Nordic Hydrology 6, 1975, 155–169
Published by Munksgaard, Copenhagen, Denmark

WATER TEMPERATURE VARIATIONS WITHIN A MAJOR RIVER SYSTEM

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This paper examines the relationships between river water temperature, air temperature and stream flow measured continuously for one year at four sites along the main stream of the river Tees in northern England. Maximum and minimum river temperatures were found to correlate fairly closely with equivalent air temperatures at each site, but some emphasis was placed on the effects of hydrological factors on water temperature variations within the 818 km^2 basin. The range of water temperature fluctuations was shown to increase upstream and the highest river maxima were also recorded in the upper reaches of the river, owing to the relatively low volume of discharge. On a shorter time scale, stream flow was also found to exert an important influence on river temperature during snowmelt and peak flow events arising from storm rainfall. A multiple regression analysis indicated that air temperature and stream flow together accounted for up to 85 % of the variation of daily maximum and minimum river temperatures in summer.

The temperature of river water is an important environmental parameter and has both an ecological and an economic significance, as outlined by Smith (1972). Most fresh-water biologists, such as Reid (1961) and Macan (1974), regard the thermal regime of a river as the primary physical factor influencing aquatic communities. At the same time, many rivers are being used increasingly for industrial cooling purposes and this has led to a recent rise in thermal pollution. In most countries, the condenser water released by the electricity-generating industry is the main source of heated effluents. For example, over 50 % of the electricity produced in Britain is already generated at power stations sited on rivers and the Central Electricity Generating Board takes approximately half of all the licensed water abstractions in England and Wales for cooling, almost all of it coming from surface sources (Water Resources Board, 1973). Evidence reported by Lester (1967) and Alabaster (1969) suggests that temperatures in the middle and lower reaches of some of the largest British rivers have been substantially modified by heated discharges and a review of the ecological inplications on the rivers Trent and Severn has been presented by Langford & Aston (1972). To some extent, however, all such studies have been restricted by an inadequate understanding of thermal variations in natural, unpolluted river systems.

River water temperatures can be regarded as a function of various hydrometeorological factors operating over any drainage basin. Primarily, the heat budget of rivers will be determined by the heat balance processes of radiation, sensible heat flux and evaporation which affect any water surface but, in addition, the changing nature of stream flow will modify the resulting temperatures by purely hydrological factors. In view of the limited availability of some of the meteorological data necessary for the application of physical models based on energy balance techniques, much recent work on stream temperature prediction has relied on statistical methods using air temperature alone. Most investigators have used air temperature (T_a) as a means of approximating the so-called equilibrium temperature of a water surface, which is the temperature at which there is no net energy exchange with the atmosphere (Dingman, 1972). The river water temperature (T_w) constantly seeks to achieve the equilibrium temperature, represented by nearby air temperature, at a rate which is proportional to the difference between the two, although, in practice, the effect of other meteorological variables and the phase-lag of water temperature response ensures that equilibrium between T_a and T_w is rarely achieved. Nevertheless, air and water temperature correlations of varying degrees of sophistication have been employed by Gameson et al. (1957 and 1959) in England, Miyake and Takeuchi (1951) in Japan, Dingman (1972) in the U.S. and Cluis (1972) in Canada.

The above investigations have concentrated on the relationships between T_a and T_w at one point only along a river and rather less is known about T_w variations along a river course, especially in response to changing discharge conditions. Riverflow is important because, the lower the discharge, the lower is the capacity of the stream for heat storage, and the more responsive the river temperature becomes to changes in the energy balance. In certain circumstances, the river temperature may be influenced by the thermal characteristics of the dominant source water, whether this be snowmelt, storm rainfall or ground water. Recent work by Smith and Lavis (1975) has demonstrated the importance of such hydrological factors in a small headwater basin but little has been attempted on larger scales. Therefore, the aim of this paper is to examine the variation of river water temperatures within a major river system in relation to both air temperature and discharge.

EXPERIMENTAL BACKGROUND

The river Tees is one of the longest rivers in northern England and flows down the eastern flank of the Pennine hills into the North Sea. The drainage basin above the Broken Scar gauging station, shown in Fig. 1, ranges from 893 m to 37 m in altitude and is essentially rural in character. There are no important releases of heated effluent to the river and, until the recent construction of a reservoir on the main stream, reservoir development on the tributaries of the Lune and Balder, indicated in Fig. 1, was the only potential source of thermal modification. Results presented by Lavis and Smith (1972) for the Lune suggested that, for much of the year, any thermal modification due to storage would probably decay a short distance below the dam but compensation water released from depth within the reservoir hypolimnion during low flow periods in summer was found to depress maximum river temperatures by

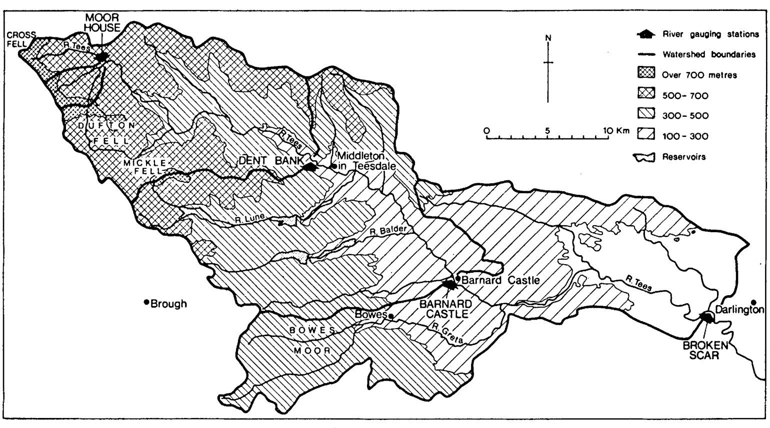

Fig. 1.
The river Tees basin showing the four observation sites.

Table 1.
Gauging stations along the river Tees.

Station	Catchment Area (km^2)	Altitude (m)	Mean Flow (m^3/s)
Moor House	11.4	533	0.516
Dent Bank	217.0	227	7.636
Barnard Castle	509.0	154	16.258
Broken Scar	818.0	37	17.817

(After Cairney & Storey 1970).

at least 3°C down to the confluence with the main river. After the confluence, the water has to travel a further 12 km, with additional opportunities for achieving greater equilibrium with air temperatures, before reaching the measuring site at Barnard Castle.

The existence of four River Authority flow gauging stations at approximately equal linear intervals along the main river provided convenient sites for assessing downstream changes in water temperature. At each station listed in Table 1, dual mercury-in-steel thermographs operating on weekly charts were installed, in order to supply a continuous record of T_a and T_w during the calendar year 1969.

The T_a probes were located in standard Stevenson screens erected on the river bank, whilst the T_w measurements were obtained in constantly flowing water some 1–4 m from the bank. The water probes were shielded from receiving excess of direct solar radiation under low flow conditions by enclosure within perforated white plastic tubes. The thermographs were calibrated regularly against an NPL certificated thermometer and it is believed that for most of the time the instruments were accurate to within ± 0.5°C. A complete record of streamflow, air and water temperature was obtained for all sites until 19th November 1969, when a flood destroyed the T_w probe at Barnard Castle.

ANNUAL AND SEASONAL REGIME

The mean annual values of air and water temperatures at the four stations, together with the range between the warmest and coldest month, are shown in Table 2. At all sites, the mean T_w was either the same or higher than T_a. This is a common feature in mid-latitudes and is due partly to the fact that,

Table 2.
Annual and seasonal temperature regime (°C).

Station	Mean Temperature		Maximum Monthly Range	
	Air	Water	Air	Water
Moor House	4.36	6.25	6.56	3.25
Dent Bank	6.95	7.64	7.42	2.66
Barnard Castle	6.95	8.27	6.86	1.72
Broken Scar	8.34	8.34	6.92	1.67

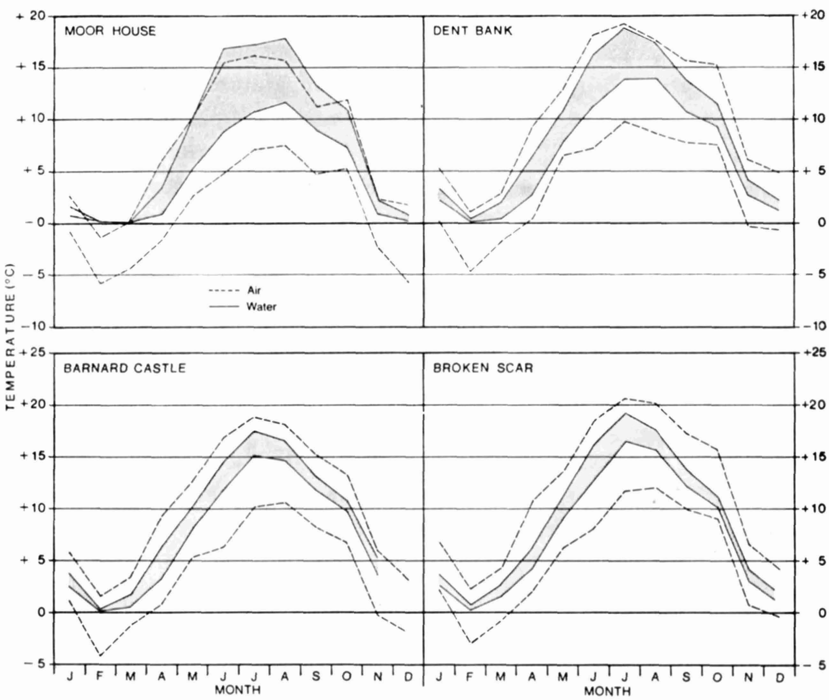

Fig. 2.
Mean monthly maximum and minimum air and water temperatures at the four stations along the Tees. The shaded areas indicate the range of monthly river temperature variation.

unlike the air temperatures, river temperatures do not normally fall below 0°C in winter whilst, during summer, water temperatures may be higher than the air for long periods in the day-time.

Both of these effects are most apparent in the upper parts of a river system where lower air temperatures and smaller stream flows combine to produce relatively high water temperatures throughout the year. The maximum monthly range of mean T_w at all stations was less than half the equivalent T_a variation but, whereas the air temperature range differed by less than 1°C between the sites, a progressive upstream increase in mean river temperature range caused the range to almost double from 1.67°C at Broken Scar to 3.25°C at Moor House.

Fig. 2 illustrates the thermal variation in terms of monthly mean maxima and minima. All stations show a comparable pattern of air temperature variation which is generally consistent with the normal atmospheric lapse rate with altitude up the valley. There is some evidence that both T_a and T_w are slightly low at Barnard Castle, possibly due to the incised nature of the valley at this point. At the two lower stations the seasonal march of T_w was closely related to the T_a and the monthly range between mean maximum and minimum water temperatures lay well within the range of air temperature variations throughout the year. However, at Dent Bank the T_w range increased markedly, both absolutely and relative to T_a, whilst at Moor House the water temperature lay outside the range of air temperatures in February and for several months in summer. The February anomaly was due to the fact that, at this high-altitude station, the mean T_a maximum reached only –1.47°C whereas the stream remained at 0°C for almost the entire month. The summer discrepancy, on the other hand, was caused by the large T_w range at Moor House due, in turn, to high maxima which exceeded air temperatures from June to September. In June and August, mean T_w maxima at Moor House exceeded the maxima at all other stations, despite the fact that equivalent air temperatures at Broken Scar were 3.13° and 4.42°C higher respectively. Thus, although there was a fairly regular decrease in mean and minimum T_w values with distance upstream, summer maxima increased with altitude.

DAILY TEMPERATURE VALUES

Examination of the daily T_a and T_w data for 1969 confirmed that, whilst the values were reasonably close for much of the year, the main differences occurred in mid-winter and mid-summer. A general emphasis has been placed on the analysis of daily maxima and minima rather than daily averages, since

Table 3.

Number of days during 1969 when T_W remained at 0°C throughout 24 hours.

Station	J	F	M	A	M	J	J	A	S	O	N	D	Year
Moor House	7	23	31	0	0	0	0	0	0	0	8	15	84
Dent Bank	0	2	1	0	0	0	0	0	0	0	0	0	3
*Barnard Castle	0	17	1	0	0	0	0	0	0	0	–	–	18
Broken Scar	0	7	0	0	0	0	0	0	0	0	2	1	10

* Incomplete data

the former are more sensitive physical variables and are also more significant from both an ecological and an economic standpoint.

Severe winter conditions were experienced at Moor House. For much of the time the headwaters were either a mixture of ice and water or fed mainly by snowmelt, and Table 3 shows that there were 84 days in the year when T_w remained at 0°C throughout the 24-hour period. From 9th February to 1st April, Moor House T_w remained continuously at 0°C, despite T_a occasionally rising to around 5°C.

At Dent Bank, milder conditions produced only three days in this period when the maximum T_w failed to rise above 0°C. Although winter maximum T_w normally showed a progressive downstream increase, this did not occur

Table 4.

Number of days when maximum T_W exceeded maximum T_a.

Station	J	F	M	A	M	J	J	A	S	O	N	D	Year
Moor House	6	21	20	7	18	25	23	30	26	8	13	10	207
Dent Bank	2	14	14	1	4	3	12	16	4	0	5	3	78
*Barnard Castle	3	4	7	1	4	1	6	5	1	1	7	–	40
Broken Scar	1	5	12	1	7	3	8	4	0	0	2	6	49

*Incomplete data.

during the coldest weather and both Barnard Castle and Broken Scar had more days with T_w maximum of 0°C than Dent Bank. On most days this was attributed to relatively large volumes of snowmelt entering the Tees via the tributaries upstream.

Generally, T_w maxima were lower than T_a maxima, but the reverse occurred frequently, as indicated in Table 4, and at Moor House the reverse was, in fact, the normal situation.

All stations showed a marked increase in the excess of T_w maximum over T_a maximum in winter and summer. The winter incidence was mainly due to freezing temperatures giving T_a maxima well below 0°C, whereas in summer, during dry weather, low streamflow conditions allowed T_w to rise to a higher temperature than the air. Since both low winter temperatures and low flows are mainly a feature of the upper basin, the higher stations had more days with relatively high T_w maxima. Overall, however, the largest daily differences between T_a and T_w occurred with winter minima, and, at all stations, nocturnal air minima fell at least 11°C below minimum river values.

The highest maximum water temperatures were consistently observed at the upper stations during dry, anticyclonic weather conditions when the decrease in river flows usually ensured that the highest maximum T_a and T_w values occurred on the same days. The absolute maxima were recorded during a short spell of stable weather in mid-July and it can be seen from Table 5 that, despite a T_a maximum almost 2°C higher at the lower station, Moor House had a T_w maximum over 1°C higher than Broken Scar.

The same pattern of high T_w maxima upstream is also evident in Table 6. The low incidence of T_w maxima greater than 20°C at Barnard Castle could well reflect the discharge of cold compensation water from the tributary reser-

Table 5.
Absolute maximum temperatures in 1969.

Station	Maximum Temperature °C	
	Air	Water
Moor House	25.2	25.0
Dent Bank	25.5	24.6
Barnard Castle	26.1	22.2
Broken Scar	27.0	23.9

Table 6.
Number of days when T_w maximum reached at least 20°C.

Station	Month					Year
	May	June	July	Aug	Sep	
Moor House	0	8	7	9	1	25
Dent Bank	0	7	12	11	0	30
Barnard Castle	0	0	6	1	0	7
Broken Scar	0	5	14	4	0	23

voirs, whilst slightly higher air temperatures give Dent Bank the advantage over Moor House.

During the year as a whole, there are many days when T_w maxima are higher upstream than at Broken Scar, as shown in Table 7.

STREAM FLOW EFFECTS

The influence of discharge was best observed on daily and hourly time-scales. Under low stream flow conditions a regular diurnal pattern of T_a and T_w variation emerged, as illustrated in Fig. 3 for an anticyclonic spell in mid-June 1969. At all sites, the relatively large diurnal range of T_a is reflected in the daily variation of T_w, which shows a general trend towards a reduced ampli-

Table 7.
Number of days when upstream stations recorded higher T_W maxima than Broken Scar.

Station	Month												Year
	J	F	M	A	M	J	J	A	S	O	N	D	
Moor House	0	0	0	1	5	19	6	16	9	8	0	0	64
Dent Bank	3	10	2	15	10	15	12	18	11	11	11	7	125
*Barnard Castle	12	0	0	16	3	0	0	3	0	1	7	–	42

* Incomplete data.

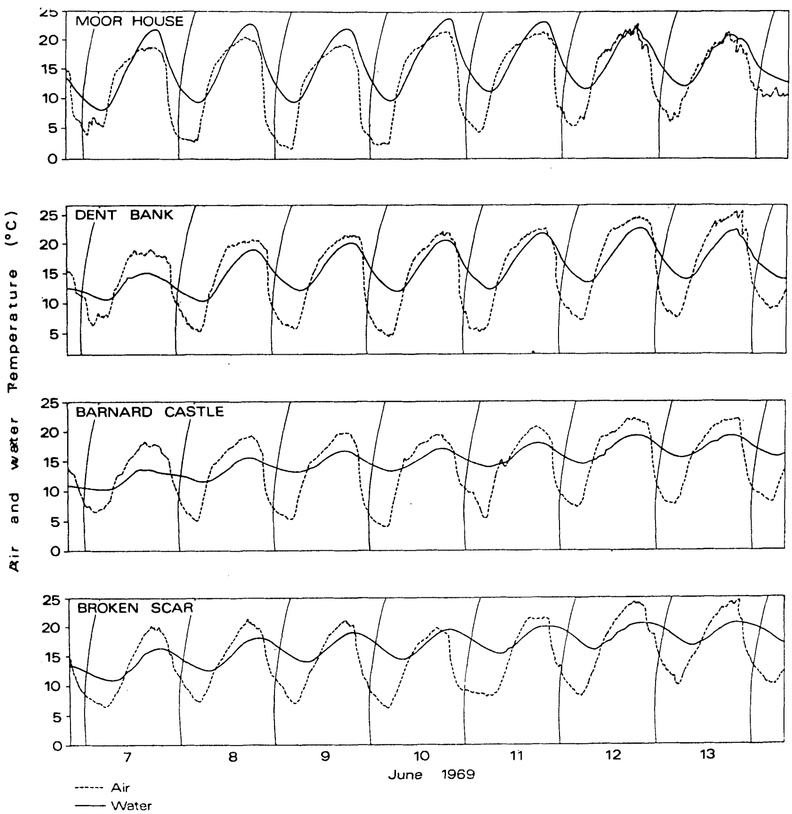

Fig. 3.

The regular diurnal cycle of air and water temperatures during an anticyclonic spell from 7–13 June, 1969.

tude and an increasing phase-lag with distance downstream, largely in response to the greater volume of discharge. These features are depicted more clearly in Fig. 4, which shows the mean hourly temperature fluctuations over the same 7-day period for the highest and lowest altitude stations. In Fig. 4a it can be seen that, although the mean air temperature range was slightly greater at Moor House than Broken Scar, the river temperature range was almost three times as high at 14°C compared with only 5°C at the lower station. Diurnal fluctuations may be reduced to non-dimensional terms by comparing mean temperatures for particular hours with the average daily temperature and expressing the differences as a percentage of the total daily fluctuation, as indicated in Fig. 4b. At Moor House there was a lag of only one

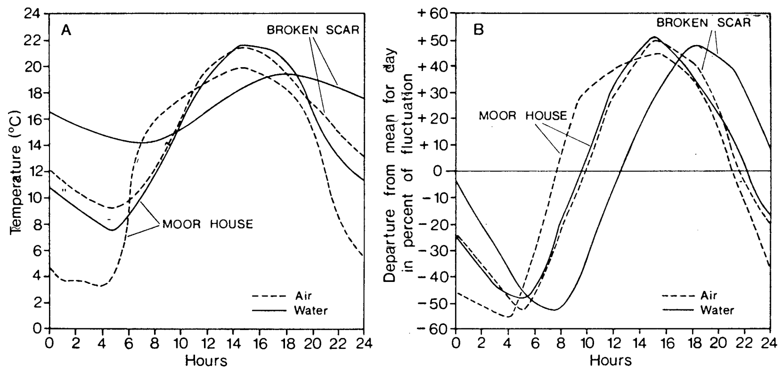

Fig. 4.
Mean hourly variation of air and water temperatures at Moor House and Broken Scar between 7–13 June, 1969.

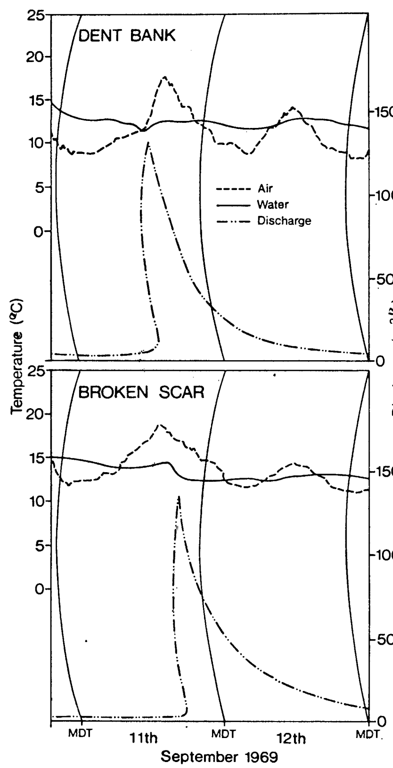

Fig. 5.
The effects of an isolated summer storm on river water temperatures at Dent Bank and Broken Scar.

hour between minimum T_a and T_w and the maxima were coincident at 1500 hours BST, whereas at Broken Scar both maxima and minima showed a lag of 2–3 hours behind air temperatures and T_w extremes on the upper river. At both stations the change from minimum to maximum T_a and T_w occurred during an interval of 10 to 11 hours compared with the change from maximum to minimum over a 13 to 14 hour period.

It was often found that a sudden increase in stream flow tended to produce a fall in stream temperature. Thus, during the summer, storm rainfall led to a fall in stream temperature if the volume of discharge increased at a faster rate than it could be heated in the stream channel. A good example occurred on 11th September 1969 when an isolated rainstorm caused the flood depicted in Fig. 5 for Dent Bank and Broken Scar. At Dent Bank, the hydrograph reached its peak in the early afternoon and, although T_w fell abruptly by about 1°C, the river temperature did recover in response to the increasing air temperature once the flood pulse had passed. When the flood reached Broken Scar almost 5 hours later, it caused a drop of some 3°C in T_w which had already begun to rise with the air temperature earlier in the day. During the winter half-year, a roughly comparable situation could be identified when an increase in air temperature beyond a critical threshold generated a snowmelt flood. An interesting example of this is shown in Fig. 6, where a large daily range of air temperature under anticyclonic conditions in spring produced a regular diurnal pattern of snowmelt down the river. At Moor House, T_a rose to between 5°–10°C each day but the relatively large volume of snowmelt maintained T_w at an almost constant 0°C. By the time the snowmelt had reached Broken Scar some 7 hours later, it had attained greater equilibrium with air temperatures and T_w on the lower river had a double maximum daily around 5°C. The first maximum occurred during the afternoon, directly following the diurnal air temperature cycle, but it can be seen that a second, marginally higher, rise was recorded around 0100 hours, coincident with the arrival of the daily melt water peak. This second rise was due solely to the downstream travel of water warmed earlier in the day by air temperatures which rose to nearly 15°C and emphasises the fact that, with an increasing volume of water in the lower reaches of a river, thermal changes are often effected more easily by mass transfer of the water than by heat transfer from the air.

A multiple regression exercise was conducted in order to establish the relative importance of air temperature and mean daily stream flow as factors influencing the daily variation of maximum and minimum T_w at Moor House and Broken Scar. The analysis was restricted to the three summer months (June, July and August) because of the ecological importance of summer temperatures, especially in relation to possible thermal pollution, and also because this

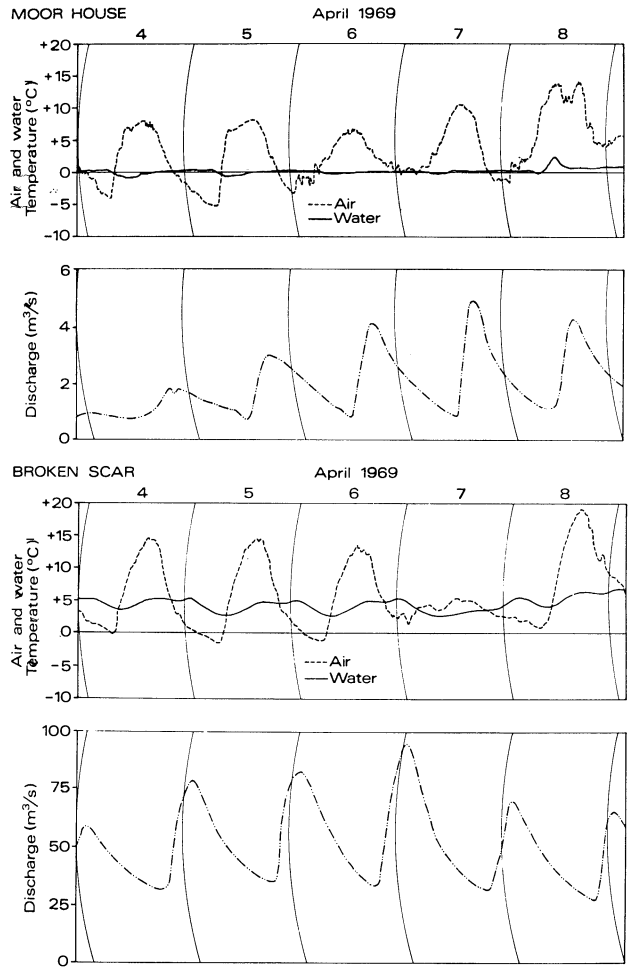

Fig. 6.
The effects of snowmelt discharge during spring on river water temperatures at Moor House and Broken Scar.

period avoided the more complex situations involving low temperatures and snowmelt. The results in Table 8 show that river temperatures were highly correlated with equivalent air temperatures at both stations, and the relationship between maximum values was highly significant.

Mean daily stream flow was inversely correlated with maximum and minimum T_W, and the slightly higher correlations for Broken Scar probably reflected the less flashy discharge characteristics at the lower station. At both

Table 8.
Comparison of correlation coefficients with T_w as the dependent variable.

Moor House	Multiple r	r^2	r
T_a maximum	0.918*	0.843	0.918*
Streamflow	0.923*	0.852	-0.465*
T_a minimum	0.769*	0.592	0.769*
Streamflow	0.805*	0.648	-0.281
Broken Scar	**Multiple r**	**r^2**	**r**
T_a maximum	0.822*	0.676	0.822*
Streamflow	0.847*	0.717	-0.495*
T_a minimum	0.776*	0.603	0.776*
Streamflow	0.827*	0.684	-0.523*

*Significant at the 0.1 % level.

stations, the multiple correlation coefficient accounted for over 70 per cent of the variation of daily maximum river temperatures and the explanation level reached 85 per cent at Moor House. The fluctuation of minimum T_w values was less well explained, and the variation actually accounted for ranged from 68 per cent at Broken Scar to 64 per cent at Moor House.

CONCLUSION

This investigation has attempted to show how water temperature variations along the length of a river may be related to changes in air temperature and discharge. It has been demonstrated that, although air temperature is a primary influence on river temperatures, the effects are by no means constant, either throughout the year or with distance along the river. In particular, the range of river water temperature variation increased markedly upstream in response to lower discharge and, despite a general reduction in air temperature with altitude, the highest water temperatures in summer were invariably recorded in the upper basin. After allowing for the particular conditions which prevailed when stream flow was strongly controlled by either storm rainfall or snowmelt, statistical analysis has suggested that, for an area where stream temperatures are unavailable, a first approximation to the range of thermal behaviour of a river can be based on air temperature and discharge data.

ACKNOWLEDGMENT

The author wishes to record that this work was undertaken with the aid of a research grant from the Natural Environment Research Council.

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Received February 1975.

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