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Water and Soil Science Centre
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Christchurch

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New Zealand River Temperature Regimes

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Periodic water temperature data for 254 New Zealand flow recorder sites for which more than thirty measurements have been made are assembled. For each site, best-fit sine curves have been fitted to the observations, to show how mean daily temperature varies through the year. Plots of the temperature data and the best-fit curves for all 254 sites are presented, and the parameters of the curves, together with minimum and maximum recorded temperatures, are tabulated.

Easily measured catchment characteristics have been used in an effort to develop a simple statistical model which may be employed to predict the temperature regime at a site for which no data are available. Mean temperature is predictable from catchment latitude and mean elevation, and the phase shift coefficient of the sine curve has a remarkably constant value throughout the country. However, no simple model can predict either the amplitude of or the scatter of points around the sine curve; these must be estimated from inspection of the plots presented in the report.

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CONTENTS

INTRODUCTION

Water temperature is an important aspect of physical water quality which may have a significant impact upon the suitability of a given river for such instream uses as water-based recreation, freshwater fisheries, or pollution abatement (Macan 1974; Bovee, 1978). Overseas work on the analysis and prediction of river water temperatures (Crisp 1977; Langford 1972; Morse 1972; Smith 1979) demonstrates that water resource development may significantly modify stream temperature regimes, and there is increasing concern that the impacts of such developments in New Zealand be fully evaluated. Man-induced changes cannot always be assumed to be adverse; for example, an expected temperature increase of 3°C due to addition of heated effluent from a power plant may increase the biological productivity of the river downstream and produce a significant improvement in a commercial fishery. Hence, only where the optimum requirements of the instream use, the present conditions, and the expected changes are all known, can impacts be properly evaluated.

Recent studies by Dymond & Henderson (1981) and Hockey *et al.* (1980) have considered the effect of flow reduction upon water temperatures, using an energy balance approach developed from the work of Brocard & Harleman (1976), Brown (1969), Morse (1972), and Raphael (1962). Where such a model is to be used, however, information is still required on the temperature regime of the waterway in its undisturbed condition. In New Zealand, little readily usable information on river temperature regimes is available for either unmodified streams or for streams affected by water resource development. Published work is limited to that of Grant (1977) on water temperatures at three stations in the Ngaruroro, and by Johnson (1971), in the headwaters of Broken River, Craigieburn Range. Nevertheless, unpublished water temperature data are available for several hundred water-level recorder sites in New Zealand, because it is standard practice to measure water temperature after a discharge measurement (flow gauging) at each site. This body of data provides both a broad picture of temperature regimes for much of the country, and a basis for developing and testing models of water temperature that may be used to predict temperature regimes at sites for which no data are available.

A number of studies have demonstrated (Johnson 1971; Limerinos 1978; Shampine 1977; Walker & Lawson 1977; Ward 1963) that the annual cycle of river water temperatures may be fitted by a sine curve of the form.

$$T_i = \bar{T} + A \sin(2\pi t_i + \theta) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which T_i is the temperature (°C) at time t_i ($0<t_i\leq1$, with 0 at 0000 h on 1 January and 1 at 2400 h on 31 December), $\bar{T}$ is mean temperature (°C), A is amplitude of the sine curve (°C) and θ is phase shift of the curve (radians). Limerinos (1978) concluded that more than 80% of the annual variation in temperature could be explained by the sine functions calculated for 82 sites in California. At the same time, Johnson (1971), Shampine (1977) and Walker & Lawson (1977) have found that it may be possible to predict the parameters of equation 1 from catchment characteristics; in particular, $\bar{T}$ seems to be readily predictable from catchment elevation and/or latitude.

The purpose of the present study was therefore to collate and synthesize water temperature data that are already available in New Zealand, and to develop an empirical model so that water temperature regimes may be predicted for sites at which no data are available.

DATA BASE

The Ministry of Works and Development (MWD) hydrological data system includes many thousands of temperature measurements made during flow gaugings at several hundred water-level recorder sites during the last 25 years. Because gaugings are carried out at more or less widely spaced intervals, the temperature measurements cannot provide a detailed record of temperature variations at a site for a specific period; indeed, many sites with stable stage-discharge rating curves may have less than 20 temperature measurements because more gaugings were unnecessary to establish the rating curve. Grant (1977) has discussed the inadequacies of periodic data, but Limerinos (1978) demonstrated that periodic measurements define the parameters in equation 1 as accurately as continuous data obtained from thermograph records. The measurements used herein were primarily made between the hours of 0900 and 1600; histograms for selected sites indicate that in general, observations are evenly spread throughout the working day, with a tendency for most to be made between 1100 and 1300 hours. Data assembled by P. J. T. Smith, MWD, Dunedin (pers. comm.) for the Clutha River, Hockey *et al.* (1980) for the Hurunui River, and Brown (1969) for small streams in the USA, indicate that mean daily water temperature occurs in the early afternoon on large rivers, and between 1000 and 1200 hours in small streams. Hence, the periodic data used herein should provide a reasonable estimate of the trend of mean daily temperature in medium to large rivers, but of some temperature in excess of the mean in smaller rivers and streams.

Preliminary analysis indicated that at least 30 measurements were desirable for defining the annual temperature regime at a site. On this basis, a sample of 254 sites was selected for analysis (Figures 1 and 2). Plots of the temperature data for these sites are presented in Appendix 1, by MWD district.

Figure 1—Location of North Island sites used in the study.

Figure 2—Location of South Island sites used in the study.

ANALYSIS

A computer program written by R. P. Ibbitt (MWD, Christchurch) was used to compute, by an iterative least-squares procedure, the parameters $\bar{T}$, A and θ in equation 1 for each site. Values of these parameters, of maximum and minimum observed temperature (T_{max} and T_{min}) and of the standard error of estimate (se) of the best-fit curve are tabulated in Appendix 2.

For each site, the following readily measured physical variables were measured from NZMS1 maps: latitude (LAT, in decimal degrees); recorder elevation (RECEL, in m); maximum catchment elevation (MAXEL, in m); elevation at the point halfway between the recorder site and the highest point measured along the stream channel (MNEL, in m); catchment area (AREA, in km^2). Where available, figures for mean discharge, $\bar{Q}$, standard deviation of instantaneous flows, Q_{sd}, (both in m^3s^{-1}) and coefficient of variation of instantaneous flows, $Q_{cv} = Q_{sd}/\bar{Q}$, were obtained (Appendix 2). Shampine (1977) measured a number of additional physical variables (slope, length, and azimuth of stream; percentage of area in lakes; mean monthly and annual air temperatures), but his analysis indicated that they were unimportant, so they were excluded from the present study. Although air temperatures have been shown by Johnson (1971) and Walker & Lawson (1977) to be closely correlated with water temperatures, no attempt was made to include air temperature in the analysis, because of the relatively small area of New Zealand for which reliable measurements are available and the lack of a ready source of appropriate data (A. I. Tomlinson, New Zealand Meteorological Service, pers. comm.). Similarly, other factors such as cloudiness which are known to influence temperature regimes could not be included because of the small amount of reliable information available. The relationships between the water temperature parameters and the physical catchment characteristics were examined with multiple correlation and stepwise regression analyses. Logarithmic transformation was used to normalise the distributions of some variables, and their logarithms used in the analyses.

RESULTS AND DISCUSSION

The plots of temperature data presented in Appendix 1 confirm that periodic temperature measurements can be fitted by a sine curve; although no other mathematical functions were tested, the sine curve appears to be perfectly acceptable.

The matrix of correlation coefficients between the sine curve parameters and the physical variables is presented in Table 1. Table 2 shows means, standard deviations, etc, of the parameters.

Table 1 Matrix of correlation coefficients between temperature parameters and catchment characteristics for 254 sites.

	T_{max}	T_{min}	$\bar{T}$	A	θ	se
T_{max}	1.0					
T_{min}	0.222	1.0				
$\bar{T}$	0.705	0.747	1.0			
A	0.669	− 0.342	0.188	1.0		
θ	0.223	− 0.176	0.034	0.255	1.0	
se	0.594	− 0.438	0.038	0.686	0.292	1.0
latitude	− 0.363	− 0.669	− 0.711	0.129	− 0.077	0.111
area	− 0.100				− 0.254	− 0.191
log (area)		− 0.200	− 0.130	− 0.175		
recelev	− 0.445	− 0.451	− 0.611	− 0.111	0.034	− 0.023
meanelev		− 0.525	− 0.694		0.048	0.029
Log (meanelev)	− 0.483			− 0.145		
maxelev	− 0.444	− 0.369	− 0.535	− 0.130	− 0.210	− 0.137

Note: Coefficients > 0.13 are significantly different from zero, P ⩽ 0.05.

Table 2 Selected Statistical Parameters for the Temperature Variables, 254 Sites.

	T_{max}	T_{min}	$\bar{T}$	A	θ	se
Mean	21.8	5.1	12.6	5.2	1.23	2.01
Standard Deviation	3.9	3.0	2.6	1.6	0.15	0.51
Standard Error of Mean	0.25	0.19	0.16	0.10	0.01	0.03
Minimum	12.5	0.0	2.95	0.55	0.74	0.58
Maximum	33.0	12.0	18.2	8.9	1.97	3.32
CV=SD/Mean	0.18	0.59	0.21	0.30	0.12	0.25

Sine Curve Parameters

Best-fit regression equations for the parameters were computed in which, firstly, only catchment variables and, secondly, both catchment and discharge variables could be entered by the stepwise computation procedure. Sample sizes were, respectively, 254 and 198 sites. Although statistically significant equations could be computed for all of the temperature parameters, only one, for mean temperature, $\overline{T}$, "explained" more than 30% of the variation in the parameter.

$$\overline{T} = 95.8 - \underset{(2.8)}{46.5} \log \underset{(52\%)}{(LAT)} - \underset{(0.26)}{3.46} \log \underset{(21\%)}{(MNEL)} \quad \ldots (2)$$

The standard errors of the coefficients and percent of variance explained by the independent variables are shown beneath equation 2; the overall standard error of estimate is 1.38°C. The implication of equation 2 is that mean temperature may be reliably predicted in terms of the latitude of the measurement site and the catchment elevation parameter, MNEL; these two variables account for 73% of the variation in $\overline{T}$ for the sample of 254 sites. This conforms closely to the findings of Johnson (1971) and Shampine (1977). Examination of the residuals from equation 2 provided no clues as to the factors that explain the remaining 27% of variance in $\overline{T}$; neither geographic location (a surrogate for climatic zone), channel characteristics, nor hydrologic character (e.g., lake-fed, spring-fed) were noticeably related to the magnitude of the residuals. No doubt measurement error and lack of fit of equation 1 to the data are responsible for a significant portion of the unexplained variance.

Shampine (1977) was unable to develop a statistical model to predict amplitude, A, from physical catchment variables for streams in Indiana, and the data presented by Johnson (1971) similarly provide no evidence for any dependence of A upon catchment characteristics. The present study conforms to this; only 6% of the variance in A was accounted for by catchment variables included in the analysis (catchment area and maximum elevation). However, examination of the data indicated some dependence of A on hydrologic regime; a bivariate scatter plot of $\overline{T}$ and A (Figure 3) suggests a number of groupings which show the influence of climatic or hydrologic factors. Most noticeable is a group of sites with values of A less than 2.5°C which are all located around Lake Rotorua and are spring fed; or are located on limestone outcrops (site 14604, Figure 4). Clearly, the annual range of water temperature in these streams is moderated by the predominantly subterranean source of stream flow. Another grouping of sites with low values of A includes many located on the West Coast of the South Island; it is considered that the equable climate and frequent cloud cover is here responsible for the low range in temperatures (site 84701, Figure 4). On the other hand, sites in inland Otago and Canterbury tend to have large values of A (although mean temperatures are low) (sites 62105, 71103, Figure 4). Generally clear skies promote rapid heating and cooling of the water both during the day and over the year, and many of these watercourses also tend to be wide and braided, which again promotes rapid heating and cooling. Sites in the East Cape-Gisborne region also have a tendency for large values of A (site 19716, Figure 4). In most cases, this is perhaps less a function of climatic conditions than of the generally small size of the streams included in the sample from this area.

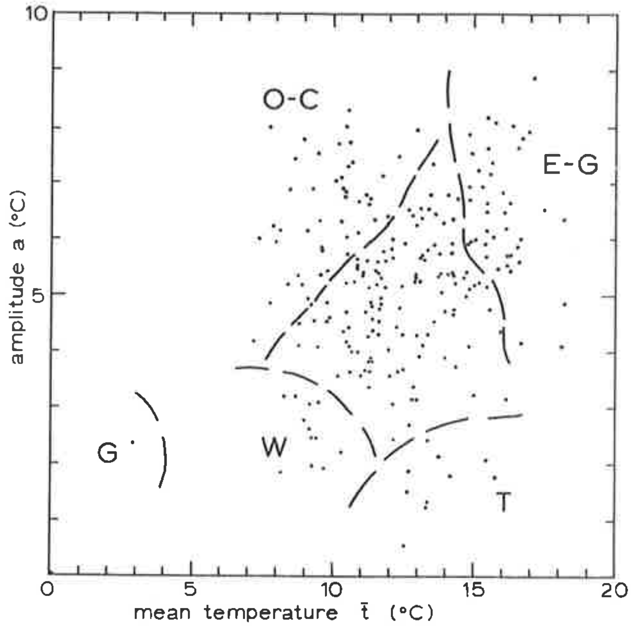

Figure 3 Bivariate plot of $\overline{T}$ and A. The groupings around the main mass of points were identified with the help of cluster analysis, using computer program BMDP3M (Dixon 1975). The groupings are only tendencies, because many sites in those groups actually plot in the central body of points. Groups are: O–C: Otago and Canterbury; E–G: East Cape and Gisborne; W: West Coast, South Island; T: Taupo pumice/limestone; G: Glacial.

Nevertheless, an equation which included variables indicative of hydrologic regime explained less than 30% of the variance in A, and there is no justification for attempting to develop regional equations for A, because many sites in the four districts mentioned above are intermixed with sites from the rest of the country.

Amplitude appears, therefore, to be a function of a variety of factors, most of which are as yet unrecognised or unquantified. If synthesis of the annual temperature regime at a given site is required, the only method (apart from actually making measurements) appears to be to examine the data set presented in the appendices, identify those sites most similar (in terms of geographic location or climate, channel morphology, hydrologic regime, etc.) to the site of interest, and select the appropriate value of A.

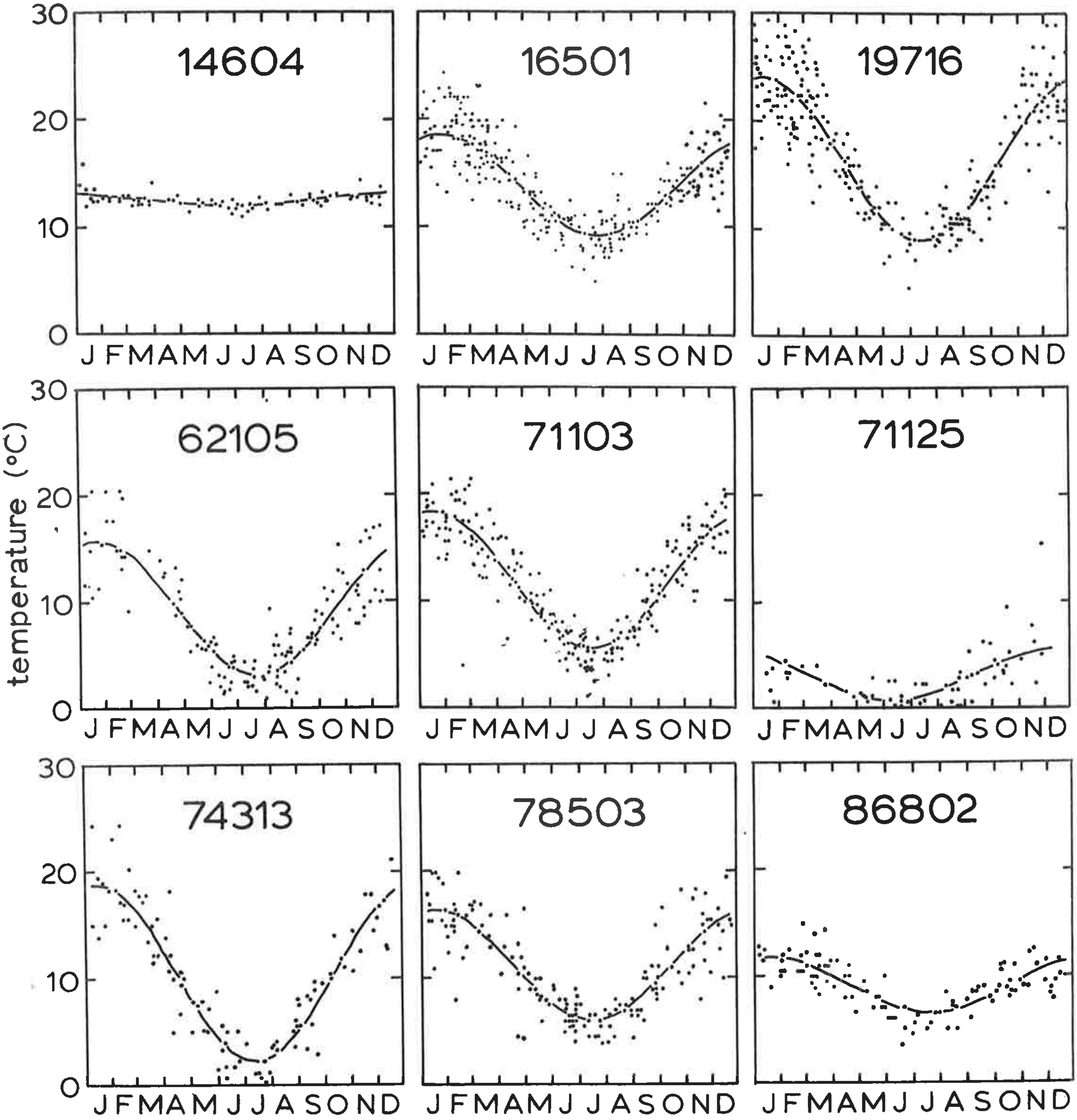

Figure 4 Representative temperature plots and best-fit sine curves. Pertinent details are:

	Site	NZMS1 Grid Reference	$\bar{T}$(°C)	A(°C)	θ(radians)	se(°C)	Latitude
14604	Awahou	N76.685149	12.5	0.55	1.63	0.58	38.1
16501	Motu	N70:057358	13.9	4.72	1.13	2.18	37.86
19716	Waipaoa	N89:273614	16.5	7.60	1.35	2.87	38.47
62105	Clarence	S47:265862	9.5	6.31	1.20	2.39	42.46
71103	Hakataramea	S118:125112	12.0	6.40	1.29	2.14	46.72
71125	Hooker (glacial)	S79:787304	3.0	2.36	1.97	1.98	43.74
74313	Taieri	S135:843534	10.5	8.28	1.35	2.40	45.19
78503	Waihopai	S177:431045	11.3	5.16	1.33	2.30	46.39
84701	Cleddau	S113:908108	9.1	2.63	1.22	1.50	44.69

Most sites have rather similar values of phase shift, θ, which is an index of the timing of the maximum temperature during the year. The mean value of θ for the 254 sites is 1.23 radians, with a standard deviation of only 0.15 radians; this implies that the peak temperature occurs on average on January 26, and that temperature at about 67% of the sites peaks between January 19 and February 2. As catchment size increases, there is a weak tendency for θ to decrease—that is, the temperature peak occurs later in the year, as might be expected. However, for the purpose of synthesizing a temperature regime relationship, the mean value of 1.23 radians should be adequate.

Maximum Temperature and Temperature Variability

For the purpose of evaluating the suitability of a river for instream uses such as fish habitat, such aspects of the water temperature regime as maximum temperature, diurnal variability of temperature, and rates of change of temperature are of great importance. Indices of these aspects used herein are maximum recorded temperature, T_{max}, and the standard error, se, of equation 1 for each site, the latter being an index of the amount of scatter of points about the best-fit sine curve. Unfortunately, neither of these parameters can be satisfactorily predicted from simple catchment characteristics, although T_{max} is to some extent ($R^2 = 29\%$) determined by latitude and the elevation parameter MNEL. This is perhaps not surprising because both parameters depend strongly on the precise conditions pertaining at the time temperature measurements are taken—that is, on time of day, on meteorological conditions such as degree of cloudiness, on depth, clarity, and volume of water, etc.—and on physical characteristics of the channel upstream such as amount of shading (either from overhanging vegetation or surrounding hills), the character of the stream bed, channel width, and so on. Physically based models to predict water temperatures require much detailed information on physical conditions, so that it is not surprising that a simple statistical model cannot be developed. As with sine curve amplitude, therefore, it appears that the only method available for predicting maximum temperature and variability of temperature at a given site is to examine the data set in the appendices and to select the site that is most similar to the site of interest. If the study warrants it, the alternative is to use a simulation model of the type developed by Hockey *et al.* (1980), or to make actual measurements at the critical period (most probably at the end of January), if annual maximum temperature is of specific concern.

CONCLUSION

Periodic measurements of water temperature at 254 sites in New Zealand may be fitted by sine curves, if measurements for different years are combined, as shown by Shampine (1977), Ward (1963) and others. Inspection suggests that the best-fit sine curves are unlikely to be improved upon by use of any other mathematical function. As few as thirty points randomly spaced through the year appear adequate to define the parameters of the curve, although fifty or more are desirable; periodic data have been shown by Limerinos (1978) to provide an estimate of the parameters as good as that given by continuously measured data. The measurements used herein provide an estimate of water temperature at about noon, which in medium to large rivers is the time when mean temperature tends to be passed in the diurnal temperature cycle.

Attempts to develop a model to predict, for a site at which no data are available, the annual temperature regime from easily measured catchment characteristics had a similar degree of success to that of Shampine (1977) in Indiana. The parameter $\overline{T}$ of the sine curve (mean annual temperature) may be accurately predicted by an equation (equation 2) that includes latitude and catchment elevation. The parameter A (amplitude of the curve) cannot be predicted to an acceptable level of accuracy and it is suggested that the only way in which the body of data available for the study may be used is by selecting those sites which are most similar (in respect of climatic zone, geographic location, channel character, etc.) to the site of interest and using their value of A. The third parameter, θ, of the sine curve has a remarkably stable value throughout New Zealand, and its mean value may be adopted.

It proved impossible to predict maximum temperature and the dispersion of temperatures about the trend line. If this information is required for a given location, inspection of the data set for a similar site may provide an estimate, but the only wholly acceptable solution seems to be to make field measurements or to use a simulation approach. In the latter case, the annual trend line obtained by the three step procedure outlined in the preceding paragraph may provide an acceptable basis. If measurements are to be made, the study indicates the most appropriate time of year for data collection if attention is focussed on maximum temperatures (late January), and the number of periodic measurements likely to be required (a minimum of thirty, but preferably fifty, or one per week for a year).

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