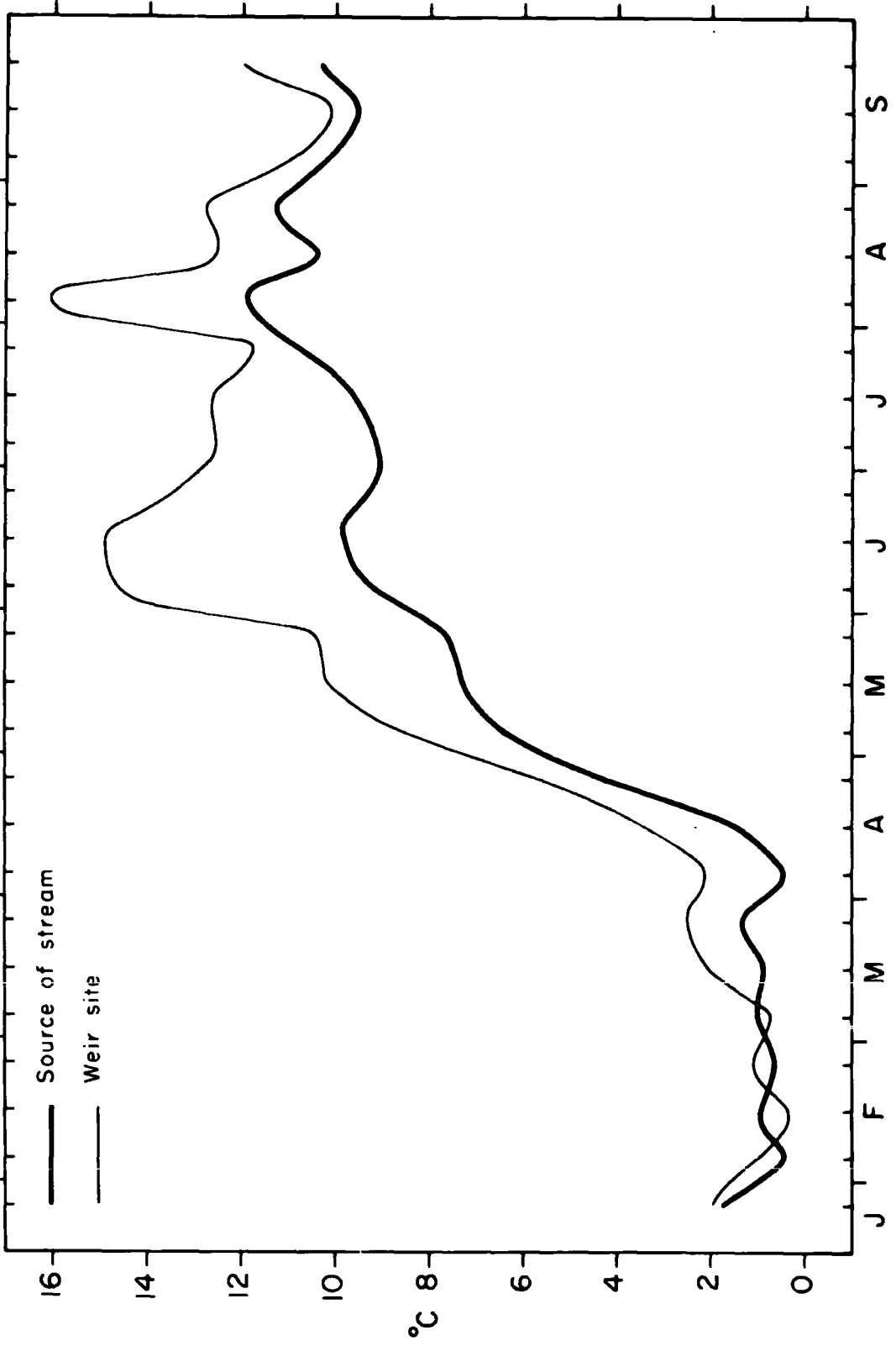


was a larger volume of water to be influenced by the atmospheric environment and because the water moved more quickly through the catchment and was therefore influenced by air temperature for a shorter period. Mean daily flows greater than 2.5 cusecs occurred during 12% of the year.

## II Variations in the stream water temperature with distance from the stream source

Since January 1970, a continuous record of the temperature of the stream water at the head of tributary B was maintained. The thermograph was installed at site 9 where the tributary began to adopt a recognisable main channel. Although the temperature of the water at the source site did respond to changes in air temperature there was no close relationship between the two. During the summer the mean temperature of the air was 2 - 3°C warmer than the water at the source, but on overcast days the maximum daily temperatures differed by only 1°C while on sunny days the difference might be as great as 10°C (Fig.49). Air temperature and direct solar radiation influence the daily maximum temperature but the daily minimum temperature appeared to be dominated by the temperature of the ground water supply which, when measured in the lead mine adit, did not vary from 7°C during the period of recording between October 1968 to January 1970. During the summer months the minimum temperature of the source water fell to 7°C on 23 out of 61 days, and during May the mean temperature was 7.2°C. Air temperature fell to or below 7°C on 19 days during

FIG 49  
MEAN WATER TEMPERATURES ON STREAM B, 1970

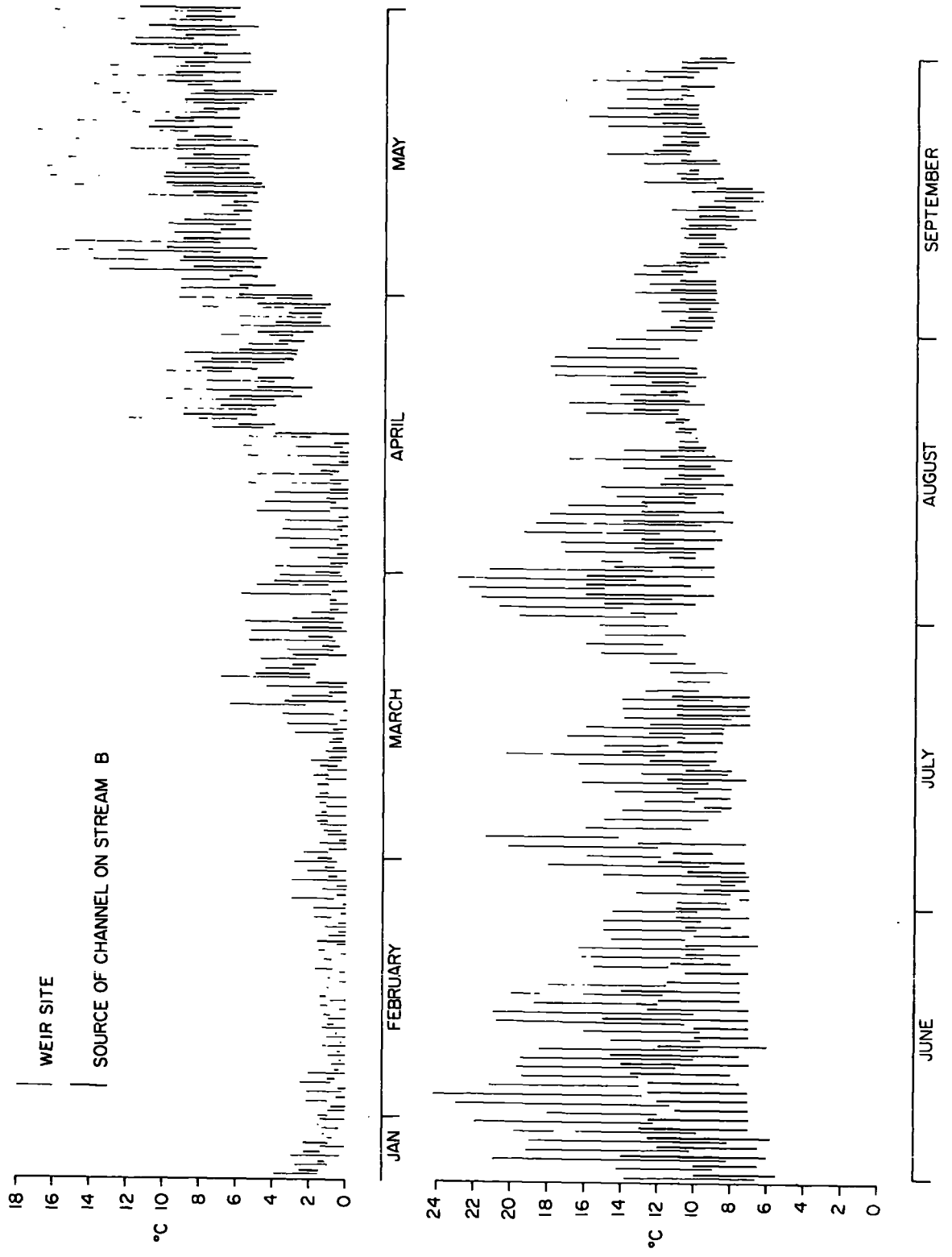


May, ten days during June and five days during July. Apart from short periods during the winter, the stream water temperature became greater with distance from the source to the weir site. The main reason for this was that the stream water at the source was greatly affected by the temperature of the sub-surface water draining from the peat which had very conservative temperature characteristics. With distance from the source the air temperature and solar radiation were able to exert a greater influence upon the stream water since the longer the water had been flowing in the stream channel the longer the time it had been under these influences. As a result of this the daily range of temperature also became greater downstream (Fig.50). The greatest difference was noticed during the spring and autumn when the range at the weir (site No.1) was often five or six times as great as at the source (site No.9). In March and April when the source water site had a mean daily range of only 1 - 2°C compared with 5 or 6°C at the weir. During the summer the source water had a daily range of 5°C, while at the weir site the range was 8 - 10°C. During the winter the daily range of temperature was very small at both sites, normally less than 1°C at the source site (no.9) and 2°C at the weir, the weir site range was normally about three times that of the source site.

The effect of air temperature upon water temperature varied with the time of day. There was a tendency, in general, for the water temperature to lag behind air temperature movements. During the morning the water began to warm later in the day than the air, and continued

# DAILY RANGE OF WATER TEMPERATURE 1970

FIG 50



to warm later in the afternoon, often beginning to cool several hours after the air temperature had reached its peak. The relationship between the air and the water was therefore different at various times during the day.

Consequently, it was meaningless to attempt to compare the relationship of temperature sequences taken along a stream course if the values were obtained for different times of the day. The temperature sequences were, therefore, taken along the course of the stream starting at the fixed time of 1500 BST, with each sequence taking about twenty minutes to execute. This hour was selected because it was the time of day when the stream water temperature was likely to be near its peak. The actual time of day was perhaps irrelevant here, since it was more important that the same time was used each day so that valid comparisons could be made between days. Since the measurements were made at a fixed time, and since they were always taken at the same measuring site, the temperature sequences were comparable in terms of time and channel conditions, while the volume of discharge and the air temperature remained the variable factors to be considered.

Sampling sites were chosen approximately every 100 m. along each tributary (Fig.51). It was decided to take the water temperature measurements in a flow of stream water within three metres of a fixed sampling site rather than pin point the exact site in the stream so that stagnant water could be avoided at low flows and ice covered pools avoided in the winter.

On each occasion the temperature was taken in a flow

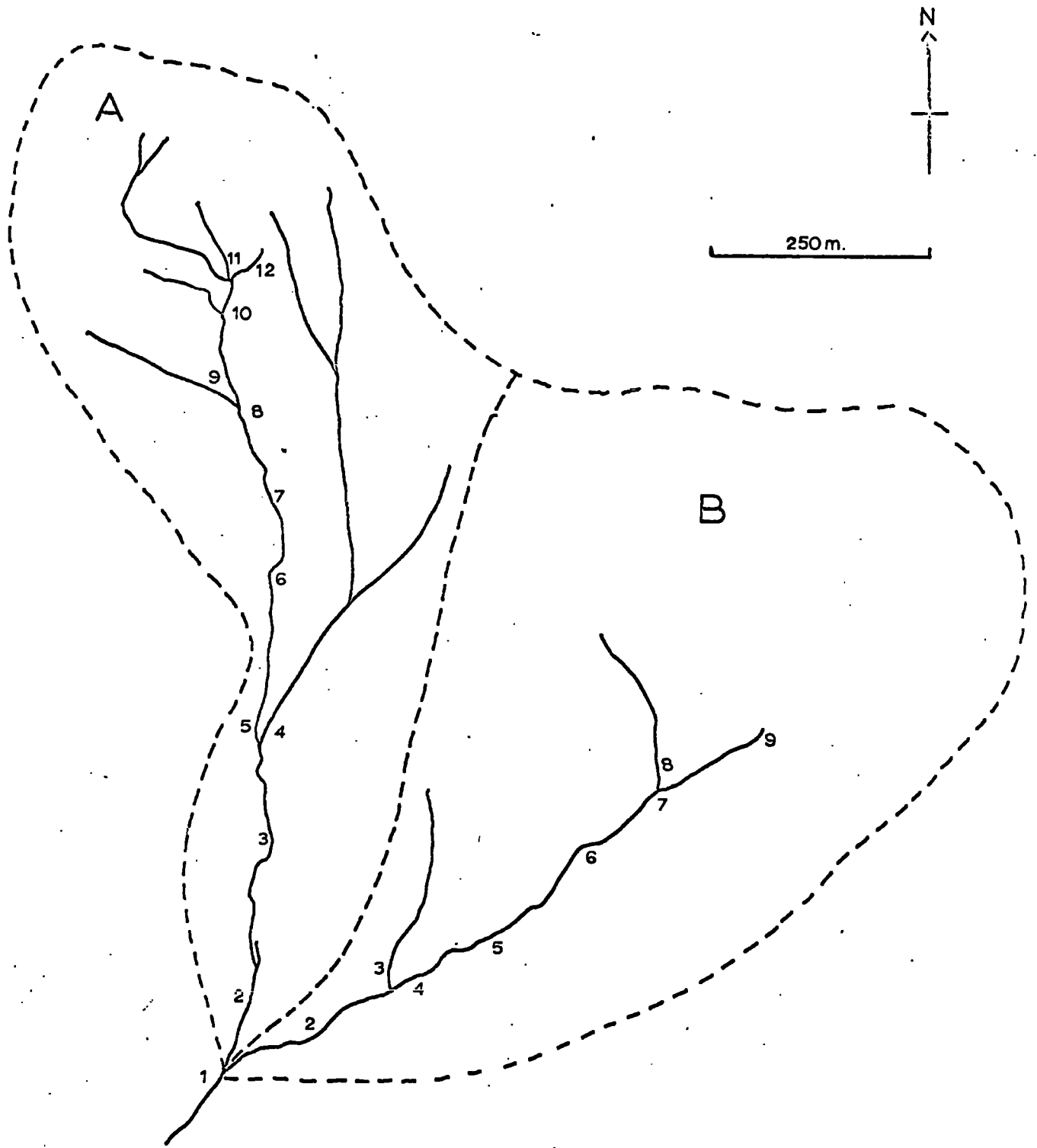
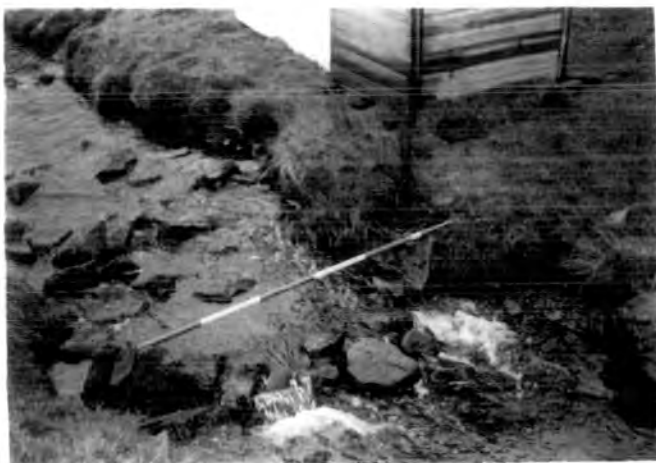
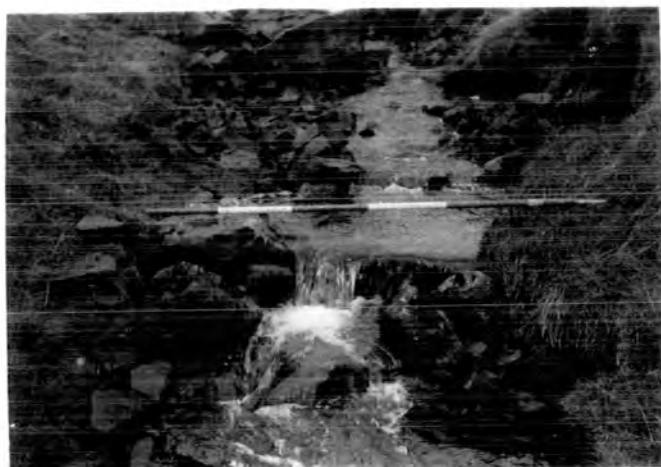


FIG. 51 SAMPLING SITES FOR POINT MEASUREMENTS OF WATER TEMPERATURE

of moving water, and where the flow was over, rather than through, the gravels. The temperature was measured with a NPL certificated mercury-in-glass thermometer readable to  $0.05^{\circ}\text{C}$ . This was placed in the stream and the temperature noted only after it had continued to give a constant reading for 15 seconds. During very cold air temperature conditions it was important to ensure that a thin film of ice had not formed over the bulb of the thermometer. This was done by heating the thermometer to  $+5^{\circ}\text{C}$  in the hand before immersing it in the stream. Normally a complete temperature sequence took twenty minutes to execute.



Site 1 The weir site. This was below the confluence of the two streams A and B and could be used as the base for the comparison of temperature sequences in each tributary. The channel was about 2m wide and lined with large gravels, small stones and boulders. During low flows there was insufficient water to maintain moving water across the width of the channel, but during high flows the stream overflowed its banks.



Site 2 Shallow grass banks and only very slightly incised. The stream flowed over bedrock, an outcrop of Four Fathom Limestone, in a series of rapids and rock pools.



Site 3 This site was on a small tributary which drained a complex of subsurface water courses and surface sphagnum flushes. The channel was 0.6-1.0m deep, and in parts 2.5m wide, and was supplied by a narrow channel cut in the peaty podsol soil. At the site itself the channel was lined with gravel and small stones.



Site 4: The channel became very narrow and relatively steep. The banks were grassy and very shallow, and the channel was lined with medium and small sized stones.



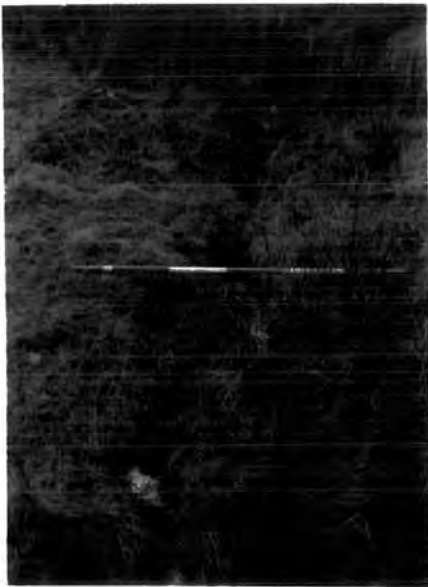
Site 5: The site was on an outcrop of Great Limestone. The channel was about 0.5m wide and characterised by a series of rock pools and rapids containing small and medium sized stones but no gravels.



Site 6: The channel became relatively shallow and meandering. The banks were grassy and not deeply incised and the channel itself, though lined with stones was devoid of gravels.



Site 7. Sited on an outcrop of iron stone, where the channel form was a series of rock pools about 50 cm. deep and 30 cm. wide.



Site 8. A second tributary draining an area of *Juncus effusus* flush, though there was a clear channel for about 30 m. The channel was 20 - 30 cm. wide with a gradient of 1:8.



Site 9. This site was at the point where tributary B first formed a recognisable main channel. The channel was incised in a peaty/podsol soil. The drainage area above this point had several clear drainage channels through the peat, but the main supply was surface flow.

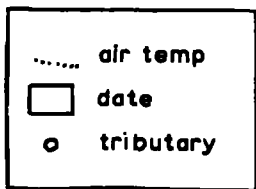
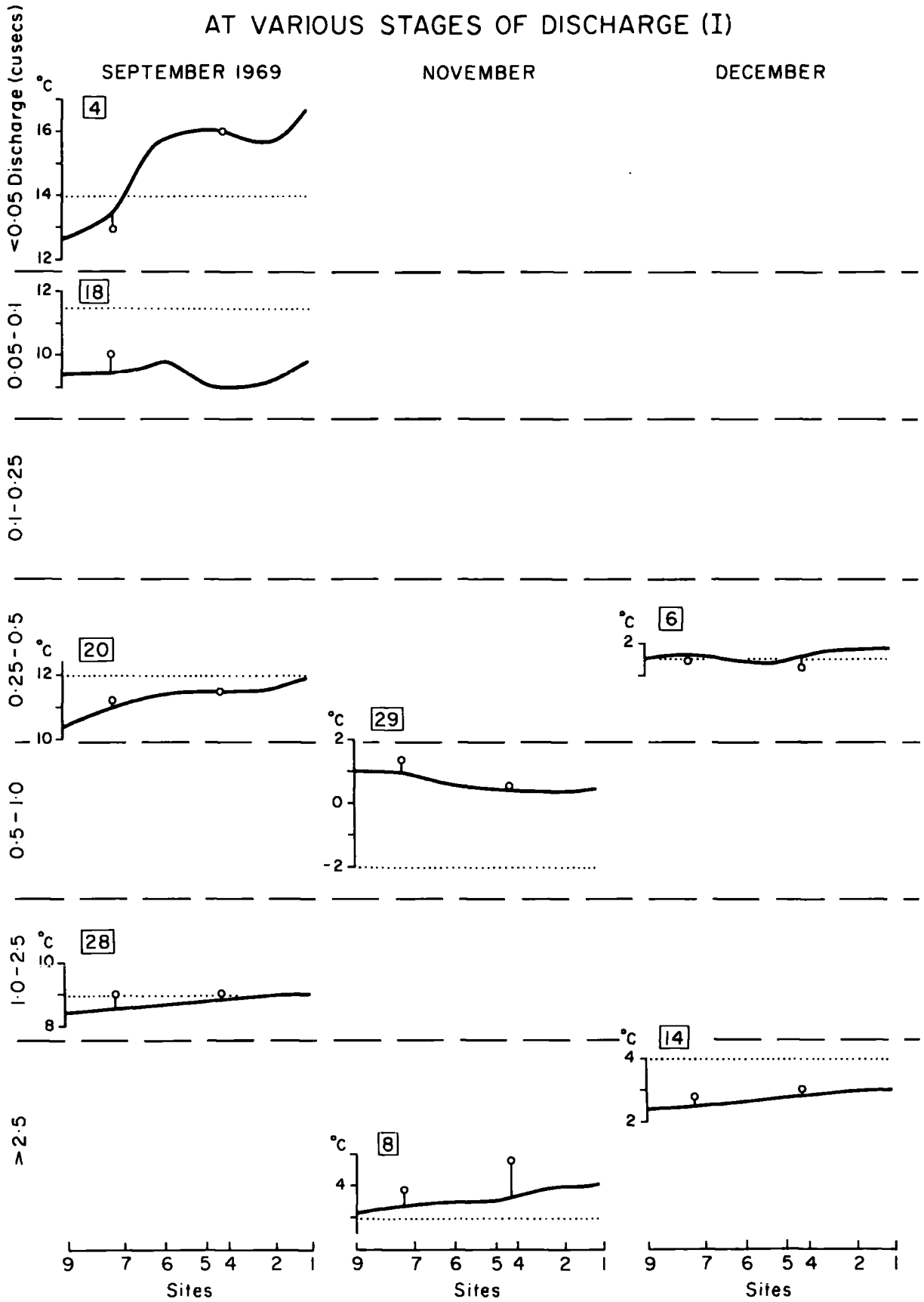
As already noted the volume of discharge was likely to have a very significant influence upon the effect that the air temperature would have upon the stream water. The smaller the volume of water the greater would be the relative surface area in contact with the air and, therefore, the greater the effectiveness of the air contact with the water.

In figures 52-55 temperature sequences for each month during the water year 1969/70 have been drawn and set against the volume of discharge. The measurements were made between 1500 - 1530 BST on the date given with each graph; the air temperature at the weir site is indicated by the dotted line. The temperature of the tributaries at sites 3 and 8 are shown as ringed points and related to the temperature sequences by a vertical line to demonstrate the temperature difference between the stream and the tributaries. These temperature sequences have been presented in this way to indicate (a) the effect of the different volumes of discharge, and (b) the changing response that occurred through the year.

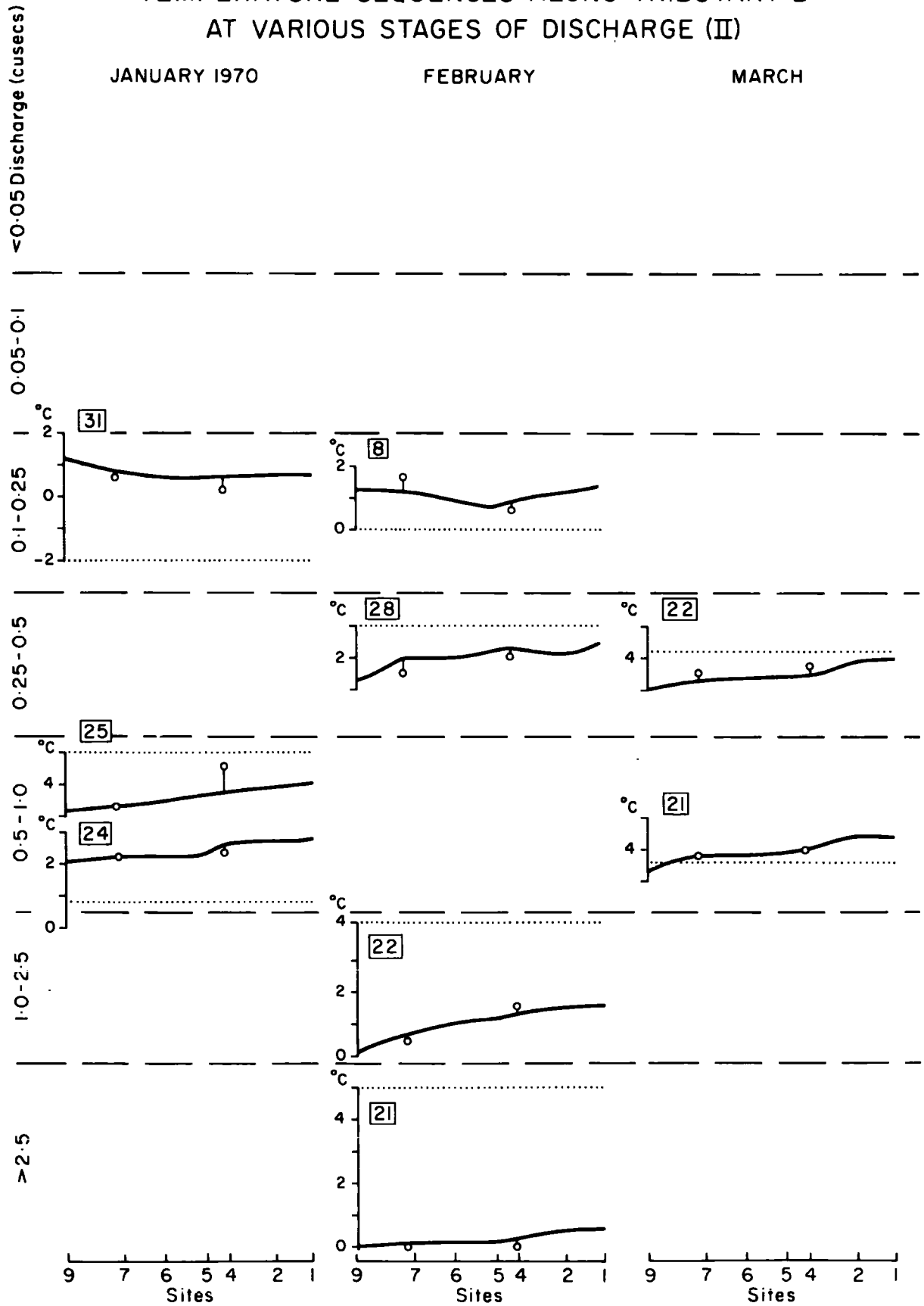
The stream water temperature usually became warmer downstream, even during the winter period. This was not altogether surprising since the sequences were taken at 1500 BST, the warmest part of the day, when the air temperature was very often warmer than the temperature of the stream at source. When the air temperature was considerably lower than the water temperature, as it was on 29th November, 1969, and on 31st January 1970, the water temperature did become colder downstream. However, the mere fact that the air temperature was colder than the

**FIG 52**

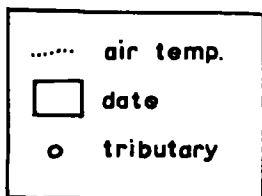
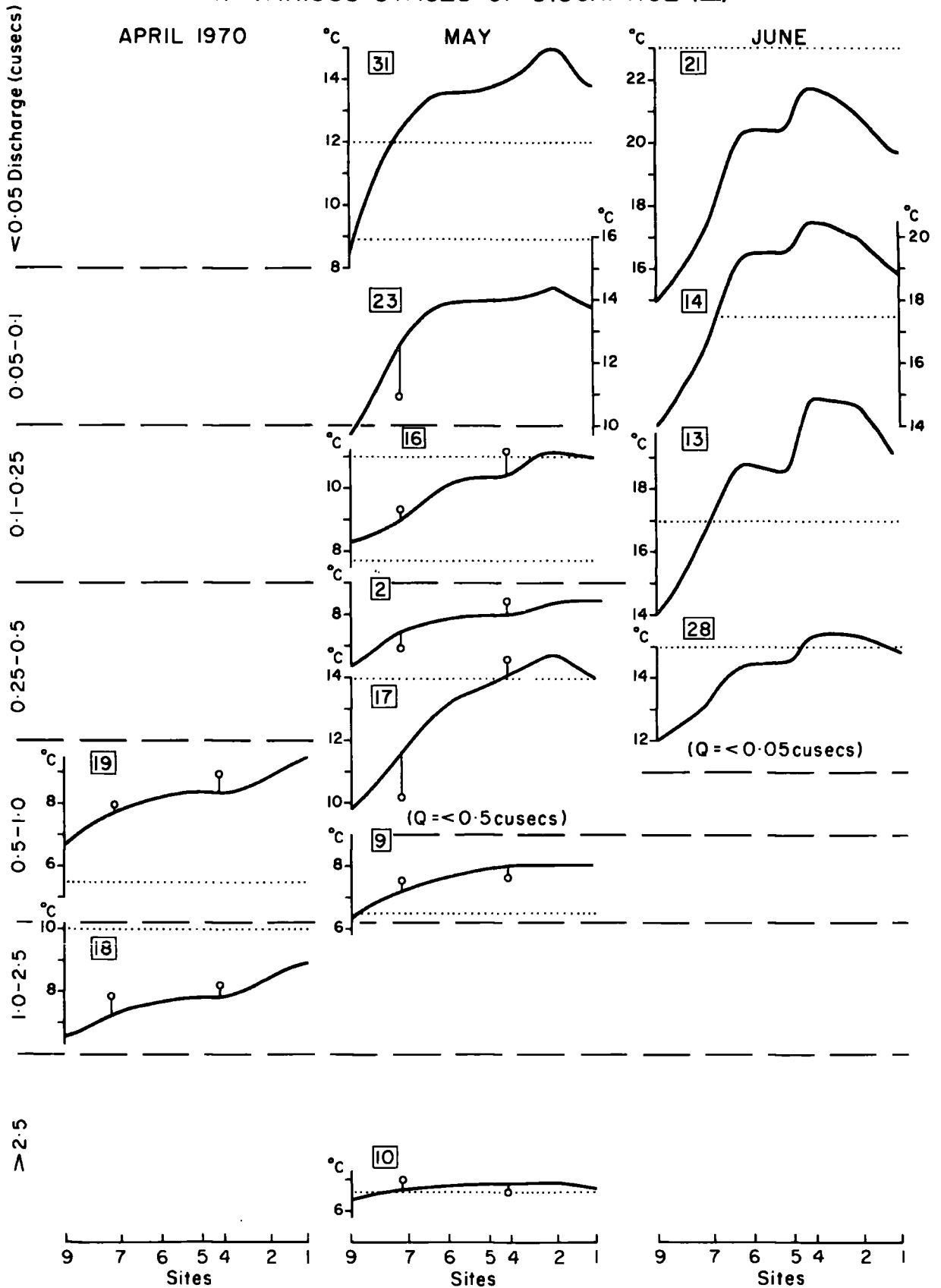
**TEMPERATURE SEQUENCES ALONG TRIBUTARY B  
AT VARIOUS STAGES OF DISCHARGE (I)**



**FIG 53**  
**TEMPERATURE SEQUENCES ALONG TRIBUTARY B**  
**AT VARIOUS STAGES OF DISCHARGE (II)**

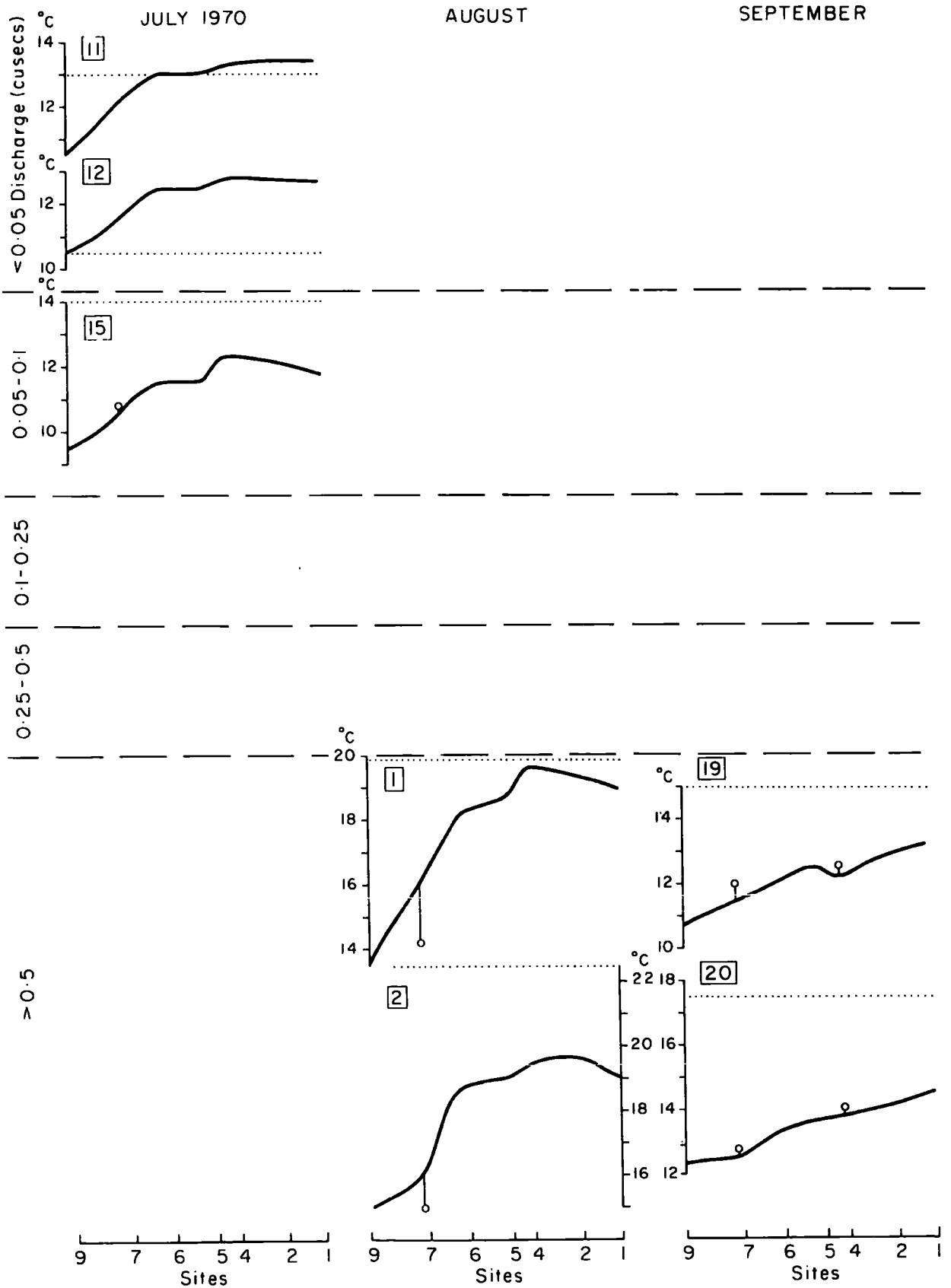


**FIG 54** TEMPERATURE SEQUENCES ALONG TRIBUTARY B  
AT VARIOUS STAGES OF DISCHARGE (III)



**FIG 55**

**TEMPERATURE SEQUENCES ALONG TRIBUTARY B  
AT VARIOUS STAGES OF DISCHARGE (IV)**



water temperature did not always produce a cooling effect upon the stream water. On 19th April 1970, the stream water became warmer downstream despite the fact that the air temperature was 1°C cooler than the stream water at the source and 4°C cooler than at the weir site. During the summer period, May, June and July particularly, the stream water temperature frequently became warmer than the air temperature.

Under similar air temperature conditions, the amplitude of the water temperature changes along the stream were greatest where the volume of discharge was lowest. This was particularly true of the summer period when the air temperatures were highest, and when the discharge volumes were lowest. As the volume of discharge increased the nature of the temperature profiles became less irregular and began to indicate an overall trend downstream. When the volume was small, each site also tended to reflect the effects of very local influences, the most noticeable of which was due to the effect of groundwater contributions. The June and July profiles show this most clearly, and sites 5 and 2 were much cooler than the trend of sites 9, 7 and 6 would suggest. This was because the outcrops of limestone at these sites contributed a large proportion of the discharge in the form of ground water draining from the aquifers. The weir site was also relatively cold as a result of the contribution from stream A which, during these periods of low flow, was derived almost entirely from a spring 50 m. upstream from the confluence. As the volume of discharge increased these irregularities, though they occurred in

the same pattern, were not so marked. During these low flow periods the most rapid increase in temperature occurred between sites 9 and 5, but during higher flows, the increase in temperature was much more gradual and was spread over the whole stretch of the stream.

The August profiles were, in many ways, exceptions to these generalisations. This was due to the occurrence of the very high air temperatures, and, despite a discharge greater than 0.5 cusecs, the temperature profiles showed the greatest increase in temperature of all the sequences taken. The volume had been sufficiently large to absorb the effects of the ground water at sites 5 and 2 and, although there was the fastest rise in the water temperature between sites 9 and 5 at 1 - 1.2°C per 100 m. there was a continued rapid rise of 0.5°C per 100 m. until site 2.

The temperature sequences described above could only be regarded as representative of the situation during the middle of the day. In order to study the changes of temperature along the stream throughout a 24-hour period, separate surveys had to be made. While it would have been ideal to have surveys every hour this would have been impossible in practical terms, and the additional precision obtained would not have justified the extra effort involved.

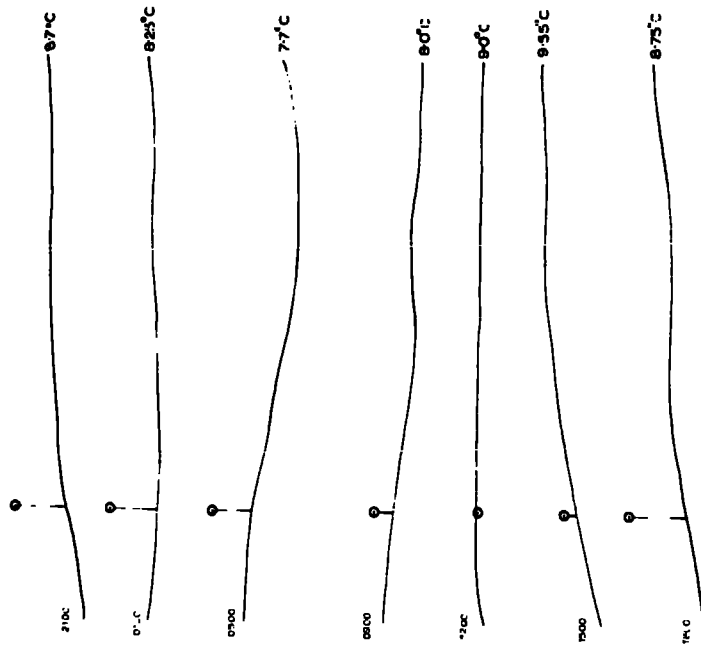
During the daylight period, when the most rapid responses occur, a survey was made every three hours, at 0900, 1200, 1500 and 2100 BST. During the night the period was extended to four hours, at 2100, 0100, 0500 and 0900 BST., thus reducing the number of night-time traverses

by one - a practical consideration. Each temperature sequence in the 24-hour period was essentially similar to those taken in the middle of the day and described above.

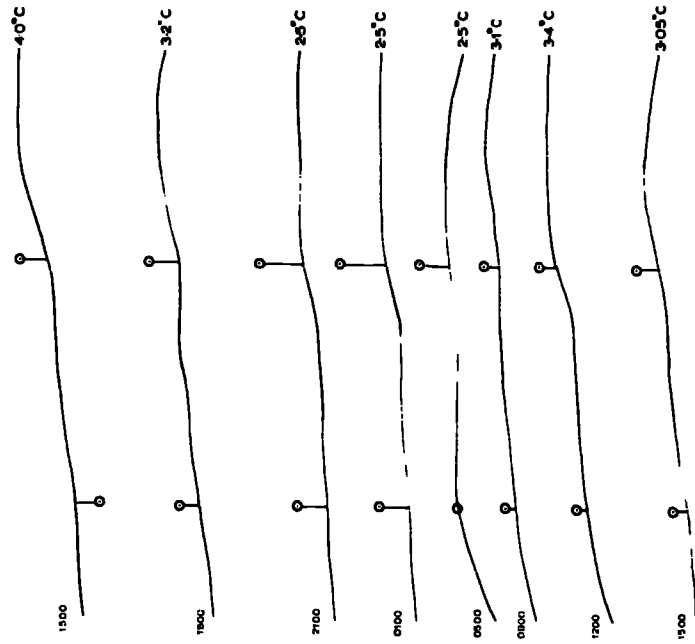
Such a survey was carried out over a 30-hour period once each month from October 1969 to September 1970 in order to give a representative spread over a complete year. The study period in each month was invariably over a weekend, and where possible, though not always, near the time of the full moon since the light provided by the moon assisted the difficult task of walking the length of the stream during the hours of darkness. Each survey represented the conditions over that 24-hour period only and should not in any way be regarded as typical for that month.

In figures 56 and 57 the temperature sequences taken over the 24-hour period have been presented to show the changes that occurred in the temperature sequences through the period. The time of each sequence is indicated on the left hand axis and the position of each sampling site in the sequence is shown on the horizontal axis. The temperature of the tributaries at sites 3 and 8 are shown as ringed points, and related to the temperature sequence by a vertical line to demonstrate the temperature difference between the stream and the tributaries. The temperature reading on the right hand axis is given as a reference figure. It is the temperature of the water at the weir site and since the vertical temperature scale is given it is possible to evaluate the extent and nature of the changes in water temperature down the stream, and to compare the temp-

25/26 OCTOBER 1969



22/23 NOVEMBER 1968



24/25 JANUARY 1970

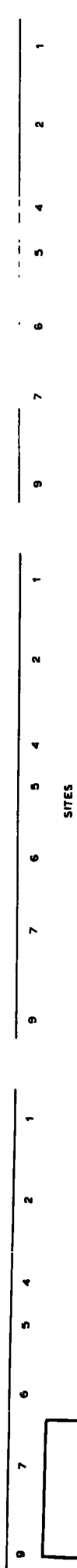
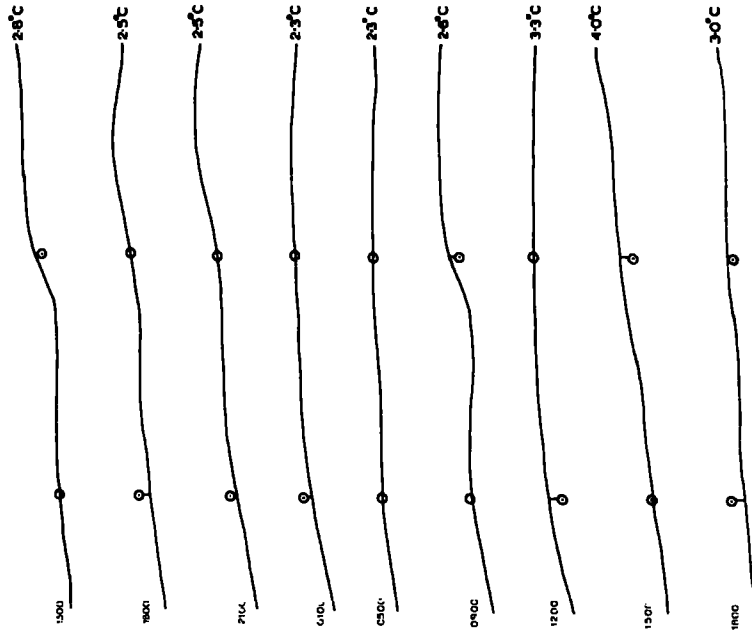


FIG 56 TEMPERATURE SEQUENCES ALONG TRIBUTARY B (I)

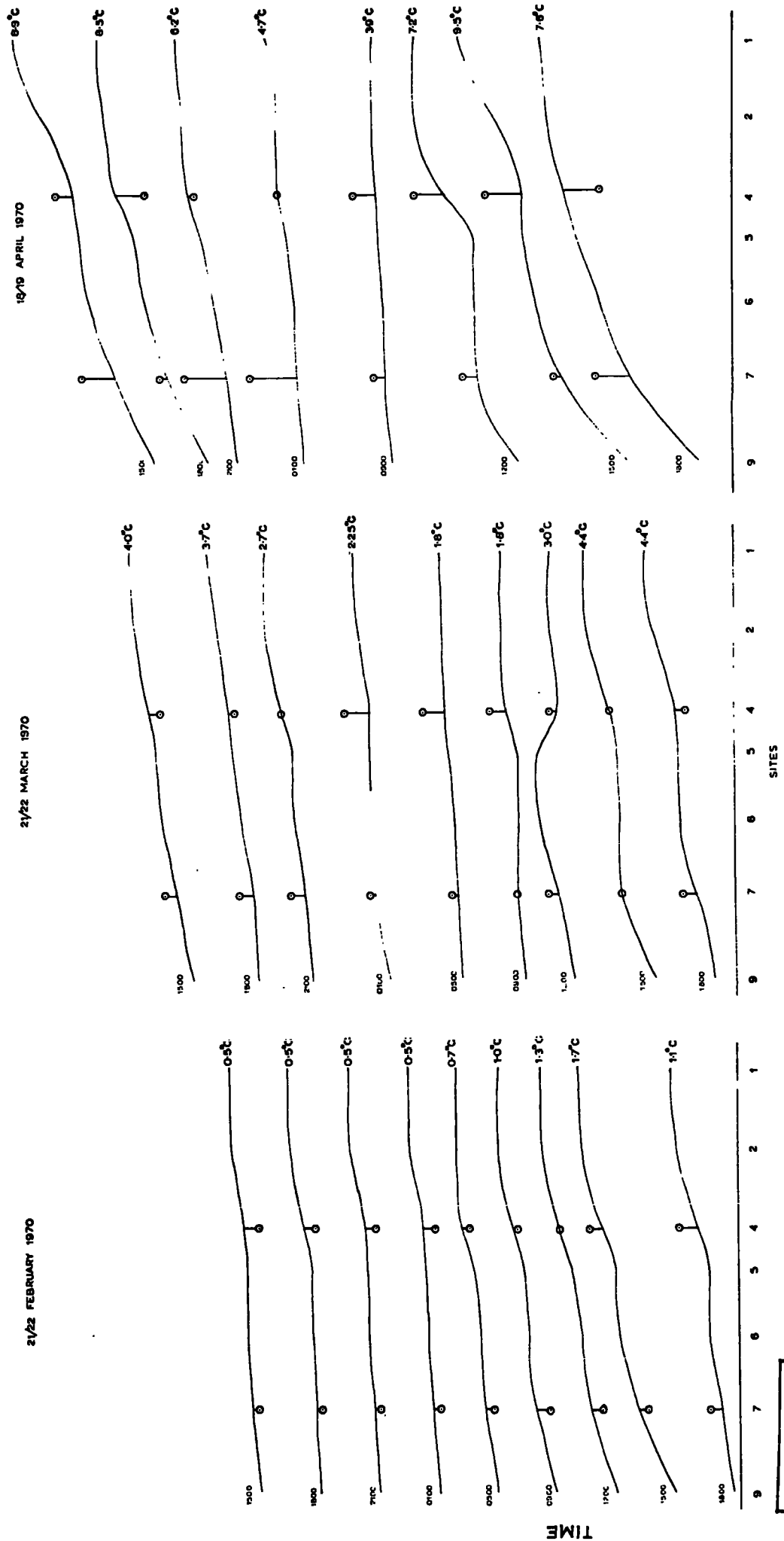


FIG 56 TEMPERATURE SEQUENCES ALONG TRIBUTARY B (II)

Scale: f°C  
 O TRIBUTARY

erature sequences through the 24-hour period (furthermore, it is possible to calculate the exact temperature at each site in all the sequences, but for convenience these data are listed in Appendix 4).

As a generalisation, it can be seen that the stream became warmer with distance from the source. During the day the magnitude of this heating effect was much greater than during the night, and indeed on some occasions such as 26th October 1969 (0500 and 0900 BST), there was a downstream cooling of the stream during the night.

Similarly, in March and April the early morning sequences showed a small change in temperature, while during the day the water became noticeably warmer downstream. The greatest changes of temperature invariably occurred at 1500 or 1800 BST. The summer conditions showed a similar diurnal pattern, although the amplitude of the fluctuations was much greater. August alone, during the summer of 1970, did not show a marked flattening of the temperature profile during the night period.

Specific conditions are illustrated by reference to each of the temperature sequences in turn.

#### 25th/26th October 1969

The discharge was c 0.75 cusecs, while the air temperature varied between 7°C and 12°C. The volume of the stream was sufficiently low to allow the water temperature to reflect air temperature changes, and yet not low enough to be dominated by the ground water contribution. The tributary stream very clearly reflects the air temperature conditions, being very warm during the day,

but cooling to the temperature of the main stream during the night.

#### 22nd/23rd November 1969

This series of temperature sequences was taken during a period of high flow. On 22nd November the discharge was 7 cusecs falling to 0.7 cusecs on 23rd November. Air temperature fluctuated between 0°C and 5°C. Despite the large discharge the stream did respond to air temperature changes, but quite clearly the response was not as great as that of the minor tributary streams at sites 4 and 7. Although the volume of discharge on 23rd November was very much smaller than the day before, the temperature profiles were not markedly different because any differences that could have been expected due to the smaller volume were cancelled by the different air temperature conditions. On 22nd November, the air temperature was 5°C, while the stream reached a temperature of 4°C at site 1; on 23rd November, the air temperature was never greater than 3°C but the stream water temperature was 3.4°C at 1200 and 3.05°C at 1500 BST.

#### 24th/25th January 1970

During this 24-hour survey, the discharge gradually dropped from 2.8 - 1.4 cusecs, while the air temperature reached a maximum of 1°C on the 24th and 6°C on the 25th January. There was very little relationship between air temperature and water temperature conditions during this period. Even the minor tributary channels at sites 4 and 7 remained very similar to the main stream temp-

eratures and did not reflect air temperature conditions. However, since the night-time profiles did not become heated to the same extent as the day-time profiles, this did indicate an environmental control. During this period the discharge was maintained partly from snow melt and partly from ground water sources, and together these had overridden the effect of the air temperature changes, and had maintained a stream water temperature warmer than the air. Nevertheless the marked increase in air temperature on the 24th January was reflected in the temperature profile taken at 1500 BST.

#### 21st/22nd February 1970

The February sequences showed a quite remarkable pattern. During this 24-hour period the stream experienced a flood of snowmelt/rain, which reached a maximum flow of 40 cusecs at 2300 BST on 21st February. The recession was rapid and by the 1800 BST profile, the volume had fallen to 6 cusecs. Air temperature remained constant varying very little around 4°C. The temperature profiles clearly indicated the dominating effect of the very large volume of discharge. The stream was dominated by melt water at near freezing temperatures, with the minor tributaries remaining colder than the main stream despite the relatively warm air temperature. As the volume of discharge became less, the influence of the air temperature became greater, and consequently there was a marked difference between the temperature profiles obtained at 1500 and 1800 BST on 21st February, with those obtained on 22nd February. Nevertheless, the influence of

the air was still very small and the temperature of the stream water at the weir site was still far less than the air temperature. The minor tributaries, due to their much smaller volume, did reflect the progressively increasing effect of the air temperature and the lessening dominance of the discharge from 2400 BST onwards.

#### 21st/22nd March 1970

These profiles were taken during a period of hydrograph recession, following a series of small snowmelt floods. The volume dropped from 1 - 0.7 cusecs, during the 24-hour period. The air temperature, following the normal diurnal fluctuation ranged between 2°C and 5°C. The temperature profiles along the stream increased in temperature by only 0.3°C, while during the daytime it was greater than 1°C. The two tributaries (at sites 4 and 7) showed different responses during this period.

The minor tributary at site 4 was dominated by a contribution of groundwater or sub-surface flow and was, despite its smaller volume, influenced to a lesser extent by changes in air temperature than by stream B. During the daytime, tributary B was warmer, and during the night cooler, than the smaller tributary. The minor tributary at site 7 was composed mainly of surface flow contributions. Since it was much smaller in volume than stream B it responded much more quickly to, and much more closely with, the changes in air temperature. Consequently during the daytime it tended to warm more quickly, and to a greater extent, than the main stream.

18th/19th April 1970

The discharge during this period was similar to that of the March period, but the temperature profiles were clearly very different. The air temperature varied between  $9^{\circ}\text{C}$  at the beginning of the period and fell, apart from a midday rise to  $7^{\circ}\text{C}$ , to  $4^{\circ}\text{C}$  at the end of the 24 hours. The stream temperature profiles reflected this pattern. During the day the stream became warmer downstream very rapidly, heating to as much as  $2.5^{\circ}\text{C}$  at 1500 BST on 19th April, while during the night it was heated by less than  $0.5^{\circ}\text{C}$ . This pattern was the same, though more clearly demonstrated on this occasion, as those obtained during the earlier months.

The minor tributaries at sites 4 and 7 displayed the same characteristics as they did on 21st/22nd March. The tributary at site 7 tended to be warmer than the main tributary during the day, while the tributary at site 4 tended to be cooler than the main stream when the latter was at its warmest. The relative warmth of the tributary at site 4 at 1200 and 1500 BST on 19th April was attributable to the influences upon stream B rather than to those upon the minor tributary. These other influences, particularly the channel conditions, are studied later in sub-section IV.

16th/17th May 1970

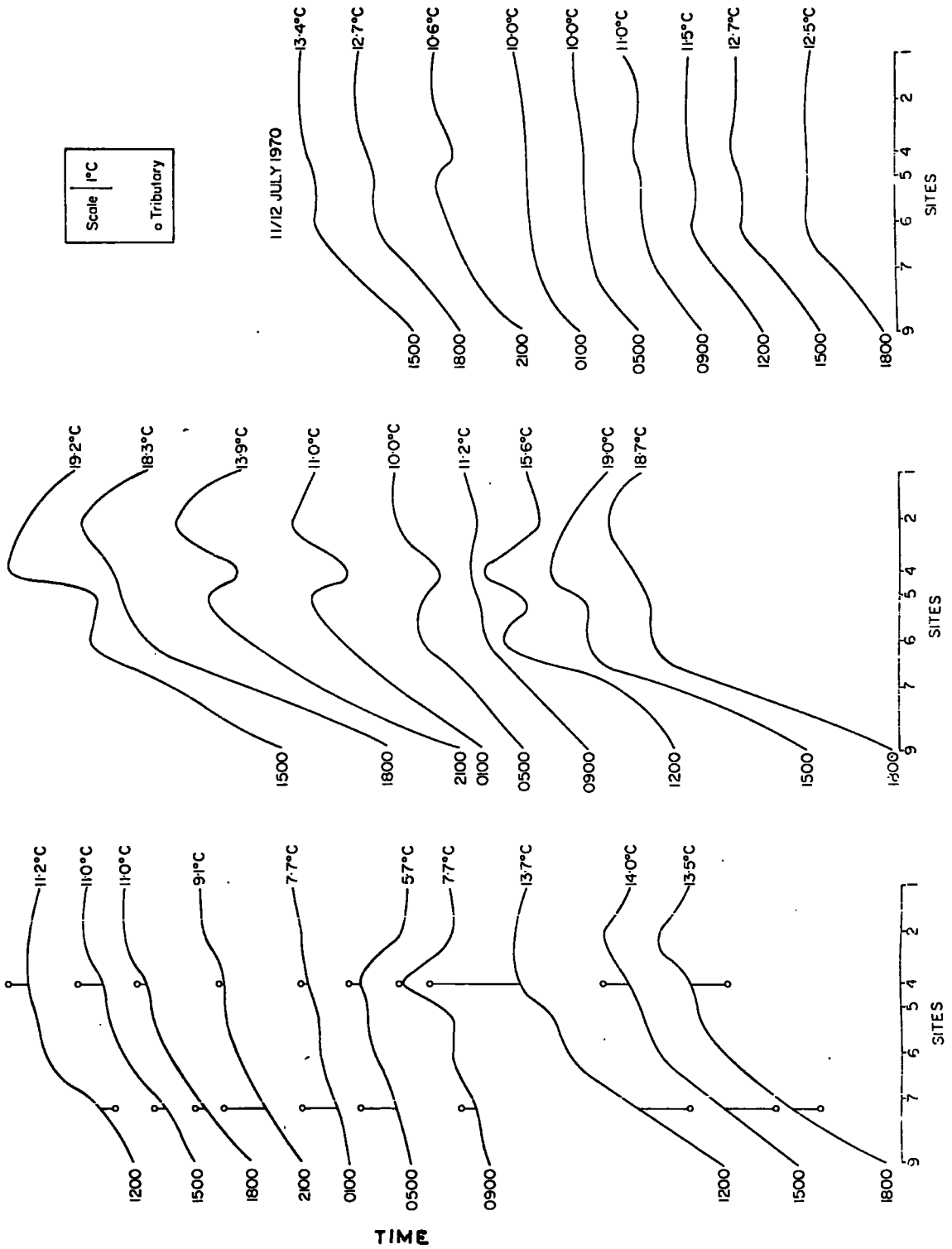
During this period the discharge was low at 0.25 cusecs, and composed largely of groundwater. Since the volume remained constant throughout the 24 hours, any

FIG 57

# TEMPERATURE SEQUENCES ALONG TRIBUTARY B (III)

16/17 MAY 1970

13/14 JUNE 1970





changes in the temperature profiles must be attributed to changes in the atmospheric influences, either air temperature or radiation. Air temperature fluctuations were large, varying from  $12^{\circ}\text{C}$  at 1700 BST on 16th May to  $2^{\circ}\text{C}$  at 0500 BST and  $15^{\circ}\text{C}$  at 1400 BST on 17th May. The stream temperature profiles reflected this air temperature pattern.

On the 16th May the stream temperature was c  $3.0^{\circ}\text{C}$  warmer at the weir than at the source, (site 9) and on the 17th May, the warmer day, the heating effect was  $5^{\circ}\text{C}$ . These maximum temperatures occurred at 1800 BST on both days. During the night the stream was much cooler, and only became  $1.3^{\circ}\text{C}$  warmer between the source and the weir site. The minor tributary at site 4 was at very low flow, so much so that it was virtually a series of still pools. Consequently, during the day-time it became heated to a greater extent than the main tributary, but lost heat much more rapidly as the air temperature fell and, by 1800 BST on 17th May, it had become colder than the main stream.

#### 13th/14th June, 1970

Once again, the discharge was constant during this period, and very low at 0.06 cusecs. The diurnal air temperature fluctuation was  $14^{\circ}\text{C}$ , falling from  $19^{\circ}\text{C}$  at 1600 BST on 13th June, to  $4.5^{\circ}\text{C}$  at 2400 BST and rising again to  $17.5^{\circ}\text{C}$  at 1500 BST on 14th June. Not surprisingly, under these conditions the stream water temperature responded to the air temperature changes, and heated very quickly. The most rapid heating of the water had occurred

by the time it reached site 6 and during the night by the time it reached site 5.

The lower section of the temperature profile demonstrated a pattern associated with other controls. At the weir site the contribution of water from stream A had a cooling effect, more so during the day than during the night. At site 4 there was a marked drop in temperature during the night time, but during the day there was a heating effect. At sites 5 and 2 the stream passed over outcrops of limestone and it was possible that these profiles could be understood in terms of a sudden localised increase in the proportion of ground water. The effect of this would be to make sites 5 and 2 relatively colder during the day and relatively warmer during the night. In these profiles each station is shown in relation to its neighbouring stations and in consequence a heating effect at sites 5 and 2, as for example at 1200 BST on 14th June would have the effect of making site 4 look like a cold station. The fact that the profiles taken at 1800 and 0900 BST showed a much more gradual change in temperature between adjacent sites indicated that the profiles were being influenced during the hottest and coldest periods by the more conservative conditions at sites 5 and 2.

11th/12th July 1970

The discharge during this study period was similar to that during the 13th/14th June period, but unlike the June study, the air temperature fluctuations were much smaller, about 3.5°C. The greatest heating effect upon

the stream water was achieved by the time it had reached station 6, and downstream from this point there was very little increase in the stream temperature. The volume of discharge was so low that the stream water had reached equilibrium with air temperature in this short distance. There were no substantial contributions of groundwater at this time since the source had been largely depleted, following a period with little rain. Since the study period was overcast and with drizzle, this meant that there were no extremes of temperature, either hot or cold, acting upon the stream water.

#### 1st/2nd August 1970

During this period flow remained constant at 0.09 cusecs and air temperature remained relatively high between 15 and 20°C. Since the night-time temperatures were high (15°C), there was a considerable amount of heating of the stream during the night which was sufficient to raise the temperature by 4°C from 11°C at the source to 15°C at the weir. During the day the heating effect was greater still, and as much as 6.5°C at 1800 BST on 1st August, and 6.0°C at 1800 BST on 2nd August.

The minor tributary at site 7 was dominated by sub-surface contributions, and like the situation in May, remained much less responsive to air temperature effects. During the day-time this minor tributary remained cooler than stream B, while during the night it was much warmer.

19th/20th September 1970

Throughout this period there was a flow of 0.5 cusecs, and an air temperature fluctuation between  $12.5^{\circ}\text{C}$  and  $18^{\circ}\text{C}$ . The maximum heating effect occurred during the day-time with little or no heating of the stream water downstream during the night. The greatest heating effect occurred at 1800 BST, when the source waters were beginning to cool, and when the weir site was reaching its maximum. This resulted in a rise of temperature of  $3^{\circ}\text{C}$ , compared with the night time minimum rise of  $0.5^{\circ}\text{C}$ .

The tributary at site 4 maintained a temperature very similar to that of the main stream. During the hours of 1500 - 1900 BST on 19th September, it was colder than the main stream, but for the rest of the period it was the same or slightly warmer. The tributary at site 7 behaved differently. During the day of 19th September, it became much warmer than the main stream as a result mainly of the air temperature and radiation acting more effectively upon the smaller volume of water. On the 20th September, although the air temperatures were comparable with those of the 19th, it was overcast and with reduced direct radiation resulting in less heating of the tributary stream.

As a result of these observations certain generalisations can be made. From the graphs in figures 52-55 it can be seen that the rate of water temperature change varies not only with the seasons, but also with the volume of discharge. These conclusions are summarised in figure 58. Representative graphs have been drawn for various categories of discharge, and have been constructed

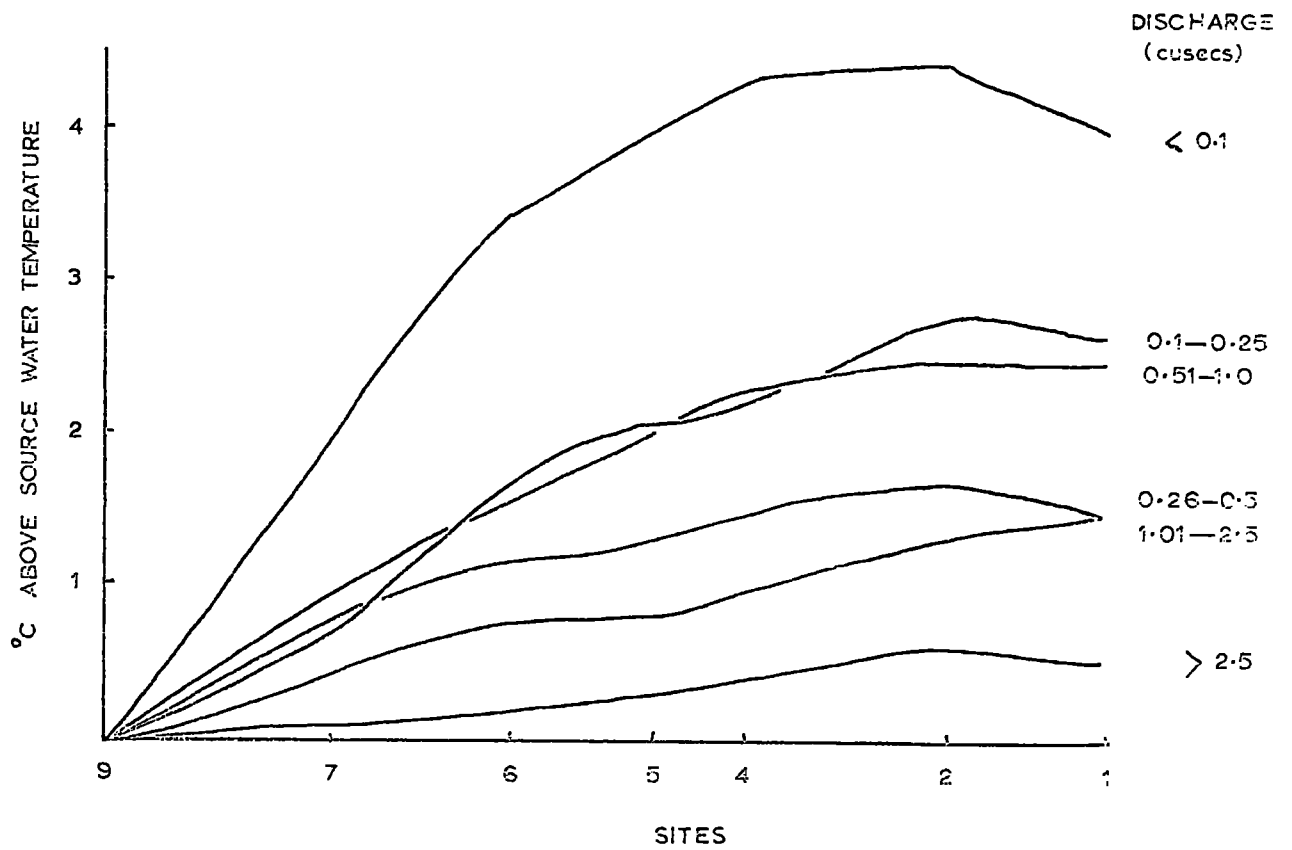


FIG 58 AVERAGE STREAM TEMPERATURE PROFILES FOR VARIOUS STAGES OF DISCHARGE



FIG 59 THE AVERAGE VARIATION IN WATER TEMPERATURE BETWEEN THE SOURCE AND THE WEIR SITES DURING A 24 HOUR PERIOD

from the mean values of all the graphs in figures 52-55, where air temperature was greater than the stream water at the source. From figure 58 it can be seen that the range of water temperature change in the stream decreased as the volume of discharge increased (the graph for the 0.5 - 1.0 cusecs category was an exception to this generalisation, because it had been distorted by the extreme conditions of the 1st/2nd August 1970).

Clearly, the volume of discharge cannot have a direct effect upon the heating of the stream water, but can only act as an indirect influence modifying the effectiveness of the atmospheric environment. In order to measure the ability of the atmospheric environment to warm the stream water, the range of water temperature change between the source and the weir must be compared with the air temperature. The relationship between air and water temperatures at various stages along the stream course is studied in Section III. From figure 58 it can be seen that for flows of less than 0.1 cusec the stream water reached equilibrium with the air temperature within 200 m. of the source of the stream, and from there downstream relatively minor changes in water temperature resulted from air temperature influences, although sources of groundwater did have a marked local effect upon the stream water temperature. As the volume increased, equilibrium between the air and water was reached progressively further downstream.

Figure 59 shows the changes in the downstream heating of the stream water which occur through a 24-hour period. This is based upon the mean data obtained from

24-hour surveys through 1969/70. Although maximum daily temperatures usually occurred about 1500 BST, the greatest heating effect in the stream, comparing source with the weir site, invariably occurred at 1800 hours. This was because the source waters had already begun to cool rapidly while the recorder at the weir site was still recording the temperature of water that was in the stream channel during the hottest time of the day. When the discharge was high this delay did not occur and the maximum amplitude of heating occurred during the 1500 BST profile.

Direct solar radiation exerts a very important influence upon the stream water temperature. This influence is greatest when (a) the radiation is greatest, (b) where the surface area of the stream in relation to the volume of the water is greatest, and (c) where the period of influence is longest. Periods of low flow are therefore the periods when the effects of direct radiation are greatest, the area of the surface of the stream is very little less than during high flows but the volume may be between 30 or even 100 times smaller. The time taken for the stream water to pass between the temperature control sites at the source of the stream and the weir site were found to be as much as six hours at 0.25 cusecs compared with an half hour during a discharge of 20 cusecs, and as a result the differences in temperature between the source and the weir sites during low flows reflect a much longer period under the influences of the environment, air temperature and direct solar radiation.

It was difficult to estimate the exact volume of the

groundwater contribution to the stream throughout the year, but it appeared to vary between 0.5 cusecs in the winter and 0.05 cusecs in the summer. The proportion of groundwater in the total discharge might be as large as 100% both during the summer and winter, when the discharge was low. This groundwater contribution, by virtue of its origin, was independent of the air temperature, as has been demonstrated by measurements in this catchment, and consequently it could exert an influence upon the stream temperature which was unrelated to the conditions of the immediate atmospheric environment.

Groundwater contributions were most noticeable at sites 5 and 2, and were clearly demonstrated during the June period. It was obvious also that the contribution from stream A, not indicated in these profiles, caused the stream water to be colder at the weir site relative to site 2, because it was entirely derived from a groundwater spring 50 m. above the confluence with stream B during periods of low flow. More will be said about this when the two streams, A and B are compared in Section IV of this chapter.

By virtue of their smaller volume, the tributaries should tend to be more responsive to air temperature changes than the main stream, and this was true to a large extent in the case of the tributary at site 7. The tributary was fed almost entirely by surface water, and groundwater contributions were negligible, except during the very lowest flows in the summer. The catchment of this tributary is partly flush with a large surface area in comparison with its volume. It was therefore not

surprising that the tributary closely reflected air temperature changes. During the low flows of the summer period these marshes became overgrown with vegetation and virtually stagnant, thus the temperature of the water was greatly affected by the soil temperature, but shielded by the vegetation from direct solar radiation.

The tributary at site 4 was fed partly from groundwater but mainly from sub-surface water courses. The catchment of this tributary was much larger than the surface channels indicate being supplied by a network of subsurface streams often 300 m. in length and breaking the surface only occasionally as flushes. This tributary was affected by groundwater and soil temperatures rather than air temperatures when the discharge was less than 1 cusec. However, during the periods of extremely low flow immediately preceding the cessation of stream flow, the movement of water was so slow that direct radiation and high air temperatures caused it to become very warm, as it did during the May study period.

When they occurred the contributions of snowmelt tended to override all other influences and to dominate the temperature of the stream water. The supply of water occurred not only in relatively large volumes, thus reducing the effectiveness of the air temperatures as explained above, but also at a low temperature, 0°C. The air temperature was above freezing point as it was instrumental in causing the snow to melt (see Chapter 6), but the stream water temperature did not reflect this change. Furthermore the volume of discharge was sufficiently large to obscure any heating effects derived from groundwater.

### III The variations in the relationship between air and water temperature with distance from the stream source

In Section II it was established that the temperature of the stream water changes with distance from the stream source, and therefore the relationship between air temperature and stream water temperature at the weir site was not likely to be valid for all sites on the stream course. From the studies of water temperature changes along the stream course it was clear that the volume of discharge was an important factor modifying the influence of other factors such as the groundwater contribution, direct solar radiation, the time of travel of water in the stream course and, more particularly, the air temperature.

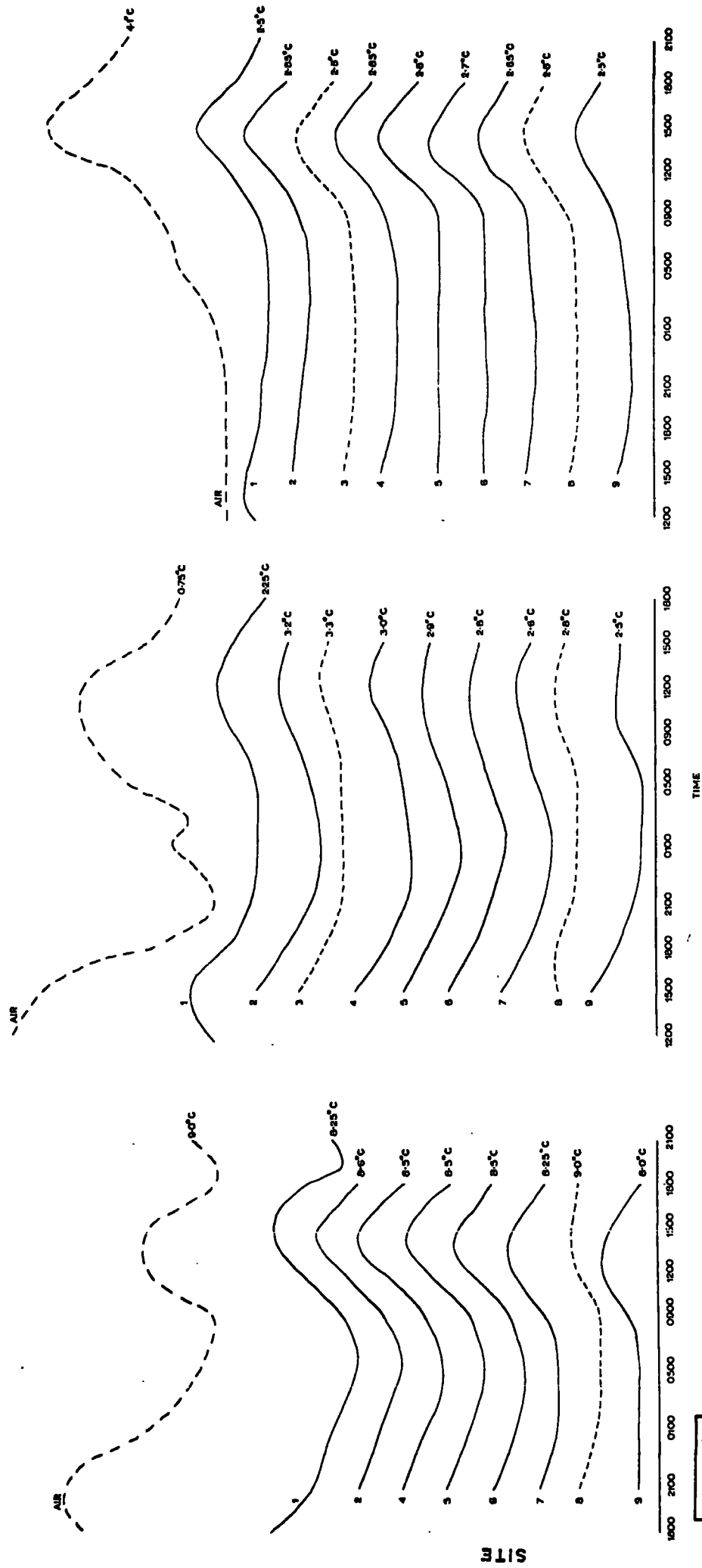
Using the data obtained from the monthly 24-hour study periods the variations in stream water temperature at each site down the stream have been compared with the prevailing air temperature conditions.

The procedure for obtaining these data has been described above, and again it is important to emphasise that, although data was collected for one 24-hour period in each month in order to give a spread of information throughout the year, these data cannot be regarded as "typical" for that month. In figure 60 the temperature sequences taken during the 24-hour periods have been presented to show water temperature changes at each site, together with the air temperature trace for the same period. The site to which the graph refers is noted on the left-hand axis and the horizontal axis represents time. The temperature reading on the right-hand axis is given as a reference figure, and is the value of the last

23/26 OCTOBER 1969

22/23 NOVEMBER 1969

24/25 JANUARY 1970



SCALE - 1°C  
 1°C

FIG 60 WATER TEMPERATURE CHANGES AT SITES ALONG TRIBUTARY B (I)

15/70 APRIL 1970

21/22 MARCH 1970

21/22 FEBRUARY 1970

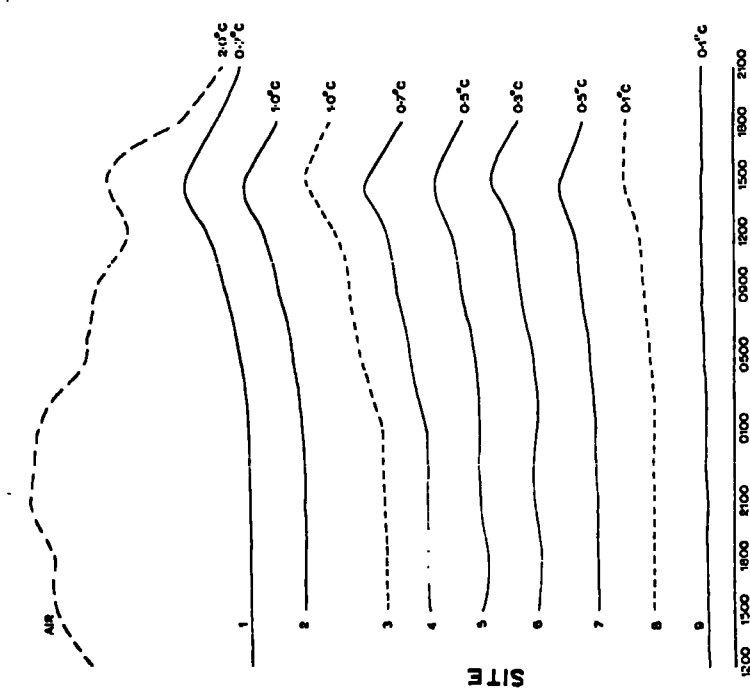
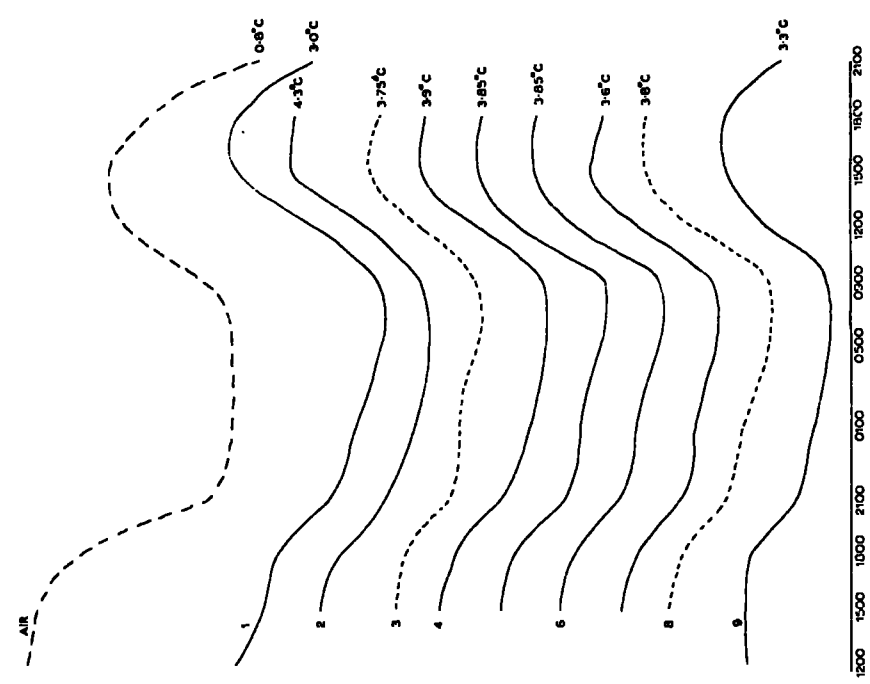
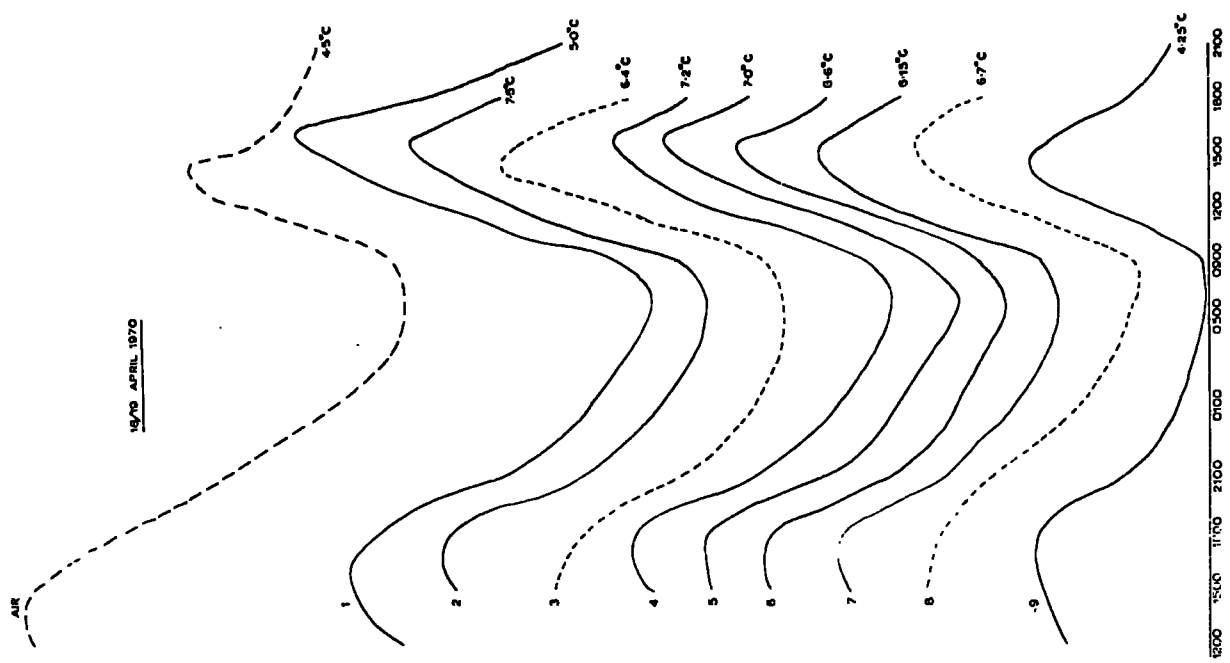
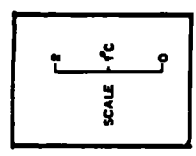


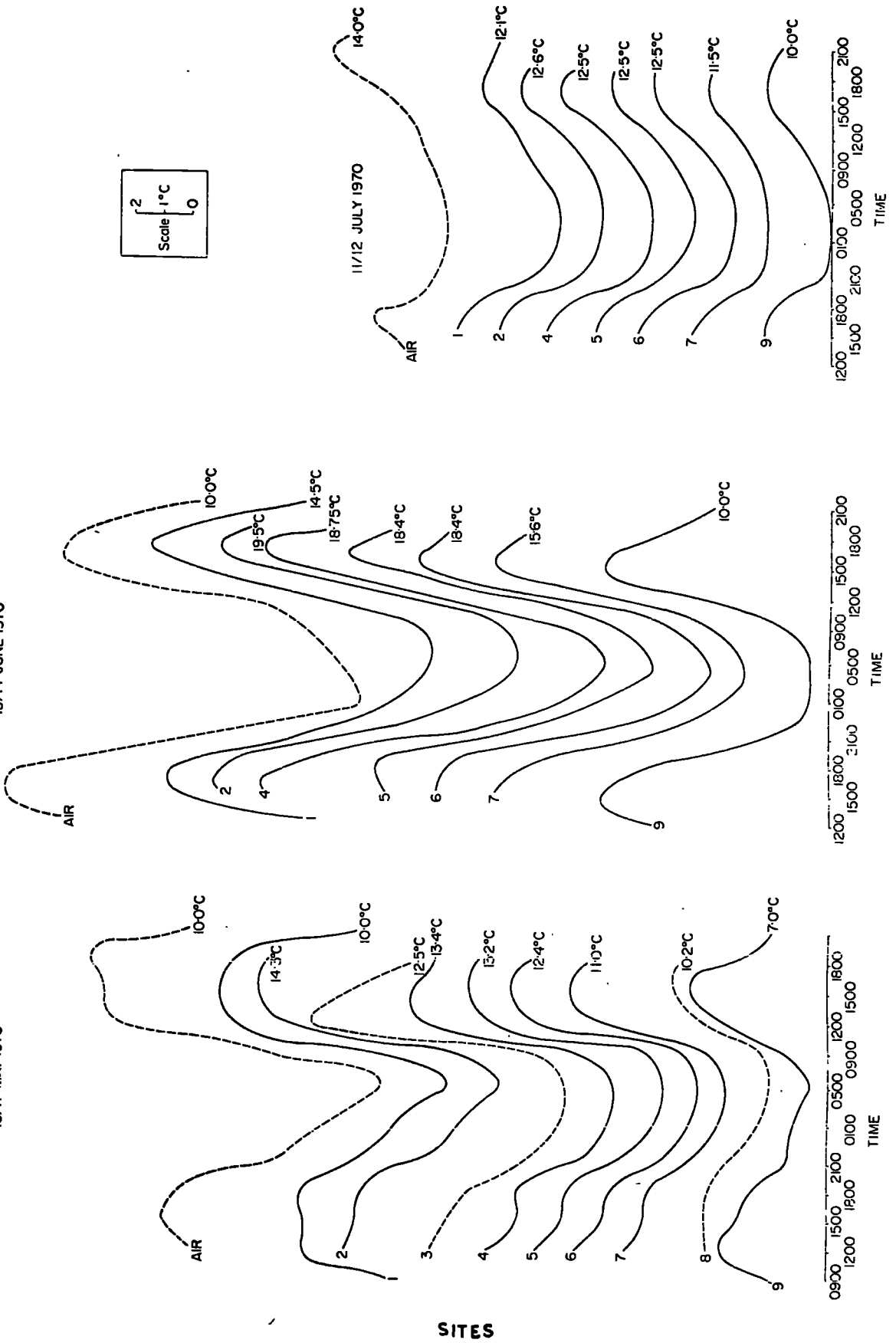
FIG 60 WATER TEMPERATURE CHANGES AT SITES ALONG TRIBUTARY B (II)

FIG 60

WATER TEMPERATURE CHANGES AT SITES ALONG TRIBUTARY B (III)

16/17 MAY 1970

13/14 JUNE 1970

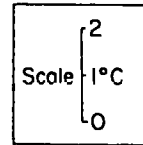
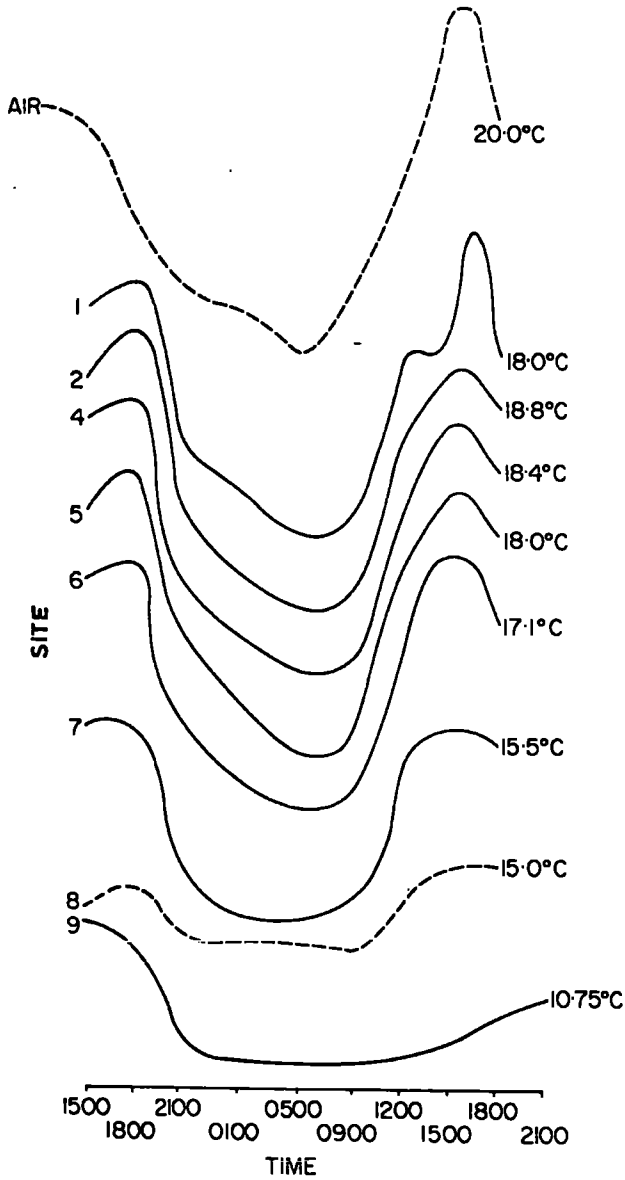


SITES

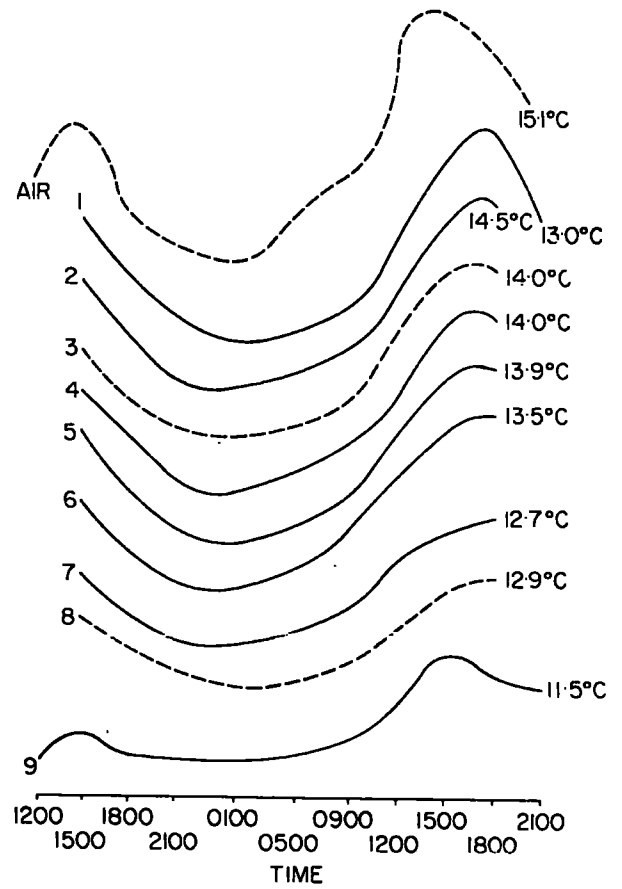
FIG 60

# WATER TEMPERATURE CHANGES AT SITES ALONG TRIBUTARY B (IV)

1/2 AUGUST 1970



19/20 SEPTEMBER 1970



reading in that graph. From this, with the temperature scale given, it is possible to evaluate the extent and nature of the changes in temperature for each graph.

Each study period has been described in detail in section II above and, therefore, this need not be repeated here. From section I it is clear that although air temperature cannot be regarded as the only control over the stream water temperature, it could be regarded as an indication of a number of factors influencing the atmospheric environment, particularly solar radiation, which were affecting the water temperature. One major control over the effectiveness of the atmospheric environment was clearly the volume of discharge, and as has been shown in section II, the effectiveness of this control varied with distance down the stream, not least perhaps because the volume itself varied with distance from source.

During the February study period (21st/22nd February 1970) the volume of discharge was very large, an average flow of 15 cusecs and never less than 5 cusecs for the whole of the study period (rising from 7 cusecs at 1200 BST to 40 cusecs at 2300 BST on 21st February, and falling to 6.0 cusecs at the end of the study period). Not only was the volume of discharge large, but being melt water, the temperature of the water supplied was at 0°C. The stream water became progressively warmer downstream at all stages of the day since the water was under the influence of the atmospheric environment for progressively longer periods when it reached the lower sites on the stream. When the discharge volume became less after

2300 BST, the influence of 'air temperature' became greater despite the fact that the actual air temperatures were less; the stream water began to warm, reaching its maximum temperature at all sites at 1600 BST. The range in temperature at each site became slightly greater downstream, from  $0.6^{\circ}\text{C}$  at sites 7 and 8 to  $1.2^{\circ}\text{C}$  at the weir.

On 24th/25th January 1970, the discharge volume was 2.2 cusecs. The stream water at all sites clearly reflected the diurnal pattern of air temperature, the range in water temperature becoming slightly <sup>greater</sup> downstream from  $1.2^{\circ}\text{C}$  at site 8, to  $1.7^{\circ}\text{C}$  at the weir. Maximum temperature for water and air occurred at 1500 BST. The two tributary streams also reflected the diurnal pattern of the stream elsewhere, and the air temperature. Air temperature was never lower than the water temperature at the source, but it heated more rapidly than the stream water reaching a maximum of  $6^{\circ}\text{C}$  at 1500 BST compared with a water temperature maximum of  $4^{\circ}\text{C}$ .

During the March (21st/22nd March 1970) and the April (18th/19th April 1970) study periods the volume of discharge was 0.8 cusecs. The average air temperature for the March period was  $3.2^{\circ}\text{C}$  colder than for the January ( $4^{\circ}\text{C}$ ) and February ( $4^{\circ}\text{C}$ ) periods, and considerably colder than April ( $6.5^{\circ}\text{C}$ ). Despite this the range of water temperature was large. At the source of the stream the range was  $1.8^{\circ}\text{C}$  and at the weir site it was slightly greater at  $2.6^{\circ}\text{C}$ , compared with an air temperature range of  $3.2^{\circ}\text{C}$ . There was a gradual increase in the actual water temperatures and the diurnal fluctuation of water temperature

with distance downstream and clearly the traces reflected the increasing influence of air temperature downstream. During the April period, due to the greater fluctuations of air temperature (range  $7^{\circ}\text{C}$ ), the water temperature fluctuations were greater than those observed during the March period. The range at the source of the stream was  $3.9^{\circ}\text{C}$  compared with  $6^{\circ}\text{C}$  at the weir site and accompanied by a progressive increase in the range of temperature variation with distance downstream.

During the October study period the discharge of 0.75 cusecs was very similar in volume to that during the March and April periods. The stream water temperature and the range of temperature change both became greater downstream. However the extent of these increases were not so marked downstream from site 5. The most rapid changes, and the greatest fluctuations in temperature, occurred in the upper reaches of the stream. The timing of the maximum water temperature at each site became progressively later with distance downstream varying from 1200 BST at site 9 to 1600 BST at the weir. The peak air temperature occurred at 1500 BST although air temperature was still warmer than the stream water at the weir when the water reached its peak at 1600 BST.

During periods of low flow such as on 13th/14th June 1970 and 11th/12th July 1970 (both 0.06 cusecs) the diurnal pattern of the water temperature change was very similar at all sites. In both periods the temperature range at site 7 was very similar to that at the weir site. During the July period the range at site 7 was  $10.2^{\circ}\text{C}$  compared with  $10.2^{\circ}\text{C}$ ,  $10.2^{\circ}\text{C}$  and  $9.2^{\circ}\text{C}$  at sites 5, 2 and 1

respectively. The range of the air temperature was 11.5 which was less than the range that occurred in the water temperature at site 4. (12.1°C). The timing of the maximum temperature became progressively later downstream from 1500 BST at the source to 1800 BST at the weir; the air temperature reached its maximum at 1800 BST. The diurnal pattern was essentially similar for the July period, although the range and the maximum temperatures were not so great due to overcast conditions. The diurnal pattern at site 6, with a range of 3.4°C, was similar to that at the lower sites (site 5, 3.3°C, site 4, 3.6°C, site 2, 3.5°C and weir site, 3.6°C). The maximum temperature did not become later downstream but occurred at all sites at 1700 BST. Air temperature did not reach its maximum until 2000 BST.

On 16th/17th May 1970 the diurnal patterns were very similar from site 5 downstream, with a range of temperature of 7.0°C. The time of the maximum and minimum temperatures was similar in all profiles, being 0600 BST and 1700 BST respectively. The August period demonstrated the effect of a spell<sup>of</sup>/high air temperature. The flow during this period was 0.9 cusecs. Water temperatures responded very closely to air temperatures, particularly at the sites farther downstream. Stream water temperature increased by 5°C between the source and the weir site throughout the whole period, and nearly all sites had a diurnal range of temperature of 4.5 - 5°C. (The only exception being site 7 where the range was only 4°C). The time of the maximum water temperature became progressively later downstream, from 1500 BST at site 6 to 1700 BST at the

weir site. Air temperature reached its peak, 22.5°C at 1600 BST.

From the case studies described above it is clear that the pattern of the water temperature trace becomes closer to that of the air with distance from the source of the stream.

The studies made in each month covered such a wide variety of environmental conditions that it was not valuable to make a direct comparison between the traces. However, since air temperature could be regarded as a useful integration of the thermal atmospheric environment, the pattern of the water temperature trace at each site down the stream has been compared with the pattern of the air temperature trace. This enabled the pattern of the water temperature trace at various sites along the stream to be compared. Furthermore, it was possible for the changes which occurred along the stream course during one study period to be compared with those which occurred on other occasions, since it was a comparison of the ability of the stream water to establish equilibrium with the air temperature conditions.

To refer to the pattern of the temperature trace is in essence to refer to the average temperature and to the amplitude or range of the trace although clearly the time of occurrence of the maximum and minimum temperatures is also important.

In figures 61 and 62 the average and range of water temperature at various sites down the stream have been related to the air temperature. Each graph in each set represents the situation at a specific site on stream B.

FIG 61 THE RELATIONSHIP BETWEEN AVERAGE WATER TEMPERATURE AT SITES 2,4,5 and 7 ON  
 STREAM B AND AVERAGE AIR TEMPERATURE WITH DISCHARGE

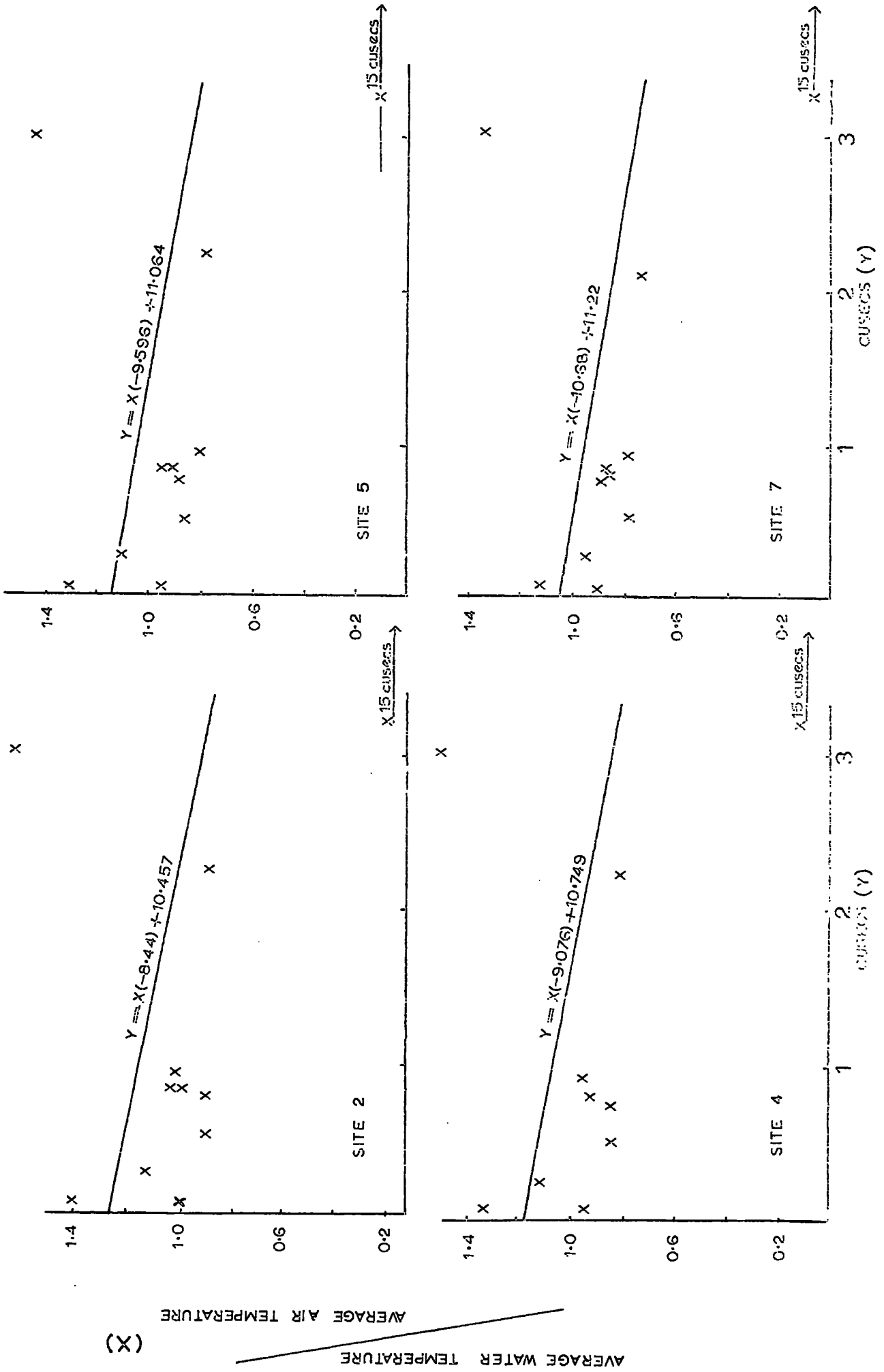
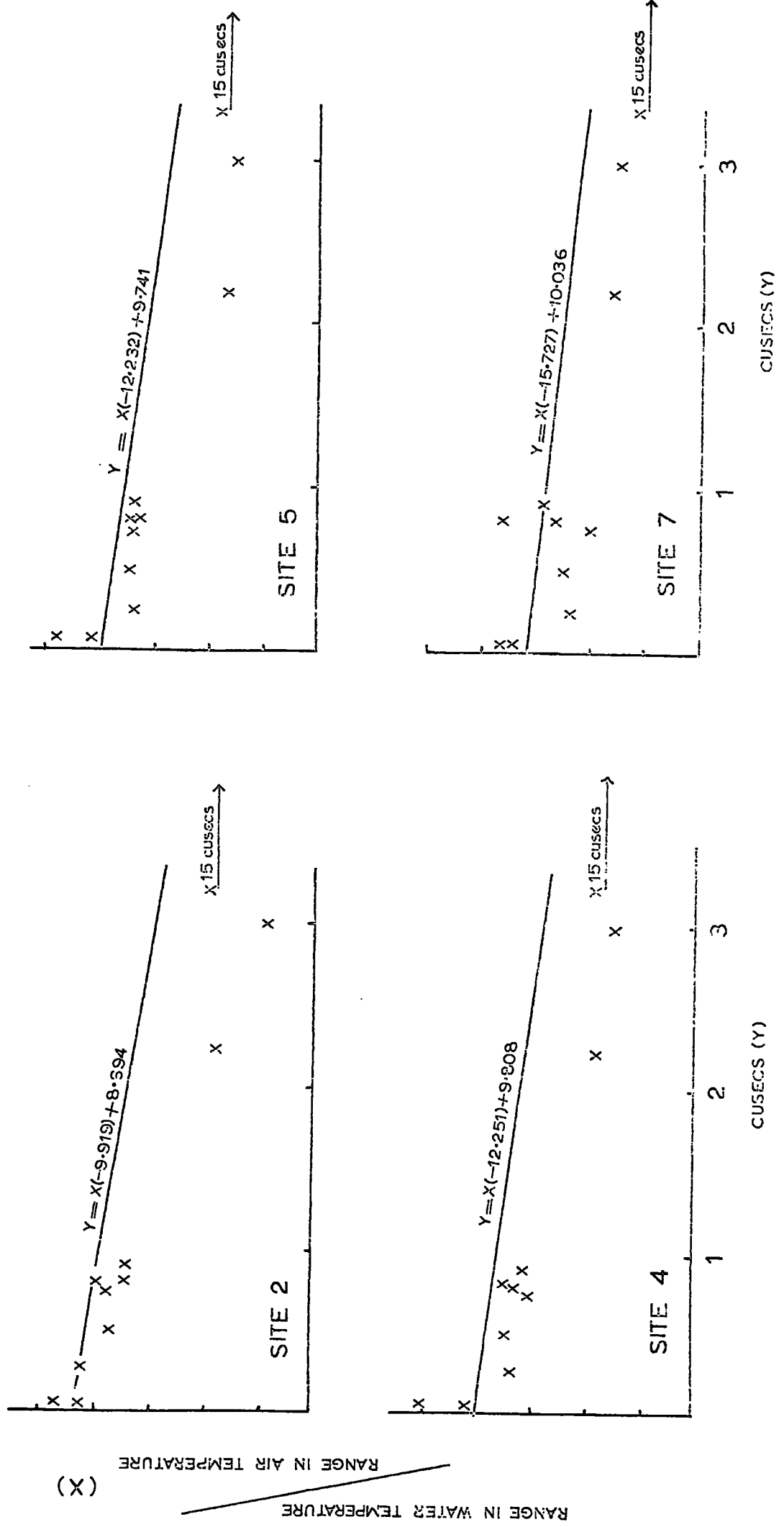


FIG 62 THE RELATIONSHIP BETWEEN THE RANGE IN WATER TEMPERATURE AT SITES 2,4,5 and 7 ON  
 STREAM B AND RANGE IN AIR TEMPERATURE WITH DISCHARGE



In figure 61 the mean water temperature is expressed as a fraction of the mean air temperature for each study period. In figure 62 the range of water temperature is expressed as a fraction of the range of air temperature during the study period. In both sets of graphs the horizontal axis represents the volume of discharge.

Studies have been made of the temperature change occurring at sites 7, 5, 4 and 2 because these gave an even spread of samples downstream. Site 9 was avoided because the source water temperature would be completely unrelated to the air temperature conditions,,and the weir site (no.1) was avoided because during the very low flows of the summer - the June and July study periods - it was affected by the very cold spring water derived from stream A.

In figure 63 the regression lines have been transposed from the graphs in figures 61 and 62 and superimposed upon each other in order to demonstrate the changing relationship between the patterns of air and water temperature traces which occur with distance from the stream source.

From figure 63B it can be seen that for flows of less than 0.6 cusecs the average mean temperature of the stream water was usually in equilibrium with air temperature by the time it reached site 7, while for flows greater than 2.0 cusecs equilibrium was not usually achieved within this length of the stream channel. For flows between 0.6 and 2.0 cusecs, equilibrium between mean air and water temperature was usually reached somewhere between site 7 and site 2.

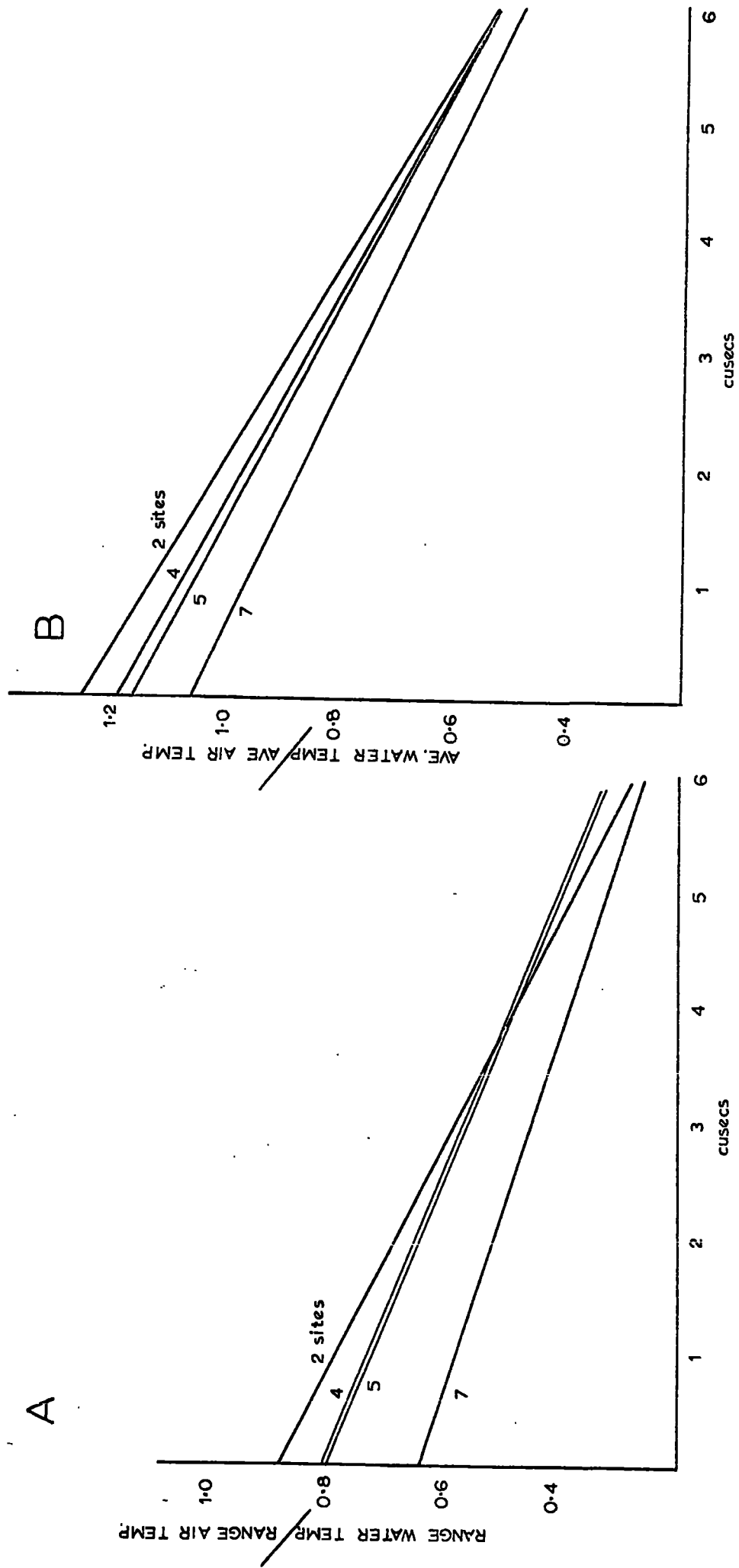


FIG 63 THE RELATIONSHIP BETWEEN AIR AND WATER TEMPERATURE AT SITES 2,4,5 and 7 ON STREAM B WITH DISCHARGE

A similar situation occurred when the range of temperature was analysed. From figure 63A it can be seen that at no point along the stream course studied did the temperature range of the water equal that of the air temperature. Clearly this was a result of the shortness of the length of the stream studied and no doubt had this study been extended further down the valley a point would have been reached where the range of water temperature was in equilibrium with the range of air temperature.

With data of this kind from sites farther downstream it would be possible to construct a scale perpendicular to the regressions lines on figure 63 which would represent distance from the source of the stream, and from this it would be possible to predict the time taken for water temperature to establish equilibrium with the air temperature for various flow conditions. As the volume of discharge increases the length of time required for the water to establish equilibrium with air temperature also increases and the point at which this equilibrium was reached becomes progressively further from the source of the stream.

#### IV The effect of the stream channel in modifying the temperature of the stream water

The influences that the nature of the channel can exert upon the temperature of the stream water have already been demonstrated in the temperature sequences along stream B and particularly in the tributaries connected with that stream. Not only has the presence of a limestone outcrop contributing a supply of ground water had an

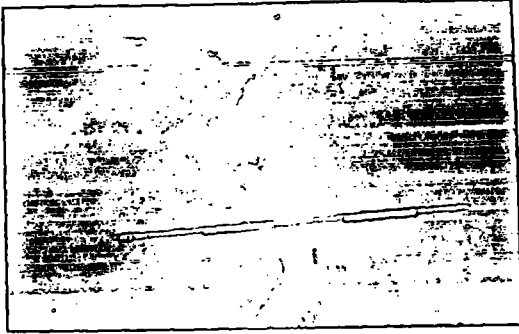
influence upon the temperature of the water, but, in the tributaries, the nature of the channel, whether it was overgrown with reeds or whether it was part of a flush, has had an influence upon the water temperature.

If the effects of channel conditions upon the temperature of the water were minimal, then it could be expected that the two streams comprising the Lanehead catchment would have similar temperature profiles. The two sub-catchments lie adjacent to each other, and therefore it can be assumed that both experience a very similar environment in terms of air temperature, sunshine and rainfall. The physical characteristics of the two streams are, however, far from similar as was described in the introduction. Stream A is much steeper than B, falling 120 m/km., and its channel is cut in, or lined with gravels rather than bedrock. Catchment A is an area of blanket peat supporting calluna vegetation, the drainage is mainly by surface channels and isolated flushes, but with very little groundwater resources. Consequently stream A is more flashy, with a tendency to flow through the river gravels during periods of little rainfall, and even to dry up completely during dry summers. Catchment B is covered with Juncus squarrosus or Juncus effusus grasslands and the water courses are either through flushes or as subsurface channels. The mainstream flows across outcrops of bedrock and did not dry up during the period of study October 1968 - October 1970.

In order to compare the differing responses of the two streams to the atmospheric environment, measurements of temperature had to be taken at various sites along each

stream at approximately the same time. Immediately following the recording of the temperature sequences along stream B at the nine sites described above, a series of temperature measurements were made down stream A at 12 selected sites. The temperature sequence along stream B was begun at 1500 BST and down stream A at 1530 BST (approximately).

The procedure for measuring the temperature along stream A was, as far as possible, similar to that on stream B. The temperature was measured with a NPL certificated mercury-in-glass thermometer, in a flow of moving water within three metres of a fixed sampling site. These temperature sequences were taken, beginning at the weir site, up stream B and then down stream A and finishing, as beginning, at the weir site approximately one hour later. The nature of the sampling sites along stream B has been described earlier.



Site 12.

Another small tributary, draining the peat via a well defined, peat lined channel.



Site 11.

On a small tributary stream at the head of the catchment draining from the peat through a series of sphagnum flushes.



Site 10.

The first point at which there was a recognisable main channel. It was cut in peat, but lined with sandstone stones, and in places the channel ran through flushes as a subsurface stream.



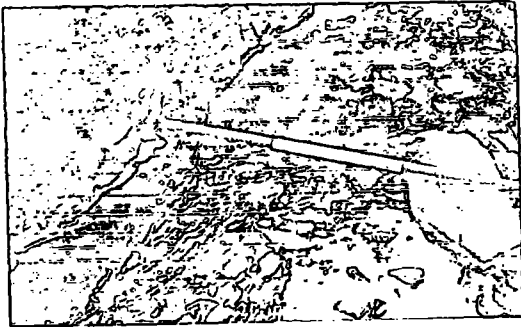
Site 9.

This station was on a second tributary draining the upland plateau of blanket peat in the western part of the catchment. The upper reaches of this tributary were small drainage channels of peat but as at Site 9, the channel was lined with flat stones of sandstone.



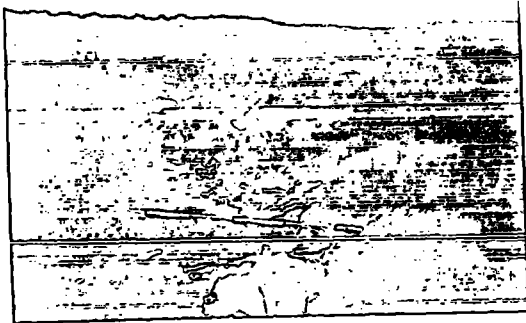
Site 8.

This site was situated where the channel began to fall away from the peat covered plateau at the top of the catchment. The channel was deeply incised, and the bed was composed of a series of falls over small sized boulders.



Site 7.

This channel was deeply incised in very fine marl sand, but the stream itself flowed over the bed-rock of shale.



Site 6.

In the middle reaches of this stream, outcrops of rock caused the channel to be very steep and composed of a series of rock falls connecting pools. The bed was lined with gravels, stones and small boulders. The banks were not clearly defined.



Site 5.

The channel was about 1m. wide, and was composed of a series of small pools although the channel was lined with gravels.



Site 4.

This site was on a small tributary, which was relatively steep, but with shallow banks and the channel was lined with limestone stones. The upper reaches of this tributary drained from the peat cover, and often through flush filled channels.



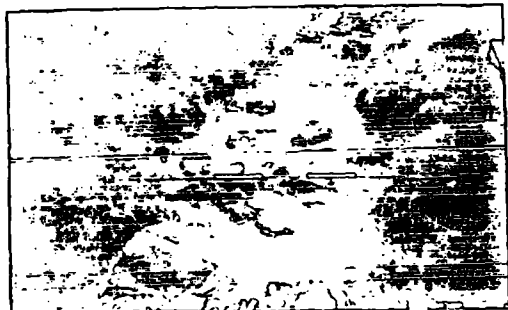
Site 3.

At this site the stream was deeply incised (in places 3 - 4 metres), and the banks and bed were of gravels and small stones. During low flow the stream flowed through these gravels.



Site 2.

The channel was well defined, and about 1 m. wide. The stream was flowing over bed rock, and the channel was lined with stones up to 10 cm. in diameter. The banks were shallow, 10 cm. high.



Site 1.

This site was the same as that used in the Stream B sequence, and therefore it could be used as a datum for the comparison of the temperature sequences in each stream.

In order to see how the sampling sites along the two streams reflected the changes in temperature, two special surveys were conducted on both streams on the 2nd and 9th May 1971. Point measurements of water temperature were taken at 21 sites along both streams, and the resultant temperature profiles compared with that which would have been obtained from the usual sites. From figure 64 it can be seen that although the more intensive study reflected much more closely the minor changes in temperature, the profile obtained from the usual sites did show the major trends in water temperature change along the stream.

The water temperature profile in stream B was very closely related to the geology since the stream temperature reflected the contributions of ground water which came from some of the limestones. This was particularly marked at the base of the Great Limestone, below site 5 where a spring exerted a sudden cooling affect upon the stream water.

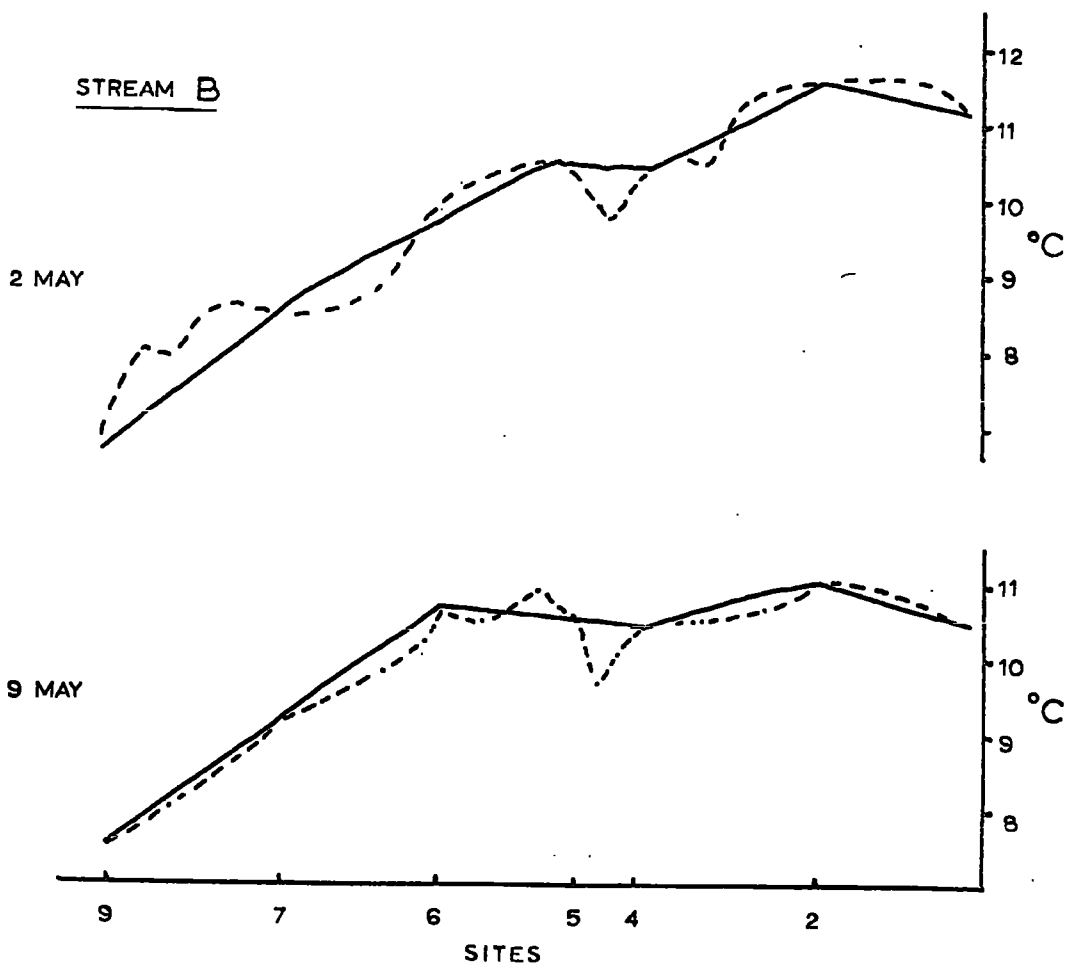
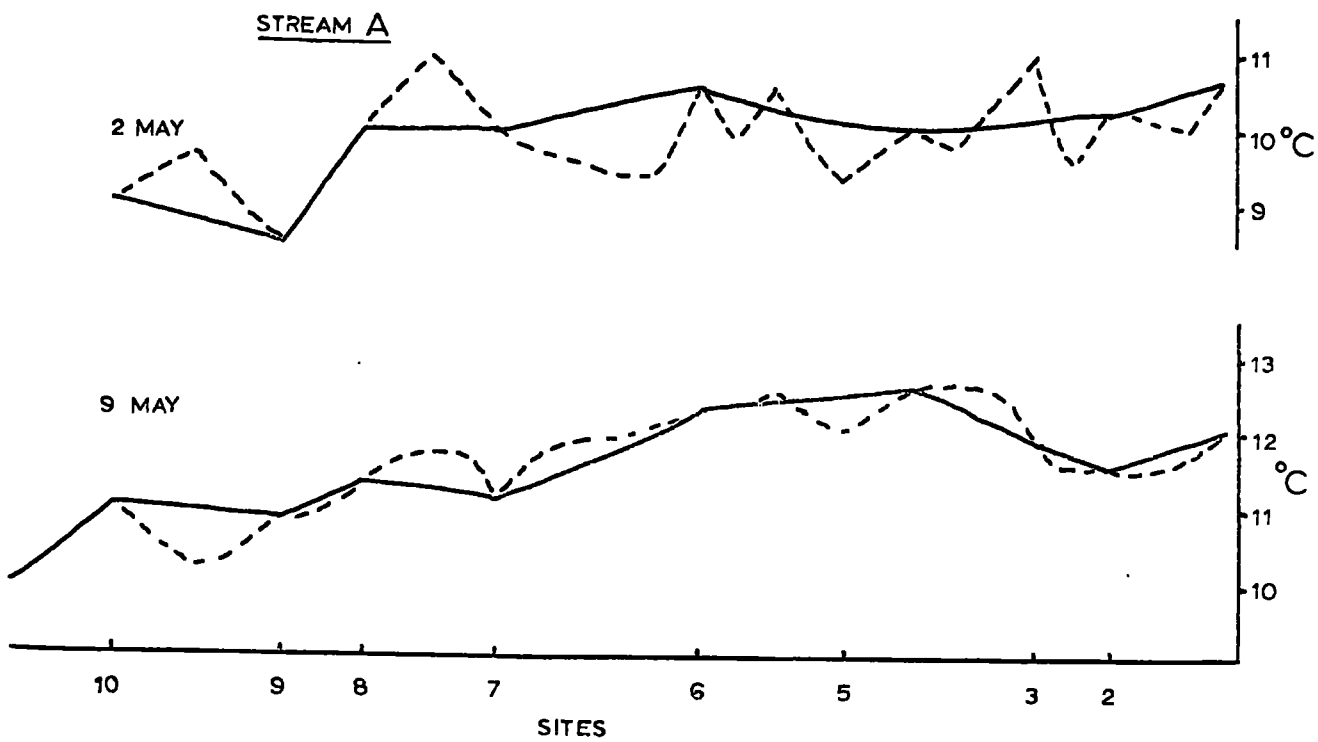
In stream A, it was not the geology but the nature of the stream channel which exerted the dominant influence. Where the gradient of the stream was shallow and covered with gravels the water movement at low flow was through the bed gravels and thus unaffected by air temperature conditions. Consequently there were marked differences in temperature between the short stretches of stream where part of the water was flowing through the gravel and where all the water was flowing over bed rock and therefore exposed to the atmosphere.

During freezing air conditions stream B became colder downstream from source to weir, and the colder the air the

**KEY:**

--- Profiles resulting from 21 site readings

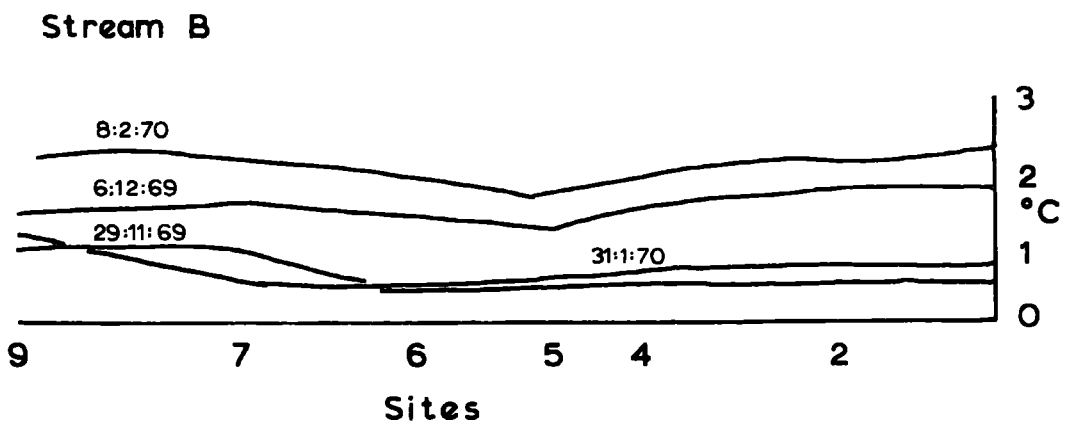
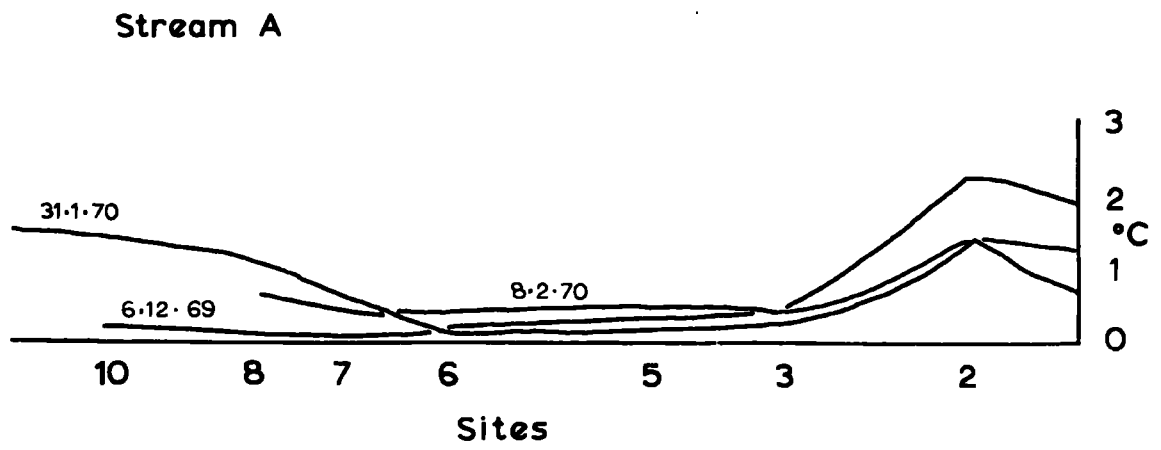
— Profiles based upon readings at the selected sampling sites



**FIG 64 TEMPERATURE SEQUENCES RESULTING FROM 21 POINT MEASUREMENTS**

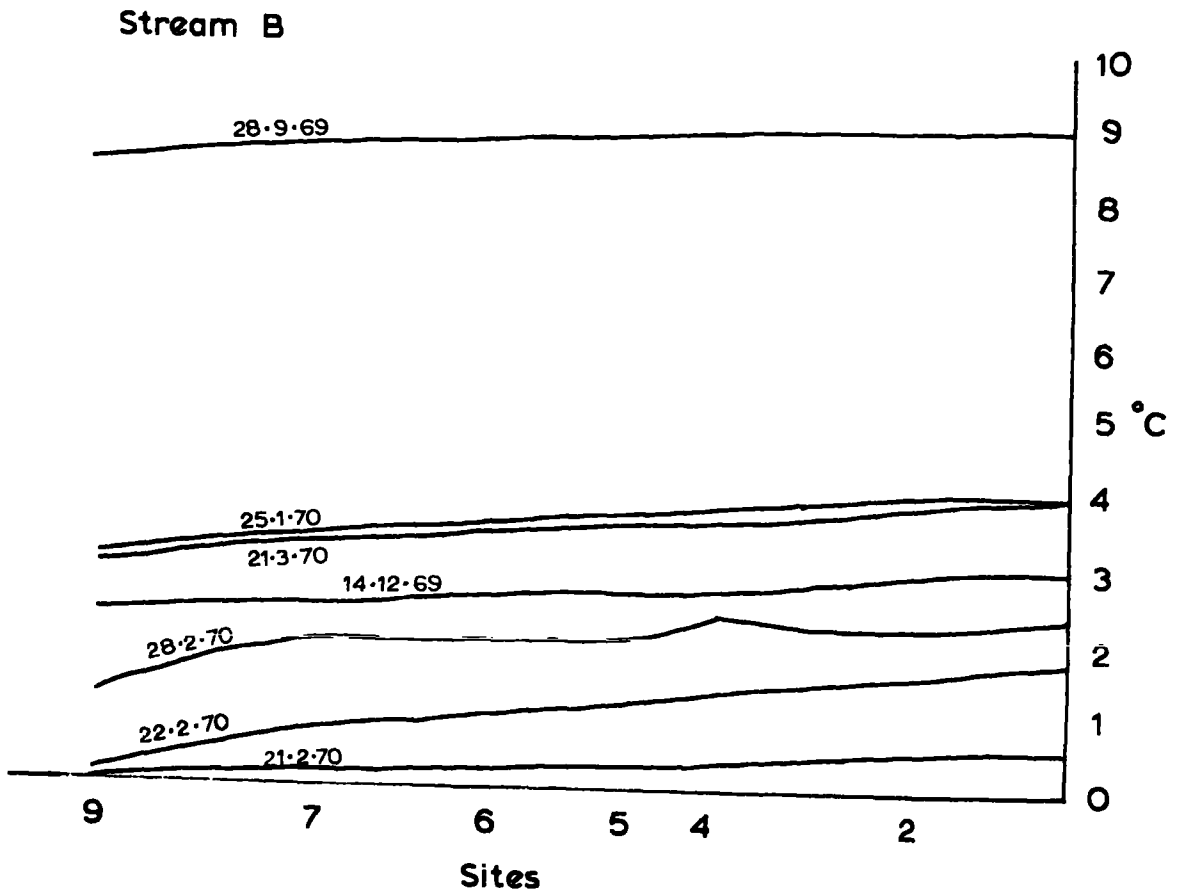
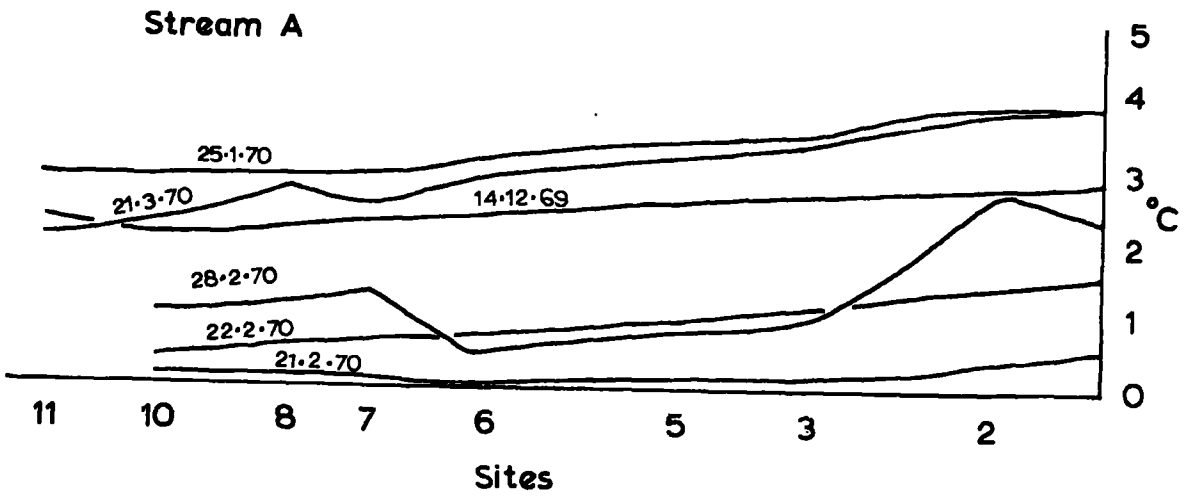
greater the cooling affect it exerted on the stream water as on 29th November 1969 (Fig.65). When the air temperature was just above freezing point, as on 6th December 1969, or 8th February 1970, it was unable to counteract the warming effect of the ground water contribution below site 5, and therefore the water temperature tended to become warmer as the proportion of relatively warm ground water obtained from the various limestone bands became greater. The tributaries at sites 4 and 8, though they were occasionally sub-surface, were supplied from surface runoff. While the tributary at site 8 was approximately the same temperature as stream B, the tributary at site 4 tended to be much cooler than the main stream because it was not being heated by any contribution of groundwater.

The response of stream A to these conditions was very different (Fig.65). The temperature of the stream fell from a relatively warm temperature at the source, to just above freezing point at site 6 at which temperature it remained until it was heated by the contribution of warm groundwater from the spring upstream from site 2. In the upper reaches of the stream, the water was derived from groundwater sources, and it was as a result of its passage in a surface channel, in contact with the air, that the cooling of the water took place. Between sites 6 and 2, the water fell over a number of small waterfalls, maximising the influence of the air. The spring above site 2, the largest single source of groundwater in catchment A, caused a warming effect upon the stream, and therefore it became locally very warm. At the weir site, below the confluence with the colder stream B, the temperature was reduced.



**FIG:65 STREAM TEMPERATURE PROFILES DURING**  
**FREEZING AIR CONDITIONS**

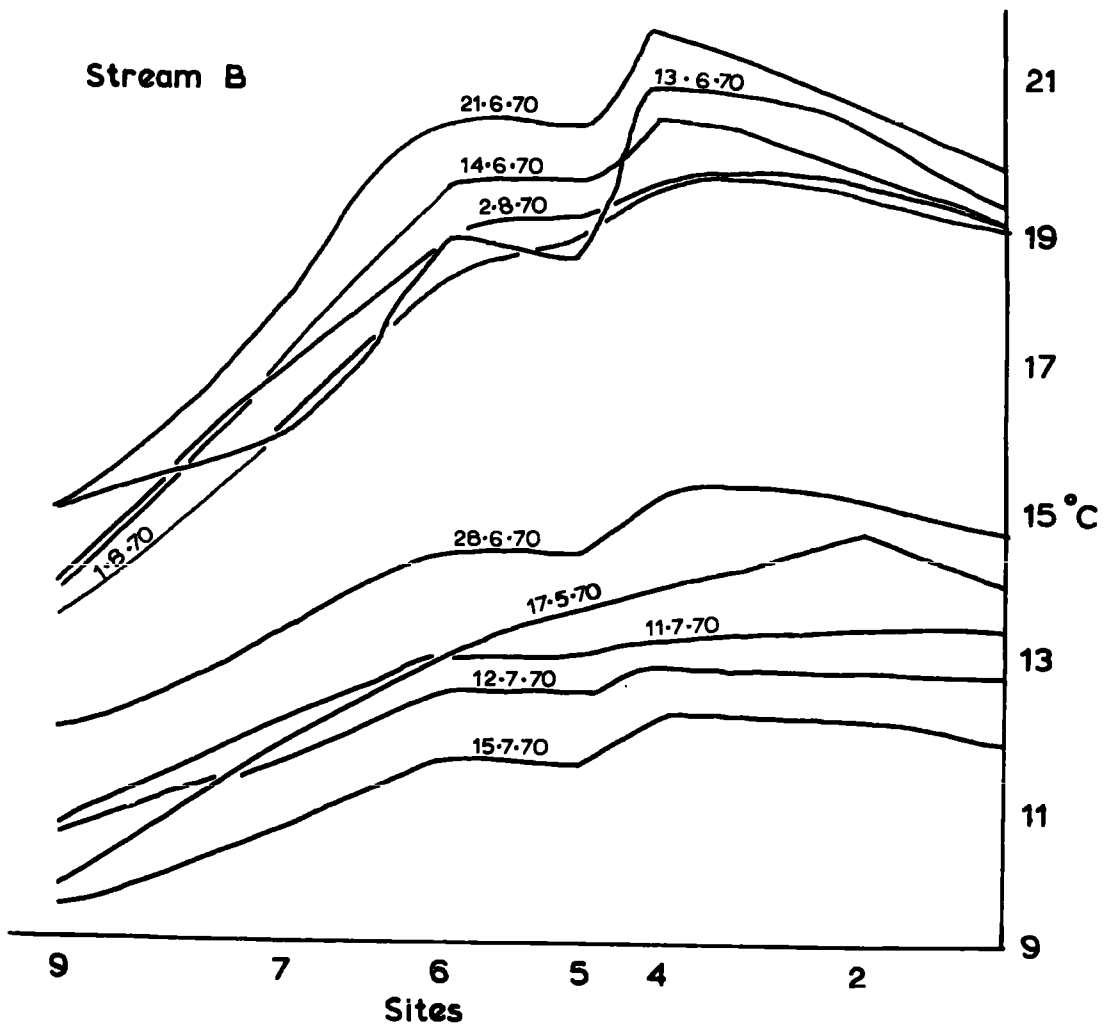
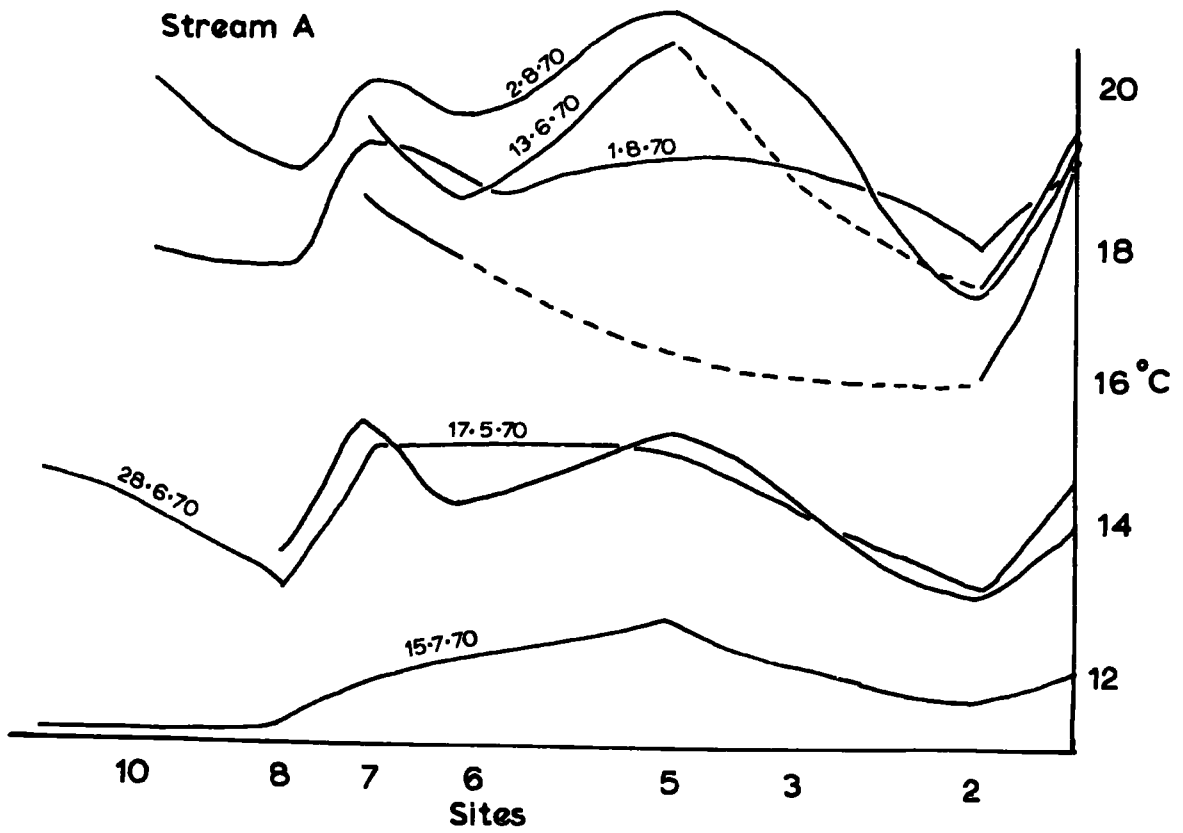
When the temperature was near or below freezing point, it exerted a dominant influence upon stream B, but as the air temperature became warmer its effect was increasingly modified by the volume of water. From figure 66 it can be seen that for periods when the air temperature was about 5 or 6°C with a discharge between 1.5 - 2.0 cusecs, as on 25th January 1970 and 21st March 1970, the stream water warmed by about 0.5°C to air temperature at the weir site. Thus it can be seen that the water was in equilibrium with air temperature as the air temperature at the source of the stream would have been 0.5 - 1°C, colder than it was at the weir due to the lapse rate with altitude. As the volume of discharge became greater, to 7.0 cusecs on 22nd February 1970, 7.5 cusecs on 14th December 1969 and to 14 cusecs on 21st February 1970, the effect of the air temperature was reduced. On 14th December, the water was only 3°C while the air temperature was 4.0°C; on 22nd February 1970, despite the fact that the stream water was being warmed quite rapidly at a rate of 1°C/500 metres, it was still 2.5°C colder than the air at the weir site. The groundwater at site 5, though small in volume compared with the stream discharge, did, nevertheless, cause a marked increase in stream water temperature. On 21st February 1970, the water temperature quickly established equilibrium with the air temperature between sites 9 and 7. Due to the small volume of water, the groundwater contribution just below site 5 caused a small rise in water temperature which was reflected at site 4, but this effect was obliterated by site 2, when the water was again in equilibrium with the air temperature.



**FIG 66** WATER TEMPERATURE PROFILES

During these conditions, stream A responded consistently to the changes in air temperature and discharge conditions. During the low flow on the 28th February 1970, the stream water temperature reflected the conditions of the stream channel. Between sites 7 and 6 the stream flowed through a channel lined with bed gravels, and thus the water assumed the temperature of the soil which, at that time of the year would be near freezing point. Above site 2, the contributions of groundwater caused a marked heating effect upon the stream water. As the volume of water increased, these influences became less significant. The sequence measured on 21st March 1970, 25th January 1970, 22nd February 1970, 14th December 1969 and 21st February 1970 all indicated a gradual rise of temperature downstream, ranging between  $0.17^{\circ}\text{C}/100\text{ m.}$  for a discharge of 0.4 cusecs to  $0.06^{\circ}\text{C}/100\text{ m.}$  at 14 cusecs. On no occasion during these sequences did the water temperature become warmer than the air.

During periods of warm air temperature and low flow in the summer, the stream channel exerted a very strong modifying influence upon the control that the air temperature and direct radiation had upon the temperature of the water (Fig.67). In stream B the source water was much colder than the air temperatures since it was derived from subsurface sources and flushes where, though relatively stagnant, it was insulated from the air and direct sunshine by the vegetation growing above it. It had reached its maximum temperature by site 4, after which it began to cool, due partly to another supply of groundwater from the Four Fathom Limestone outcrop at site 2,



**FIG 67 STREAM TEMPERATURE PROFILES DURING  
LOW FLOW CONDITIONS**

and partly to stream A being fed almost entirely from a groundwater spring 50 m. above its confluence with stream B.

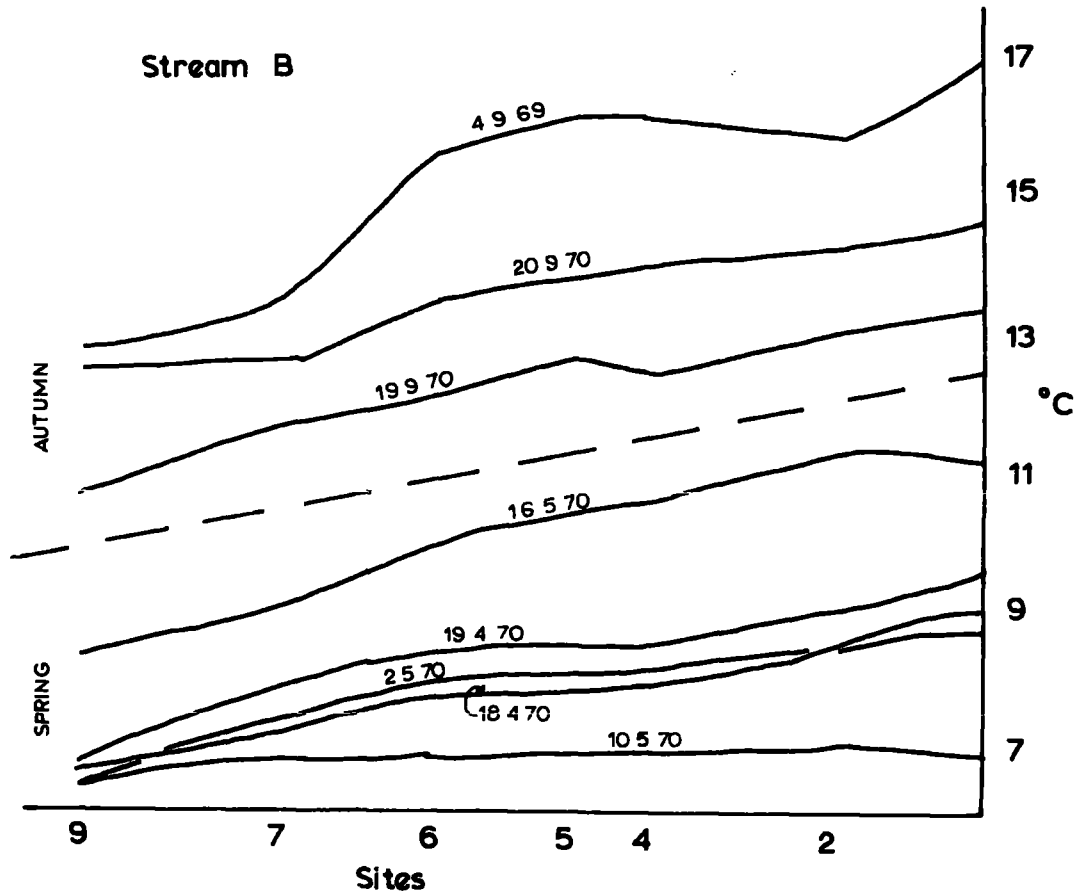
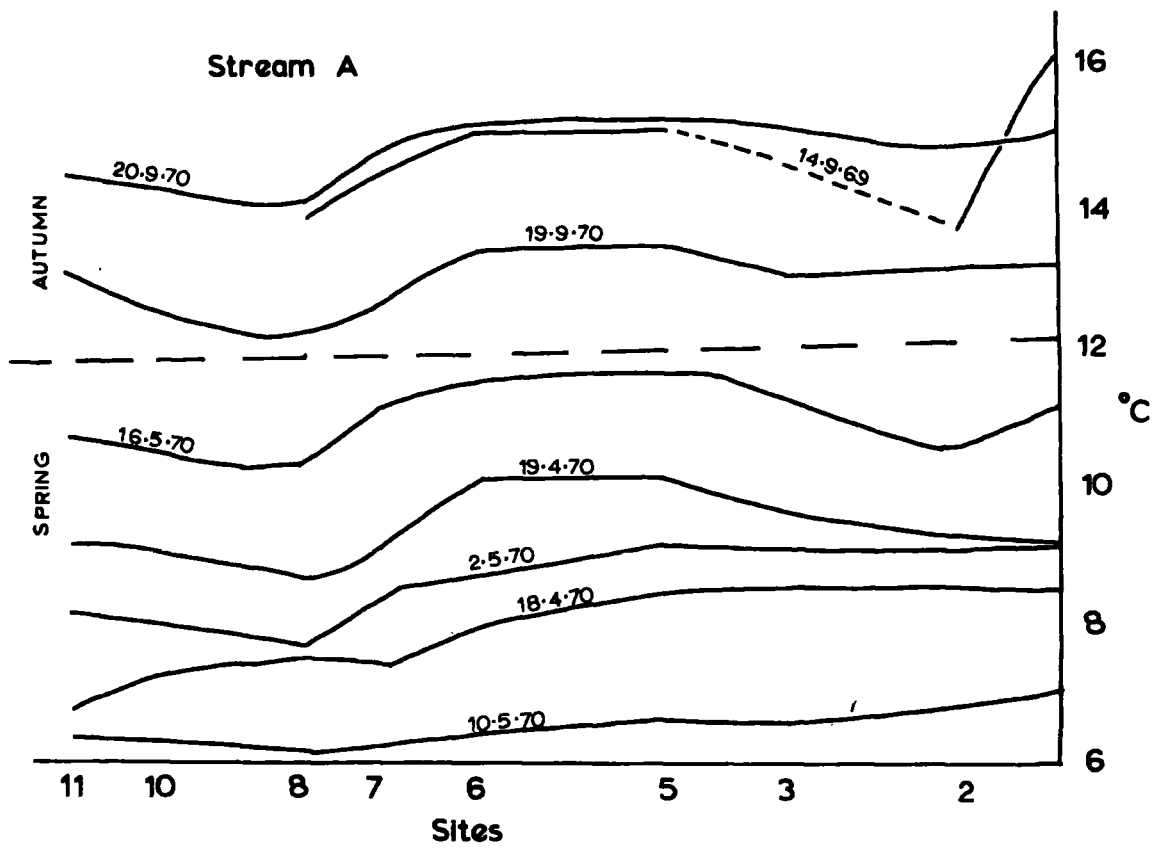
The rate at which the water warmed in its movement downstream depended upon the air temperature and the volume of water. When the volume of water was low, as on 11th and 12th July 1970, and on 13th 14th and 28th June 1970, the effect of the groundwater contributions from the Great Limestone at site 5 was completely to nullify the heating effect upon the stream water. The greater the air temperature, and therefore the greater the heating effect upon the stream, the more marked was the influence of the groundwater. Similarly, the smaller the volume of discharge the greater the modifying effect of the groundwater contribution since it became a greater proportion of the stream volume. This was not clearly demonstrated during the very low flow conditions of 11th and 12th July 1970 because, by the time the groundwater contribution had become significantly large at site 5, the stream water was already warmer than the air. (It is probable that a more intensive study of the stream water temperature between sites 4 and 5 for those two days would have revealed a very marked fall in stream temperature at the base of the Great Limestone and a gradual recovery of the temperature before it reached site 4). On the other hand, when the volume of discharge became slightly greater than 0.05 cusecs, as on 1st and 2nd August 1970, although there was a distinct cooling effect caused by the groundwater, its volume in relation to the total stream flow was not sufficient to prevent the stream temperature from becoming warmer.

Stream A, unlike stream B was not a permanent stream, and the upper reaches tended to dry up during the summer, and therefore fewer temperature sequences are available for this period. The flow at the source of stream A was not confined to a main channel, and there was a gradual cooling of the water temperature as the volume of water derived from the sub-surface channels increased at the expense of the water derived from the near stagnant surface channels in the peat.

From site 8, the stream was confined to one main channel. It flowed across bedrock, or over a thin layer of bed gravels, and was exposed to air and direct radiation and consequently became locally heated. Site 6 was on the outcrop of the Little Limestone, and the local supply of groundwater from this strata cooled the temperature of the stream water. Surprisingly, the cooling effect from this limestone did not become more significant as the flow of the stream became less, probably because it was not a large reservoir of water like the Great Limestone. Indeed, it had no significant effect upon the temperature of stream B, and probably contributed only a small amount of groundwater for a short period after rainfall. Between sites 6 and 5 the stream gradient was 1 : 6.5 and included a number of small waterfalls. The water temperature was affected by its contact with air and the direct radiation it received and thus by site 5 the water temperature had become warmer, at the rate of  $1^{\circ}\text{C}/100\text{ m}$ . Downstream from site 5 to site 2, the water temperature fell as a result of the supply of

groundwater from the various strata of the Great Limestone. The largest single source of groundwater was from the base of the Great Limestone just upstream of site 2. During the low flow conditions on 11th and 12th July 1970, this was the only source of water in stream A and at this site the temperature was  $9^{\circ}\text{C}$ ,  $3^{\circ}\text{C}$  colder than the water at the weir, 150 m. downstream. Furthermore, between sites 5 and 2, the stream channel contained a great deal of gravel material, and during low flows particularly, much of the stream water flowed through, rather than over the gravels and therefore the water was effectively shielded from the influence of the air and more particularly from direct radiation.

The spring and autumn conditions produced characteristic temperature profiles in each stream, which were very different from those produced in the more extreme conditions of summer and winter. During April and May stream B warmed from about  $7^{\circ}\text{C}$  at its source to approximately air temperature at the weir. Normally this involved a heating rate of about  $1^{\circ}\text{C}/500\text{ m}$ . From the profiles in figure 68 it can be seen that the effect of the groundwater contribution at site 4 became less significant as the volume of discharge increased, so much so that on 10th May 1970 when the discharge was 8 cusecs, there was no cooling of the stream water. In stream A, after the initial cooling of the stream water from the source to site 8 due to the increasing proportion of subsurface water draining into the stream, the water warmed to near air temperature in the middle reaches of the stream. On 19th April 1970 the stream water temperature was on average  $3.5^{\circ}\text{C}$  warmer than the air temperature due to the



**FIG 68 STREAM TEMPERATURE PROFILES DURING THE SPRING AND AUTUMN**

heating effects of direct solar radiation. The groundwater from the Great Limestone below site 5 was only effective in cooling the stream water temperature when the discharge was less than 0.75 cusecs, and indeed when, on 10th May 1970, the discharge was 8 cusecs, the temperature of the stream continued to rise during this stretch of channel.

The temperature profiles obtained during the autumn were very similar to those of the spring. The degree to which the stream became warmer with distance from its source, and the effects of groundwater supplied were again conditioned by the air temperature and sunshine, but above all by the volume of discharge. On 4th September 1969, high air temperatures were associated with very low flow conditions. The very rapid rise in water temperature from source to site 5 ( $1^{\circ}\text{C}/100\text{m}$ ) was checked by the supply of colder groundwater just below site 5, and indeed the stream temperature became colder as a result of the further supplies of groundwater at site 2.

On stream A, a completely different situation occurred. Due to the low flow, the upper reaches of the stream were dry. From its temporary source at site 8, the water temperature warmed at a rate of  $1^{\circ}\text{C}/100\text{ m.}$ , but below site 6, much of the stream flow was through the channel gravels giving the appearance of a dried-up course for long stretches. As a result, there were often no readings for site 3. Being shielded from the air and sunshine in this way, the water temperature remained relatively constant. The supply of groundwater from the spring above site 2 exerted locally a dominant influence upon the water temp-

erature.

Figures 65-68 are summarised in figures 69 and 70. For each of the groups of profiles shown for each of the streams in figures 65-68 a representative profile has been constructed using the mean value of the measured profiles. Thus in figures 69 and 70 there is a profile which attempts to represent a typical temperature sequence down the stream under certain environmental conditions. These representative profiles are shown in apposition to a brief description of the nature of the stream channel.

From these representative profiles it is clear that the nature of the channel did exert a modifying influence upon the relationship between the stream water temperature and the atmospheric environment. In stream A the contribution of groundwater at site 2 had a marked effect upon the temperature of the stream water; during cold weather it had a heating effect and during warm weather it had a cooling effect upon the stream water. The same was true to a lesser extent of the Little Limestone. The most effects were exerted by the stream gravels; during low flows these tended to insulate the stream water from the direct effects of air temperature.

In stream B there was very little gravel. Groundwater seaped into the stream channel from the base of both the Great and the Four Fathom Limestones. The most noticeable impact from these contributions occurred during periods<sup>of</sup>/low flow and high air temperature, but it was evident in all profiles as shown in figure 70. During the winter period the effect of the groundwater was to warm the stream water, except when the stream water temp-

FIG 69 TYPICAL TEMPERATURE SEQUENCES ALONG  
STREAM A DURING CERTAIN CONDITIONS

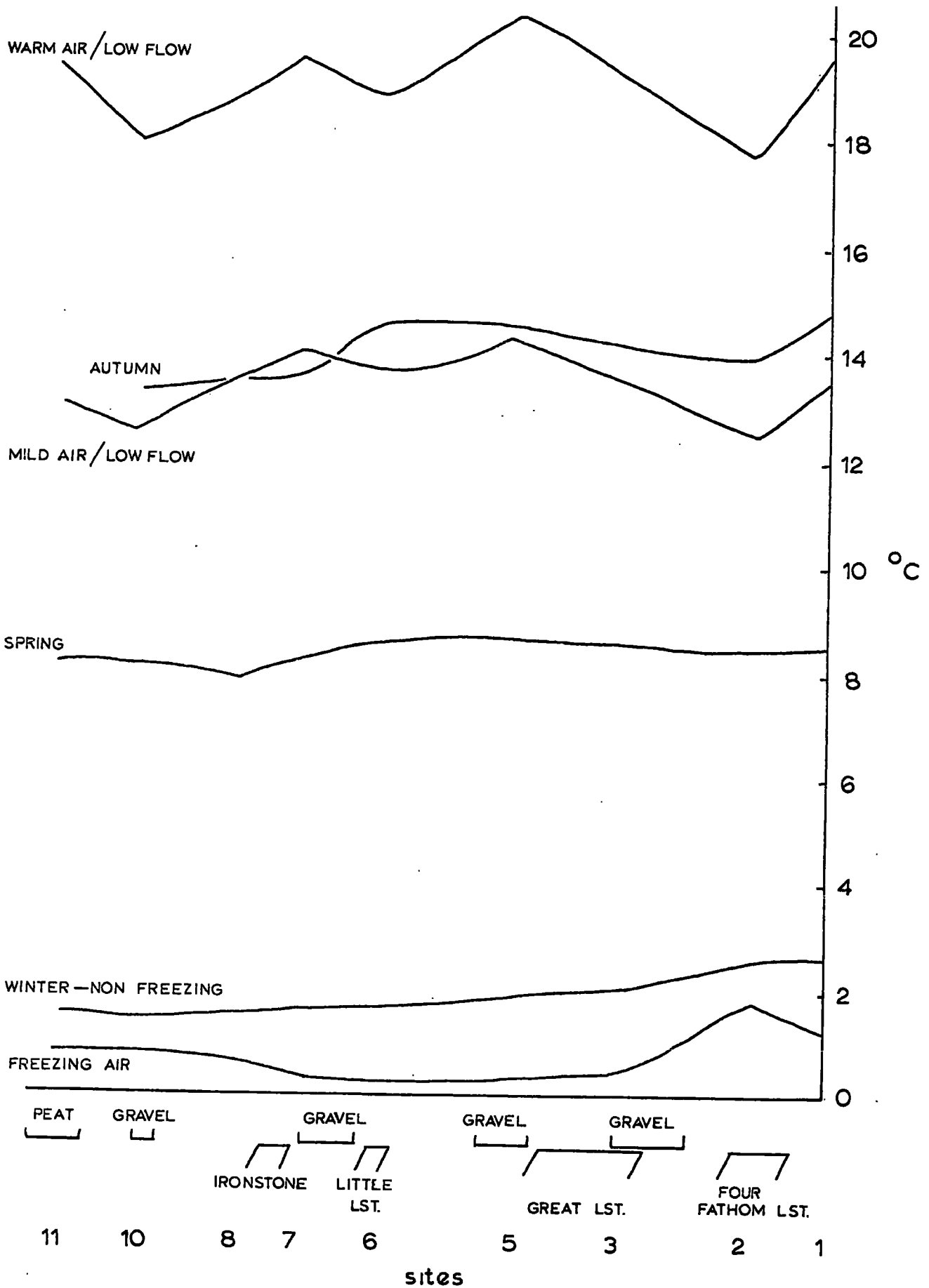
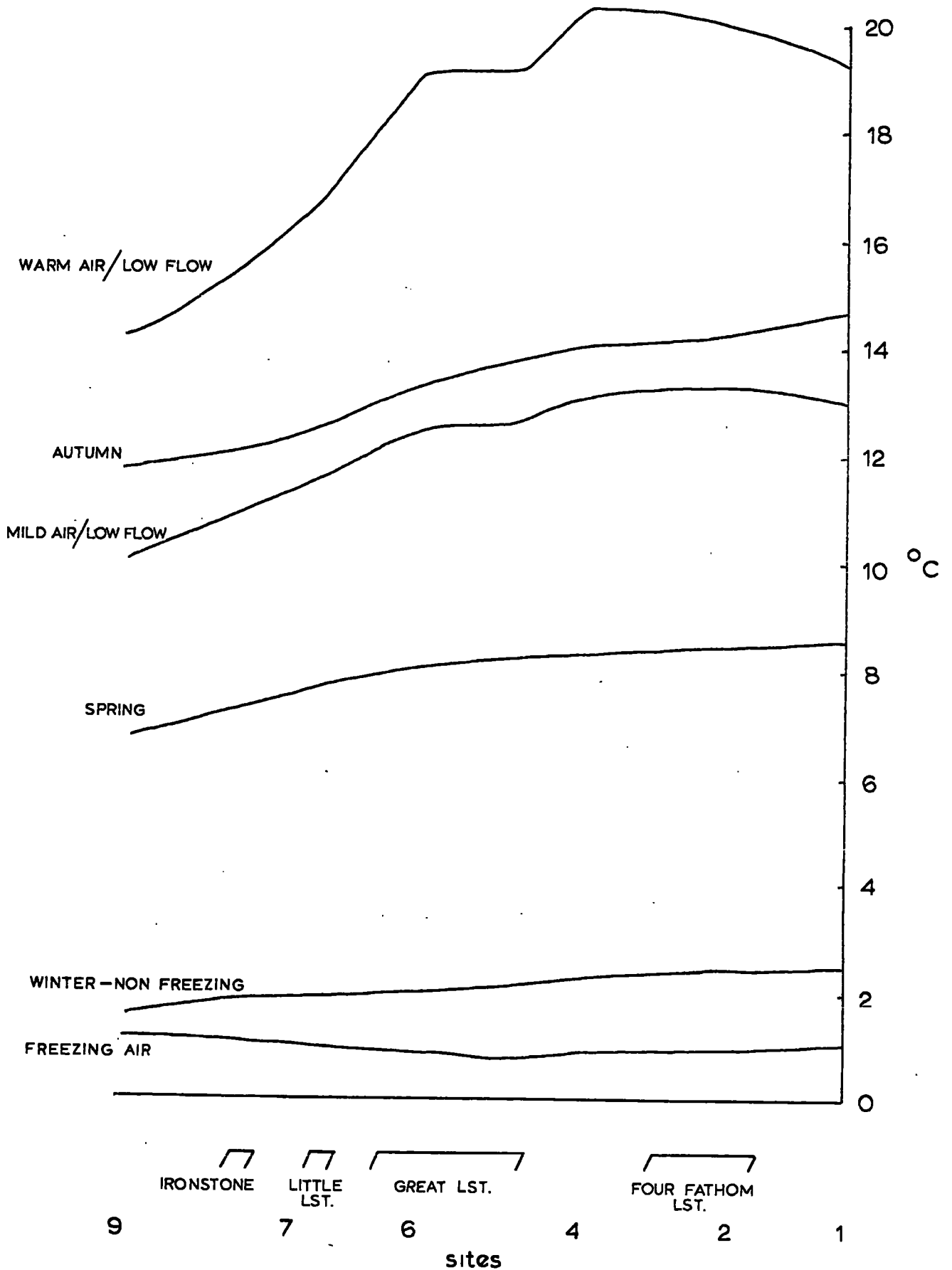


FIG 70 TYPICAL TEMPERATURE SEQUENCES ALONG  
 STREAM B DURING CERTAIN CONDITIONS



erature was warmer than the groundwater ( $7^{\circ}\text{C}$ ). The effect was not always sufficiently large to cause a fall in the temperature of the stream water, but invariably it slowed down the rate at which the temperature of the stream water was rising.

The temperature of the stream water resulted from the action of the air temperature and the direct radiation upon it. The effectiveness of these two factors was controlled by the extent to which they were able to act upon the water. The smaller the volume of discharge, the greater the surface area of the stream in relation to its volume, and since it also moved less quickly through the catchment, the longer the time during which it was subjected to the atmospheric influences. The major controls upon the water temperature were therefore the air temperature, the direct radiation influences and the volume of discharge, but the stream channel also exerted a strong influence in so far as it modified these controls. Groundwater supply changed the temperature of the stream out of relationship with the influences of the atmospheric environment because this source of water, unlike the surface stream, had been completely shielded from any influences of either air temperature or solar radiation. Similarly, where a stream was able, through the nature of its channel, to flow as a subsurface stream or through bed gravels, it was removed from the atmospheric influences and consequently its temperature had little relationship with the atmospheric environment. Conversely, where a stream flowed over a wide bed rock channel which did not contribute groundwater, or over a series of small

waterfalls, the influence of the atmospheric environment was maximised since all the water would be brought into contact with the air and under the influence of any direct radiation.

The two streams in the Lanehead catchment demonstrated these controls. Stream B clearly demonstrated the effects that local supplies of groundwater would have upon the temperature of a stream which otherwise reflected the dominant influence of air temperature and radiation. Stream A had little variation due to groundwater contributions apart from the large spring above site 2, but the nature of the channel itself affected the temperature of the water. Parts of the channel were lined with deep gravels through which much of the water flowed during low flow periods, thus causing a cooling effect upon the water. While in other parts of the channel the water flowed over a series of small waterfalls which had the result of maximising the influence of the air temperature particularly. At the source of stream A, the gradient of the channel was very shallow and the waters remained relatively still and susceptible to heating from solar radiation.

## CONCLUSION

The aims and problems of this research project fell very clearly into two categories; that of obtaining accurate data in a difficult environment and that involving the analysis of results.

The recording of precipitation was a two-fold problem. Firstly a minimum number of sites had to be selected that would give representative measurements for the catchment, and secondly recording equipment that would give an accurate and reliable record for the year, particularly during the winter period, had to be selected and installed. The first problem was solved by setting up a pilot study of rainfall in the catchment over a six month period. From the eight rain gauges installed throughout the catchment, two sites were selected to give the best estimate of the average rainfall in the catchment. The second problem of obtaining an accurate and continuous record of rainfall at these two selected sites was more difficult. At these sites the gauges were protected from over-exposure to wind by being placed at ground level and surrounded by an anti-splash surface. The use of plastic grids for this purpose proved satisfactory once the problem of draining the pits without causing an obstruction to the uniform flow of air over the gauges had been solved. These precautions were very necessary, as was indicated by the greater catch recorded compared with the catch in gauges set in the standard way.

The continuous recorders were not totally reliable under these upland conditions, particularly since the

clock mechanisms, added to give more detailed records, were very vulnerable to changes in humidity and temperature. Despite much attention a complete record was not achieved. In retrospect too much attention was perhaps directed towards obtaining high quality data and, in so doing, continuity was sacrificed to some extent. Thus it might have been better to install only one Dines recorder with an extended chart mechanism, and to maintain the other with a standard weekly clock. Although the standard clock would have given less useful records it would have been more reliable. However, between them the two recorders did give a record for 80% of the rainstorms during the summer period.

The difficulties of maintaining precipitation records in regions with severe winter conditions such as the Northern Pennines have been discussed in Chapters 2 and 5. For more reliable data to be collected it would have been necessary to think in terms of an electricity supply at each recording site to run heaters to protect the recorders from extremes of cold. The use of heaters would not, on the other hand, be a total answer to the problem when studying snow melt since it would be the time and nature of the melt rather than the time of fall that would be important. For this reason also, the winter records of actual precipitation fall were not as vital as those in the summer.

Many of the problems associated with obtaining precipitation data result from errors due to the over exposure of the gauge to wind. In an upland catchment these problems are great and consequently the reliability

of the various types of gauges have been studied by comparison with each other. The Dines recorder gauges were found to be less accurate than the standard gauge, varying quite considerably, but on average recording 15 - 20% less. However these gauges were not required to measure the amount of rain but the time of occurrence and the intensity.

The catch of the ground level gauges was greater than that of the standard installation, but the discrepancies were not as great as might be expected considering the exposed nature of the sites and the altitude of the catchment. For a third of the time the ground level gauges collected only 5% more than the standard gauges and for over half the time the catch was less than 15% greater. These results compare very favourably with those obtained elsewhere in the country and listed by Rodda (1970).

The rainfall totals for the sites were very similar. For 50% of the time the readings from the standard gauges were within 10% of each other, while for the ground level gauges, the variation was only  $\pm 5\%$ . The ground level gauges were not only surprisingly accurate but the consistently similar catch of the gauges at both sites A and B suggest that the average of these two gauges gave a reliable measure of the rain falling in the catchment.

The problems of temperature measurements unlike those of precipitation, proved to be related to siting rather than reliability. Throughout the two-year study period the water temperature recorder's maintained a continuous, accurate record. The air temperature records were slightly less accurate, partly because the Stevenson

screen and the recorder became filled with wind-driven snow during periods in mid-winter, and partly due to some mechanical failures of the Negretti and Zambra recorder soon after its installation in January 1970.

The use of a continuous recorder to measure the temperature of the groundwater at the disused leadmine adit was soon found to be unnecessary since this water did not vary from 7°C, and this recorder was in time moved and more usefully located at the source of stream B. The importance of careful siting of the water temperature recorders was demonstrated with the weir site recorder. While it was sited in the stilling pool above the weir it was often recording the temperature of stagnant rather than running water. On the other hand, when it was moved to a section of channel with running water, it had to be carefully located so that the flow of water was deep enough to cover the probe, and it had to be regularly cleared of accumulated silt.

The water temperature sequences taken with the mercury-in-glass thermometers were designed to provide measurements at regular intervals down the stream rather than to identify and record various problems such as the occurrence and the effects of contributions of groundwater along the stream. These temperature sequences were one of the most rewarding aspects of the research project. The continuous records of water and air temperature provided a context into which a very detailed analysis of variations in the stream water temperature could be placed. The purpose of these sequences was to produce a record of the changes that occurred throughout

the day, and through the year. The effects of ground-water contributions upon stream temperatures have been demonstrated by this study, but more detailed analysis can only result from a project instrumented specifically to that end.

A great deal of time was spent upon the choice of gauging structure, with particular reference to the type of environment in which it had to operate. The choice of a prefabricated flat vee weir was entirely satisfactory. The prefabricated nature of the weir made it possible for the structure to be installed with a minimum of labour, and a minimum of site preparation. At the same time the specifications of the gauge ensured that accurate records were obtained throughout a wide range of flows despite the very steep approach conditions inherent at the site. The structure withstood the extremes of climate to which it was subjected, both the expanding action of the ice in the winter, the high temperatures in the summer resulting from direct sunshine and the pounding of several large floods, without suffering any serious damage or developing any faults. Greater strength would perhaps have been given to the structure if the joints had been covered with fibreglass during installation.

Several other details of the installation might have been improved. A comment has already been made about the problems caused by leaving the sides of the weir, and particularly the connecting pipe from the weir to the float well, exposed to the air. The purpose of this was to examine the water tightness of the weir sides, but one

effect was to cause a loss of records through the freezing up of the connecting pipe. Back-filling the sides of the weir would also have given it much greater strength to withstand the pressures exerted on it by the expanding ice. The stilling pool had to be dug out more frequently than was originally expected, and in view of this, it would have been valuable if a better by-pass system had been built in one of the wing walls with a concreted by-pass channel having a steep fall. The problem with the sluice gate system in the present weir was that, although the water level could be lowered, it was never possible completely to drain the immediate approach to the weir.

The head/discharge calibration for the weir was calculated by formula based upon laboratory tests run by the Hydraulics Research Station. This was checked against salt dilution tests at low discharges and found to be accurate for flows up to 5 cusecs. The accuracy of the structure at high flows could not be checked. The initial discharge table was calculated by computer programme. Following the installation of the Ott punch tape recorder in January 1970 a conversion programme was compiled to convert the punched head measurement to values of discharge. A further programme was added so that the output from the punch tape recorder could be made available as a graph record in addition to the summary data of maximum, minimum and mean flows for each 24-hour period.

From the results obtained from Part II of the thesis it is possible to construct a diagrammatic model for the processes involved in the control of river water temperature

(Fig. 71). The two major controls over water temperature are ambient air temperature and the volume of discharge. Both of these result from direct and indirect influences within the environment. The total possible volume of discharge is controlled in a direct way by the amount of precipitation and the amount of groundwater contribution, but in fact the volume of discharge results from a combination of modifying influence such as the state of the catchment, the nature of the precipitation and the rate of release of snowmelt. Similarly air temperature, which results from the interactions of various elements in the atmospheric environment, has its effect upon water temperature modified by such factors as the nature of the stream channel.

#### Volume of discharge:

Because the volume of discharge has an important modifying influence upon the relationship between the atmospheric environment and the stream water temperature, the causes of, and the variations in, stream discharge have been described in length. The mean daily discharge from the catchment throughout the year varied according to the distribution of precipitation. Since a small catchment was involved, the response to rainfall was rapid and generally there was very little storage of surface water from day to day except during the winter period when there was a certain amount of storage of water in the form of lying snow which would tend to be released in one flood.

The relations between rainfall and runoff varied

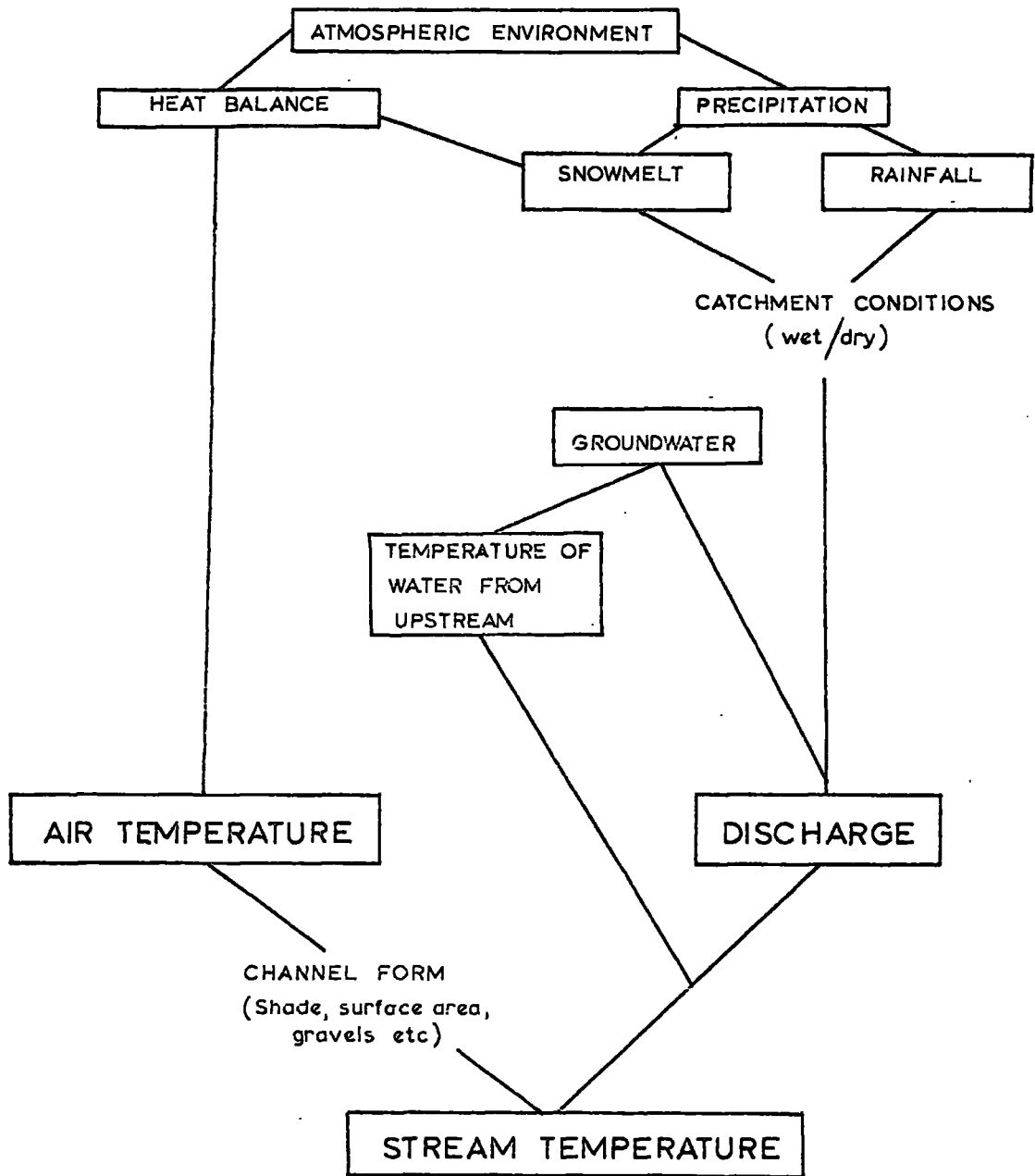


FIG 71 A SYSTEMS CONCEPT OF STREAM WATER TEMPERATURE

according to the antecedent conditions of the soil. If rain fell on wet soil then there was little absorption of the water and the rate of runoff was fast. If the soil was dry as a result of 24 hours without rain, then a certain amount of the rainfall would be absorbed by the soil, and the resulting discharge would not only be slower, but also smaller in quantity than would be expected on a wet catchment. Not only was it the case that the effectiveness of a fall of rain was influenced by the condition of the soil, but it was also demonstrated that the nature of the hydrograph also reflected this. The hydrographs resulting from a rainstorm falling on a wet catchment had a much steeper rise, a sharper peak and were overall shorter in duration than those resulting from dry catchment conditions.

Winter conditions were treated separately from those of the summer since much of the winter precipitation was as snow and the conditions governing the release of snow as discharge were very different from those governing the direct runoff from rainfall. Consequently in addition to its direct effect upon the stream water temperature, heat, either as air temperature or solar radiation, had an indirect effect upon the thermal characteristics of the stream water through its control of the volume of discharge. Very low temperatures could lock up as ice the drainage of water from the catchment and thus produce very low flows, while on the other hand high temperatures were needed to release discharge from accumulations of snow in the catchment. Consequently the highest and the lowest flows might be the result of thermal conditions

rather than direct precipitation.

Air temperature was not the main factor controlling the rate of snowmelt in the catchment but it could be used, in exactly the same way as it had to study the variations in stream water temperature, as an indication of the trends in the atmospheric environment. Snowmelt occurred only after the amount of available heat had exceeded  $20^{\circ}\text{C}$  degree/hours and after a period of at least three hours of non freezing air temperature conditions. Not only was a specific amount of heat required to cause snowmelt but, conversely, the lack of heat would cause a freeze up in the supply of discharge. This could clearly be seen during periods when a diurnal fluctuation of air temperature above and below freezing point produced a series of diurnal snowmelts. During the night the amount of available heat was insufficient to maintain the rate of snowmelt and hence there was a reduction in the volume of discharge at that time.

Although the available heat, expressed in the form of air temperature was responsible for the snowmelt, it did not control either the rate or the nature of the flood. Snowmelt floods occurred after periods of non freezing conditions lasting at least three hours and contributing in excess of  $20^{\circ}\text{C}$  degree/hours of heat to melt the snow. Any greater supply of heat would not produce either a faster or a greater flood since the time of travel controlled the speed of supply and the amount of lying snow controlled the volume available for release.

### Air temperature:

The thermal characteristics of the stream were viewed in a three dimensional sense of time and space. The changes in water temperature were viewed in the context of the diurnal cycle, the changing conditions which occur with distance from the stream source and finally the differing overall atmospheric environment which varied from season to season. The relationship between the air and water temperatures at the weir site were studied. The water temperature was not always dominated by a transfer of heat to or from the air since fluctuations of water temperature did occur when <sup>water</sup>air temperature was in fact higher than the air. The air temperature was however a very useful index of the changes in the climatic environment. The volume of water was also found to be an important factor. The larger the volume of discharge the slower the response of the water to a given amount of heat, and this was clearly demonstrated by falls in water temperature as a result of increased discharge following rainstorms.

The response of the water temperature to the atmospheric environment differed with distance from the stream source. Apart from short periods during the winter, the water temperature and the range of the diurnal fluctuation of water temperature increased downstream. This was partly because the water temperature at the source was dominated by relatively cold water from subsurface sources, but mainly because, the greater the distance from the source, the longer became the time over which the weather could influence the temperature of the stream. The effect of the weather could influence the

temperature of the stream. The effect of the weather varied through the day. The water temperature tended to lag about two hours behind the movements of air temperature, thus the water temperature might be warmer than air temperature soon after mid-day as the air temperature cooled.

The magnitude of these changes in temperature downstream varied through a 24-hour period. During the night the difference between the temperature of the water at the source with that at the weir was less than during the day. When the volume of discharge was 0.6 to 2 cusecs the water temperature tended to follow the trend of air temperature, but during higher flows the response of the water was not so rapid. During flows of about 1 cusec the water temperature reached equilibrium with air temperature very rapidly, and normally within 200 m. of the source of the stream. For flows of less than 1 cusec the temperature of the ground water tended to be dominant. The maximum temperatures occurred at about 1500 BST, but the greatest heating effect in the stream, when comparing the difference between the source water temperature with that at the weir, occurred at 1800 BST.

Direct radiation appeared to be an important influence upon the temperature of the stream. Its effect was greatest when the stream discharge was low and the surface of the water was large in relation to its volume and when it was moving at its slowest rate through the catchment and was therefore under the influence of the radiation for longer.

The stream channel exerted a strong control upon the

water temperature by virtue of the fact that it modified the influence of factors such as air temperature and direct radiation. Ground water seeping into the stream through the stream channel changed the temperature of the water out of relationship with the influences of the climate because this source of water was not directly dependent upon prevailing weather conditions. Where stream water flowed through gravels in the stream channel the water was shielded from direct atmospheric influences and thus the channel exerted a dominating control upon the temperature of the water. On the other hand, where the stream flowed over bed rock the effect of the atmospheric influence was maximised.

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**APPENDICES**

## APPENDIX 1

### Definitions

- Coefficient of discharge : Ratio of measured discharge to the discharge calculated according to theoretical considerations.
- Froude number : Non dimensional number  $\frac{V}{\sqrt{gD}}$
- Hydraulic jump : The abrupt change from super to sub-critical flow.
- Modular flow : Flow over a weir or flume is modular when the upstream level is independent of the downstream level.
- Stage : The elevation of the surface of a stream relative to a datum.
- Super-critical flow : Froude number greater than one.  
A small gravity wave cannot travel upstream against this current.
- Sub-critical flow : Froude number less than one.  
A small gravity wave is not washed away by this flow.
- CV : Coefficient of velocity
- CD : Coefficient of discharge
- f : froude number
- c : Chezy resistance coefficient
- $\alpha$  : energy coefficient
- s : channel bed slope
- g : gravity
- h : head

: width of crest.

P : height of crest

n : cross slope

Q : discharge

$m^3$  : cubic meter (cusec)

cfs : cubic foot sec (cusec)

CVQ : Coefficient of variation of Q defined as  $(100\sigma/Q)$

$\sigma_Q$  : Standard deviation of sets of Q

A : Area

S : Slope

R : Rainfall



Appendix III Vegetation species in the catchment.

	i	ii	iii	iv	v
<i>Juncus squarrosus</i>	+	+	+		+
<i>Galium saxatile</i>	+	+	+	+	
<i>Deschampsia flexuosa</i>	+	+	+		
<i>Nardus stricta</i>	+	+	+		+
<i>Pleurozium schreberi</i>	+	+	+		
<i>Polytrichum commune</i>	+	+		+	+
<i>Sphagnum recurvum</i>		+		+	+
<i>Juncus effusus</i>		+		+	+
<i>Carex nigra</i>		+	+	+	
<i>Dicranum scoparium</i>		+	+		
<i>Agrostis canina</i> ssp <i>canina</i>				+	+
<i>A. tenius</i>	+	+	+		
<i>Eriophorum angustifolium</i>		+		+	
<i>Scirpus caespitosus</i>	+	+			
<i>Plagiothecium undulatum</i>	+	+			
<i>Rhytidiadelphus squarrosus</i>	+				
<i>Sieylingia decumbens</i>	+				
<i>Hylocomium splendens</i>	+				
<i>Sphagnum plumulosum</i>		+			
<i>S. rubellum</i>		+			
<i>Ptilidium ciliare</i>		+			
<i>Aulaucunium palustra</i>		+			
<i>Calypogeia trichomanes</i>		+			
<i>Lophocolea bidentata</i>		+			
<i>Sphagnum cuspidatum</i>				+	
<i>Equisetum fluviatile</i>				+	
<i>Viola palustris</i>				+	
<i>Sphagnum subsecundum</i>					+
<i>Calluna vulgaris</i>			+		
<i>Vaccinium myrtillus</i>			+		
<i>Empetrum nigrum</i>			+		
<i>Parmella physodes</i>			+		
<i>Cladonia pyxidata</i>			+		
<i>C. macilenta</i>			+		
<i>C. furcata</i>			+		
<i>C. squarrosa</i>			+		
<i>Hypnum cupressiforme</i>			+		
<i>Lophozia floerkii</i>			+		
<i>Erica tetralix</i>			+		
<i>Cladonia coccifera</i>			+		

APPENDIX IV

Temperature Sequence along Stream B through 24 hour Periods.

<u>Site</u>	<u>25/26 October.</u>								<u>S.S.T.</u>	
	<u>1500</u>	<u>1800</u>	<u>2100</u>	<u>0100</u>	<u>0500</u>	<u>0900</u>	<u>1200</u>	<u>1500</u>		<u>1800</u>
1			8.7	8.25	7.7	8.0	9.0	9.5	8.7	
2			8.6	8.1	7.6	8.0	9.0	9.5	8.6	
3			8.6	8.1	7.6	8.0	9.0	9.5	8.5	
4			8.6	8.0	7.7	8.0	9.0	9.4	8.5	
5			8.5	8.0	7.7	8.1	9.0	9.2	8.5	
6			8.4	8.0	8.0	8.2	9.0	9.0	8.2	
7			9.0	8.6	8.5	8.5	9.0	9.1	9.0	
8			8.1	8.1	8.05	8.3	8.9	8.7	8.0	
Air			12.0	10.0	9.0	8.5	10.0	10.0	8.5	

22/23 November.

1	4.0	3.2	2.7	2.5	2.5	3.1	3.4	3.1	
2	4.0	3.3	2.7	2.5	2.7	3.2	3.4	3.2	
3	4.0	3.4	3.0	3.0	3.0	3.2	3.5	3.3	
4	3.7	3.0	2.5	2.4	2.6	3.0	3.3	3.0	
5	3.5	3.0	2.5	2.2	2.5	3.0	3.1	2.9	
6	3.5	2.9	2.5	2.2	2.5	2.9	3.0	2.8	
7	3.3	2.7	2.3	2.1	2.5	2.7	2.9	2.6	
8	3.0	3.0	2.6	2.5	2.5	2.9	3.0	2.8	
9	3.2	2.5	2.2	2.0	2.0	2.5	2.5	2.5	
Air	4.0	1.5	0.0	1.0	2.0	3.0	3.0	1.5	

24/25 January

<u>Site</u>	<u>1500</u>	<u>1800</u>	<u>2100</u>	<u>0100</u>	<u>0500</u>	<u>0900</u>	<u>1200</u>	<u>1500</u>	<u>1800</u>	<u>B.S.T.</u>
1	2.8	2.5	2.5	2.3	2.3	2.6	3.3	4.0	3.0	
2	2.7	2.6	2.5	2.4	2.3	2.6	3.3	3.8	2.9	
3	2.5	2.3	2.2	2.3	2.3	2.5	3.3	3.5	2.8	
4	2.6	2.3	2.2	2.3	2.3	2.5	3.3	3.7	2.8	
5	2.3	2.2	2.2	2.2	2.2	2.3	3.2	3.5	2.3	
6	2.2	2.2	2.1	2.2	2.2	2.2	3.2	3.4	2.7	
7	2.2	2.1	2.0	2.1	2.2	2.2	3.1	3.3	2.6	
8	2.2	2.2	2.1	2.1	2.2	2.3	2.9	3.3	2.8	
9	2.1	1.9	1.7	1.8	2.0	2.2	2.8	3.1	2.5	
Air	1.8	1.8	1.8	2.0	3.0	3.5	4.5	6.0	5.0	

21/22 February

1	0.5	0.5	0.5	0.5	0.7	1.0	1.3	1.7	1.1	
2	0.5	0.5	0.5	0.5	0.7	1.0	1.2	1.6	1.0	
3	0.0	0.05	0.05	0.05	0.5	0.7	1.0	1.5	1.0	
4	0.2	0.2	0.2	0.2	0.6	0.8	1.0	1.3	0.7	
5	0.2	0.1	0.2	0.2	0.4	0.6	0.8	1.05	0.5	
6	0.2	0.1	0.2	0.2	0.3	0.5	0.6	1.0	0.5	
7	0.05	0.05	0.1	0.1	0.2	0.4	0.5	0.7	0.3	
8	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.5	
9	0.0	0.0	0.0	0.0	0.05	0.1	0.1	0.1	0.1	
Air	5.2	5.2	5.6	5.5	4.6	4.4	3.8	4.2	2.8	

21/22 March

<u>Site</u>	<u>1500</u>	<u>1800</u>	<u>2100</u>	<u>0100</u>	<u>0500</u>	<u>0900</u>	<u>1200</u>	<u>1500</u>	<u>1800</u>	<u>B.S.T.</u>
1	4.0	3.7	2.7	2.2	1.8	1.8	3.0	4.4	4.4	
2	3.9	3.5	2.7	2.2	1.8	2.0	3.0	4.4	4.3	
3	3.5	3.3	2.5	2.4	2.1	2.0	3.0	4.0	3.7	
4	3.7	3.4	2.5	2.0	1.7	1.7	2.9	4.0	3.9	
5	3.5	3.3	2.3	2.0	1.7	1.5	3.2	3.9	3.8	
6	3.4	3.2	2.2	2.0	1.6	1.5	3.2	3.8	3.8	
7	3.3	3.0	2.1	1.9	1.5	1.5	2.9	3.8	3.6	
8	3.4	3.2	2.3	2.0	1.6	1.5	3.05	3.8	3.8	
9	3.0	2.9	2.0	1.7	1.5	1.4	2.6	3.3	3.3	
Air	5.2	4.4	2.0	2.0	2.0	2.0	3.5	3.8	3.0	

18/19 April

1	8.9	8.5	6.2	4.7	3.3	3.9	7.2	9.5	7.6	
2	8.4	8.4	6.1	4.5	3.3	3.9	7.2	8.9	7.5	
3	8.2	7.7	5.9	4.5	3.2	4.2	7.2	9.0	6.4	
4	7.9	8.2	6.0	4.5	3.1	3.8	6.7	8.4	7.2	
5	7.8	7.9	5.8	4.3	3.1	3.8	6.2	8.4	7.0	
6	7.7	7.7	5.6	4.2	3.0	3.7	6.2	8.2	6.6	
7	7.2	7.4	5.4	4.2	2.9	3.7	6.1	7.8	6.1	
8	7.8	7.5	6.1	5.0	2.8	3.9	6.4	7.9	6.7	
9	6.6	6.7	5.2	4.1	2.8	3.6	5.5	6.7	5.0	
Air	10.0	8.5	6.0	4.0	3.0	3.2	6.0	6.0	5.0	

16/17 May 1970

<u>Site</u>	<u>1200</u>	<u>1500</u>	<u>1800</u>	<u>2100</u>	<u>0100</u>	<u>0500</u>	<u>0900</u>	<u>1200</u>	<u>1500</u>	<u>1800</u>	<u>B.S.T.</u>
1	11.2	11.0	11.0	9.1	7.7	5.7	7.7	13.7	14.0	13.5	
2	11.4	11.1	11.0	9.0	7.5	5.9	7.7	14.0	14.7	14.3	
3	12.0	11.2	10.7	8.6	7.5	7.25	8.9	16.2	14.7	12.5	
4	11.5	10.5	10.5	8.5	7.3	7.0	8.9	13.9	14.0	13.4	
5	11.3	10.4	10.3	8.5	7.0	6.8	7.6	13.0	13.7	13.2	
6	11.0	10.0	9.8	8.0	6.9	6.5	7.6	12.5	13.1	12.4	
7	9.7	9.0	9.0	7.5	6.5	6.0	7.0	10.7	11.6	11.0	
8	9.3	9.3	9.2	8.5	7.5	7.0	7.4	9.5	10.3	10.2	
9	8.8	8.3	7.8	6.5	6.3	5.7	6.7	8.7	9.8	8.5	
Air		11.0	10.5	7.0	5.0	3.0	7.0	13.0	13.0	13.5	

13/14 June 1970

1		19.2	18.3	13.9	11.0	10.0	11.2	15.6	19.0	18.7	
2		20.6	20.0	15.7	11.6	10.8	10.9	15.3	20.0	19.5	
3		-	-	-	-	-	-	-	-	-	
4		20.9	19.2	13.9	10.1	8.8	11.0	16.7	20.5	18.7	
5		18.6	19.0	14.8	11.1	9.3	10.8	15.5	19.5	18.4	
6		18.8	18.4	13.7	10.3	9.3	10.6	16.2	19.5	18.4	
7		16.7	15.6	11.7	8.9	8.0	9.5	13.1	16.7	15.6	
8		-	-	-	-	-	-	-	-	-	
9		13.9	12.2	8.4	6.7	6.7	8.0	11.7	13.9	12.2	
Air	15.0	17.0	14.5	10.0	4.5	5.5	7.0	12.0	15.0	14.0	

11/12 July 1970

<u>Site</u>	<u>1500</u>	<u>1800</u>	<u>2100</u>	<u>0100</u>	<u>0500</u>	<u>0900</u>	<u>1200</u>	<u>1500</u>	<u>1800</u>	<u>B.S.T.</u>
1	13.4	12.7	10.6	10.0	10.0	11.0	11.5	12.7	12.5	
2	13.4	12.8	10.6	9.9	9.9	10.6	11.5	12.7	12.6	
3	-	-	-	-	-	-	-	-	-	
4	13.25	12.5	10.1	9.7	9.7	10.7	11.5	12.8	12.5	
5	13.0	12.3	10.5	9.7	9.7	10.5	11.3	12.5	12.5	
6	13.0	12.2	10.1	9.6	9.6	10.5	11.4	12.5	12.5	
7	12.0	11.2	9.6	9.4	9.4	10.0	10.6	11.5	11.5	
8	-	-	-	-	-	-	-	-	-	
9	10.5	10.1	8.3	8.3	8.3	9.0	9.6	10.5	10.5	
Air	13.0	12.0	11.2	10.9	11.0	11.6	12.0	13.0	14.5	

1/2 August 1970

1	19.0	19.5	16.2	15.1	15.0	15.0	17.6	19.0	18.0	
2	19.5	20.5	16.8	15.3	15.3	15.3	18.25	19.6	18.8	
3	-	-	-	-	-	-	-	-	-	
4	19.6	20.0	16.1	15.0	14.9	14.8	18.0	19.5	18.4	
5	18.7	19.5	16.0	14.6	14.5	14.5	17.5	19.0	18.0	
6	18.2	18.5	15.1	14.0	14.0	14.0	17.2	18.7	17.1	
7	16.0	16.0	13.0	12.0	12.0	12.5	15.5	16.0	15.5	
8	14.2	14.5	13.5	13.4	13.4	13.3	14.4	15.0	15.0	
9	13.5	13.0	11.0	10.5	10.5	11.7	13.5	15.0	12.0	
Air	20.0	18.0	16.5	16.0	15.0	17.0	19.3	22.5	20.0	

19/20 September 1970

<u>Site</u>	<u>1500</u>	<u>1800</u>	<u>2100</u>	<u>0100</u>	<u>0500</u>	<u>0900</u>	<u>1200</u>	<u>1500</u>	<u>1800</u>	<u>B.S.T.</u>
1	13.2	12.0	11.0	10.5	10.7	11.5	12.9	14.5	14.8	
2	12.9	11.6	10.7	10.5	10.7	11.5	12.7	14.1	14.5	
3	12.3	11.3	10.7	10.5	10.6	11.5	13.0	14.0	14.0	
4	12.5	11.5	10.5	10.3	10.5	11.5	12.6	13.9	14.0	
5	12.5	11.3	10.5	10.2	10.3	11.5	12.7	13.7	13.9	
6	12.0	11.0	10.4	10.2	10.3	11.2	12.5	13.4	13.5	
7	11.5	10.6	10.1	10.0	10.0	11.0	12.0	12.5	12.7	
8	12.0	11.4	10.9	10.6	10.5	11.2	12.0	12.7	12.9	
9	10.6	10.1	10.0	10.0	10.0	10.5	11.4	12.3	11.75	
Air	15.0	13.2	12.5	12.2	13.3	14.3	17.6	17.5	16.7	

APPENDIX V.

Temperature sequences at 1500 BST (°C)

<u>Site.</u>	<u>Stream A.</u>					
	<u>1969:</u> <u>25 Jun.</u>	<u>4 Sept.</u>	<u>20 Sept.</u>	<u>28 Sept.</u>	<u>26 Oct.</u>	<u>9 Nov.</u>
1	13.0	16.0	11.2	8.4	9.5	4.0
2	12.7	15.0	11.1	8.2	9.5	3.5
3	13.15	15.5	11.1	8.1	9.5	3.0
4	-	-	10.9	8.5	-	4.2
5	13.5	15.0	11.1	8.0	9.3	2.5
6	13.0	15.0	11.0	7.9	9.1	2.5
7	13.2	14.3	10.8	7.9	9.0	2.3
8	12.1	13.8	10.5	7.8	8.5	2.4
9	-	-	10.7	7.5	-	2.0
10	12.4	-	10.5	7.9	8.5	2.4
11	11.9	-	10.2	7.8	8.7	2.7
12	12.5	-	10.5	7.8	8.8	2.9
	<u>22 Nov.</u>	<u>23 Nov.</u>	<u>6 Dec.</u>	<u>14 Dec.</u>	<u>21 Jan.</u>	<u>25 Jan.</u>
1	3.5	2.7	1.7	2.9	2.6	3.8
2	3.1	2.5	2.2	2.7	2.4	3.8
3	3.0	2.0	0.5	2.5	2.0	3.3
4	3.2	2.7	0.8	2.5	2.2	2.8
5	2.7	2.0	0.3	2.4	1.7	3.3
6	2.5	1.7	0.1	2.2	1.7	3.1
7	2.5	1.6	0.5	2.2	1.6	2.9
8	2.5	1.6	1.0	2.2	1.7	2.9
9	2.2	1.0	-	2.2	1.25	2.8
10	2.5	1.5	1.3	2.0	1.7	2.8
11	2.9	2.0	1.1	2.5	1.8	3.3
12	2.9	2.1	1.5	2.3	1.7	2.8

1970

<u>Site:</u>	<u>31 Jan.</u>	<u>8 Feb.</u>	<u>21 Feb.</u>	<u>22 Feb.</u>	<u>28 Feb.</u>	<u>21 Mar.</u>
1	0.6	1.25	0.6	1.6	2.4	3.9
2	1.4	1.4	0.3	1.5	2.7	3.8
3	0.3	0.4	0.1	1.3	1.0	3.4
4	0.05	-	0.1	1.0	1.0	2.6
5	0.1	0.4	0.1	1.0	0.8	3.2
6	0.1	0.4	0.1	0.7	0.5	2.9
7	0.05	0.4	0.1	0.5	1.3	2.5
8	0.05	0.6	0.1	0.4	1.1	2.3
9	-	-	-	-	-	2.7
10	0.2	-	-	-	4.0	2.2
11	0.1	-	-	-	-	2.3
12	0.3	-	-	-	-	2.0

	<u>5 Apr.</u>	<u>11 Apr.</u>	<u>19 Apr.</u>	<u>28 Apr.</u>	<u>2 May</u>	<u>9 May</u>
1	3.0	4.4	8.9	8.4	9.0	7.8
2	3.3	4.4	9.1	8.4	8.9	7.7
3	2.8	3.6	9.4	8.4	8.9	7.5
4	1.7	1.7	7.3	6.1	8.2	6.8
5	2.5	3.3	10.0	8.2	9.0	7.6
6	2.0	2.8	10.0	7.9	8.6	7.5
7	1.7	2.2	9.0	7.5	8.3	7.0
8	1.3	1.3	8.5	7.3	7.6	6.7
9	1.7	-	8.4	7.4	7.3	6.0
10	1.1	1.7	9.0	7.3	7.9	7.0
11	1.6	1.7	9.1	6.7	8.1	7.0
12	1.1	0.6	7.3	6.2	7.5	6.5

<u>Site</u>	<u>10 May</u>	<u>16 May</u>	<u>17 May</u>	<u>23 May</u>	<u>31 May</u>	<u>13 June</u>
1	7.0	11.0	14.5	13.3	12.5	19.5
2	6.7	10.5	13.0	12.0	11.5	17.3
3	6.5	11.1	14.0	13.0	12.2	-
4	6.1	11.0	15.0	-	-	-
5	6.5	11.5	15.7	14.0	13.0	20.6
6	6.3	11.4	15.0	15.7	13.0	18.5
7	6.1	11.0	15.0	14.0	13.5	19.5
8	6.0	10.2	13.0	12.5	12.0	-
9	6.1	-	-	-	-	-
10	6.2	10.3	14.0	12.8	-	-
11	6.3	10.6	14.6	14.0	-	-
12	5.5	10.0	12.6	12.1	-	-

	<u>28 June</u>	<u>15 Jul.</u>	<u>1 Aug.</u>	<u>2 Aug.</u>
1	14.0	12.0	19.2	20.2
2	13.0	11.6	17.7	18.2
3	14.4	12.0	18.7	19.8
4	-	-	-	-
5	15.2	12.6	19.0	21.0
6	14.2	12.0	18.5	19.6
7	15.3	11.7	19.1	20.0
8	13.5	11.1	17.4	18.7
9	-	-	-	-
10	-	11.0	17.6	20.0
11	-	-	-	-
12	-	-	-	-

Stream B.

<u>Site.</u>	<u>1969</u>					
	<u>25 Jun.</u>	<u>29 Jul.</u>	<u>19 Aug.</u>	<u>20 Aug.</u>	<u>22 Aug.</u>	<u>24 Aug.</u>
1	13.0	14.5	16.0	12.0	12.3	14.5
2	13.8	14.0	15.9	11.9	12.4	14.5
3	-	-	-	-	-	-
4	13.6	13.5	16.0	12.0	12.4	14.2
5	13.5	13.5	15.5	12.0	12.3	14.0
6	13.2	13.0	15.4	12.0	12.2	13.8
7	12.1	12.1	13.5	11.2	11.6	13.0
8	12.0	12.5	-	-	12.0	12.1
9	10.5	10.0	11.5	10.7	11.0	11.5
	<u>29 Aug.</u>	<u>4 Sept.</u>	<u>18 Sept.</u>	<u>20 Sept.</u>	<u>28 Sept.</u>	<u>8 Nov.</u>
1	16.2	16.7	9.7	11.9	9.0	4.0
2	16.6	16.0	9.2	11.5	9.0	4.0
3	-	-	-	-	9.0	4.9
4	16.5	16.0	9.0	11.5	8.9	3.6
5	15.9	15.5	9.0	11.5	8.8	3.5
6	15.7	14.9	9.8	11.4	8.7	3.5
7	13.6	13.4	9.5	11.0	8.6	3.4
8	12.5	13.0	10.0	11.1	9.0	3.9
9	13.0	12.7	9.5	10.4	8.5	3.1

<u>Site:</u>	<u>30 Nov.</u>	<u>6 Dec.</u>	<u>14 Dec.</u>	<u>1970</u>		
				<u>24 Jan.</u>	<u>25 Jan.</u>	<u>31 Jan.</u>
1	0.5	1.8	3.0	2.8	4.0	0.6
2	0.5	1.7	3.0	2.7	3.8	0.6
3	0.4	1.2	3.0	2.5	4.5	0.2
4	0.5	1.6	2.8	2.6	3.7	0.6
5	0.5	1.4	2.7	2.3	3.6	0.5
6	0.5	1.5	2.6	2.2	3.4	0.6
7	1.0	1.6	2.5	2.2	3.3	0.6
8	1.4	1.5	2.7	2.2	3.3	0.6
9	1.0	1.5	2.4	2.1	3.1	1.1

	<u>8 Feb.</u>	<u>21 Feb.</u>	<u>22 Feb.</u>	<u>28 Feb.</u>	<u>5 April</u>	<u>11 April.</u>
1	1.4	0.5	1.7	2.4	3.0	5.1
2	1.0	0.5	1.6	2.2	2.8	4.6
3	0.6	0.0	1.5	2.0	2.8	3.3
4	0.9	0.2	1.3	2.2	2.6	4.1
5	0.7	0.2	1.0	2.0	2.3	3.8
6	0.9	0.2	1.0	2.0	2.3	3.4
7	1.1	0.0	0.7	2.0	2.2	2.8
8	1.6	0.0	0.5	1.5	2.4	2.5
9	1.2	0.0	0.1	1.3	1.7	1.7

<u>Site.</u>	<u>18 Apr.</u>	<u>19 Apr.</u>	<u>2 May</u>	<u>9 May</u>	<u>10 May</u>	<u>16 May</u>	<u>17 May.</u>
1	8.3	9.5	8.5	8.0	6.3	11.0	14.0
2	8.4	8.9	8.4	8.0	6.9	11.1	14.7
3	7.9	8.4	8.5	7.8	6.6	11.2	14.7
4	8.2	9.0	8.0	7.9	6.8	10.5	14.0
5	7.8	8.4	8.0	7.8	6.8	10.4	13.7
6	7.7	8.2	7.8	7.7	6.8	10.0	13.1
7	7.2	7.3	7.3	7.2	6.7	9.0	11.6
8	7.8	7.9	7.0	7.5	7.0	9.3	10.3
9	6.6	6.7	6.4	6.5	6.4	8.3	9.8
	<u>23 May</u>	<u>31 May</u>	<u>21 Jun</u>	<u>28 Jun</u>	<u>11 Jul.</u>	<u>12 Jul.</u>	<u>15 Jul.</u>
1	13.7	13.8	19.7	14.8	13.4	12.7	11.6
2	14.4	15.0	20.9	15.2	13.4	12.7	12.8
3	-	-	-	-	-	-	-
4	14.0	14.0	21.7	15.3	13.2	12.8	12.3
5	14.0	13.7	20.4	14.5	13.0	12.5	11.5
6	13.75	13.6	20.4	14.4	13.0	12.5	11.5
7	12.5	12.2	17.4	13.2	12.0	11.5	10.5
8	11.0	-	-	-	-	-	10.7
9	9.7	8.5	15.0	12.0	10.5	10.5	9.5

## Appendix VI

1. Conversion of ferranti code.
2. Print out of converted punch tape data.
3. Conversion of data file to values of discharge in cusec.
4. Composite programme to produce a graphical display from paper tape data.

## Appendix VII

Rainfall data

		SITE A		SITE B	
1963		ST.	GL.	ST.	GL.
November	20	1.9	1.8	1.8	1.5
	27	21.4	24.3	23.8	24.1
December	4	20.1	20.2	21.4	18.1
	11	3.8	4.0	3.3	3.7
	22	35.1	42.9		
1969					
January	6	44.0	52.2	35.7	
	14	40.8	41.7	30.4	
	22	23.2	29.3	25.9	47.5
	29	6.1	8.1	7.35	7.5
February	5	6.2	6.2	14.8	18.9
	19				
	23				
April	9	5.7		1.3	1.9
	16	28.2	39.5	27.8	36.3
	23	24.25	23.7	23.6	24.3
	30	26.3	31.4	26.7	28.6
May	7	23.8	23.6	21.4	23.3
	14	20.1	22.4	20.1	21.3
	21	26.0	27.0	23.9	23.6
	28	26.3	26.4	25.3	23.4

		SITE A		SITE B	
1969		ST.	GL.	ST.	GL.
June	4	32.8	33.8	31.8	32.6
	11	0	0	0	0
	18	19.2	22.9	21.2	23.8
	26	29.0	31.0	29.7	30.0
July	10	14.9	15.7	14.6	15.1
	16	1.7	2.0	1.1	1.4
	25	5.5	6.3	5.5	5.8
	31	17.9	18.6	17.4	18.2
August	7	51.2	52.3	48.6	49.3
	18	10.5	10.8	11.3	12.0
	22	17.4	17.45	17.1	17.1
	29	11.4	12.0	11.5	11.5
September	4	0.3	0.3	0.25	0.25
	13	47.8	49.7	46.4	47.4
	20	38.4	38.5	35.1	38.9
	29	24.3	27.6	25.8	25.2
October	3	10.04	13.3	12.25	11.9
	12	1.6	2.9	2.0	2.2
	18	0	0	0	0
	26	10.5	11.7	11.3	11.0

		SITE A		SITE B	
1969		ST.	CL.	ST.	CL.
November	2	12.0	13.9	12.6	12.3
	9	67.3	73.2	65.3	61.1
	23	82.0		116.6	
	30				40.00
December	6	38.0	53.5	16.5	13.2
	14	20.7	21.8	17.3	22.4
	21	13.5	40.8	20.4	67.7
	27	9.2	11.1	9.6	10.0
1970					
January	24	102.7	85.7	105.6	92.6
February	8	47.7	39.0	35.0	43.2
	22	38.8	102.8	72.38	216.7
	28	15.2	18.2	17.3	17.9
March	10	14.4	16.6	13.8	14.6
	16	14.7	27.6	11.0	36.2
	21	16.7	19.0	13.9	13.3
	30	24.3	27.8	26.2	26.9
April	4	24.7	31.3	28.5	30.8
	11	38.1	64.5	35.6	45.3
	18	23.3	30.7	16.3	49.4
	25	19.7	23.5	21.7	21.2



		SITE A		SITE B	
1970		ST.	GL.	ST.	GL.
May	2	17.3	18.0	13.1	13.1
	9	11.5	11.1	9.8	10.6
	16	18.1	18.1	17.3	18.0
	23	11.6	12.7	12.5	12.2
	31	3.8	4.5	3.9	3.9
June	6	1.9	2.2	2.4	2.4
	13	0.8	0.9	0.4	0.7
	21	3.4	3.3	2.6	3.0
	28	11.6	12.5	12.7	13.0
July	3	2.65	2.71	2.85	2.74
	11	9.4	9.9	9.7	9.7
	15	14.0	14.5	14.0	13.4
	23	20.0	19.8	20.0	20.4
August	1	27.2	29.0	27.5	27.7
	7	0.4	0.4	0.3	0.5
	13	10.1	10.2	10.1	9.6
	20	89.7	99.4	93.7	92.8
	27	38.0	40.5	33.2	35.0
September	1	10.2	11.3	12.3	11.5
	7	10.9	12.7	12.3	12.7
	14	41.5	43.3	42.6	40.6
	19	9.0	11.7	11.2	11.6
	25	2.1	2.3	2.3	2.5
October	3	21.4	23.5	25.2	23.4

/\* ROUTINE TO CONVERT FERRANTI PAPER TAPE CODE

\*/

I

```

      STMT LEVEL NEST
1 1 1 1
2 1 1 1
3 1 1 1
4 1 1 1
5 1 1 1
6 1 1 1
7 1 1 1
8 1 1 1
9 1 1 1
10 1 1 1
11 1 1 1
12 1 1 1
13 1 1 1
14 1 1 1
15 1 1 1
16 1 1 1
17 1 1 1
18 1 1 1
19 1 1 1
20 1 1 1
21 1 1 1
22 1 1 1
23 1 1 1
24 1 1 1
25 1 1 1
26 1 1 1
27 1 1 1

```

```

/* ROUTINE TO CONVERT FERRANTI PAPER TAPE CODE
   PERCODE & PRODC ( RESULT ) &
   DCL RESULT FIXED BIN ,
   CH(4) CHAR(1) ,
   CODE(10) CHAR(1) INIT (
     '0','1','2','3','4','5','6','7','8','9','S','3'
   ) & /* FERRANTI DIGITS 0 - 9
   SET TO SCARDS OR SYSIN
/*
/* ON ENDFILE ( SCARDS ) GOTO SETEND &
/*
/* READ & GET EDIT ( CH(1) ) ( A(1) ) &
   IF CH(1) = ' ' THEN GOTO READ & /* BLANK /EE /*
   IF CH(1) = ' ' THEN GOTO READ & /* CHECK NULL /EO /*
   IF CH(1) = ' ' THEN GOTO READ & /* CHECK BLANK /*
   ELSE
     GET EDIT ( ( CH(1) ) DO I = 2 TO 4 ) ( 3 A(1) ) &
     RESULT = 0 & K = 1000 &
     DO I = 1 TO 4 &
       DO J = 1 TO 10 &
         IF CH(I) = CODE(J)
           THEN GOTO NEXT &
         ELSE GO TO READ &
       END &
     RESULT = RESULT + (J-1) * K &
   NEXT &
   END &
   K = K / 10 &
   GOTO RETRN &
   SETEND & RESULT = -32676 & /* SET TO LARGEST NEGATIVE INTEGER*/
   RETRN & RETURN &
   END &

```

/\* TO PRINT OUT DATA FILE OF PAPER TAPE ENTRIES HAVING CONVERTED\*/

II

```
STAT LEVEL NEST
1
2
3
4
5
6
7
8
10
11
12
13
14
15
16
17

/* TO PRINT OUT DATA FILE OF PAPER TAPE ENTRIES HAVING CONVERTED*/
/* THEM TO EBCDIC FROM FERRANTI CODE.
PRINT%
DCL (RESULT,1,LINE(16)) FIXED RIN (15)%
PUT PAGE%
PUT EDIT (' DATA FILE IN EBCDIC.') (A)%
FIRST% LINE(*)=0%
DO I= 1 TO 16%
CALL PERCODE(RESULT)%
IF RESULT % 0 GO TO ENDRTN% /* RESULT LT 0 */
LINE(I) = RESULT%
END%
PUT SKIP EDIT (LINE(*)) (COLUMN(5),16(F(6)))%
GO TO FIRST%
ENDRTN% PUT SKIP EDIT (LINE(*)) (COLUMN(5),16(F(6)))%
PUT SKIP EDIT (' END OF DATA FILE.') (A)%
PUT PAGE%
END PRINT%
```

\*LAST SIGNON MADE 17:00:34 12-02-70

USER EPH7E SIGNED ON AT 17:526.46 ON 12-02-70

ACREATE -CONVER2

FILE 2-CONVER2 HAS BEEN CREATED.

ACREATE MCONVER

FILE 5MCONVER HAS BEEN CREATED.

NUMBER

ELNUMBER

ELIST MCONVER

```
1 CONVER 2 PROC OPTIONS (MAIN)2
2 DCL (R,E,V,FEET,TOTAL,MAX,MIN) DECIMAL FIXED (10,8),
3 (Q,REC) DECIMAL FIXED (10,5),
4 READING CHARACTER (5),
5 MEAN DECIMAL FIXED (10,8),
6 K DECIMAL FIXED (3),
7 (I,J) FIXED (3)2
8 FIRST2 DO I= 1 TO 962
9 GET FILE (TAPE) EDIT (READING) (A(5))2
10 PUT EDIT ('*** DEBUG *** RECORD= *** ',K,REC,FEET,READING)
11 (LINE,COLUMN(20),I(30),F(3,0),F(10,8),F(10,8),A(5))2
12 ON ENDFILE (TAPE) CALL ENDRTN2
13 REC = READING2
14 FEET= REC / 0.03280832
15 IF K 2 5 THEN
16 PUT EDIT ('PAPER TAPE READINGS CONVERSION PROGRAM. ')
17 (PAGE,COLUMN(15),A(39))2
18 ELSE2
19 PUT EDIT ('VALUES OF Q PERIOD ',J)
20 (LINE(2),COLUMN(20),A(20),F(3.0))2
21 V = SQRT(FEET **5)2
22 E = (4* 0.619 *2 * 37.1765)/52
23 R = (V -((FEET-C.35)** 2.5))2
24 IF FEET 2 0.35 THEN Q = E*R2
25 ELSE Q = V*R2
26 TOTAL = TOTAL + FEET2
27 IF FEET 2 MAX THEN MAX = FEET2
28 IF FEET 2 MIN THEN MIN = FEET2
29 PUT EDIT ('VALUES OF Q FOR PERIOD ',J) (LINE(2),COLUMN(20),
30 A(24),F(3))2
31 IF I = 96 THEN CALL TOTALS2
32 ELSE2
33 GO TO FIRST2
34 TOTALS2 PROC2
35 MEAN = TOTAL /962
36 PUT EDIT ('*** TOTALS FOR 24 HOUR PERIOD *** MAX=',MAX,
37 'MIN=',MIN,'MEAN=',MEAN,'PERIOD= ',F)
38 (LINE(2),COLUMN(15),A(44),F(6,4),A(4),F(6,4),A(5),F(6,3),
39 A(8),F(3))2
40 MAX = 0.02
41 MIN = 99.992
42 J = J+1 2
43 K = K+1 2
44 TOTAL = 0.02
45 END TOTALS2
46
47
48
49
50
```

51  
52  
53  
END OF FILE

CALL TOTALS  
END ENDRTN  
END CONVER

```

/* PAPER TAPE CONVERSION PROGRAM */
/* READINGS IN MILLIMETERS CONVERTED TO FEET AND CORRESPONDING */
/* RUN-UP VALUES COMPUTED, RESULTS ANALYSED IN 96 READING UNITS*/
/* 15 24 HOUR PERIODS. GRAPHICAL DISPLAY AVAILABLE. */
CONVERSE PROC OPTIONS (MAIN)
DCL (Q,QMAX,QMIN,QMEAN,POP,REC,R,FEET,MAX,MIN,MEAN,TOTAL,V)
      FLOAT,
      (PP) FIXED BIN,
      CH CHARACTER (1) INITIAL (**),
      (I,J,K,L,M,II,MM,READING) FIXED BIN (15)
      MM = 05
      M = 05
      DCL PAGE(50,90) CHARACTER (1)
      PAGE(*,*) = ' '
      DO PP= 2 TO 5
      PAGE(1,PP)='0'
      PAGE(12,PP) = '0'
      PAGE(24,PP) = '0'
      PAGE(36,PP) = '0'
      ENDS
      K = 15
      I = 05
      TOTAL = 0.05
      MAX = 0.05
      MIN = 99.995
      J = 15
      QMIN= 9999.95
      QMAX = 0.05
      QMEAN =0.05
      R = ((SORT(32.1765)) * 4 * 0.619 * 10)/55
      GET SKIP2
      FIRSTS BEGIN
      I = I +15
      IF I =1 THEN DO
      M = 15
      DO PP=8 TO 90
      PAGE(*,PP) = ' ' /* ZEROIZE ARRAY */
      ENDS
      PAGE(*,7) = '**'
      PAGE(48,*) = '**'
      ENDS
      CALL PERCODE(READING)
      IF READING 0 THEN GOTD ENDRTRN
      REC = READING
      FEET= REC * 0.003280835
      IF FEET = 0.0
      THEN DO
      Q = 0.05
      V = 0.05
      ENDS
      ELSE DO
  
```

Line	Level	Nest
1	1	
2	1	
3	1	
4	1	
5	1	
6	1	
7	1	
8	1	
9	1	
10	1	
11	1	
12	1	
13	1	
14	1	
15	1	
16	1	
17	1	
18	1	
19	1	
20	1	
21	1	
22	1	
23	1	
24	1	
25	1	
26	1	
27	1	
28	1	
29	1	
30	1	
31	2	
32	2	
33	2	
34	2	
35	2	
36	2	
37	2	
38	2	
39	2	
40	2	
41	2	
42	2	
43	2	
44	2	
45	2	
46	2	
47	2	
48	2	
49	2	
50	2	

SIGHT LEVEL NEXT

```

51 2 1 1 V = SORT(FEET **5)
52 2 1 1 IF FEET < 0.35 /* II FEET GT THAN 0.35 */
53 2 1 1 THEN DO
54 2 2 2 Q = R * (V - (SORT((FEET - 0.35)**5)))
55 2 2 2 ENDO
56 2 2 1 ELSE DO
57 2 2 2 Q = V**3
58 2 2 2 ENDO
59 2 2 1
60 2 2 1 ENDO
61 2 2 1 TOTAL = TOTAL + FEET
62 2 2 1 IF FEET > MAX
63 2 2 1 THEN MAX = FEET
64 2 2 1 IF FEET < MIN
65 2 2 1 THEN MIN = FEET
66 2 2 1 QMEAN = QMEAN + Q
67 2 2 1 IF Q > QMAX
68 2 2 1 THEN QMAX = Q
69 2 2 1 IF Q < QMIN
70 2 2 1 THEN QMIN = Q
71 2 2 1 /* CALL QTOT MAY BE INSERTED HERE IF LISTING OF Q VALUES REQ'D */
72 2 2 1 CALL QTOT
73 2 2 1 CALL GRAPH
74 2 2 1 IF I = 96
75 2 2 1 THEN DO
76 2 2 1 CALL TOTALS
77 2 2 1 CALL TOTALS
78 2 2 1 ENDO
79 2 2 1 ELSE DO
80 2 2 1 ENDO
81 2 2 1 GO TO FIRST
82 2 2 1 END FIRST
83 2 2 1 QTOT PROC
84 2 2 1 IF I = 1 THEN GO TO PH
85 2 2 1 IF I <= 49 THEN GO TO PQ
86 2 2 1 PH PUT EDIT ('PAPER TAPE READINGS CONVERSION PROGRAM.')
```

(PAGE,COLUMN(5),A(39))

PUT EDIT ('VALUES OF READING IN FEET ',  
'VALUES OF RUN OFF IN CUBIC FEET/SEC. PERIOD',  
'SKIP, COLUMN(20), F(10,6), COLUMN(76), F(10,6))

PUT EDIT (FEET,Q)  
PQ PUT EDIT (FEET,Q)

END QTOT  
TOTALS PROC  
IF TOTAL = 0 THEN DO  
MEAN = Q  
ENDO  
ELSE DO  
MEAN = TOTAL / I  
ENDO  
IF QMEAN = 0 THEN DO  
QMEAN = Q  
ENDO  
ELSE DO  
QMEAN = QMEAN / I



/\* PAPER TAPE CONVERSION PROGRAM \*/

STMT LEVEL NEST

149	2	1	11 = 11 + 72
150	2	1	PAGE(M,11) = CH2
151	2	1	
152	2	1	END2
153	2		END GRAPH2
154	1		ENDRTN2 BEGIN2
155	2		RESULT = 02
156	2		CALL TOTALS22
157	2		CALL TOTALS2
158	2		END ENDRTN2
159	1		END CONVER 2

CH = '0'2