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Scale-related water temperature behavior

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Abstract Studies of water temperature at two scales that hitherto have been relatively neglected are presented. Long-term data available for 10 Austrian rivers through the twentieth century show significant rises in monthly mean water temperature for the period 1901-1990 in seven cases. The magnitude of the increase varied from 0.47 to 1.26°C and was more closely related to increasing human impact over the present century than to changing hydrometeorological conditions. Detailed measurements for 11 study reaches in the River Exe, Devon, UK, reveal considerable local-scale variability in the composition of the river heat budget. Inter-reach contrasts in the importance of different processes by which heat is lost or gained are particularly related to channel morphology, valley topography, riparian vegetation, substratum nature and streamflow.

INTRODUCTION

The nature and controls of water temperature behavior depend on the spatial and temporal perspective from which the stream or river is viewed. In a spatial sense, global patterns of variation in river temperature are strongly controlled by factors such as latitudinal position, altitude and continentality. At regional and catchment scales, hydrologic conditions exert an important influence, and local differences in receipt of solar radiation cause variations in water temperature along river reaches (Ward, 1985). In a temporal sense, river temperature follows a clear annual cycle in response to the seasonal march (Ward, 1963), whereas marked changes in stream temperature over a few hours may be generated by the diurnal cycle of solar radiation receipt (Rutherford *et al.*, 1993), or during storm events by the arrival of runoff from different sources (Shanley & Peters, 1988).

The fundamental control that air temperature exerts over water temperature varies with the length of time and size of river system studied. For example, results from the Straight River, near Park Rapids, Minnesota, USA, reveal a close and sensitive relation between air and water temperature when data averaged over week periods were considered, but a much more scattered and less sensitive relation when 2-h data were employed (Stefan & Preud'homme, 1993). The same study showed that water temperature variations increasingly lag behind those of air as river size increases.

Although previous investigations indicated the importance of spatial and temporal perspective in understanding water temperature in streams, some time and space scales have been neglected. The latter include the extent of long-term changes in river temperature, and the nature of local variability in the heat-budget environment of water courses. Water temperature variations at these scales are the subject of recent investigations in Austrian and UK rivers and are reported here.

LONG-TERM TRENDS IN RIVER TEMPERATURES

Monthly mean water temperature data are available from the State Hydrographic Service for 10 Austrian rivers, 1901-1990. The data are mainly daily observations and relate to a range of conditions of drainage area, elevation and mean water temperature (Table 1). The non-parametric seasonal Kendall test and seasonal Kendall slope estimator (Hirsch *et al.*, 1982) were used to determine the significance and magnitude of monotonic trends in water temperature during the period as a whole. Trends for individual months were established by linear regression analysis.

Nature of trends

A significant increase in monthly mean water temperature was evident for seven rivers (Table 2), but the magnitude of the rise varied from 0.47°C in the River Gail at Federaun to 1.26°C in the River Traun at Wels. No significant trend in monthly mean values was detected in the smallest catchments, the River Krems at Kremsmünster and the River Salzach at Mittersill, nor downstream in the River Salzach at Salzburg.

At the main stream sites of Schärding on the River Inn, and Linz and Ybbs on the

Table 1 Study sites on Austrian rivers.

Study site	Drainage area (km^2)	Elevation (m)	Mean annual water temperature (°C)
Krems at Kremsmünster	142.4	338.8	8.4
Salzach at Mittersill	591.2	783.0	4.8
Lieser at Spittal	1 036.0	549.1	6.9
Gail at Federaun	1 304.8	499.5	7.9
Traun at Wels	3 498.6	304.7	9.2
Salzach at Salzburg	4 427.3	408.1	7.1
Mur at Graz	6 988.9	340.4	8.2
Inn at Schärding	25 663.8	299.8	8.3
Danube at Linz	79 490.1	247.7	9.2
Danube at Ybbs	92 464.2	212.2	9.4

Table 2 Trends in water temperature, 1901-1990, based on application of the seasonal Kendall test and slope estimator (Hirsch *et al.*, 1982) to monthly mean values.

Study site	Slope of trend	Significance of trend (*P*)	Change over study period (°C)
Kremsmünster	0.000 00	0.303	0.00
Mittersill	0.000 00	0.961	0.00
Spittal	0.009 68	0.000	0.87
Federaun	0.005 26	0.000	0.47
Wels	0.014 04	0.000	1.26
Salzburg	0.000 00	0.140	0.00
Graz	0.007 27	0.000	0.65
Schärding	0.006 01	0.000	0.54
Linz	0.008 93	0.000	0.80
Ybbs	0.011 11	0.000	1.00

River Danube, rises in water temperature were strongest in October and November, exceeding 2.0°C in some cases (Table 3). In contrast, these stations exhibited no significant trends in May through July. Significant midsummer temperature change also was lacking for the River Mur at Graz and the River Gail at Federaun. Trends were insignificant in most months at the River Krems at Kremsmünster and the River Salzach at Mittersill; these sites had a *decrease* in mean temperature of more than 0.5°C over the study period for some months in spring (Table 3). Significant upward trends were recorded for all months for the River Traun at Wels, and for April through October for the River Lieser at Spittal. Rises at the latter site approached 3°C for July and August. The River Salzach at Salzburg exhibited significant and relatively strong *decreases* of 0.8 to 1.0°C for mean water temperature in midsummer, but significant rises were observed for most winter months.

Potential controls

It is tempting to correlate the significant rise in water temperature recorded during the twentieth century in Austrian rivers to climate change. Long-term change in monthly mean air temperatures monitored at sites close to some study rivers, however, do not indicate equivalent increases over the study period nor similar change for individual months (Webb & Nobilis, 1995). There is evidence that higher mean annual river temperatures in recent years in the study rivers is related more to the mildness of winter conditions than to high summer temperatures; it is also likely that increasing human impact has had an important role in raising Austrian river temperatures during the present century.

Since 1900, heated effluent to rivers has risen, and there have been major schemes to canalize and regulate main rivers (Liepolt, 1972; Dokulil *et al.*, 1993). In 1955

Table 3 Trends in water temperature for individual months, 1901-1990, based on linear regression of monthly mean values.

Study site	January	February	March	April	May	June	July	August	September	October	November	December
Kremsmünster	−	+	−	−	−0.82	−	−	+	+0.53	+	+	−
Mittersill	+	−	**−0.64**	−0.61	−	−	+0.53	**+0.73**	**+0.67**	+	+0.58	−
Spittal	+	+	+	**+1.00**	**+1.19**	**+1.26**	**+2.73**	**+2.89**	**+2.16**	**+1.19**	+	−
Federaun	**+0.88**	**+1.84**	**+1.35**	**+0.62**	+	−	+	+0.56	+0.59	+	−	−
Wels	**+1.16**	**+1.30**	**+0.71**	**+1.21**	**+1.50**	**+1.14**	**+1.32**	**+1.16**	**+1.60**	**+1.39**	**+1.50**	**+0.90**
Salzburg	**+0.74**	**+1.17**	**+0.77**	+	−0.66	**−1.00**	**−1.01**	**−0.79**	+	**+0.63**	**+0.98**	+0.51
Graz	**+1.02**	**+1.53**	+0.67	**+0.67**	+	−	−	+	**+1.04**	**+1.03**	**+1.10**	**+0.72**
Schärding	+	+0.72	+	+0.62	+	+	+	**+0.77**	**+1.04**	**+1.27**	**+1.26**	+0.55
Linz	+0.76	**+1.28**	+	+	+	−	+	**+0.94**	**+1.51**	**+1.74**	**+2.03**	**+1.28**
Ybbs	+0.70	**+1.32**	+	+0.66	+	+	+	**+1.37**	**+1.89**	**+2.15**	**+2.00**	**+1.19**

+ = increase; − = decrease; bold figures indicate change significant at $P < 0.05$, other figures indicate change significant at $P < 0.10$

through 1984, for example, nine barrages were built across the River Danube between the German Border and Vienna to generate hydroelectric power. The dams impound extensive sections where water velocity and flow residence time are reduced and river heating is encouraged. At the main river sites on the Inn and Danube, the greatest rises in temperature occurred in the low-water period of October and November. River discharge and thermal capacity are lowest at this time and the water courses are sensitive to impoundment and other human impacts. The influence of channel modification on water temperature trends is seen also in the strong rises of summer water temperatures in the River Lieser. Since 1977, flow has been diverted from 130 km^2 of the upstream catchment area, which has removed a source of cold runoff during the meltwater season and has reduced flow volume and thermal capacity of the channel below the diversion. Thus, the river at Spittal has been sensitive to summer solar heating in the last 10 years of the study period. The unusual trends recorded at Salzburg may reflect the influence of cool water discharges from a nearby generating plant.

Long-term river temperature trends in Austria may have been influenced by natural catchment features. Large lakes (Attersee and Traunsee) in the River Traun basin may magnify the effects of small air temperature changes in the study period and cause significant water temperature rises for every month at Wels. In contrast, less human modification and proximity of glacial runoff may explain the weak development of water temperature trends at Kremsmünster and Mittersill.

LOCAL VARIABILITY IN RIVER HEAT BUDGETS

Detailed hydrometeorological measurements during 495 days in 18 study periods were used to establish non-advective heat energy budgets of 11 study reaches in the River Exe, Devon, UK (Table 4). Net radiation in the wavelength range 0.3-60 m was determined using a radiometer mounted over the water surface, and associated heat flux was calculated for each reach taking into account vegetational shading. Evaporation from and condensation to the water surface were calculated from on-site measurements of wind speed, humidity and air temperature using a Penman-type equation, and associated heat losses and gains from the water surface were computed by reference to the latent heat of vaporization and the specific weight of water. Sensible heat transfer between the water course and overlying air was determined as the product of evaporative flux and the Bowen ratio. Conductive heat exchange with the river bed was computed from the measured temperature gradient in the substratum, the thermal conductivity of bed material and the calculated proportion of radiation absorbed by the bed. Energy added to the water course from fluid friction was calculated from flow volume, and channel width and gradient (Theurer *et al.*, 1984).

RESULTS

Averaging the information from the 11 study reaches reveals that net radiation, friction, sensible heat transfer, condensation and bed conduction contributed 56.0, 22.2, 13.2, 5.8 and 2.8%, respectively, of the non-advective heat energy gain to the River Exe, whereas net radiation, evaporation, sensible heat exchange and bed conduction accounted for 48.6, 30.4, 10.6 and 10.4%, respectively, of the non-advective heat loss.

Table 4 Characteristics of study reaches in the Exe basin.

Study reach	National Grid reference	Drainage area (km^2)	Channel length (m)	Channel slope (mm^{-1})	Valley orientation	Riparian characteristics
R. Barle Tributary 1	SS 722394	0.39	28.0	0.0290	S-N	Moorland, rough grazing
R. Barle Tributary 2	SS 722394	0.40	30.0	0.0480	S-N	Moorland, rough grazing
Black Ball Stream	SS 837306	1.85	30.0	0.0320	W-E	Moorland, rough grazing
Jackmoor Brook	SX 902988	10.18	30.0	0.0030	N-S	Pasture, some trees
R. Creedy Tributary	SS 815062	11.11	31.0	0.0035	NE-SW	Dense deciduous woodland
R. Pulham	SS 959297	19.06	31.0	0.0229	NW-SE	Pasture, some trees
R. Haddeo 1	SS 961294	28.67	30.0	0.0086	E-W	Pasture, some trees, 0.3 km downstream from reservoir
Iron Mill Stream	SS 932207	32.89	30.0	0.0067	W-E	Dense deciduous woodland
R. Haddeo 2	SS 952294	51.48	24.0	0.0020	E-W	Pasture, some trees, 1.5 km downstream from reservoir
R. Culm 1	ST 021056	178.70	32.0	0.0050	NE-SW	Pasture, some trees
R. Culm 2	ST 011041	180.47	36.0	0.0016	E-W	Cattle pasture

The dominance of radiative fluxes in the heat budgets for the River Exe has been observed in several studies (e.g. Brown, 1969; Sinokrot & Stefan, 1993), but data from this investigation (Table 5) also highlight considerable inter-reach variability in the importance of different heat flux components. The contribution of radiation to heat gain was greatest (> 80%) during summer in mainstream channels such as the River Culm, and in exposed upland moorland tributaries such as the Black Ball Stream. This source of heat energy, however, was much less significant for reaches such as River Haddeo 2 and River Pulham that have strong topographic shading, especially during autumn and winter. At these sites, the dominant source of non-advective heat energy was friction, which reflects steep channel gradients and high flow during winter. The contribution of frictional energy is least, < 5%, in low-gradient channels, such as the Jackmoor Brook and River Culm, and during summer months.

Channel shading by riparian vegetation reduces radiation as a source of heat energy to the water course. This effect was evident both in the summer (Iron Mill Stream) and winter (River Creedy tributary) when deciduous trees provided shade, but also occurred, as in the Jackmoor Brook, when low-growing brambles and weeds largely overgrew a small channel. Variation in channel morphology over short distances may markedly influence radiation receipt at the water surface. This effect is illustrated by a comparison of two reaches of a small upland and moorland stream (River Barle Tributary). The upstream site on this tributary (reach 1) has a relatively narrow and deep shape, which restricted the amount of radiation it received compared with a site (reach 2) that is 30 m downstream and has a wider and shallower cross section (Table 5).

The heat energy received by the study reaches from condensation and through bed conduction was generally low. However, the former process accounted during an autumn measuring period for more than 30% of the daily average non-advective heat gain in the regulated River Haddeo close to the dam, where water temperature is frequently higher than that of the overlying air in autumn and winter. The latter process was most significant in the Jackmoor Brook, where sandy bed deposits encouraged conductive heat transfer to the stream. The gain of heat energy through sensible heat transfer tended to be most important during summer and at those sites that were shaded by vegetation (Jackmoor Brook, Iron Mill Stream) or channel morphology (River Barle Tributary 1).

Reflection of incoming radiation and back radiation from the water surface are important components in heat loss from all study reaches (Table 5). Radiation was the greatest proportion of non-advective heat loss in summer in the forested reach (Iron Mill Stream), where low wind speeds reduced the effects of evaporation in removing heat energy from the channel. Warm water temperatures in the regulated River Haddeo also promoted high heat losses through back radiation in autumn. For the same reason, loss of heat through sensible transfer to the air was of most importance in the regulated river close to the dam during autumn and accounted for 20% of the average daily non-advective losses. Evaporative loss was generally highest in the exposed and windier upland catchments, whereas loss of heat through bed conduction was highest at sites most exposed to solar radiation (River Culm, Black Ball Stream, River Barle Tributary 2).

CONCLUSIONS

Studies of two facets of water temperature behavior at scales hitherto relatively little

Table 5 Average daily percentage contribution of individual flux components to the gain (+) and loss (−) of non-advective heat energy in the study rivers.

Study reach	Period	Radiation		Evaporation		Sensible heat		Bed conduction		Friction
		+	−	+	−	+	−	+	−	+
R. Barle Tributary 1	Summer 1992	58.0	40.0	0.1	47.7	32.4	0.7	0.5	11.6	9.0
R. Barle Tributary 2	Summer 1992	70.4	38.5	1.3	31.6	18.8	1.5	1.3	28.4	8.2
	Spring 1993	75.2	45.2	1.2	32.8	10.2	9.0	1.7	13.0	11.7
Black Ball Stream	Summer 1992	83.0	35.7	0.7	23.4	11.7	5.8	0.5	35.1	4.1
	Spring 1993	72.2	30.1	0.6	44.3	9.0	14.1	0.8	11.5	17.4
Jackmoor Brook	Summer 1992	43.5	48.8	6.0	41.0	38.2	7.4	10.3	2.8	2.0
	Winter 1993	76.2	55.0	0.7	31.2	17.4	7.1	2.6	6.7	3.1
R. Creedy Tributary	Autumn 1993	20.2	42.9	11.0	33.2	23.8	15.7	4.4	8.2	40.6
R. Pulham	Winter 1993	14.1	70.6	1.5	20.7	7.0	8.4	4.9	0.3	72.5
R. Haddeo 1	Autumn 1992	52.3	56.5	30.7	21.8	3.6	20.0	0.4	1.7	13.0
	Summer 1993	77.7	40.8	4.3	38.3	10.0	8.9	1.9	12.0	6.1
Iron Mill Stream	Summer 1992	70.1	66.2	2.9	21.5	16.4	6.3	0.6	6.0	10.0
	Summer 1993	74.0	76.2	1.1	15.1	4.3	5.5	2.4	3.2	18.2
R. Haddeo 2	Autumn 1992	2.1	69.7	3.2	17.3	5.1	12.9	8.2	0.1	81.4
	Summer 1993	60.8	33.7	1.5	34.4	7.9	9.7	2.0	22.2	27.8
R. Culm 1	Autumn 1993	64.5	37.4	0.1	36.2	7.9	10.7	1.3	15.7	26.2
R. Culm 2	Summer 1992	86.9	53.1	0.3	19.4	9.8	3.4	1.3	24.1	1.7
	Autumn 1993	60.9	38.4	0.1	19.1	7.0	10.2	0.0	32.3	32.0

investigated have been reported. Information from Austrian rivers shows significant long-term increases in water temperature during the twentieth century, but also reveals inter-catchment variability in the strength of the upwards trend. These long-term changes do not appear to be a simple function of changing hydrometeorological conditions and reflect increasing human impact on European river systems since 1900. At the scale of a single river system, detailed on-site measurements in the River Exe, Devon, UK, show how composition of the river heat budget may vary considerably between reaches. Local conditions of channel morphology, valley topography, riparian vegetation, substratum nature and streamflow strongly influence the processes by which heat is gained or lost by the river channel.

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REFERENCES

Brown, G. W. (1969) Predicting temperatures of small streams. *Wat. Resour. Res.* **5**, 68-75.

Dokulil, M. T., Humpesch, U. U., Schmidt, R. & Pöckl, M. (1993) Limnologie: Auswirkungen geänderter Klimimaverhältnisse auf die Ökologie von Oberflächengewässer in Österreich. In: *Anthropogene Klimaänderungen: Mögliche Auswirkungen Auf Österreich — Mögliche Massnahmen In Österreich.* Österreichische Akademie der Wissenschaften.

Hirsch, R. M., Slack, J. R. & Smith, R. A. (1982) Techniques of trend analysis for monthly water quality data. *Wat. Resour. Res.* **18**, 107-121.

Liepolt, R. (1972) Uses of the Danube River. In: *River Ecology and Man* (ed. by R. T. Oglesby, C. A. Carson & J. A. McCann), 233-249. Academic Press, New York.

Rutherford, J. C., Macaskill, J. B. & Williams, B. L. (1993) Natural water temperature variations in the Lower Waikato River, New Zealand. *NZ J. Marine & Freshwat. Res.* **27**, 71-85.

Shanley, J. B. & Peters, N. E. (1988) Preliminary observations of streamflow generation during storms in a forested Piedmont watershed using temperature as a tracer. *J. Contaminant Hydrol.* **3**, 349-365.

Sinokrot, B. A. & Stefan, H. G. (1993) Stream temperature dynamics: measurements and modeling. *Wat. Resour. Res.* **29**, 2299-2312.

Stefan, H. G. & Preud'homme, E. B. (1993) Stream temperature estimation from air temperature. *Wat. Resour. Bull.* **29**, 27-45.

Theurer, F. D., Voos, K. A. & Miller, W. J. (1984) Instream water temperature model. *US Fish & Wildlife Service Instream Flow Information Paper* **16**.

Ward, J. C. (1963) Annual variation of stream water temperature. *J. Sanit. Engng Div. ASCE* **89**(SA6), 1-16.

Ward, J. V. (1985) Thermal characteristics of running waters. *Hydrobiologia* **125**, 31-46.

Webb, B. W. & Nobilis, F. (1995) Long term water temperature trends in Austrian rivers. *Hydrol. Sci. J.* **40**, 83-96.