JOURNAL OF HYDROLOGY
NEW ZEALAND

Published twice annually by the New Zealand Hydrological Society

Volume 21 1982 Number 1

EMPIRICAL AND THEORETICAL MODELS TO ISOLATE THE EFFECT OF DISCHARGE ON SUMMER WATER TEMPERATURES IN THE HURUNUI RIVER

J. B. Hockey, I. F. Owens and N. J. Tapper

Department of Geography, University of Canterbury, Christchurch

ABSTRACT

The control exerted over summer water temperatures in the Hurunui River by discharge and meteorological factors was investigated firstly, by regression analysis of available historical data and secondly, by applying a simple energy budget model. Statistical analysis showed that under natural flow, water temperatures are inversely related to discharge and directly related to maximum air temperature, though there was considerable scatter in the relationship. The energy budget model was quite successful in predicting temperature variations at the downstream end of a 32 km braided reach for a limited range of moderate discharges, and was used to predict changes in summer water temperature resulting from decreases in discharge below this range. Rates of increase of maximum water temperature predicted by this method and rates of temperature change determined from the statistical analysis were both approximately equal to 0.1°C per 1 m^3/s decrease of discharge for low flows.

INTRODUCTION

During December 1979, an investigation was begun to ascertain controls of summer water temperatures in the Hurunui River, North Canterbury (Fig. 1). This research was undertaken for the Ministry of Works and Development (MWD) to judge the likely thermal consequences of water abstractions for an irrigation scheme on the Balmoral Plains (Hockey *et al.*, 1980). Work elsewhere, as reviewed for instance by Gibbons and Salo (1973), has shown that river temperatures are related to both meteorological and flow variables. The objective of this paper is to examine two methods of assessing these influences. The first involves a statistical analysis of the effects of meteorological and flow variables on river temperature under natural flow conditions, while the second uses an energy

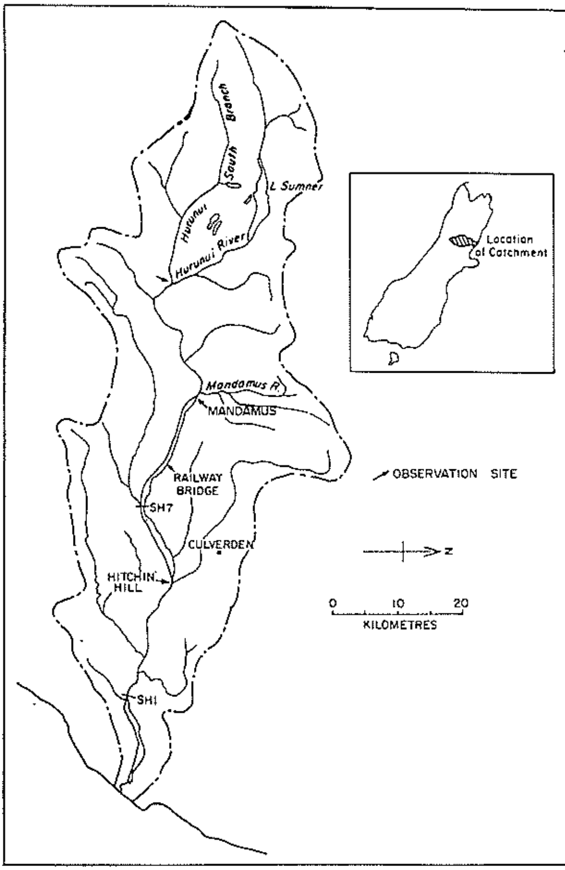

FIG. 1—Location Map.

balance model to predict the effect of decreased discharge on river temperature.

STATISTICAL ANALYSIS OF HISTORICAL DATA

Both the MWD and the North Canterbury Catchment Board routinely measure temperatures following gauging of river flows. Their data give spot observations at gauging sites at various times of the year normally between 1000 and 1500 hrs over a period of 20 years. The largest number of summer observations is available for the site at Mandamus (Fig. 1), with 41 measurements on known dates between 1957 and 1979. Data for the months December to March summarised in Table 1, show relatively little month-to-month variation compared to the variation within each month.

Previous work as summarised by Gibson and Salo (1973), suggests that

TABLE 1—Summary of water temperatures (°C) at end of gaugings at Mandamus, 1957-1979.

Month	December	January	February	March
Number of Observations	6	12	9	14
Mean	12.6	15.3	16.2	14.8
Standard deviation	2.0	3.4	2.6	2.4
Range	6.1	10.0	8.2	6.8

solar radiation and discharge would be the process variables most likely to explain variation in river temperature. Unfortunately, however, solar radiation is not recorded at the nearest meteorological station at Balmoral State Forest. Consequently, daily maximum air temperature, a variable which responds to variations in total solar radiation (Landsberg, 1960, p. 148) was used as a surrogate. This relationship may break down in synoptic conditions leading to fohn winds but in the absence of more suitable data, there was no alternative procedure. These data also present problems for statistical analysis because they do not constitute a truly random sample. In addition, because the time of observation was restricted to a few hours, the influence of the daily temperature cycle could not be isolated. Similar problems have been discussed by Grant (1977).

The data were subjected to a regression and correlation analysis. Water temperature (T_W) and discharge (Q) are plotted in Fig. 2 and water tem-

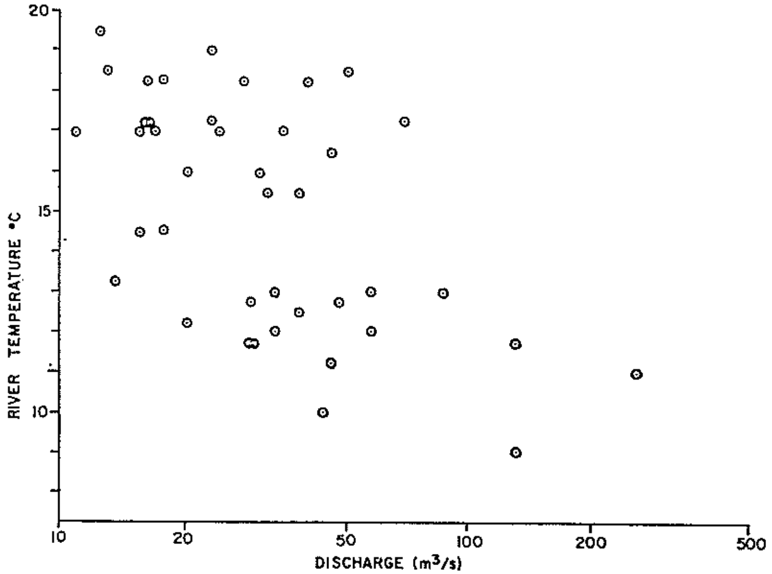

FIG. 2—Discharge vs water temperature at end of gaugings at Mandamus, December-March, 1957-1970.

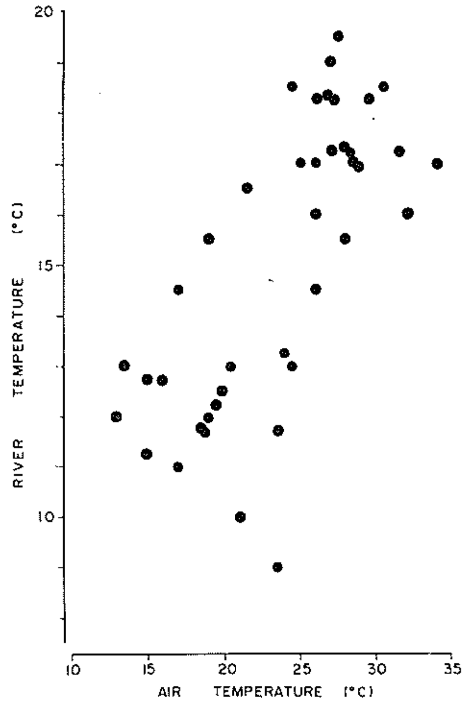

FIG. 3—Maximum daily air temperature at Balmoral vs water temperature at end of gaugings at Mandamus, December-March, 1957-1979.

TABLE 2—Correlation analysis.

	T_a(max)	ln(Q)	T_w
T_a(max)	1.00		
ln(Q)	—0.33	1.00	
T_w	0.72	—0.56	1.00

T_a(max)=maximum daily air temperature at Balmoral
ln(Q)=natural logarithm of discharge
T_w=water temperature at Mandamus

perature and an air temperature variable (T_a(max)) are plotted in Fig. 3 Correlation analysis shows that these independent variables explain 30% and 50% of the water temperature variance respectively (Table 2). The correlation matrix also shows a weak inverse relationship between the independent variables such that the multiple regression equation

$$T_w = 12.6 + 0.31T_a(\max) - 1.5\ln(Q) \quad (1)$$

explains 62% of the variance in water temperature.

Although this procedure specifies the influence of maximum air temperature and discharge on water temperature in general terms, it was considered unsatisfactory. Firstly, a model based on statistical averages relating only to natural flows may not be helpful in determining the consequences of water abstraction on a particular day. Secondly, a more precisely defined water temperature variable, such as the maximum temperature reached during the diurnal cycle, would be more useful for management purposes. Finally, the empirical model was concerned with water temperatures at Mandamus, whereas the proposed water abstraction would affect the river downstream from that site. This led to consideration of a theoretical model based on the energy balance.

PHYSICAL PROCESS MODELLING

The Model

Energy balance models have commonly been used in meteorology and climatology to predict such variables as surface temperature. They have also been applied to moving and stationary water bodies to predict water temperatures (Raphael, 1962; Edinger *et al.* 1968; Brown, 1968; Morse, 1972; Brocard and Harleman, 1976; Troxler and Thackston, 1977).

The variation of river temperature in time and one space dimension can be expressed (Paily *et al.,* 1974) as:

$$\frac{\delta T}{\delta t} + \frac{u \delta T}{\delta x} - \frac{E \delta^2 T}{\delta x^2} = \frac{\phi^*(T)}{\rho c_p h} \qquad (2)$$

where: T = river temperature (°C)
t = time (s)
x = downstream distance (m)
u = mean river velocity (m/s)
E = longitudinal dispersion (m^2/s)
ρ = river water density (kg/m^3)
c_p = specific heat of river water (J kg^{-1} °C^{-1})
h = mean river depth (m)
$\phi^*(T)$ = river surface temperature exchange (W/m^2), a function of T.

The longitudinal dispersion term, which reflects cross-sectional variations in temperature and velocity, can be ignored if pulse injections of heat are not involved (Brocard and Harleman, 1976, p. 230). Equation (2) was further simplified in this application to describe the temperature variation of small parcel water over time by:

$$\frac{dT}{dt} = \frac{\phi^*(T)}{\rho c_p h} \qquad (3)$$

This allowed calculation of the change of temperature of a series of parcels whose initial temperature at the upstream site was known. Temperature of these parcels at the downstream site was then calculated using information about average stream velocity.

Calculation of $\phi^*(T)$ requires consideration of the following energy transfers:

—incident shortwave radiation
—reflected shortwave radiation
—downward longwave radiation
—reflected longwave radiation
—upward longwave radiation
—evaporative heat transfer
—convective/conductive heat transfer

These energy transfers were calculated from meteorological information using the equations given by Brocard and Harleman (1976), Dozier and Outcalt (1979) and Paily et al. (1974) which are outlined in the Appendix.

The Study Reach

Downstream from Mandamus, the Hurunui flows for 32 km in a wide braided gravel channel across the Balmoral Plains to Hitchin Hill. A water thermograph was installed at Mandamus to give a continuous trace of water temperature, while hourly readings were taken manually at either the Railway Bridge or Hitchin Hill (Fig. 1). Discharge was obtained for the MWD stage recorder at Mandamus. Meteorological data required in the calculation of energy transfers (screen temperature, relative humidity, air pressure and wind speed) were obtained at a station established at the Railway Bridge.

Channel cross-section geometry was obtained from surveys at several points along the reach (Fig. 4), which also allowed the average velocity to be estimated. The variation of width, depth and velocity with changes in discharge is described by at-a-station hydraulic geometry (Leopold *et al.*, 1964, p. 215). Unfortunately, there is little information available on hydraulic geometry for braided streams and New Zealand studies (Mosley, 1979; Griffiths, 1980) relate only to downstream variations at particular discharge levels. Consequently, variation of mean depth and mean velocity with discharge had to be estimated by assuming a log velocity vs

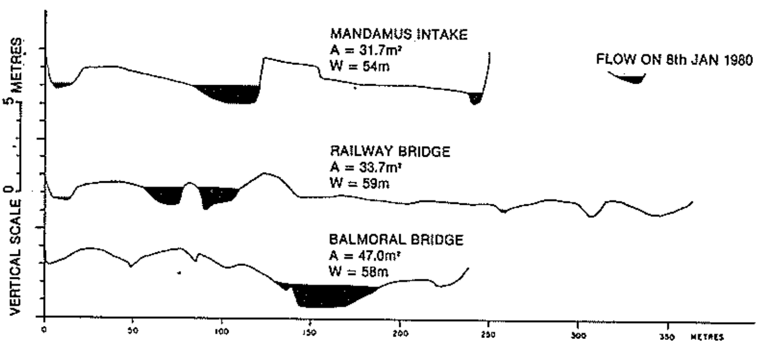

FIG. 4—Representative surveyed cross-sections of the Hurunui River on the Balmoral Plain. Discharge=70 m^3/s.
A=cross-section area (m^2)
W=stream width (m)

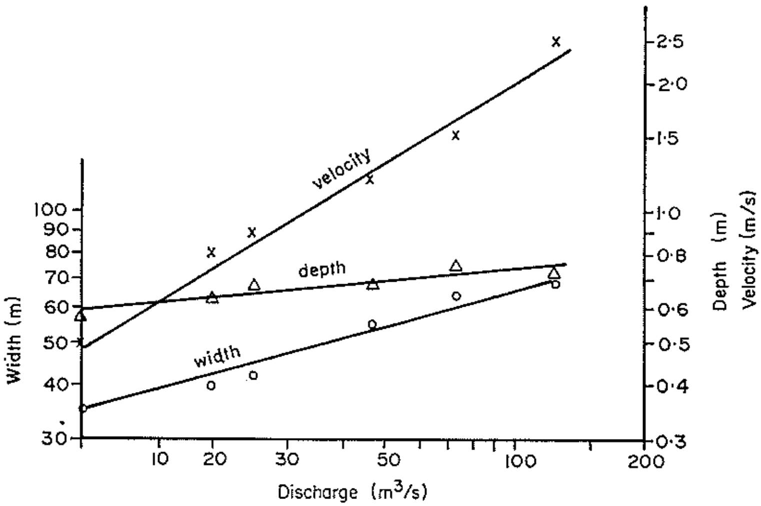

FIG. 5—At-a-station hydraulic geometry used for estimating changes in velocity and depth with discharge.

log discharge relationship (Fig. 5) and calculating appropriate changes in mean depth and mean width for given discharge levels using the surveyed cross-sections. A check on these values is then given by the fact that the slopes of the lines in Fig. 5 must sum to unity (Leopold *et al.*, 1964, p. 217). Subsequent studies in New Zealand have suggested that the slope value of velocity used here may be slightly high and the depth value too low (Mosley, pers. comm.). If this is the case, mean depths at low flows will be overestimated and the model will give conservative estimates of maximum water temperatures.

Validation of the Model

To test the model it was used with data collected on three different days in 1979: 31 December, a relatively clear day; 27 December, an overcast day; and 21 December, a partly cloudy day. In the first two examples, the model was run over the full 32 km length of the Hurunui River from Mandamus to Hitchin Hill, while on 21 December, the model was run only for the 12 km length to the Railway Bridge site. For all cases, modelling time is expressed as true solar time which, for this location, is approximately 29 minutes later than NZST.

The modelled temperatures for 31 December show a close similarity with measured temperatures, particularly in the prediction of maximum temperatures to within 0.1°C (Fig. 6). The largest discrepancy is in the rate of increase in temperature and the time of predicted maximum temperature. On the overcast day, the model slightly overestimates temperature for the period during which temperatures were observed at Hitchin Hill, although the error is never greater than 0.5°C. For 21 December, the agreement is not as good, which reflects the difficulty of estimating cloud effects on radiation inputs on this, a partly cloudy day.

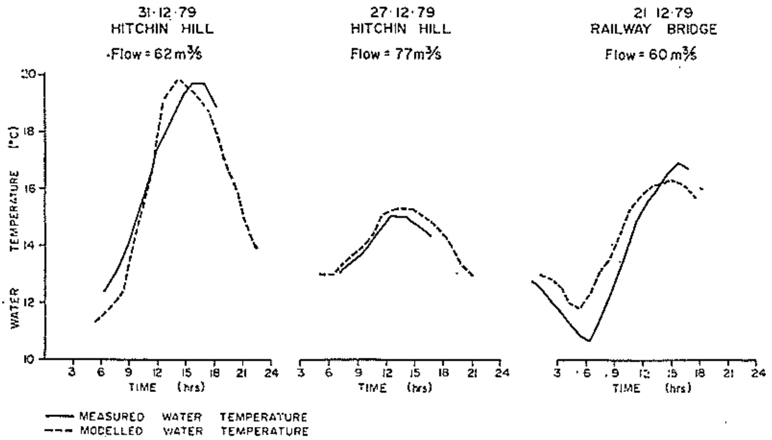

FIG. 6—Observed and simulated river temperatures for 31 December (clear), 27 December (overcast) and 21 December (partly cloudy).

Given the agreement between observed and predicted temperatures, it seems reasonable to suggest that the model represents the physical process involved quite well, and that extrapolation beyond the validation range could be attempted as a first approximation for cloudless sky, the condition associated with highest temperatures.

Use of the model

The model was run for a range of discharges under constant meteorological conditions similar to those experienced on 31 December (Table 3). The results (Fig. 7) indicate a definite increase in temperature with decreased discharge, the lowest flow (10 m³/s) giving a maximum temperature of 25°C and a temperature above 22°C for more than 6 hours. These lower discharges also exhibit more rapid heating and cooling. For instance, 10 m³/s flow heats by 9°C between 0900 and 1200 hrs while a flow of 73 m³/s increases by 6°C in temperature over the same period. Between 1800 and 2100 hrs the same flows decrease in temperature 6°C and 3°C respectively. The effect of changing discharge on maximum predicted temperature is shown in Fig. 8. For lower discharges, the curve is nearly linear and indicates an increase of approximately 0.1°C for each 1 m³/s decrease in discharge. This rate is similar to that predicted by the empirical method (Equation 1)), for discharges about 20 m³/s.

CONCLUSION

Two models which examine the influence of discharge and meteorological variables on river temperature have been examined and applied to summer river temperatures in the Hurunui River. The regression model shows that both discharge and maximum air temperature influence river temperatures under natural flow conditions though there was considerable scatter in the relationship. The theoretical model predicted temperatures

TABLE 3—Meteorological conditions, 31 December, 1979.

Variable	Value
Cloud cover (tenths)	0
Maximum air temperature (°C)	22.0
Minimum air temperature (°C)	8.5
Maximum humidity (%)	79
Minimum humidity (%)	47
Maximum windspeed (m/s)	6.0
Minimum windspeed (m/s)	1.0
Dust content (particles/m^3 x 10^{-6})	0.2
Precipitable water content (mm)	10.0

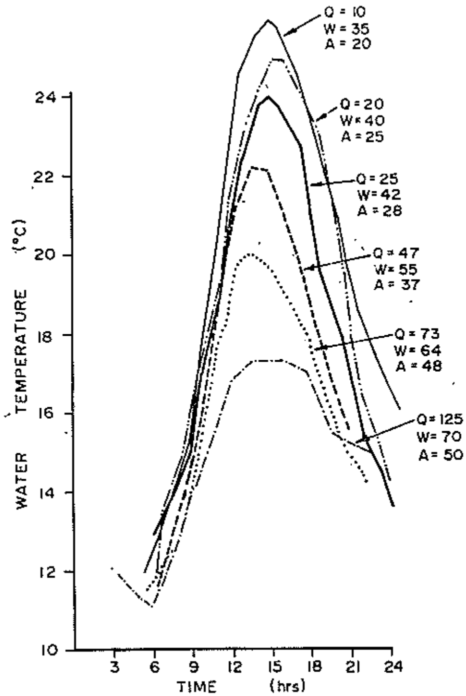

FIG. 7—Predicted water temperature at Hitchin Hill for different discharges. Meteorological conditions and Mandamus water temperatures the same as observed on 31 December, 1979.
Q=discharge (m^3/s)
W=stream with (m)
A=stream cross-section area (m^2)

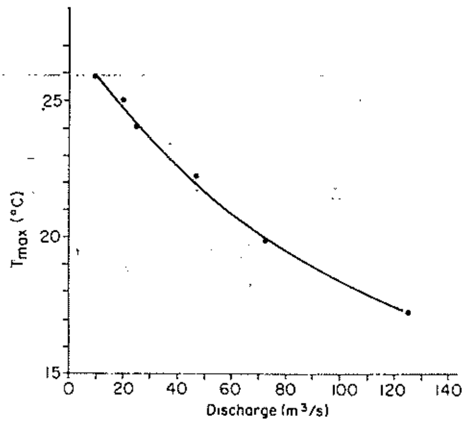

FIG. 8—Discharge vs maximum daily river temperature predicted in Figure 7.

which were in good agreement with measured values for a limited range of discharges, and because it was thought to adequately represent the physical processes involved, it was applied at much lower discharges. This indicated changes of maximum water temperature of 0.1°C for each 1 m^3/s decrease in discharge for low discharges on clear summer days. A similar rate of change of river temperature with discharge was predicted by the statistical model for discharges near 20 m^3/s.

Both of these models require further testing with more data. The regression analysis would be improved if continuous records of water temperature were available so that the daily cycle can be accounted for. The theoretical model needs to be validated for low flow conditions and associated channel form measurements should be made to improve on the hydraulic geometry estimates used here. Its value for predicting the effects of water abtsraction can only finally be tested either by carrying out abstraction or by varying downstream discharge with some form of control structure, while upstream water temperatures remain at about natural levels.

APPENDIX

Equations used in energy transfer calculations

Heat exchange across the surface (ϕ^*) is a non-linear function of stream temperature (Paily *et al.* 1974, p. 533), and was calculated following Paily *et al.* (1974) from the following equation:

$$\phi^* = \phi_i - \phi_r + \phi_{dr} - \phi_u - \phi_e - \phi_h$$

where all terms are in W/m^2 and are calculated using the following equations. Except where indicated, the equations are from Brocard and Harleman (1976, p. 231–233).

1. Incident short-wave radiation (ϕ_i)

$\phi_i = \phi_c (0.35 + 0.06(10-C))$

where C = cloud cover (tenths)

ϕ_c = clear sky radiation (W/m^2) given by:

$\phi_c = (S_o/r^2)\cos Z[\exp(-0.089(Pm/1013)^{0.75} - 0.174(wm/20)^{0.6} - 0.083(Dm)^{0.9})$
$+ 0.5(1-\exp(-0.083(Dm)^{0.9})]$ (Dozier and Outcalt, 1979, p. 71)

where S_o = solar constant (1353 W/m^2)

r = orbital radius vector

Z = solar zenith angle (^{0}) given by:

$\cos Z = \sin\theta \sin\delta + \cos\theta \cos\delta \cos H$

where θ = latitude (°)

δ = solar declination (°)

H = solar hour angle (°)

P = atmospheric pressure (mb)

m = optical air mass given by:

$m = 1/[\cos Z + 0.17(90 - Z + 3.885)^{-1.253}]$ (Dozier and Outcalt, 1979) (p. 72)

where w = precipitable water (mm)

D = atmospheric dust content (particles/m^3 x 10^{-6})

2. Reflected short-wave radiation (ϕ_r)

$\phi_r = 1.25(0.108\phi_i - 6.766 \times 10^{-5}\phi_i^2)$ (Paily *et al.* 1974, p. 548).

3. Downward long-wave radiation (ϕ_d)

$\phi_d = 5.18 \times 10^{-13} (1 + 0.17C)T_a^6$

where T_a = air temperature (°K)

4. Reflected long-wave radiation (ϕ_{dr})

$\phi_{dr} = 0.03\phi_d$

5. Upward long-wave radiation (ϕ_u)

$\phi_u = 0.97 \times 5.56 \times 10^{-8}\, T_w^4$

where T_w = water temperature (°K)

6. Evaporative energy transfer (ϕ_e)

$\phi_e = 3.9V(e_s - e_a)$

where V = wind velocity (m/s)

e_s = surface vapour pressure (mb)

e_a = air vapour pressure (mb)

7. Convective/conductive energy transfer (ϕ_h)

$$\phi_h = \phi_e \times 6.1 \times 10^{-4}P \left| \frac{T_w - T_a}{e_s - e_a} \right|$$

REFERENCES

Brocard, D. N. and Harleman, D. R. F. 1976: One-dimensional temperature predictions in unsteady flows. *Journal of the Hydraulics Division, ASCE 102 (HY3)*: 227-240.

Brown, G. W. 1969: Predicting temperatures in small streams. *Water Resources Research 5(1)*: 68-75.

Dozier, J. and Outcalt, S. I. 1979: An approach toward energy balance simulation over rugged terrain. *Geographical Analysis 11(1)*: 65-82.

Edinger, J. E.; Duttweiler, D. W. and Geyer, J. C. 1968: The response of water temperatures to meteorological conditions. *Water Resources Research 4(5):* 1137-1143.

Gibbons, D. R. and Salo, E. O. 1973: An annotated bibliography of the effects of logging on fish in the western U.S. *USDA Forest Service General Technical Report, PNW-10.*

Grant, P. J. 1977: Water temperature of the Ngaruroro River at three stations. *Journal of Hydrology (N.Z.) 16:* 106-118.

Griffiths, G. A. 1980: Hydraulic geometry relationships of some New Zealand gravel bed rivers. *Journal of Hydrology (N.Z.) 19:* 106-118.

Hockey, J. B.; Owens, I. F. and Tapper, N. J. 1980: Water temperature in the Hurunui River. *Unpub. Report to Water and Soil Division, N.Z. Ministry of Works and Development, Christchurch.* 44 p.

Landsberg, H. E. 1960: *Physical Climatology.* Gray Printing Company Inc., Du Bois, Pennsylvania. 446 p.

Leopold, L. B.; Wolman, M. G. and Miller, J. P. 1964: *Fluvial Processes in Geomorphology.* W. H. Freeman and Company, San Francisco. 522 p.

Morse, W. L. 1972: Stream temperature prediction under reduced flow. *Journal of the Hydraulics Division, ASCE 98 (HY6):* 1031-1047.

Mosley, M. P. 1979: Prediction of hydrologic variables from channel morphology, South Island rivers. *Journal of Hydrology (N.Z.) 18:* 109-120.

Paily, P. P.; Macagno, E. D. and Kennedy, J. F. 1974: Winter-regime thermal response of heated streams. *Journal of the Hydraulics Division ASCE 100 (HY4):* 531-551.

Raphael, J. M. 1962: Prediction of temperatures in rivers and reservoirs. *Journal of the Power Division ASCE 88 (PO2):* 157-181.

Troxler, R. W. and Thackson, E. L. 1977: Predicting the rate of warming of rivers below hydro-electric installations. *Journal of the Water Pollution Control Federation:* 1902-1912.