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Water temperature studies on the R. North Tyne after impoundment by Kielder dam. 3. Preliminary examination of water temperature data.

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SUMMARY

1. The report describes the results of preliminary analyses of data obtained from a series of water temperature loggers sited at various distances (0.8 to 21.8 km) downstream of Kielder dam on the R. North Tyne and in two natural tributaries.

2. The daily mid-range (i.e. $\frac{\text{maximum + minimum}}{2}$) was found to give a useful estimate of daily mean water temperature.

3. The available data suggest that the annual temperature patterns in the natural R. North Tyne and in its main tributaries within the study area were very similar.

4. The water temperature regime of water released from Kielder dam, at the point of release, differed markedly from that of comparable natural streams. The main differences were a delay of the annual temperature cycle by c. 2 months and reduction of its amplitude by c. 7°C.

5. The results suggest, but do not prove, that substantial adjustment of water temperatures, towards those of the natural river, occurs within 15.6 km of the point of release.

6. More detailed analysis of the data through empirical models (relating water temperature, distance downstream, river and tributary discharges and air temperature) would be possible and could yield deeper insights into temperature adjustment with distance downstream of the release point. Critical appraisal of the water temperature data will be needed in order to assess whether or not their quality justifies this more detailed approach.

INTRODUCTION

The general background to the study, together with the positions of the water temperature recording stations, has been given by Crisp (unpublished, 1984). Technical details of the water temperature recording and processing equipment are given by Cunningham (unpublished, 1984), together with an appraisal of its performance. The temperature loggers fell far short of the manufacturer's claims in terms of continuity of operation and accuracy of records and the latter necessitated correction for calibration error (Appendix 1).

The present report deals with three aspects of the water temperature records:

1. An analysis is made of an operational aspect of the data sets for selected stations. The question asked is: How good an estimate of the daily mean temperature is given by the daily mid-range (i.e. $\frac{\text{maximum + minimum}}{2}$)?

2. A simple examination of the effects of impoundment upon water temperature at or close to the point of release, relative to natural river temperatures. This analysis is based primarily upon monthly means for 1983. Comparisons have been made by visual inspection, aided by 95% C.L. where appropriate. Most of the differences noted are large relative to the precision of the estimates.

3. An examination of rate of change of monthly means of daily mean, maximum, minimum and range (maximum - minimum) with distance downstream of the point of release during 1983. This is a preliminary assessment based largely on inspection of graphed data.

DATA

The examination of the operational question was based entirely on Lympet logger data which could be satisfactorily (see Appendix 1) corrected for calibration error. A similar approach has been used in the preliminary examination of rates of change with distance downstream. This led to missing monthly means for some stations in some months but still yielded sufficient good data points for general trends to be identified.

The comparison between temperatures at the point of release and in unregulated tributaries presented greater problems as the exclusive use of corrected data caused some large gaps in the information available during several of the summer months. To avoid this difficulty, some uncorrected (but otherwise apparently sound data) have been used to fill the gaps and comparisons with independent data sets (Boon & Shires, 1976) have been used to assess the validity of this substitution. In addition to the Lympet logger data, data from the Northumbrian Water Authority's Grant recorder at the Kielder valve tower (see Crisp, unpublished, 1984) have been used to estimate daily mean water temperature at the point of release (Station 0).

OPERATIONAL QUESTION

1. General comments

Previous studies of river temperature have used mercury-in-steel thermographs or maximum-minimum thermometers. With these instruments daily mean can be estimated as the midpoint between daily maximum and minimum, i.e. the daily midrange. The 24 hourly readings per day obtained by the digital loggers provide a good opportunity to investigate how well the daily midrange performs as an estimator of daily mean.

From the fourteen stations sited on the River North Tyne and its tributaries, three sites were chosen for investigation. Station 1, near the dam, was a site strongly influenced by the effects of impoundment. Station 11, situated 15.6 km from the dam may be expected to be influenced far less by impoundment. Station 9, on an unregulated tributary, may be considered as typical of a natural river. These three sites also had fairly complete records except for the summer period at Station 9.

The investigation included only those days for which all 24 hourly readings were available. The mean of the 24 readings was used as the best available estimate of daily mean, against which the midrange was compared.

The water temperature is more variable during a summer day than a winter day and the performance of the midrange could depend on the amount of variability. For each station the observations of daily mean and midrange were divided up into seasons with spring defined as March to May, summer as June to August, autumn as September to November and winter as December to February.

The accuracy with which the midrange estimates the daily mean is measured by the bias. This is the average value of the midrange subtracted from the mean. If the bias is positive the midrange, on average, underestimates the mean and if negative the midrange is an overestimate. The precision with which the midrange estimates the daily mean is measured by the proportion of days where the difference between the two exceeds specified levels.

2. Midrange as an estimate of daily mean

Table 1 shows the bias of the midrange and the percentage of days where the difference between midrange and mean, both based on 24 readings, exceeded 0.1, 0.25, 0.5, 0.75 and 1.0°C for each of the three stations, for each season and for the whole year. The standard errors of the bias are given. Individual standard errors for the percentages can be calculated. However, the numbers for each season are approximately 100 and the most useful guide to standard error is that 30-60% have a 5% standard error and 20%, 10%, 5% and 1% have approximate standard errors of 4%, 3%, 2% and 1% respectively. For the whole year, where the number of days exceeds 400, these standard errors should be halved.

For Station 1 near the dam all seasons gave a small negative bias. For Stations 9 and 11 on an unregulated tributary and 15 km from the dam, respectively, the bias was small but positive. Keeping in mind that the loggers have an accuracy of ± 0.1°C the midrange can have no better resolution than ± 0.05°C since it is the average of two observations. Some bias will reflect this. The bias never exceeded 0.25°C and this suggests that the bias in the midrange as an estimate of the mean is negligible, certainly no more than 0.25°C. It is worrying however that the sign of the bias differs between Station 1 and Stations 9 and 11.

TABLE 1. Shows numbers of days (N), bias of midrange as an estimate of daily mean and percentage of days where the difference between midrange of 24 readings daily and the mean of 24 readings exceeded the given levels. Percentages are rounded to the nearest 1% and bias and standard error to 2 decimal places.

	N	Bias (S.E.)	Percentage of days				
			>0.1°C	>0.25°C	>0.5°C	>0.75°C	>1.0°C
St. 1							
Spring	120	-0.19 (0.02)	61	29	7	1	0
Summer	89	-0.13 (0.01)	67	15	1	0	0
Autumn	134	-0.05 (0.01)	31	6	1	0	0
Winter	175	-0.02 (0.01)	28	5	1	0	0
Annual	518	-0.09 (0.01)	43	13	2	0	0
St. 9							
Spring	156	0.09 (0.01)	42	15	3	0	0
Summer	0	-	-	-	-	-	-
Autumn	87	0.13 (0.02)	56	28	1	1	0
Winter	176	0.07 (0.01)	53	18	3	0	0
Annual	419	0.09 (0.01)	50	19	3	0	0
St. 11							
Spring	132	0.05 (0.01)	36	8	0	0	0
Summer	91	0.14 (0.02)	46	22	4	0	0
Autumn	96	0.05 (0.01)	25	1	0	0	0
Winter	106	0.05 (0.01)	39	7	0	0	0
Annual	425	0.07 (0.01)	36	9	1	0	0

If the magnitude of the bias had been larger and if comparisons between stations had been made using the midrange this may have led to erroneous conclusions. The difference in sign of the bias probably reflects the change in diel pattern and unusual fluctuations at Station 1 caused by impoundment.

For individual observations of daily midrange and mean, Table 1 suggests that the experimenter may expect up to 40% (29% ± 10%) of midranges to differ from the mean by more than 0.25°C. However, no more than about 10% will differ by more than 0.5°C and certainly no more than 2% by more than 0.75°C. Of 1362 days studied no midrange ever differed from the mean by more than 1°C.

For the stations investigated, the midrange of 24 readings performed well as an estimate of daily mean temperature.

EFFECTS OF IMPOUNDMENT UPON WATER TEMPERATURE AT THE POINT OF RELEASE

1. Annual temperature cycle in the unregulated R. North Tyne and in unregulated tributaries.

Data are available from the temperature loggers at stations on the lower reaches of two unregulated, or largely unregulated, tributaries (Tarset Burn & R. Rede). Unfortunately the loggers at both stations gave a period of broken and/or sub-standard data during the summer of 1983 and this necessitated the use of monthly means based on data which could not be corrected for calibration error. The data are summarized as monthly means in Figure 1 and the dubious points are distinguished from the remainder. Boon & Shires (1975) studied temperature in the unregulated R. North Tyne and the lower reaches of three of its tributaries in 1972 by means of Cambridge thermographs and weekly readings of maximum and minimum thermometers. Monthly means have

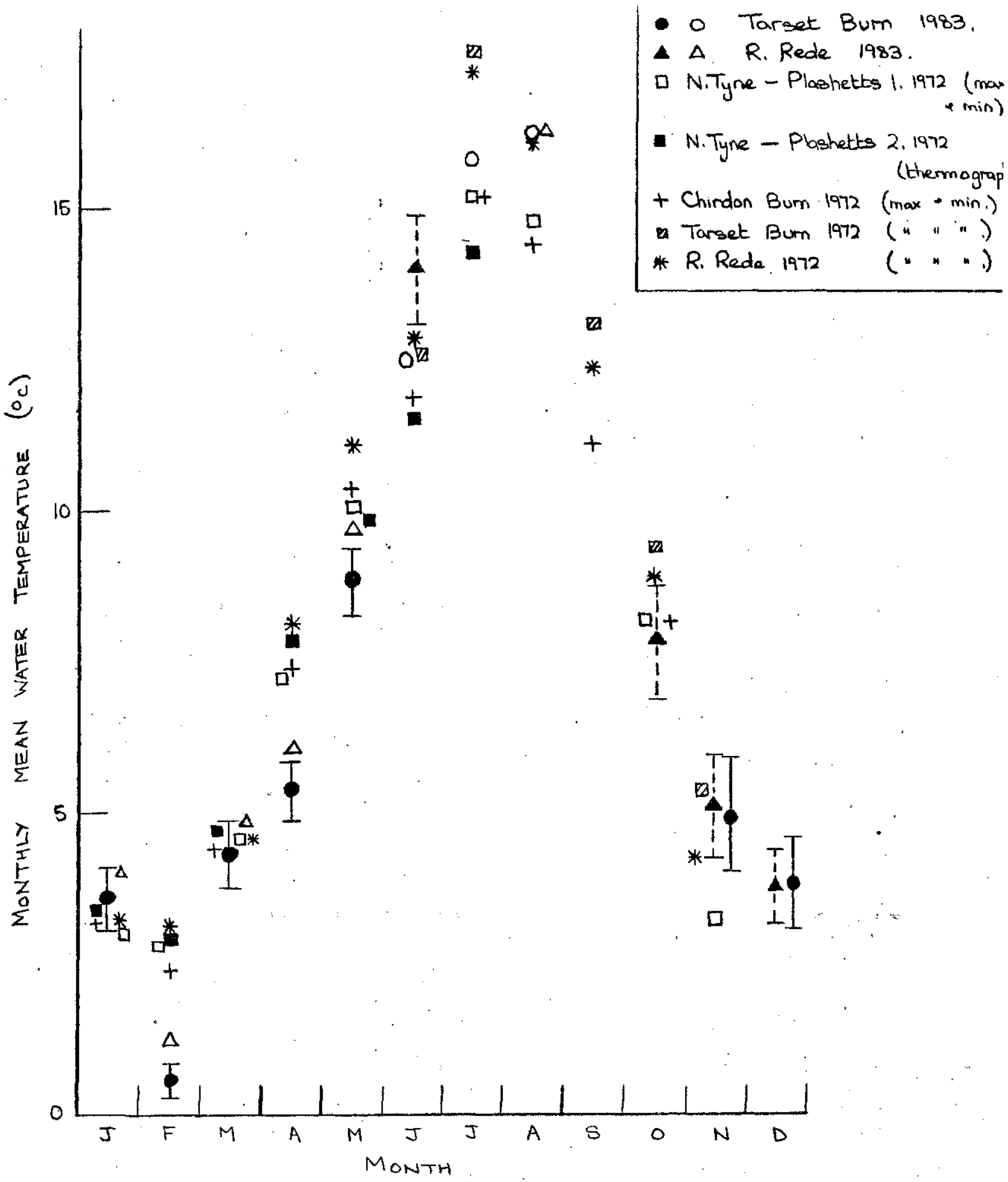


Figure 1. Monthly mean water temperatures in Tarset Burn and the R. Rede in 1983. For these two data sets solid symbols indicate the use of corrected data and open symbols the use of uncorrected data. For comparison, monthly means calculated from the raw data of Boon and Shires (1976) are shown for a station on the unregulated R. North Tyne and in three tributaries. 95% C.L. are indicated for all the 1983 data points which are based on corrected data.

been calculated from their raw data for the three tributaries and for Plashetts on the R. North Tyne (National Grid Reference NY/661900). The latter station is close to the site of the Kielder dam. The results are shown on Figure 1. Despite the fact that data from two different years have been used in this figure(and there will be some differences between years and between stations) the seven data sets show a reasonably consistent pattern in terms of the shape and the temperature values of the annual temperature cycle. The low quality of the data used means that any conclusions drawn from this graph must be somewhat tentative but the main points which arise are:

a. Temperatures recorded in the lower reaches of the three tributaries appear to be a reasonable estimate of temperatures in the unregulated main river.

b. The data of Boon & Shires show that the highest monthly mean occurred in July 1972. This is true of most unregulated streams in most years. The 1983 data suggest that the highest monthly mean was in August of that year, but this may be fortuitous because the monthly means for July and August differed from one another by less than 0.5°C and both values were based on sub-standard data.

c. The data suggest that the amplitude of the annual fluctuation (highest monthly mean - lowest monthly mean) is about 13-16°C.

It is clearly not possible to define the annual temperature cycle for the unregulated tributaries with any great precision. The best available estimates for 1983 and 1972, together with corresponding air temperatures are shown in Table 2 but these values are only an approximate guide. Comparison of the air and water temperatures suggests that some of the minor differences in water temperature pattern between years reflect differences in air temperature pattern. For example, spring (March, April, May) air

TABLE 2. Monthly means of air temperature at Kielder Castle and of approximate monthly mean water temperatures in the unregulated R. North Tyne in 1983 and 1972. The water temperatures are composites of the data shown in Figure 1. For 1983 they are means of values for Tarset Burn and the R. Rede, and the asterisks indicate the quality of the data used.

* = corrected data from one station and uncorrected data from the other.

** = corrected data from only one station.

*** = uncorrected data from one station only.

**** = a composite of uncorrected data from both stations.

Month	1983		1972	
	Air	Water	Air	Water
January	4.4	3.8*	3.0	3.2
Feburary	-0.3	0.9*	-3.4	2.8
March	-4.3	4.3*	6.6	3.2
April	4.3	5.4*	6.7	7.6
May	7.8	8.9*	8.1	10.5
June	11.1	14.0*	8.2	12.0
July	16.7	15.9***	13.4	16.4
August	14.5	16.3****	11.0	15.1
September	10.6	-	9.4	12.2
October	7.9	7.9**	8.5	8.7
November	5.5	5.0	2.4	4.3
December	4.0	3.8	6.1	-

temperatures in 1983 were rather lower than those of 1972 and this is reflected by the water temperature values in April and May which were lower in 1983 than in 1972.

2. Annual temperature cycle of water released at Kielder dam.

Figure 2 compares monthly means at the point of release with monthly means for unregulated tributaries. The latter are from Table 2, and can only be taken as a very approximate guide to the temperatures that would be expected in the unregulated R. North Tyne. Nevertheless, the observed differences between the natural and regulated annual temperature cycle are large relative to the likely errors in either of the data sets.

The most notable effects of reservoir storage are:

a. Delay of the annual temperature peak from July/August to September.

b. Reduction of the amplitude of the annual cycle with a lower peak (by c. 3°C) and a higher trough (probably by c. 3°C).

c. Some indication of a discontinuity in the cycle when stratification in the reservoir breaks down in September.

CHANGES IN WATER TEMPERATURE WITH DISTANCE DOWNSTREAM OF THE POINT OF RELEASE.

1. General Comments

The rate of change of water temperature (in terms of daily maximum, minimum, mean and range) with distance downstream of the dam will be influenced by a complex of factors which include river discharge and air temperature.

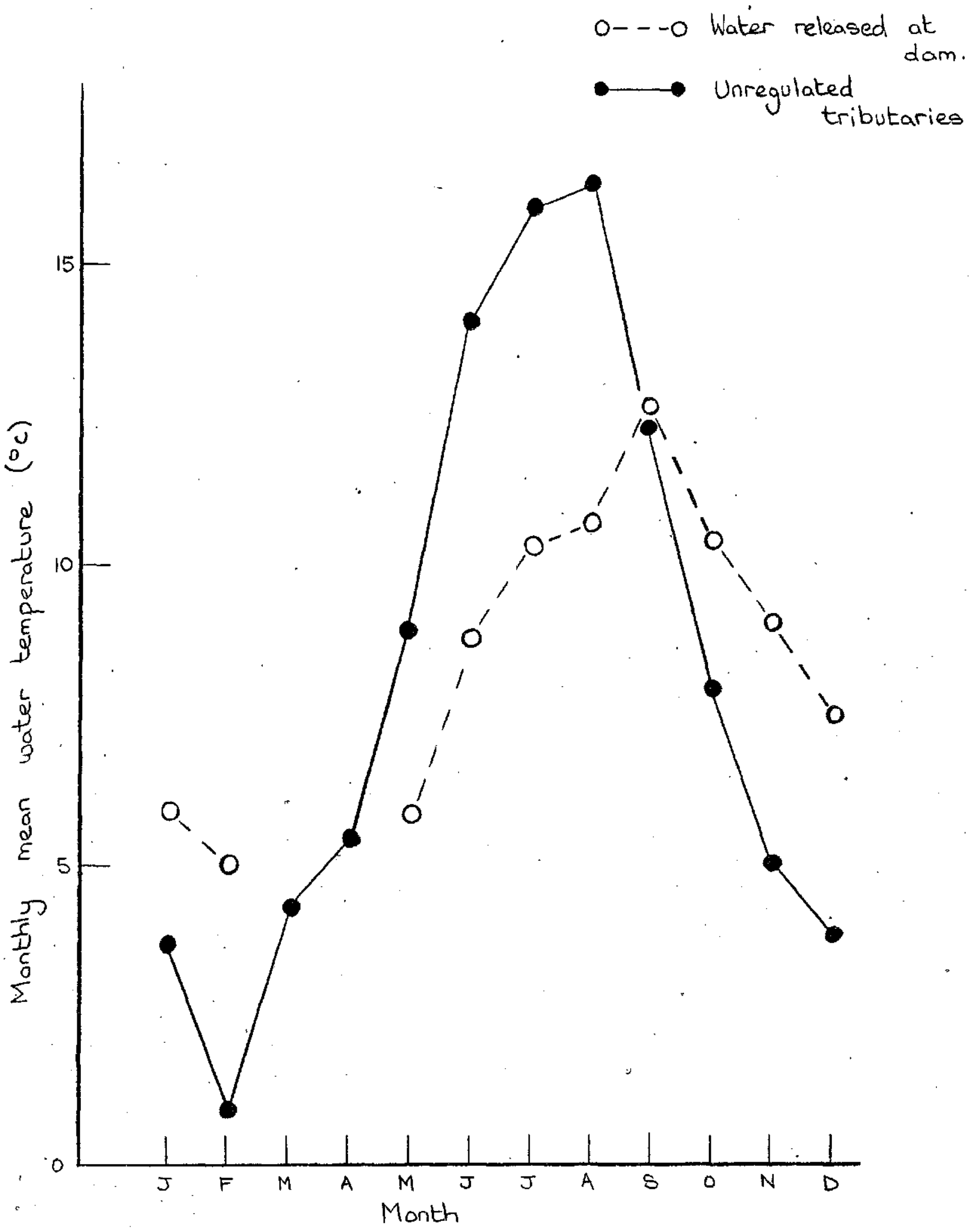


Figure 2. Monthly mean water temperatures in 1983 at the point of release from Kielder dam, and in unregulated tributaries. The latter values are taken from Table 2 and are an approximate guide only, the September value is taken from 1972.

As river discharge, in particular, may change markedly from day to day in the regulated river, it would be most appropriate to analyse the rate of change of water temperature with distance downstream on a daily basis, in conjunction with daily values of river discharge and air temperature. The present analysis is based mainly on monthly water temperature means. This approach is likely to identify any gross changes arising from impoundment but will not detect more subtle effects.

In the analyses, data have only been used from those months and stations for which corrected logger data are available for 24 or more complete days in the month. Within this criterion, almost complete data sets for 1983 are available for stations 5, 6, 8, 10 and 11, whilst the data for stations 1, 4 and 3 are complete apart from gaps in April and May at Station 1 and February and March at stations 4 and 3.

2. Annual cycle of monthly means of daily mean, maximum and minimum water temperatures and daily water temperature range, at selected stations.

Plots of monthly means of daily mean, maximum and minimum temperatures are compared between a series of pairs of selected stations in Figures 3, 4 & 5 respectively. Monthly mean temperatures (Fig. 3) show the manner in which the amplitude of the annual temperature cycle increases and the timing of the summer peak becomes earlier with distance downstream. At a distance of 10.3 km downstream of the dam, the annual cycle is close to that of the unregulated tributaries (c.f. Fig. 2). The monthly means of daily maxima (Figure 4) show a similar pattern, whereas no very clear pattern is shown by the monthly means of daily minima (Figure 5). This may imply that, in the summer months, at least, the pattern shown by the monthly means is more a reflection of elevated maxima than of elevated minimum temperatures. Monthly

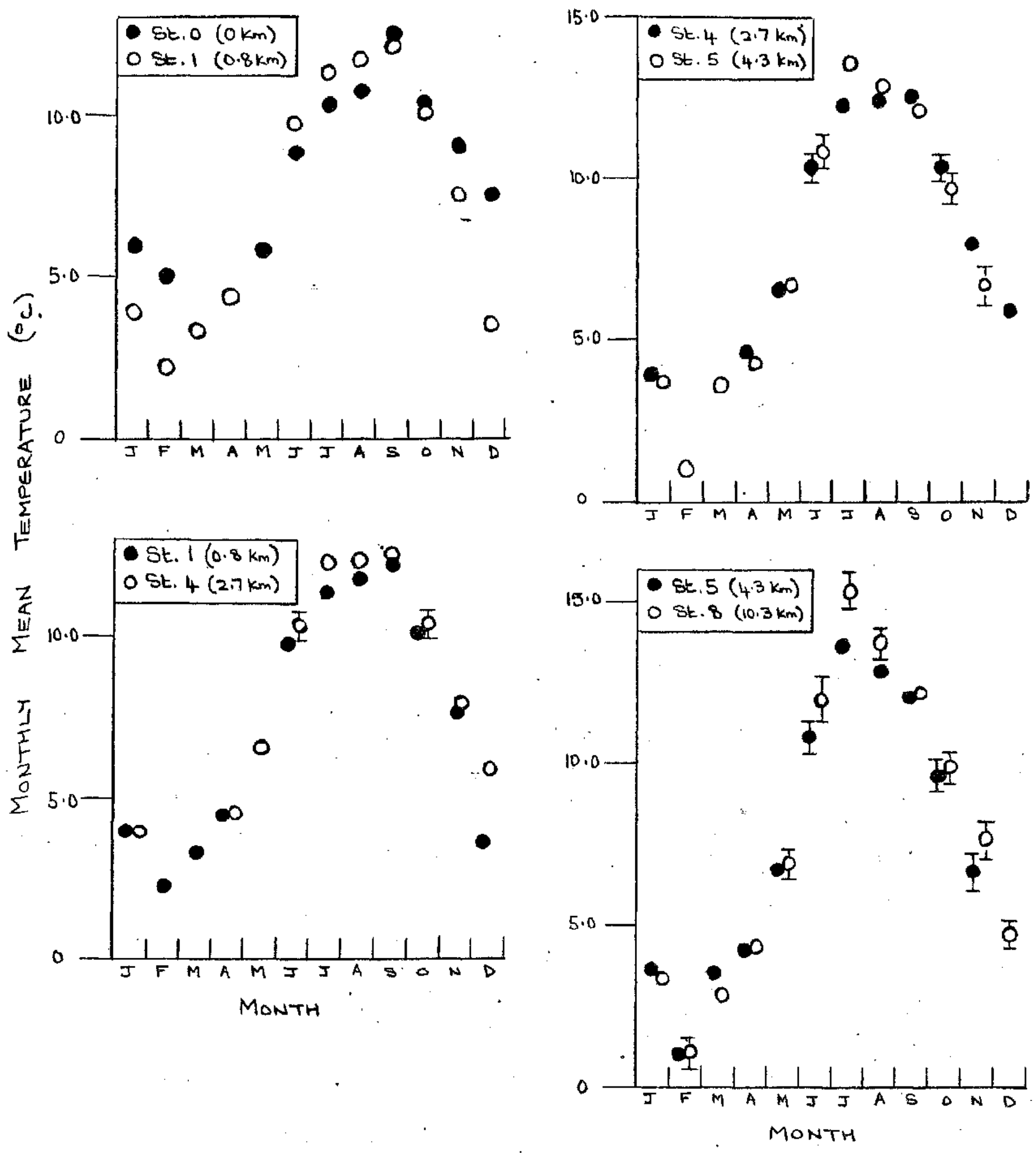


Figure 3. Monthly mean water temperatures in the regulated R. North Tyne in 1983 at selected stations. On each graph the two stations being compared are indicated, together with their distances downstream from the point of release. For stations 1–8 each data point represents the mean of 24 or more days corrected logger data. 95 % C.L. are shown for all stations other than station 0 and those instances where the C.L. are enclosed in the data points.

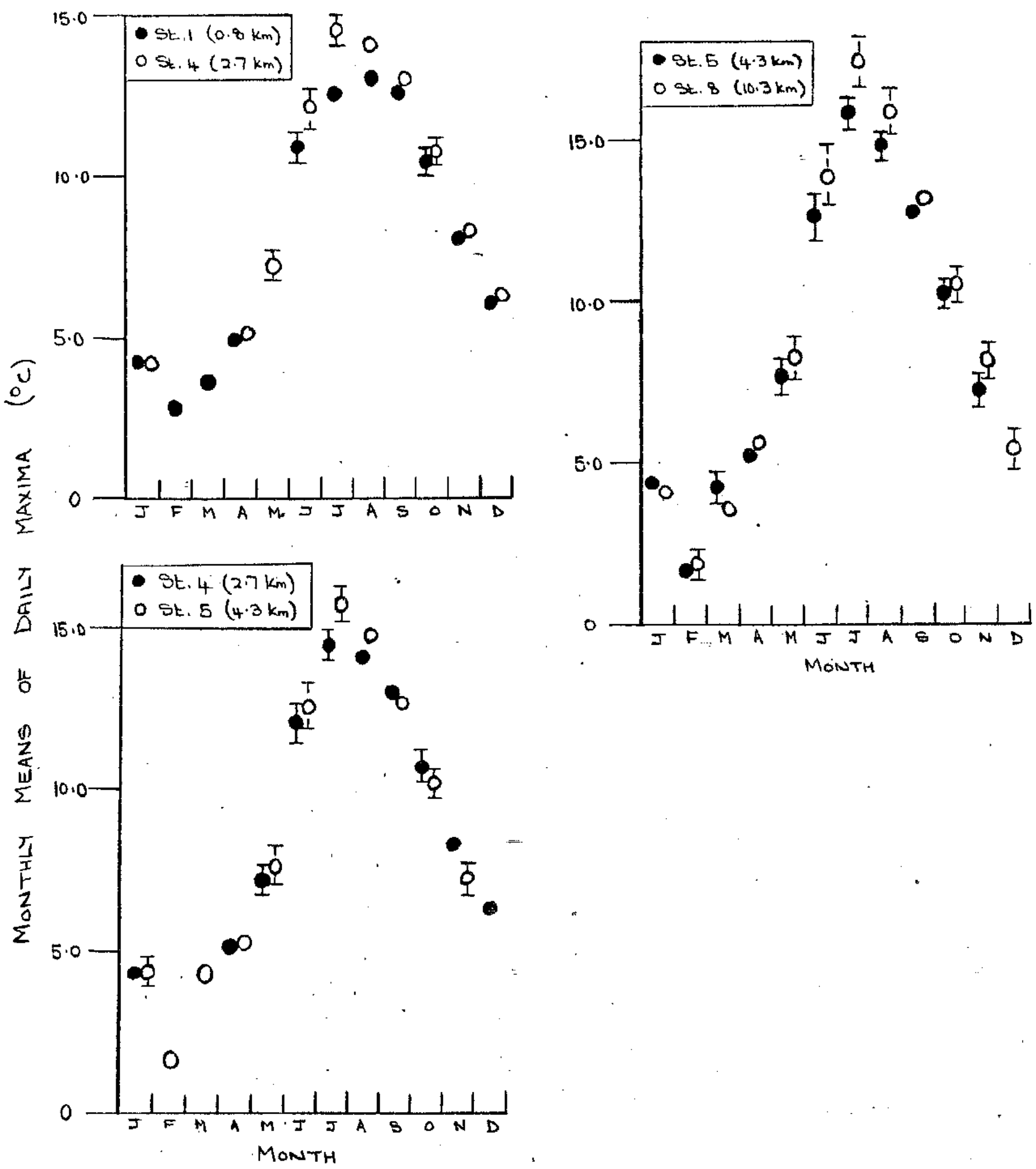


Figure 4. Monthly means of daily maxima in the regulated R. North Tyne in 1983 at selected stations. On each graph the two stations being compared are indicated, together with their distances downstream from the point of release. For stations 1-8 each data point represents the mean of 24 or more days corrected logger data. 95 % c.l. are shown except in those instances where they are enclosed by the data points.

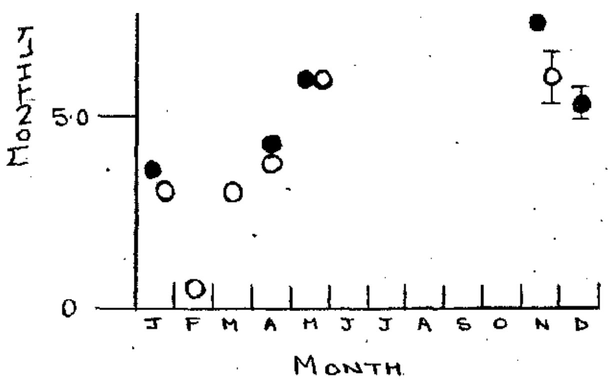
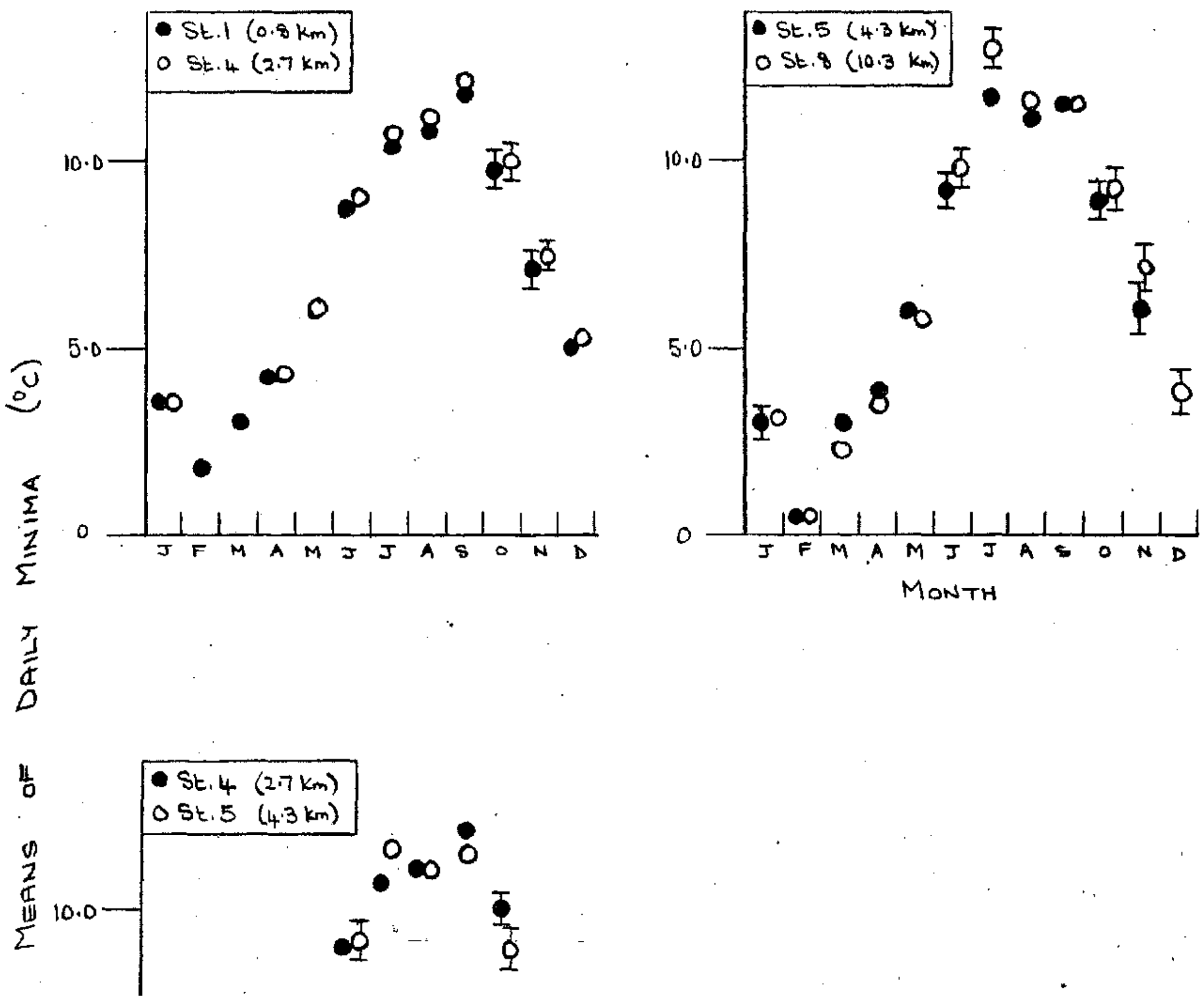


Figure 5. Monthly means of daily minima in the regulated R. North Tyne in 1983 at selected stations. On each graph the two stations being compared are indicated, together with their distances downstream from the point of release. For stations 1-8 each data point represents the mean of 24 or more days corrected logger data. 95% C.L. are shown except in those instances where they are enclosed by the data points.



St.1 (0.8 km)
St.4 (2.7 km)
St.5 (4.3 km)
St.8 (10.3 km)
St.4 (2.7 km)
St.5 (4.3 km)
Means of Daily Minima (°C)
10.0
5.0
0
J F M A M J J A S O N D
Month

means of daily temperature ranges (Figure 6) show that, at all stations, daily fluctuations were, on average, larger during summer than during winter. The size of the fluctuations increased with distance downstream of the dam, particularly during the summer months.

The pattern of change with distance downstream is examined in more detail below.

3. <u>Changes with distance downstream in the monthly means of daily mean, maximum and minimum temperature and daily temperature range; for selected months.</u>

It is clear that impoundment reduces the amplitude of both the daily and the seasonal temperature cycle and modifies the temporal pattern of the seasonal cycle. With distance downstream of the release point, the timing and amplitude are progressively modified back towards those of the natural river. Inspection of Figure 2 shows that, relative to the temperatures in the natural river, impoundment leads to similar temperatures in September, appreciably depressed temperatures in July and appreciably elevated temperatures in December. There are intermediate effects during the other months. Attention has, therefore, been concentrated upon the three named months and tentative conclusions about rates of change relative to distance downstream have been drawn. The mean discharge from Kielder dam during 1983 was 6.6 m^3s^{-1} and the July, September and December means were 1.5, 9.1 and 1.1 m^3s^{-1} respectively (Crisp, unpublished, 1984).

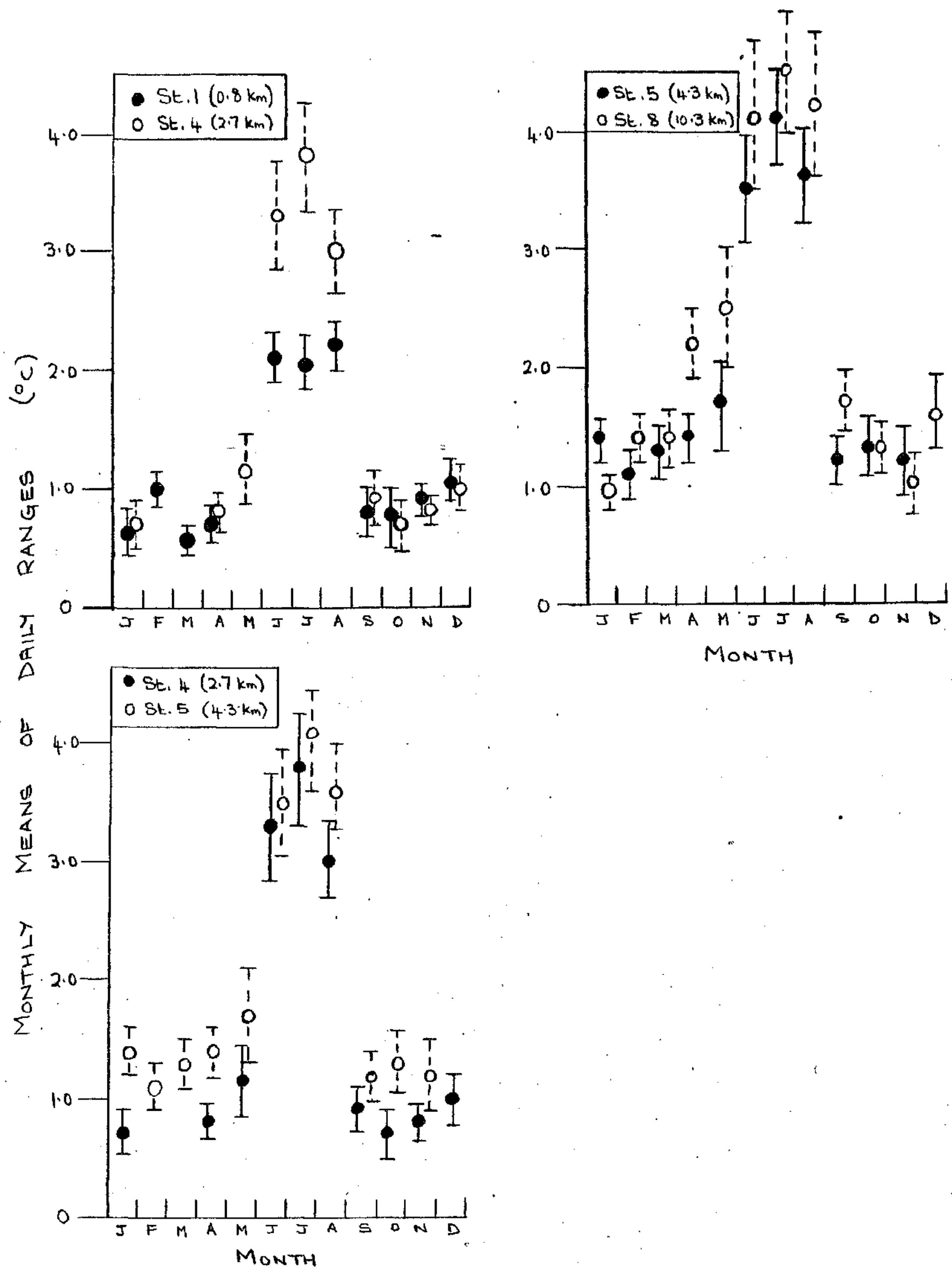


Figure 6. Monthly means of daily ranges of water temperature in the regulated R. North Tyne in 1983 at selected stations. On each graph the two stations being compared are indicated, together with their distances downstream from the point of release. For stations 1-8 each data point represents the mean of 24 or more days corrected logger data. 95% C.L. are shown.

Plots of monthly mean temperature in September against distance downstream (Figure 7) show little change throughout the 15 km of river considered, and this would be expected. The December data show a sharp decrease in temperature from the point of release (St. 0) to Station 1 (0.8 km downstream) and then a slower rate of change over the next 11 km of river length. The July data show a rise of c. 3.0°C over c. 14 km of river length. The inputs from Tarset and Chirdon Burns appear to have had little influence on temperatures at Stations 10 or 11 in September or December.

Plots of monthly means of daily maxima (Figure 8) and minima (Figure 9) show a similar general pattern to the plots of monthly means (Figure 7). On all three of these graphs there is an indication that the inputs from Chirdon and Tarset Burns may have raised main river temperatures in July between Stations 8 and 10.

Monthly means of daily temperature ranges (Figure 10) show a general increase in all three months between Stations 1 (0.8 km) and 5 (4.3 km). With increasing distance downstream the daily ranges appear to level-off and then, between stations 10 and 11, there is some indication of a decrease. This decrease may be a chance occurrence. It could also reflect increased thermal capacity of the river as a result of the entry of three major tributaries.

4. Dates of first attainment of each of two daily mean temperature values, relative to distance downstream from the release point.

Previous sections of this report have already described the "resetting" of the annual temperature cycle as a result of impoundment. An instructive, but far from precise, method of illustrating the effects of this resetting is by examination, relative to distance downstream, of the date on which one or more given temperature values are attained.

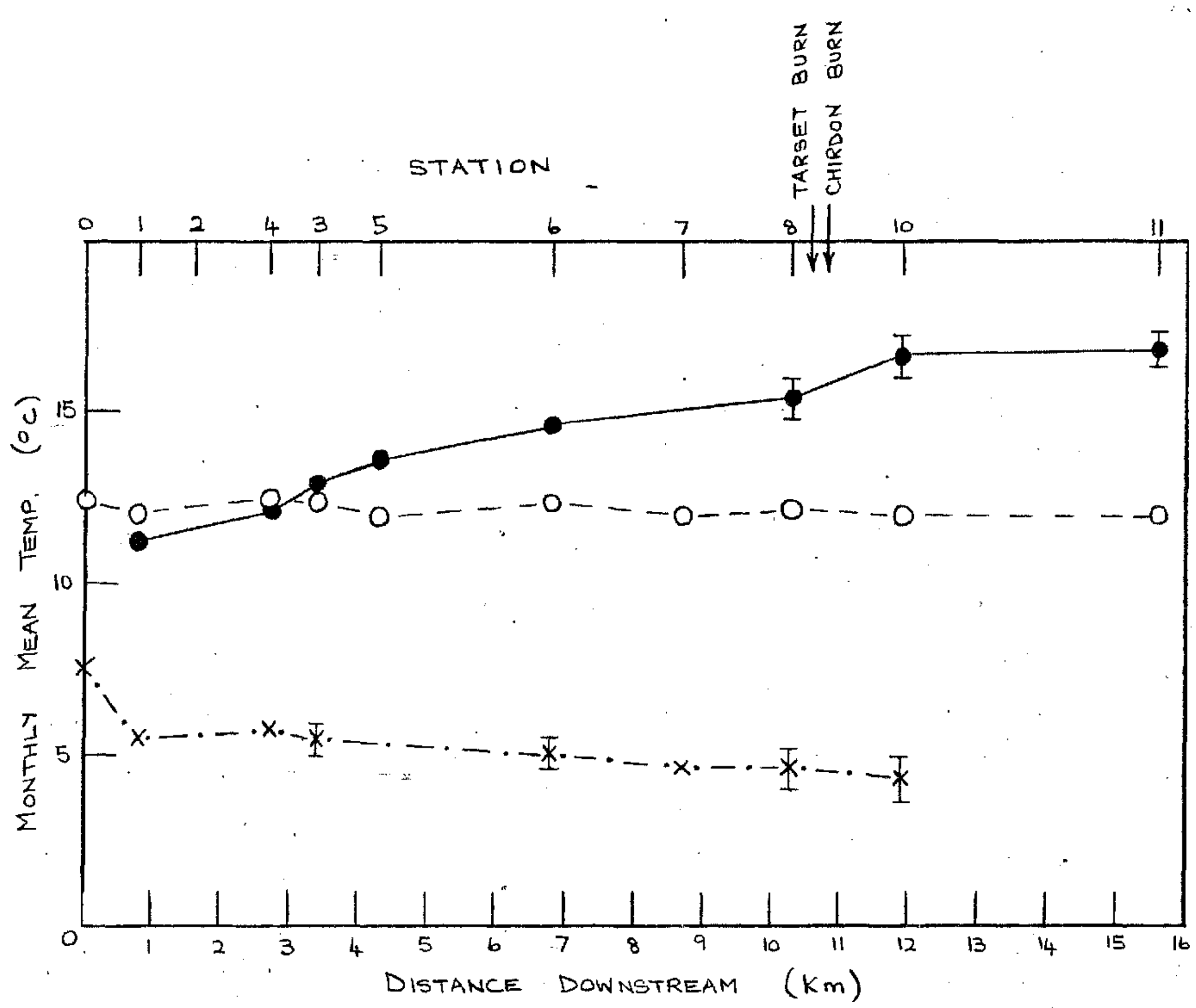


Figure 7. Monthly mean water temperatures and distance downstream of the release point for July (●), September (O) and December (x) 1983. Each data point shown is based on 24 or more days of corrected logger data. 95% C.L. are shown for all stations other than station O and those instances where the C.L. are enclosed in the data points.

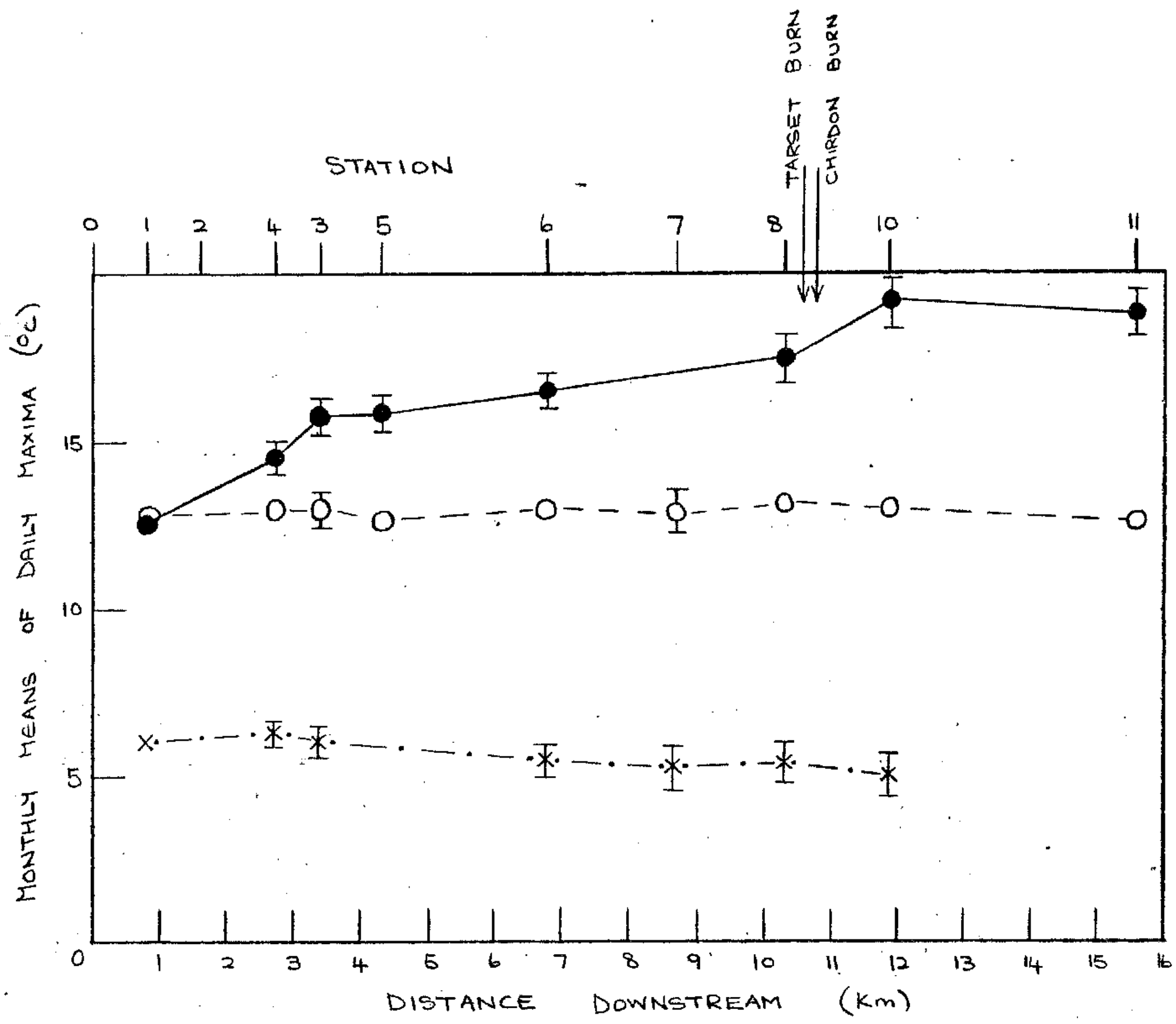


Figure 8. Monthly means of daily maxima and distance downstream of the release point for July (●), September (○) and December (×) 1983. Each data point shown is based on 24 or more days of corrected logger data. 95% C.L. are shown for all stations except where the C.L. are enclosed in the data points.

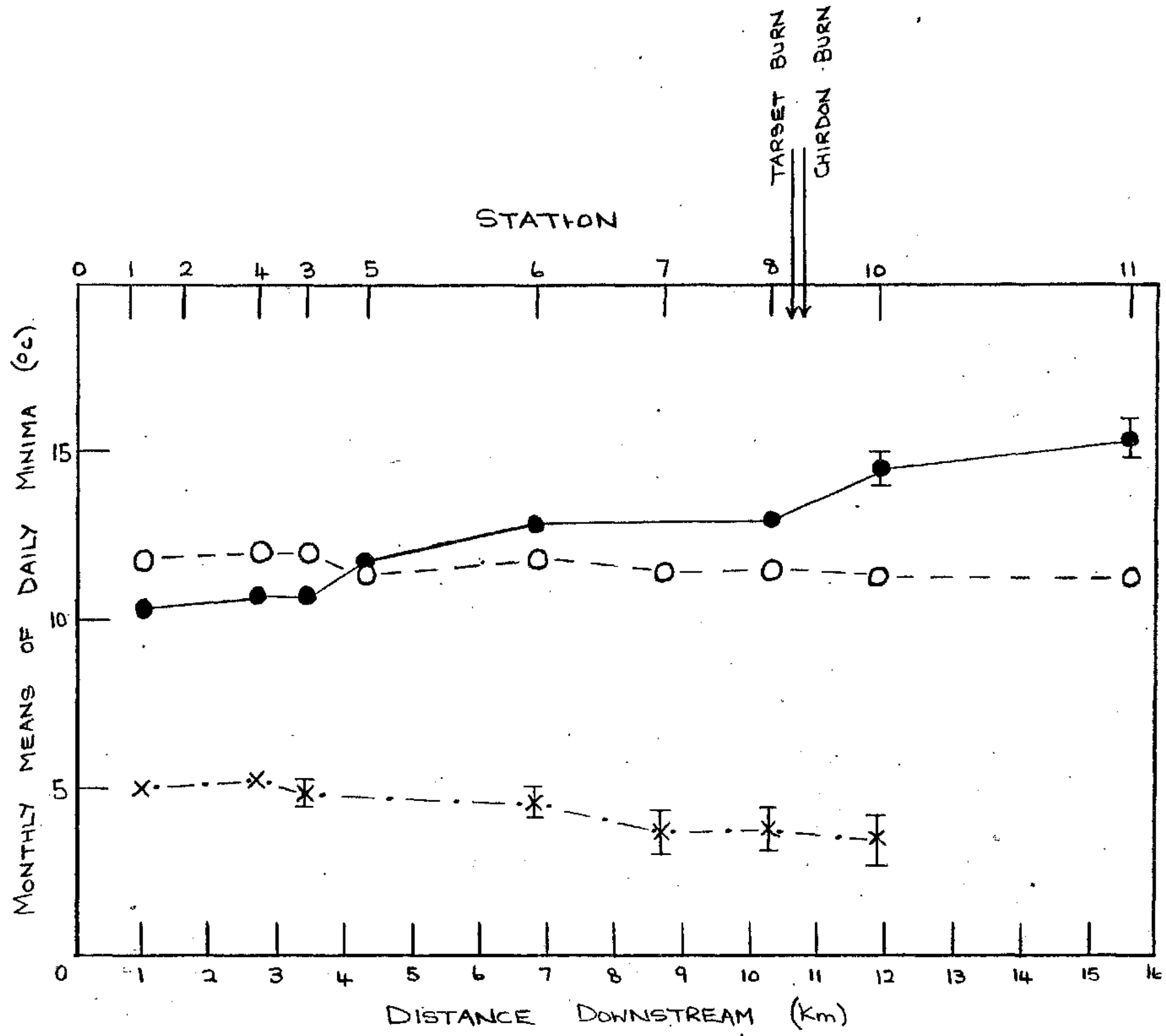


Figure 9. Monthly means of daily minima and distance downstream of the release point for July (•), September (o) and December (×) 1983. Each data point shown is based on 24 or more days of corrected logger data. 95 % C.L. are shown for all stations except where the C.L. are enclosed in the data points.

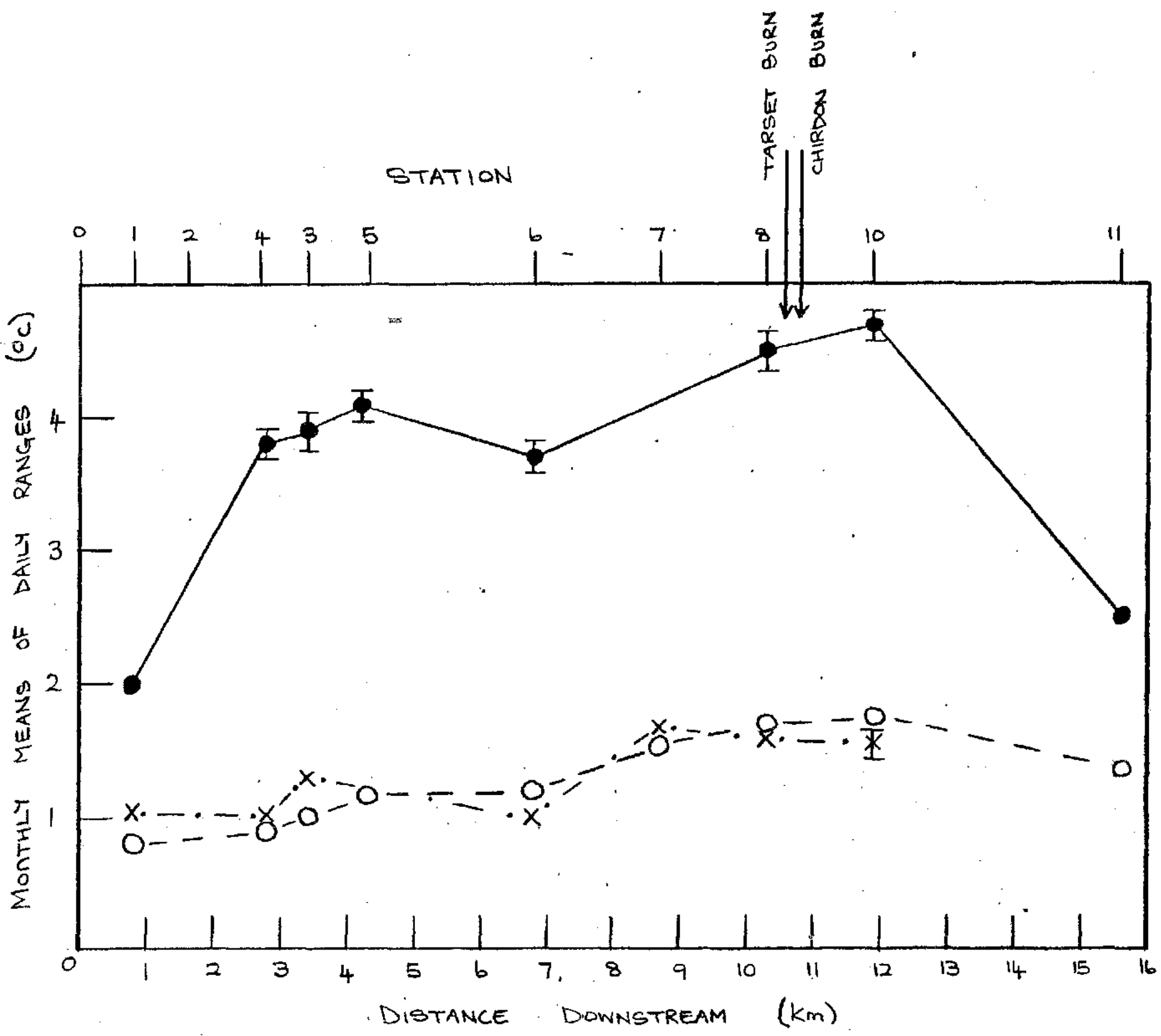


Figure 10. Monthly means of daily ranges of water temperature and distance downstream of the release point for July (●) September (o) and December (x) 1983. Each data point is based on 24 or more days of corrected logger data. 95% C.L. are shown for all stations except where the C.L. are enclosed in the data points.

Figure 11 shows the dates, during spring and summer 1983, upon which the first daily mean temperatures ⩾ 7.5 and ⩾ 12.5°C occurred. For both of these temperature values the date of first occurrence was earlier at the downstream stations than at the point of release. The difference was almost three months for 12.5°C and approximately one month for 7.5°C. Similar plots of the date of first occurrence of daily mean temperatures ⩽ 7.5°C and ⩽ 12.5°C in autumn and winter (Figure 12) show a similar pattern for 7.5°C to that observed during the spring-summer period of rising temperatures. In contrast the date of first occurrence of a daily mean temperature ⩽ 12.5°C shows, if anything, a tendency to become later with increasing distance downstream. This may reflect the choice of this particular temperature value, which is close to the annual maximum at the point of release and occurs close to the time of year when the temperatures of regulated and unregulated streams will be very similar (Figure 2).

5. Rate of change, relative to distance downstream of the point of release.

The rate of adjustment of temperature in the regulated river may be expected to vary from day to day in response to changes in river and tributary discharges and other factors. It is unlikely that the present simple analysis will give very deep insight into this problem. However, inspection of monthly mean water temperatures does lead to two tentative conclusions:

Inspection of Figure 3 suggests that the amount of change in monthly mean temperature per unit of river length is larger close to the point of release than further downstream.

Figure 13 compares monthly mean temperatures at Station 11 (15.6 km downstream of the dam) with approximate values for unregulated tributaries (from Table 2). The two annual cycles are very similar in general shape and amplitude, though they may not be identical. In particular, there is

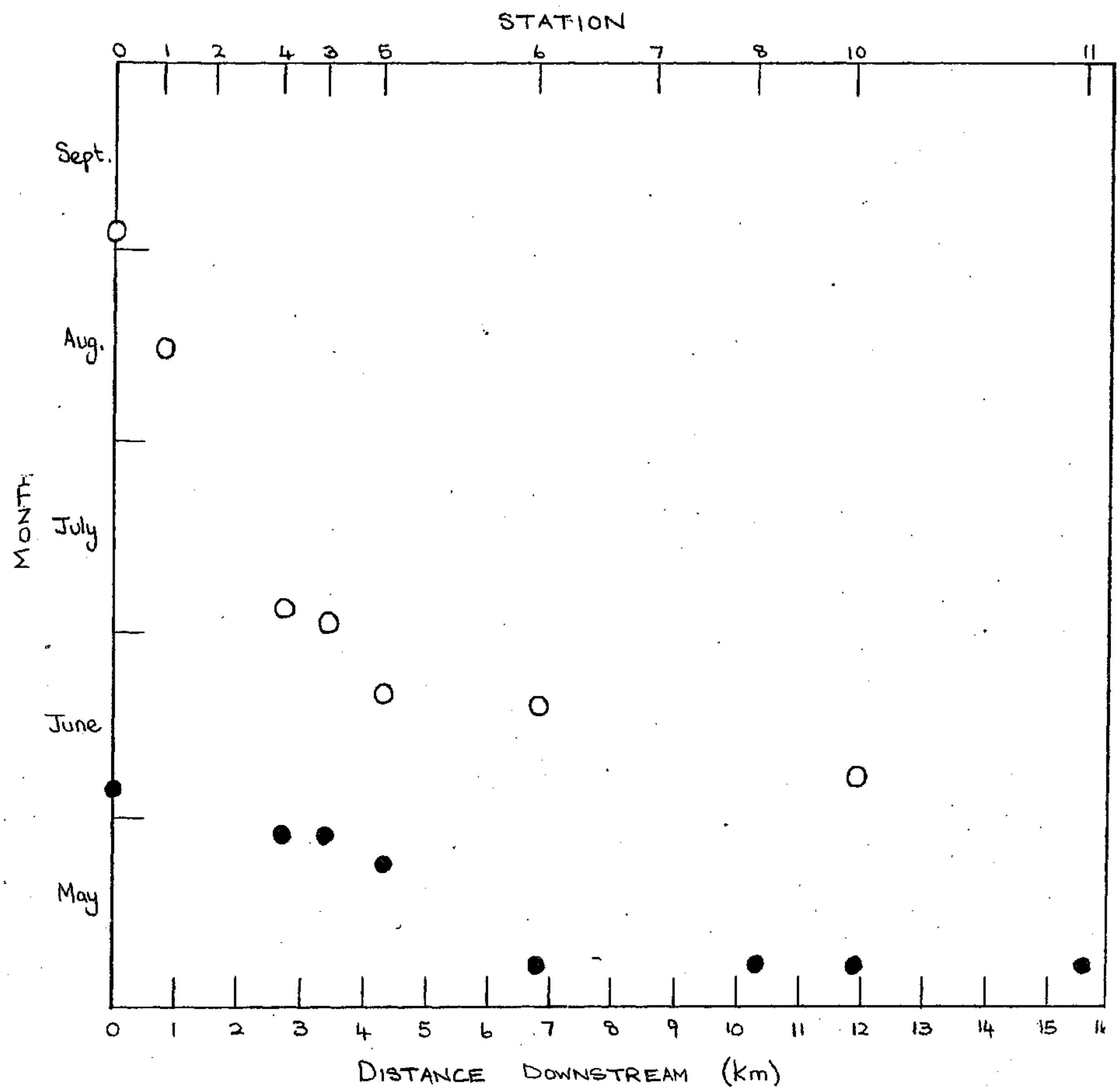


Figure 11. Dates on which the first daily mean temperature ≥ 7·5 °c (●) and ≥ 12·5 °c (o) was attained during the summer of 1983, relative to distance downstream of the point of release.

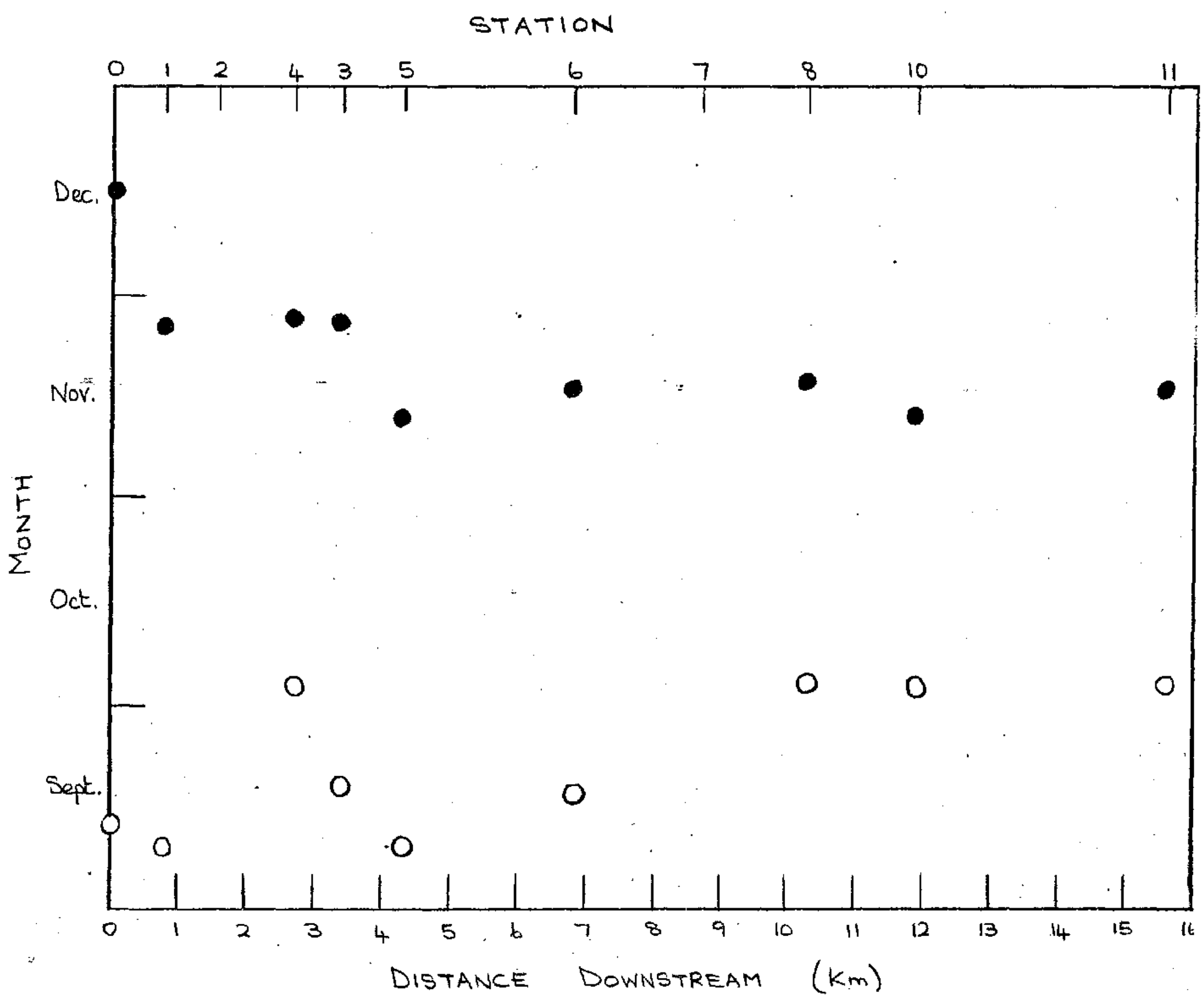


Figure 12. Dates on which the first daily mean temperature ≤ 7·5 °c (●) and ≤ 12·5 °c (○) was attained during the autumn of 1983, relative to distance downstream of the point of release.

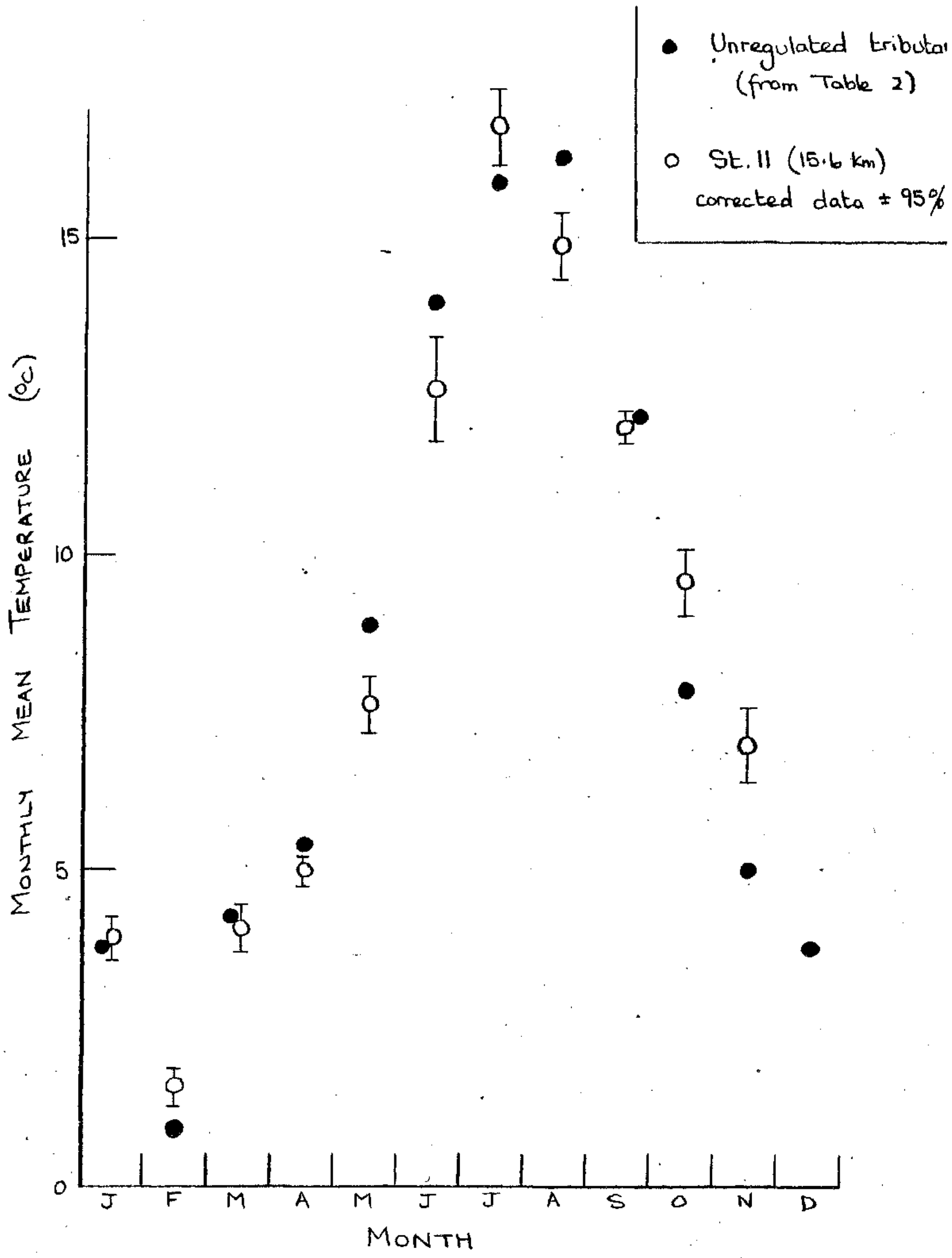


Figure 13. Comparison of monthly mean water temperatures in unregulated tributaries (from Table 2) and at Station 11 during 1983.

some indication that the rise in temperature in spring and early summer and the fall in autumn may be somewhat delayed at Station 11, relative to the unregulated tributaries. The implication is that, on average, temperature adjustment may be largely completed within 15.6 km of the point of release.

DISCUSSION

1. Operational questions

Analysis showed that daily midrange gives a good estimate of daily mean water temperature. This agrees with the findings of previous studies (e.g. Macan, 1958; Edington, 1966; Crisp & Le Cren, 1970) and could have useful applications where the main interest is in obtaining estimates of daily mean temperatures, whilst minimising the quantity of daily data that has to be collected and stored.

During the present study the loggers recorded temperatures at hourly intervals. An analysis of the effect of reduction of recording frequency upon the accuracy of estimation of the daily mean would be useful in planning any future application of electronic water temperature loggers.

2. Preliminary examination of water temperature data.

Despite some inadequacies in the data, the very simple examination of the water temperature results shows that, at the point of release, there has been substantial modification of water temperature pattern, relative to the pattern in the natural river. Changes of the type observed can have important biological impacts and an examination of some effects upon salmonid fishes will be included in Crisp (in prep.).

The importance of these effects in terms of the ecology of the whole river will depend upon how far downstream the temperature effects of impoundments persist. The present data suggest, but do not prove, that on the R. North Tyne, the effect of the Kielder impoundment upon monthly mean temperature reduces considerably within about 15 km of the point of release and that the process of equilibration may be most rapid in the first few km below the dam. This agrees with a tentative conclusion by Edwards & Crisp (1982) and Edwards (1984) with regard to U.K. impoundments. However, the above comments are almost certainly an oversimplification and more sophisticated data analysis, incorporating air temperature and river discharge, would be required in order to understand and describe the system more fully. The feasibility of such an approach will be examined.

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Crisp have been responsible for logger interrogation, data print-out and preliminary data analysis. They carried out these duties efficiently despite considerable difficulties arising from the very discouraging performance of the loggers.

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APPENDIX 1

CORRECTION FOR CALIBRATION ERRORS ON LYMPET LOGGERS.

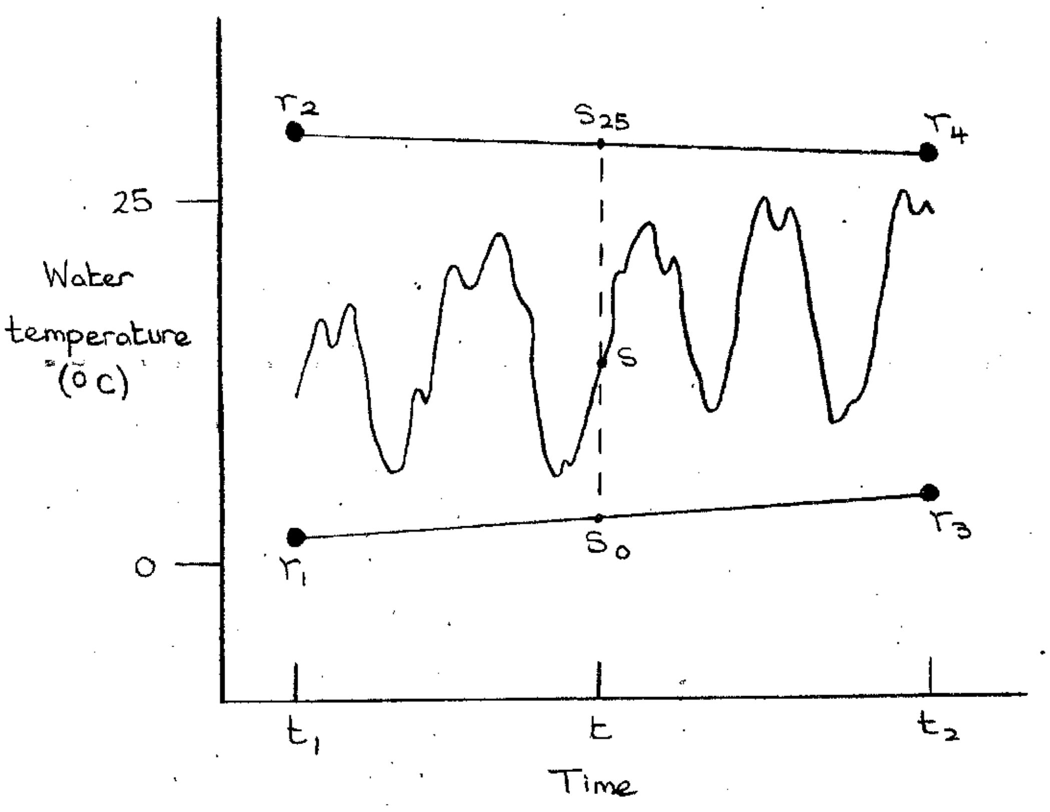
1. Theory

For each series of temperatures at a single station for a four to six week period the series is corrected in the following way. At time t_1, before the first reading, the "on" calibration check is made. The calibration module is fixed to the logger and set to simulate $0^{\circ}C$ and $25^{\circ}C$. The readings, r_1 and r_2 respectively, which are registered by the logger are recorded. A further "off" calibration check is made at time t_2 after the last temperature in the series and again the logger readings of r_3 and r_4 for $0^{\circ}C$ and $25^{\circ}C$ are recorded. The correction is based on the assumption that the values registered by the logger for $0^{\circ}C$ and $25^{\circ}C$ at time t_1 change linearly with time to those values observed at time t_2 (Fig. 1). For any reading, s, in the raw series, taken at time t, the predicted readings s_o and s_{25} for $0^{\circ}C$ and $25^{\circ}C$ at time t are obtained from,

$$s_o = r_1 + (r_3 - r_1)\frac{(t - t_1)}{(t_2 - t_1)}, \quad s_{25} = r_2 + (r_4 - r_2)\frac{(t - t_1)}{(t_2 - t_1)} .$$

With no error, the interval between s_o and s_{25} would have length $25^{\circ}C$. Since this is not the case a stretching or shrinking factor f where $f = 25/(s_{25} - s_o)$ can be applied to the interval to give it a length of $25^{\circ}C$. The observed temperature s lies between s_o and s_{25} and when the interval is stretched or shrunk the distance between s and s_o is stretched or shrunk in the same proportion. Moving s_o so that it is positioned at $0^{\circ}C$, this gives the formula for the corrected reading s' at time t,

$$s' = f(s - s_o) = 25(s - s_o)/(s_{25} - s_o).$$



Appendix

Figure 1. The original series and linearly interpolated values registered at 0°c and 25 °c.

2. Practice

The mathematical correction was applied as widely as possible to the temperature data. A prerequisite for correction of a series is an "on" calibration taken before the first reading and an "off" calibration taken after the last reading. In the practical application the following points are noted:

i. When problems with battery discharge were overcome in the first few months, the "off" calibration for one period was identical to the "on" calibration for the next period. The "off" calibration checks were then not made, and the "on" calibrations of the next period were substituted.

ii. On occasions both the "off" calibration for one period and the "on" calibration for the subsequent period were missing. This occurred when the Husky interrogator broke down. Strictly this should render both periods impossible to correct. However the mathematics requires only that the "on" or "off" calibration be before or after the first or last readings respectively. The previous or subsequent calibration checks can be substituted. This substitution was made only where it was felt that the loss of information would be too great otherwise and where the loggers were performing well in the two periods.

iii. When recording the calibration readings a fluctuation of $\pm$ 0.1°C may be expected from the accuracy of the logger. Where such fluctuation occurred the range was noted and if no more than 0.2°C the midrange was used in the calculation. Where the 0.2°C range was exceeded, the calibration check was considered unreliable and the series could not be corrected.

iv. On occasions the calibration check recorded values which were grossly inconsistent, for example, wild fluctuations. No calibration correction was possible when this happened.

v. When a logger was taken out of service and a new logger installed, the new logger was checked for calibration error. Unfortunately the "off" calibration for the old logger was usually omitted and the "on" calibration with the new logger was not an acceptable substitute. The last period with the old logger could not then be corrected. Since the old logger would only be replaced in the case of malfunction, the data would often have been omitted in any case.

3. Accuracy of data

The raw data, before correction for calibration error, can be divided into two categories; data which are correctable because "on" and "off" calibrations are available and data which are essentially uncorrectable because of problems outlined above. Once corrected, the data are deemed to be accurate to at least $\pm$ 0.5^{o}C. This judgement is based upon practical experience in carrying out the correction and is supported by arguments based on electronic considerations (Cunningham, 1984, unpublished). However little can be stated about the accuracy of those uncorrected data which could not be corrected.

4. Continuity of data

Table 1 summarizes the number of days for which no usable data (i.e. days in which less than 22 correctable hourly temperature readings were obtained) were obtained. The irregular distribution of data gaps between stations is apparent. At 50% of the stations there was less than 10% data loss, whereas at 29% of stations the losses exceeded 80%. As a consequence of this distribution, there are reasonably complete data sets for a series of 8 main river stations (numbers 1, 4, 3, 5, 6, 8, 10 and 11) between 0.8 and 15.6 km of the point of

APPENDIX TABLE 1. Number of days for which records are missing at each station and in each month during 1983. Days with missing records are defined as days for which there were less than 22 hourly temperature readings which were amenable to correction for calibration error. The percentage of days missing during the whole year are also shown.

MONTH	STATION NUMBER													
	1	2	4	3	5	6	7	8	10	11	12	14	9	13
JANUARY	0	31	0	0	0	0	0	0	0	0	31	31	0	31
FEBRUARY	0	28	27	27	3	3	3	3	3	3	28	28	3	28
MARCH	0	16	8	8	0	0	0	0	0	0	31	31	0	31
APRIL	6	2	0	1	0	0	0	0	0	0	30	25	0	25
MAY	30	3	0	0	0	0	1	0	0	0	31	1	1	5
JUNE	0	30	0	0	0	0	30	0	0	0	30	30	30	0
JULY	0	31	0	0	0	0	31	0	0	0	7	31	31	24
AUGUST	0	31	0	0	0	0	16	0	0	0	0	31	31	31
SEPTEMBER	0	30	0	0	0	0	0	0	0	0	13	30	30	14
OCTOBER	0	31	0	0	0	0	14	0	0	0	31	31	18	0
NOVEMBER	0	30	0	0	0	0	28	3	0	0	30	30	0	0
DECEMBER	0	31	4	0	12	0	0	0	0	11	31	31	0	0
% MISSING	10.7	80.5	6.7	9.9	4.1	0.8	33.7	1.6	0.8	3.8	80.3	90.4	39.5	51.8

release. Unfortunately,both of the stations on unregulated tributaries (Stations 9 & 13) had substantial gaps (39.5 and 51.8%, respectively) in their data runs and there were parallel gaps at the two stations during July, August and September 1983.