WAIORA Water Temperature Model – Validations

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INTRODUCTION

As part of a study to test the water temperature prediction part of the WAIORA decision support system, a field study was conducted at two sites near Napier and Masterton during February-April 2003. Results were then used to calibrate and test the WAIORA model.

METHODS

Study sites

Esk River
Logging thermistors (TIDBITs) were deployed at four sites along the stream channel from 5–25 February 2003. The thermistor at Site 4 (Pan Pac) malfunctioned from 18–25 February but recorded successfully from 5–17 February. Lighting was surveyed at 191 locations using a LiCor canopy analyser. Channel width, mean depth and shade geometry were surveyed at 38 locations.

Meteorological data from Napier Airport was obtained from the NIWA climate database. Flows were gauged at the thermistor sites on 4 occasions during the study, and flow was recorded continuously at Site 3 (Waipunga). Flow measurement was by the Hawkes Bay Regional Council (HBRC).

Mangatarere Stream
TIDBITs were deployed at four sites along the stream channel (Tea Creek Rd, Chester Rd, Dalefield Rd, SH2).

Flows were gauged at 5 sites on 6 occasions. Shade was surveyed using a LiCor canopy analyser. Channel widths and mean depths were surveyed at 22 locations. Meteorological data were obtained from the NIWA climate database.

NIWA
Taihoro Nukurangi

RESULTS

Esk River

Flow

Flows were low during the period thermistors were deployed (Figure 1). Daily mean flows at Site 3 averaged 1.9 ± 0.2 $m^3.s^{-1}$ over 21 days (mean ± standard deviation) although there was a small fresh on 16–17 February. Flows were similar at Sites 1-4 (viz., there were only small tributary or groundwater inflows to the study reach).

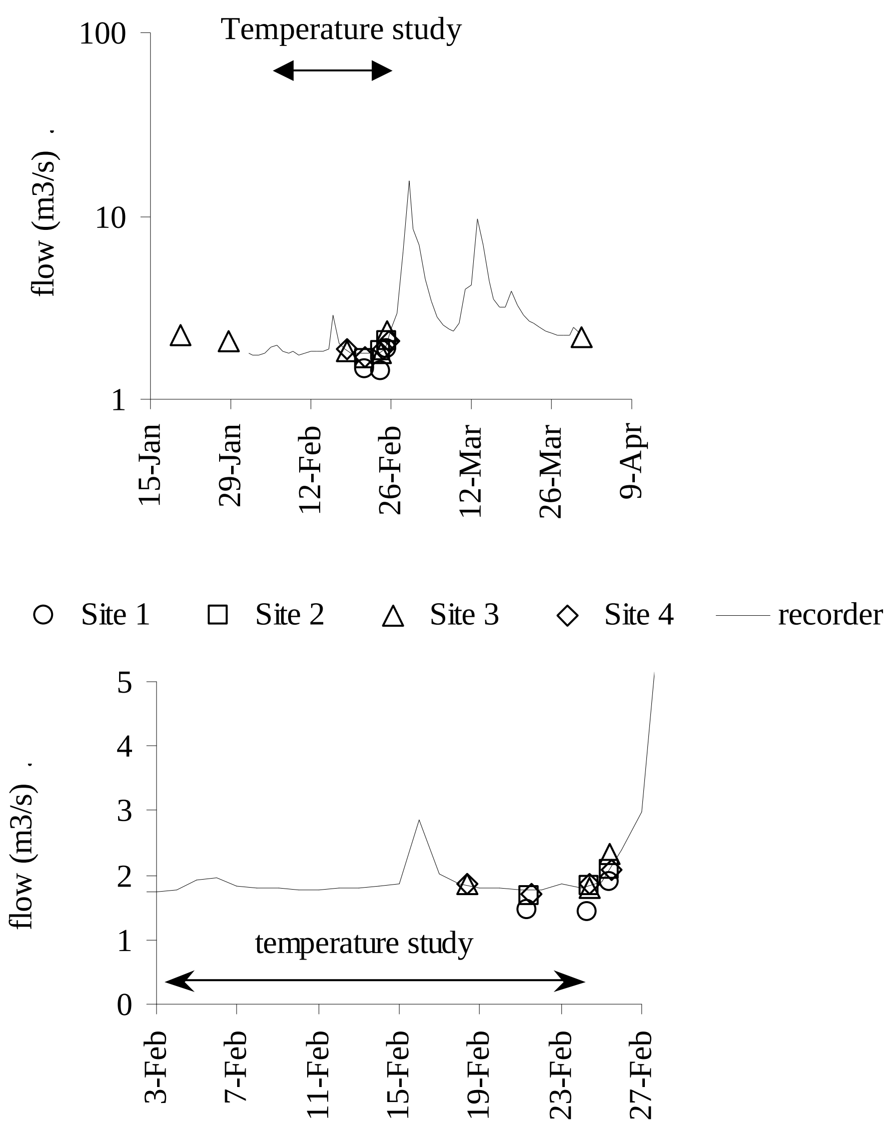


Figure 1: Daily mean flows at the Site 3 recorder (line) on the Esk River and gaugings at Sites 1-4 (symbols) during February 2003. Source: HBRC.

Channel parameters

Mean depth and width surveyed at the 38 locations are summarised in Tables 1 and 2, and Figure 2. The channel was fairly uniform throughout the study reach. The only major exception was in the immediate vicinity of the Pan Pac Intake (Site 4) where gravel extraction has created an artificial deep channel.

Figure 3 summarises the variation with flow of mean depth, width and velocity based on 12 gaugings at Site 3 and 3-4 gaugings at the Sites 1, 2 and 4. Curves were fitted to the observations of the form

$$y = aQ^b \quad (1)$$

where y = depth, width or velocity; and a and b = constants. Values of a and b were estimated separately to minimise the root mean square error between observed and predicted values, using SOLVER within EXCEL. There was no significant difference between the values of b for depth, width or velocity. Consequently the average value of b was then specified for all three variables and the values of a were re-evaluated.

Comparing channel parameters from the survey and the rating curves, mean depths are similar. However, the survey gave a slightly greater average width (12 m) and a lower mean velocity (0.51 m s^{-1}) than the rating curves (width = 10 m, velocity = 0.65 m s^{-1}). Gauging sites are often selected for ease of flow measurement rather than as being representative of the 'average' channel. In subsequent calculations the average results from the survey are used rather than results from the rating curve.

Table 1: Summary of channel parameters in the Esk River.

Parameter	Value	Comment
	Measured at 38 locations	
width [m]	12 ± 3 (38)	
mean depth [m]	0.32 ± 0.18 (38)	
area [m^2]	3.7 ± 2.2 (38)	
flow [$m^3 s^{-1}$]	1.8 ± 0.3 (13)	gaugings Sites 1-4
flow [$m^3 s^{-1}$]	1.9 ± 0.2 (21)	recorder Site 3
mean velocity [m/s]	0.51 ± 0.30	flow/area
Predicted from ratings curves		
width [m]	10	assuming Q = 2 $m^3 s^{-1}$
mean depth [m]	0.31	assuming Q = 2 $m^3 s^{-1}$
mean velocity [m/s]	0.65	assuming Q = 2 $m^3 s^{-1}$

Table 2: Parameters of rating curves relating mean depth, width and mean velocity to flow, based on gaugings at the four thermistor sites covering the period January-September 2003.

Coefficient	Mean depth	Width	Mean velocity	Comment
a	0.24	8.4	0.52	
b		0.33		average (see text)

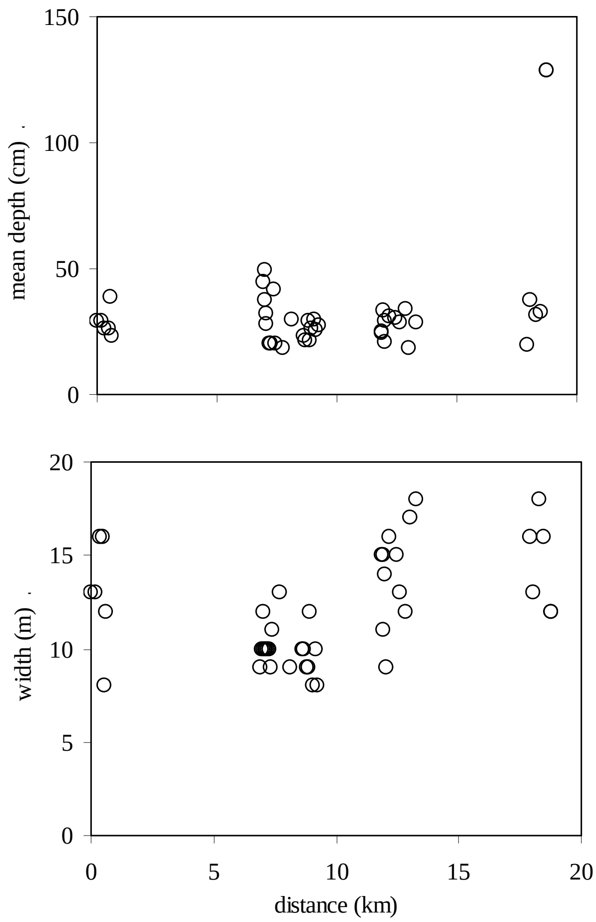


Figure 2: Mean depth and width measured at 38 locations along the Esk River during February 2003.

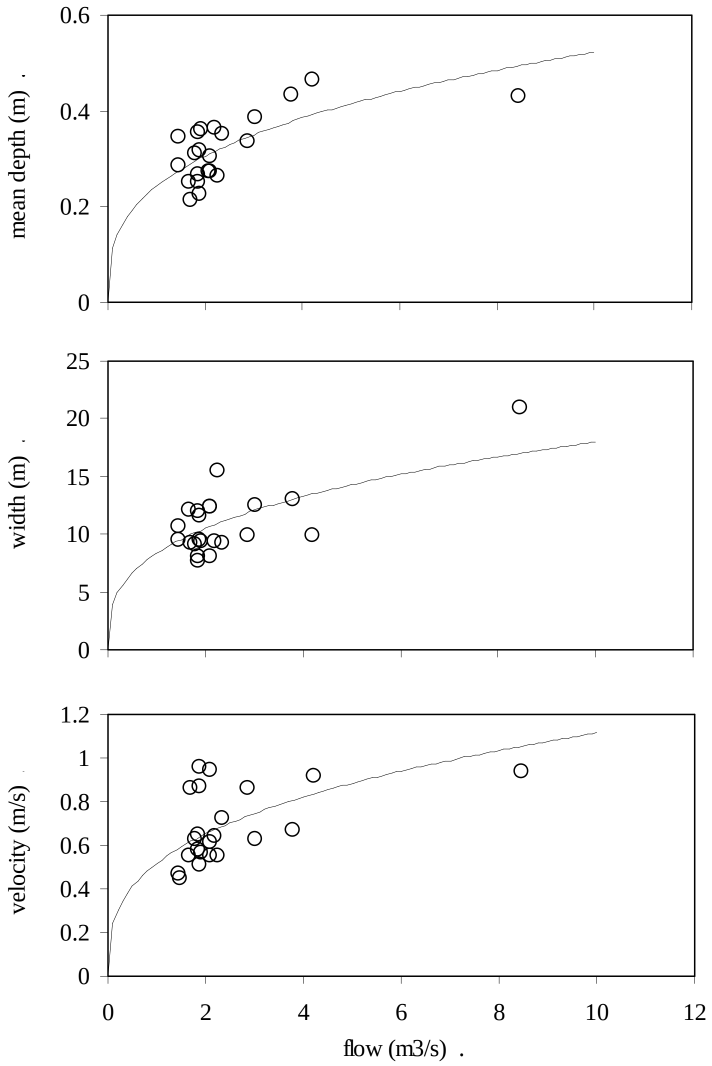


Figure 3: Variation of mean depth, width and mean velocity with flow based on gaugings at the four thermistor sites on the Esk River covering the period January-September 2003. Source: HBRC.

Shade

Table 3 summarises measured lighting (DIFN) along the study reach. Figure 4 shows the distribution of measured lighting. From Site 1-2 daily maximum water temperature increased (1.8 ± 0.4^{o}C, mean ± standard deviation, n = 21 days) over a distance of ~7 km. Lighting (DIFN) averaged 35 ± 7% and 47 ± 13% at Sites 1 and 2 respectively, but access was difficult to the middle part of this reach and no shade measurements were made from 2-6 km. From Site 2-3 daily maximum water temperature decreased slightly (-0.3 ± 0.3^{o}C) even though average lighting was slightly higher at Site 3 (60 ± 12%) than Site 2 (47 ± 13%). From Site 3-4 daily maximum temperature increased by 0.6 ± 0.3^{o}C even though average lighting was slightly lower at Site 4 (50 ± 11%) than at Site 3 (60 ± 12%).

Since shade levels were likely to be higher at and above Site 1 than from Sites 2-4, water temperatures at Site 1 are likely to be low, warming is expected from Site 1-2 and the observed temperature increase of 1.8 ± 0.4^{o}C in this reach is plausible. By the time the river reaches Site 2 (~7 km below Site 1) water temperature is likely to have adjusted to the new lighting levels and air temperatures. If so, then water temperatures will not change further until there is another significant change in shade or water depth. Lighting at Site 3 (60 ± 12%) was higher than at Site 2 (47 ± 13%) and one might have expected to see an increase in temperature from Site 2-3. However, there was no significant difference in daily maximum temperature between these two sites. The reason is that, based on a visual assessment of the channel, lighting only reached ~60% close to Site 3 and the majority of the reach from Sites 2-3 had lighting levels similar to those in the reach from Site 1-2. Consequently it is likely that water temperatures measured at Site 3 had not fully adjusted to the higher lighting measured in the immediate vicinity of Site 3. Lighting at Site 4 (50 ± 11%) was lower than at Site 3 (60 ± 12%) but daily maximum temperatures were slightly higher (0.60 ± 0.3^{o}C). Again the likely explanation is that, although there was dense riparian vegetation near Site 4, water temperatures measured at Site 4 had not fully adjusted to this lower lighting but reflected the higher lighting further upstream. Based on visual assessment, lighting levels in the reach from Site 3-4 were typical of those measured at Site 3. This study reinforces the importance of measuring or estimating shade along the entire study reach. Localised measurements (e.g., near a thermistor site) can be misleading in rivers where shade varies significantly with distance.

Meteorological data

Figure 5 summarises meteorological parameters measured at Napier Airport during the study period.

Water temperature

Figure 6 shows measured temperature profiles at the four thermistor sites. Table 4 summarises changes between sites in daily water temperature statistics. There was an increase in daily maximum temperature averaging 2.2 ± 0.6^{o}C (mean ± standard deviation, n = 21 days) between Island Farm and Pan Pac (Site 1-4) over a distance of 18.5 km (Figure 6). A temperature increase would be expected along the study reach because the Esk emerges from the hills through a narrow gorge just above Island Farm (Site 1). Water temperatures at Site 1 are low because the water has come from higher elevation where air temperatures are low and from a region where shade is high because the channel is narrow, the surrounding topography is steep and there is extensive forest cover. Between Sites 1-4 the river channel is wide, the surrounding topography is less steep and water temperatures are expected to increase as a result of warmer air temperatures and higher inputs of solar and atmospheric radiation.

Daily minimum water temperatures increased monotonically by 2.1 ± 0.3^{o}C from Site 1-4 and increases over each sub-reach are summarised in Table 4. Daily mean temperatures also increased monotonically from Site 1-4 by an average of 2.2 ± 0.3°C. It is noteworthy that the daily maximum, mean and minimum temperature all increased over the study reach by ~2°C.

It is also noteworthy that in the reach Site 2-3 the daily maximum temperature decreased (-0.3 ± 0.3°C) but the daily mean (0.4 ± 0.1°C) and daily minimum (0.6 ± 0.1°C) both increased. This is consistent with a short reach of shade from Sites 2-3 that reduces solar radiation near mid-day, thereby reducing daily maximum temperature, but heating of both the water and the stream bed above Site 2 that results in an increase in daily mean and minimum temperature.

Temperatures increased rapidly in the morning everywhere in the study reach but in the afternoon temperatures dropped more rapidly at Site 1 than at Site 4, with Sites 2 and 3 being somewhere in between (Figure 6). This is consistent with heating of both the water and the bed in the study reach. Water is colder at Site 1 (where it emerges from the hills) than further downstream. At night this cold water fills the study reach although heat stored in the streambed causes the daily minimum temperature to increase with distance downstream. During the morning the increased solar radiation and air temperature cause uniform heating everywhere along the study reach. An important factor is that not only the water but also the streambed experience daytime heating. When the sun sets, cool water emerging from the hills causes water temperatures at Site 1 to drop rapidly. However, it takes time for this cool water to make its way downstream to Sites 2-4. It also takes time for the resulting drop in water temperature to cause a drop in streambed temperature. Consequently water temperatures drop first at Site 1, then at Site 2 and so on.

Univariate relationships were sought between water temperature and the change of water temperature between sites and the meteorological variables most likely to drive those changes, namely air temperature and solar radiation. Water and air temperatures were positively correlated (Figure 7, top) but there was high variability. Temperature increases between sites were weakly correlated with solar radiation (Figure 7, bottom) but again there was high variability.

Table 3: Summary of diffuse non-interceptance (DIFN) measured at five locations along the Esk River on 2–4 February 2003, and estimated reach averages between thermistor sites.

	Distance (km)	Mean	SD	Number
Survey results				
Site 1	0	0.35	0.07	32
Site 2	6.9	0.47	0.13	60
Site 3	12.5	0.60	0.12	59
Site 4	18.5	0.50	0.11	40
Reach averages				
Site 1-2	6.9	0.41	0.10	92
Site 1-3	12.5	0.47	0.11	151
Site 1-4	18.5	0.48	0.11	191
Site 2-3	5.6	0.54	0.13	119
Site 2-4	11.6	0.53	0.12	159
Site 3-4	6.0	0.55	0.11	99

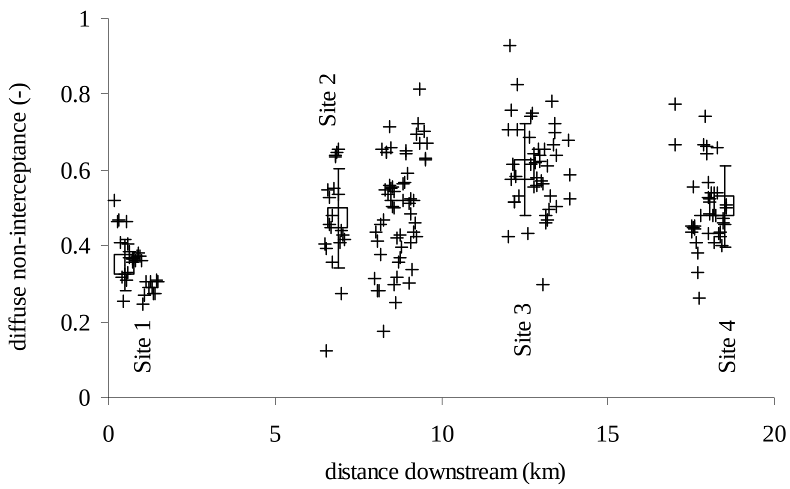


Figure 4: Diffuse non-interceptance measured at five locations along the Esk River on 2–4 February 2003.

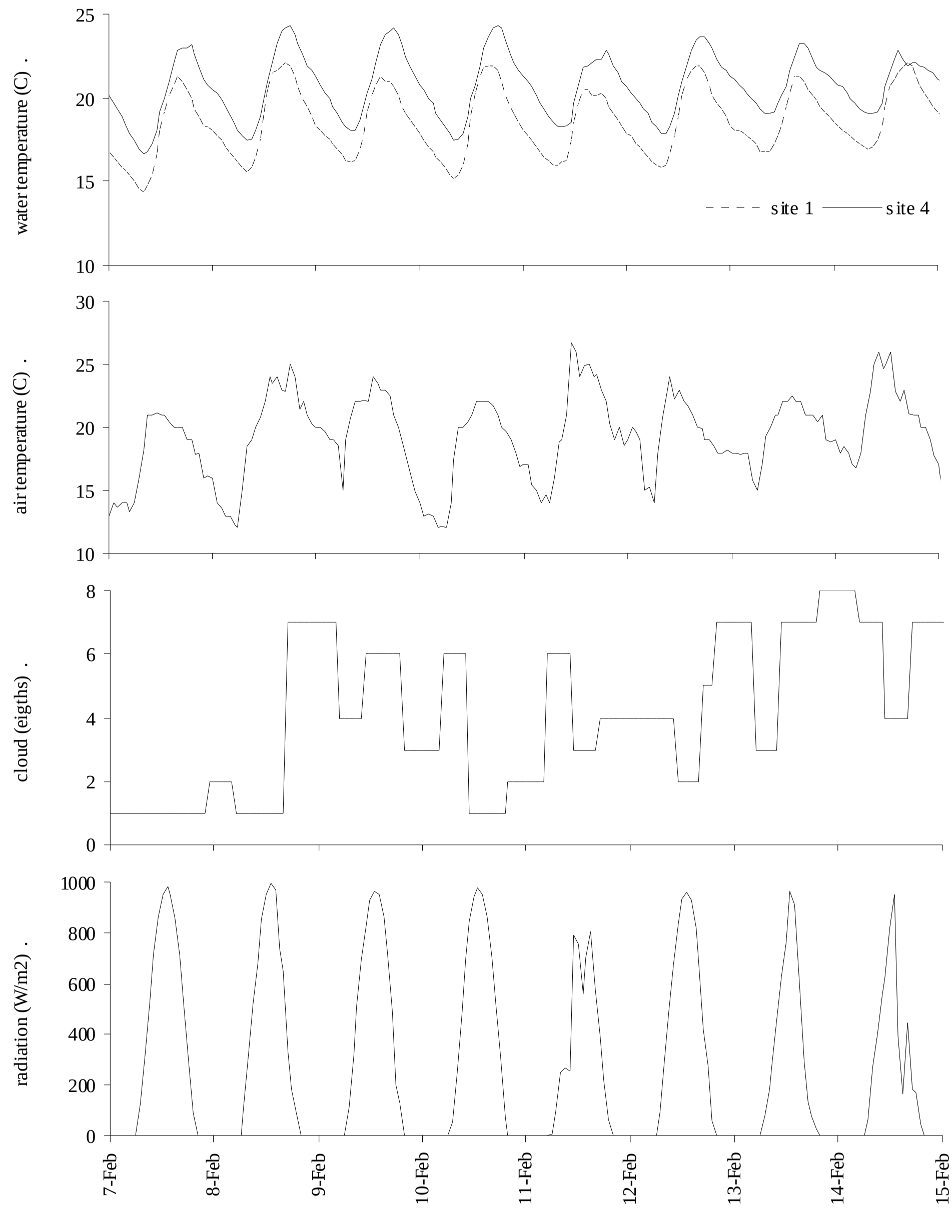


Figure 5: Measured water temperatures at Site 1 (Island Farm) and Site 4 (Pan Pac) on the Esk River during February 2003 and meteorological parameters measured at Napier Airport.

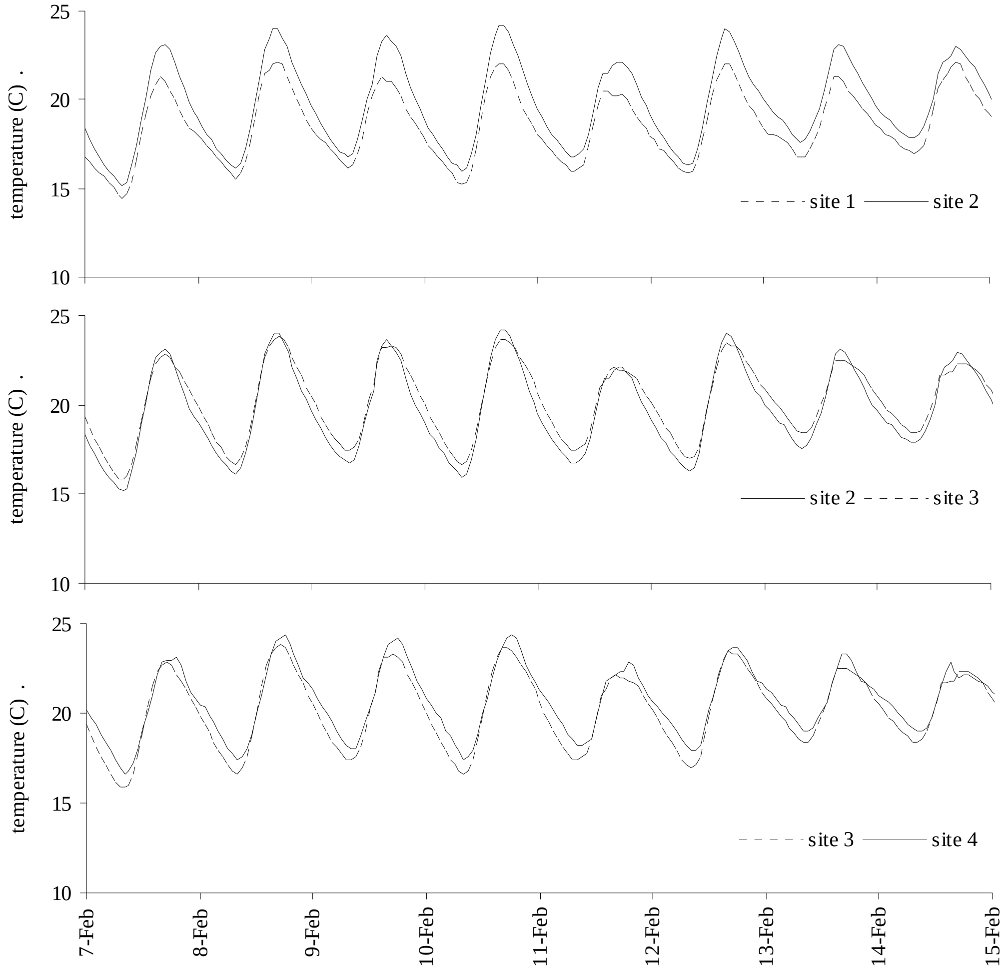


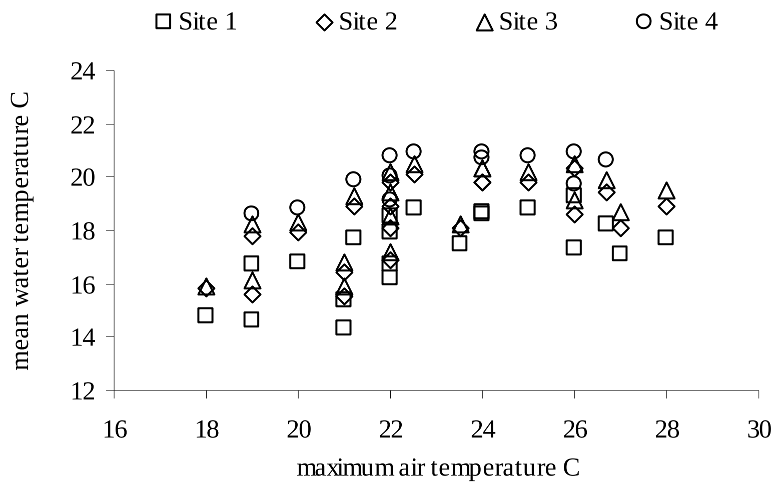
Figure 6: Measured water temperatures at four sites along the Esk River during February 2003.

Table 4: Summary of changes in water temperature between sites on the Esk River 5-25 February 2003.

	Site 1-2	Site 2-3	Site 3-4	Site 1-3	Site 2-4	Site 1-4
Daily maximum						
average	1.8	-0.3	0.6	1.5	0.2	2.2
SD	0.4	0.3	0.3	0.6	0.3	0.6
num	21	21	13	21	13	13
Daily mean						
average	1.1	0.4	0.6	1.5	1.0	2.2
SD	0.2	0.1	0.1	0.3	0.2	0.3
num	21	21	13	21	13	13
Daily minimum						
average	0.6	0.6	0.7	1.2	1.3	2.1
SD	0.2	0.1	0.2	0.3	0.3	0.3
num	21	21	13	21	13	13

SD = standard deviation

num = number of days



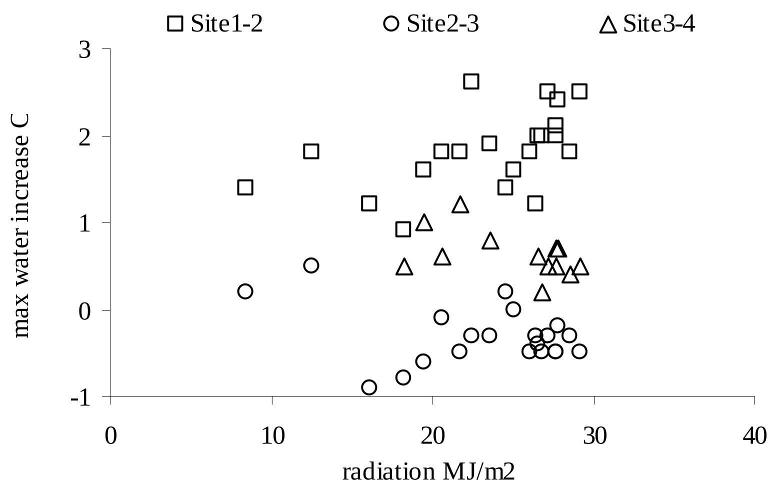


Figure 7: Univariate relationships between daily water temperature statistics from Esk River and two key meteorological variables.

Mangatarere Stream

Flow

Table 5 summarises flow gaugings at six sites along the study reach on six occasions during the study conducted by the Wellington Regional Council. Flows were markedly lower (~50%) on 21 and 27 March than on the other four occasions, which reflects the dry weather during this period.

Flows were consistently lower at Andersons Line and Belvedere Rd than at the upstream Gorge and Tea Creek Rd sites. During the shade survey it was noted that there was no visible flow in the channel for ~1 km above and below Anderson's Line although there was flow upstream and downstream. Either there was significant loss to groundwater or significant sub-surface flow within the channel in the vicinity of Anderson's Line. Although flow was visible at Belvedere and Dalefield Rd during the shade survey, the gaugings indicate that flow had not yet returned to upstream values (Table 5). Flows were consistently higher at SH2 than at the upstream Dalefield Rd. There are known to be significant surface inflows between these sites (notably from the Kaipaitangata Stream) and there may also be further gains from groundwater. No flow gaugings or temperature measurements are available from the Kaipaitangata Stream during the study period.

Table 5: Summary of measured flows in the Mangatarere River March-April 2003. Source: Wellington Regional Council. Flows on 27 February are estimated as detailed in the text.

	6 Mar.	14 Mar.	21 Mar.	27 Mar.	4 Apr.	10 Apr.	27 Feb.
Rain in previous 7 days, mm							
	9	13.4	1.2	1.1	7.7	3.4	5.6
Stream flow, L/s							
			measured				**estimated**
Gorge		321		187	328		
Tea Creek Rd	253	307	165	128	309	214	216
Andersons Ln	150	226	73	20	214	103	137
Belvedere Rd	165	278	76	49	243	115	146
Dalefield Rd	234	303	126	70	290	164	188
SH 2	515	627	348	273	514	425	414

Channel parameters

Table 6 summarises the channel parameters measured on 26–27 February. There were no consistent differences in channel parameters along the study reach, and for subsequent analysis all measurements were averaged. Channel parameters were measured on 27 February, but flow gaugings only commenced on 6 March, and so an estimate of flow was required on 27 February. In the 7 days preceding 27 February there were 5.6 mm of rain, comparable with that preceding the gaugings on 6 March, 14 March, 4 April and 10 April. Stream flows on 27 February were estimated by scaling the average measured flows on these four dates by rainfall in the preceding 7 days (Table 5).

Mean depth, width and mean velocity were also measured at the six gauging sites on six occasions during the study. Gauging sites are often chosen for the convenience of making flow measurements and are not always representative of the typical stream channel. Nevertheless at flows comparable with those during the channel survey, channel width (5-8

m) at the gauging sites was comparable with the range in Table 6, although mean depth (0.17-0.22 m) was slightly higher than the average in Table 6 (0.16 ± 0.07 m).

Table 6: Summary of channel parameters measured in the Mangatarere River on 26–27 February 2003. Estimated flow is 146-414 L/s.

Variable	Mean ± sd (number)	Comments
width (m)	6.4 ± 1.8 (22)	
area (m^2)	1.1 ± 0.6 (22)	mean depth x width
mean depth (m)	0.16 ± 0.07 (22)	5-10 measurements per section

Shade

Table 7 summarises canopy analyser measurements of diffuse non-interceptance (DIFN), which is the complement of shade. There is slightly less lighting in the lower parts of the study reach (median 51-54%, Anderson's Line to SH2) than the upper parts (median 62%, Tea Creek Rd to Chester Rd). This is consistent with the visual observation that willows are more abundant in the lower reaches.

Table 7: Measured diffuse non-interceptance (DIFN) at five sites along the Mangatarere River on 26–27 March 2003. Sites are listed in order from upstream.

	Description	DIFN	Comment
27 February	below Tea Creek Rd	0.62 ± 0.14 (12)	
		0.57 ± 0.11 (17)	model reach
26 February	above Chester Rd	0.82 ± 0.20 (18)	
27 February	below Anderson's Line	0.55 ± 0.25 (12)	channel dry
		0.33 ± 0.24 (9)	channel dry
		0.41 ± 0.25 (8)	
26 February	above Belvedere Rd	0.75 ± 0.15 (20)	
		0.60 ± 0.14 (20)	
		0.43 ± 0.17 (20)	
		0.63 ± 0.21 (20)	
26 February	between Dalefield Rd and SH2	0.54 ± 0.23 (20)	
		0.45 ± 0.20 (20)	
		0.51 ± 0.16 (20)	

Meteorological data

Figure 8 summarises meteorological parameters measured at Palmerston North and Masterton during the study period.

Water temperature

The amplitude of diurnal variations is 6-8^{o}C on warm, sunny days but only 2-4^{o}C on cool, cloudy days (Figure 9). The amplitude of diurnal water temperature varies inversely with water depth and the large observed diurnal range in Figure 9 is consistent with the shallow channel (Table 6) and the fact that it is fairly open (viz., unshaded).

On average there is an increase of ~1^{o}C in daily maximum, mean and minimum water temperature between Tea Creek Rd and Chester Rd (Figure 9 top). This reach is fairly open (see Table 5) and lies at the top end of the study reach not far downstream from where the

Mangatarere Stream flows out of the hills onto the plains. The observed increase in daily mean temperature is consistent with cool water flowing into the top end of this reach, a decrease in shade that allows increased solar radiation input to the stream channel, and fairly shallow water.

There is a significant decrease in daily maximum temperature between Chester Rd and Dalefield Rd (Figure 9 middle) although daily minimum temperatures are similar. These changes cannot be related to the amount of bank and vegetation shade along the channel between these two sites because the channel was dry for part of the distance between sites. It is not known where the flow re-emerged from the streambed and/or aquifer, nor the temperature of the emerging water. The fact that some flow was measured at Belvedere Road (albeit only ~50% of the upstream and downstream flow) indicates that the stream channel regains some water above Belvedere Rd but it continues to regain water for some distance below Belvedere Rd. Water temperature at Dalefield Rd will depend on the temperature of the water as it re-emerges into the channel and also on the amount of riparian shade between where it emerges and Dalefield Rd. Although we have measurements of riparian shade along this 'gaining' reach (Table 5), we have insufficient information to quantify the flow distribution and the temperature of the re-emerging water.

Daily maximum temperatures are similar at Dalefield Rd and SH2 (Figure 9 bottom) although daily minimum temperatures are lower at SH2 by ~1^{o}C. Daily maximum temperatures at both sites are significantly lower (by up to 2-3^{o}C) than at the upstream Tea Creek and Chester Rd sites. It is no clear whether this latter observation can be attributed solely to the fact that riparian shade is higher from Anderson's Line to SH2 (see Table 5) or whether there is an inflow of colder water from groundwater and/or tributaries like the Kaipaitangata Stream. Note that flow is significantly higher at SH2 than at any upstream site.

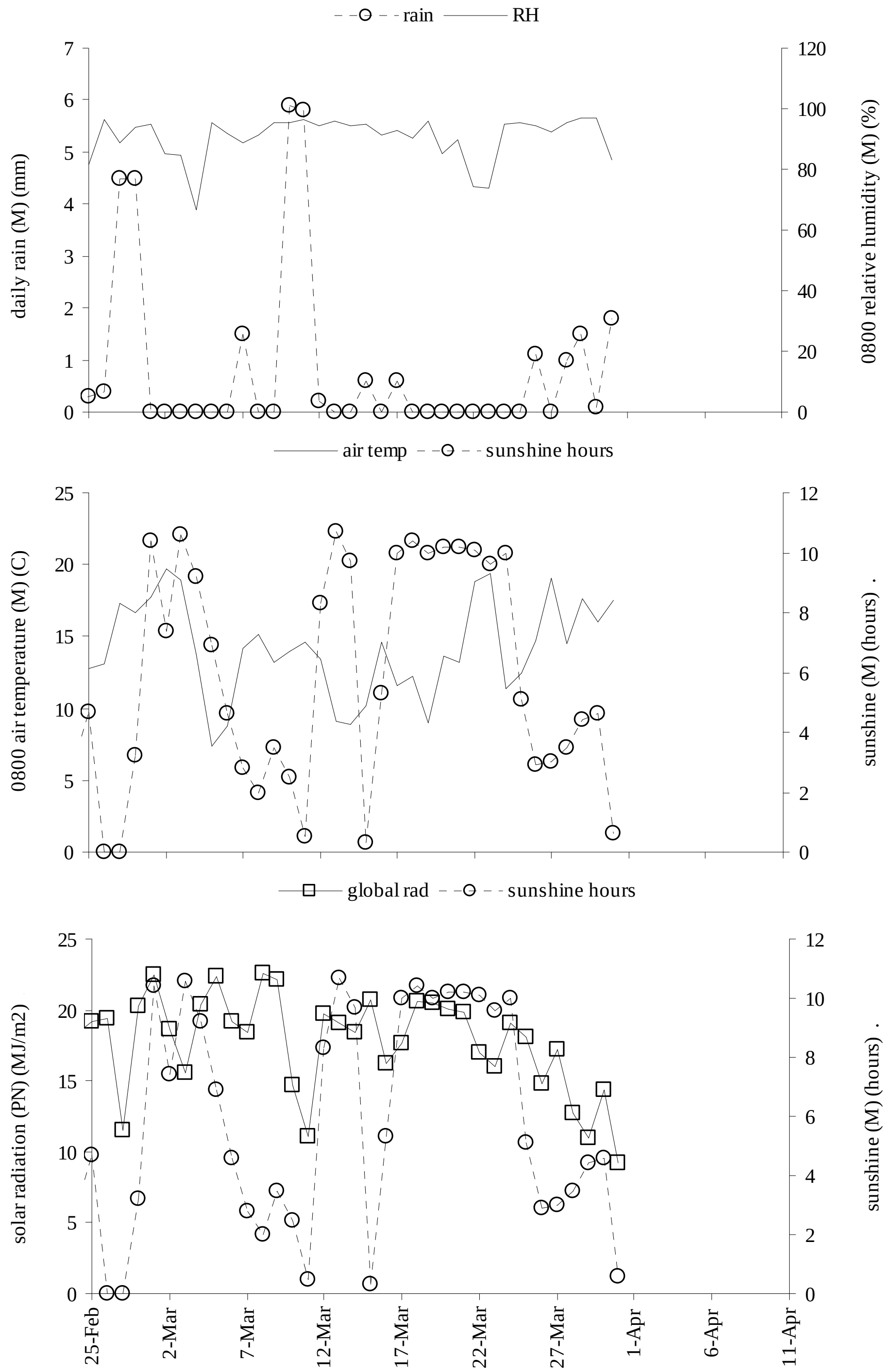


Figure 8: Meteorological variables measured at Palmerston North (PN) and Masterton (M) in February-March 2003. Rain, global radiation and sunshine hours are daily totals. Relative humidity and air temperature are 0800 values. Source: NIWA Climate Database.

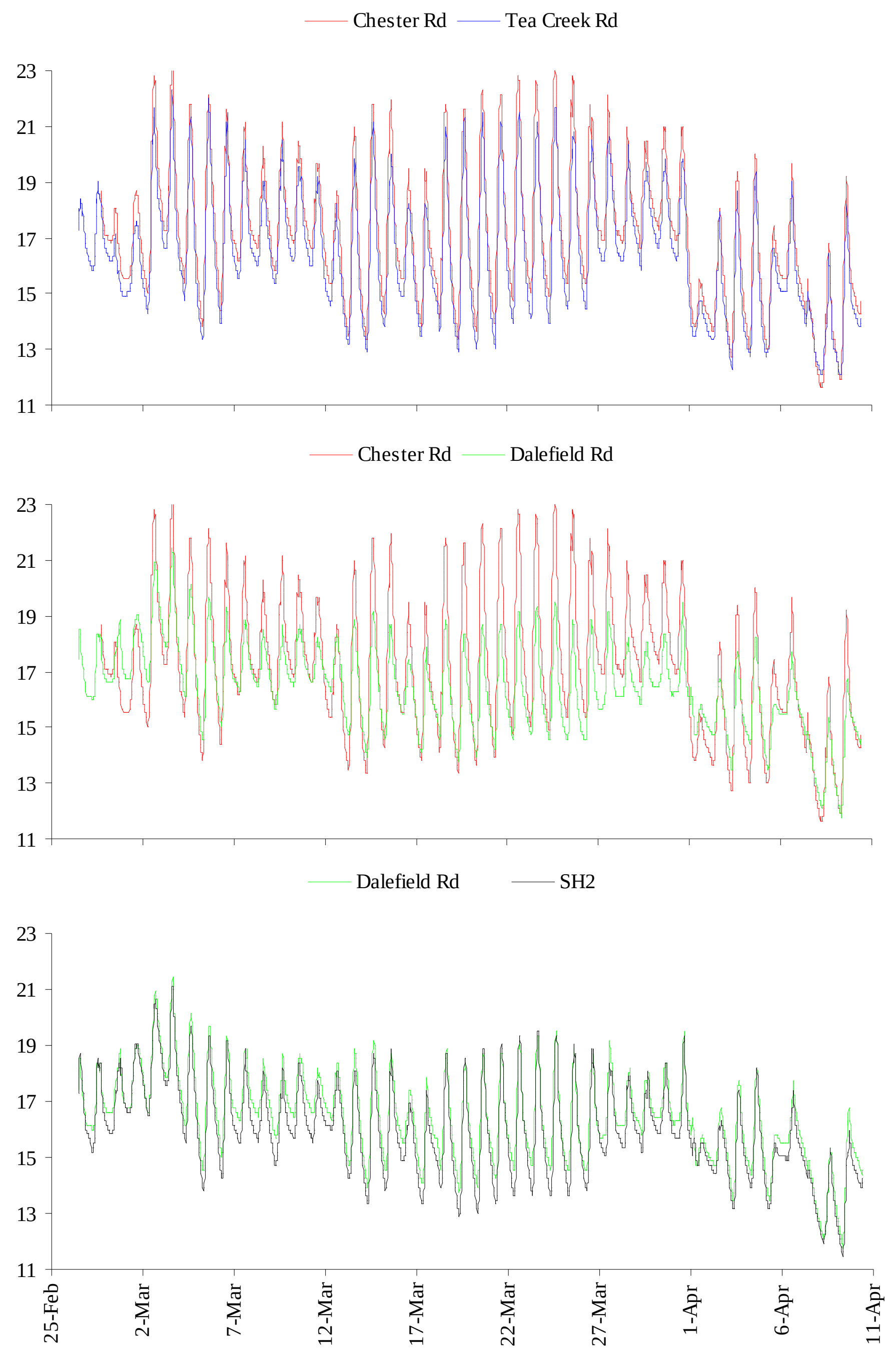


Figure 9: Measured water temperatures (^{o}C) at four sites on the Mangatarere River during March 2003. Site order from upstream is: Tea Creek Rd, Chester Rd, Dalefield Rd and SH2.

WAIORA MODELLING

Esk River

Calibration

The WAIORA model was calibrated over the reach Site 1-2 using data from 8–9 February 2003. It was then tested over the reaches Site 2-3 and Site 3-4 using data from 8-9 and 23 February 2003.

Table 8 gives the rating data used during all the calibration and testing predictions.

Table 8: Rating data for the Esk River used during WAIORA modelling.

Parameter	Source	Data Value
Flow 1 [L/s]	Measured	1900
Flow 2 [L/s]	Measured	4000
Mean depth [m]	Measured	.32
Mean stage change [m]	Measured	.07
Width 1 [m]	Measured	12
Width 2 [m]	Measured	14

Table 9 summarises model calibration. Meteorological data were set to the average over 8–9 February 2003 when conditions were similar. Upstream mean and maximum temperatures were set to the averages at Site 1 on 8–9 February. Flow was set to 1900 L/s, the observed value on at Site 3 on 8–9 February. Depth, width and velocity predicted by WAIORA are consistent with the rating curves (Figure 3).

The topography angle was set to 50^{o} because this gives the same DIFN as the average measured value from Site 1-2 (0.47 ± 0.11). No account was taken in this calibration of variability in measured lighting or uncertainty in the average lighting.

Bed thickness was set *a priori* to 1 m based on previous studies.

Bed temperature was then adjusted to match observed and predicted daily mean temperature at Site 2. This gave a bed temperature close to the observed mean water temperature at Site 2, the downstream measuring site. This was also found to be the case during calibration and testing at other sites and in other rivers. Consequently bed temperature was specified *a priori* to the observed mean water temperature at the downstream measuring site.

Finally bed conductivity was adjusted to match observed and predicted daily maximum temperature. It was found that bed conductivities in the range 75-100 J/m/s/^{o}C gave a reasonably good fit. With a bed conductivity of 75 J/m/s/^{o}C observed and predicted daily maximum temperatures matched closely, but the daily mean temperature at Site 2 was underestimated by 0.3^{o}C. With a bed conductivity of 150 J/m/s/^{o}C the daily mean was closely matched but the daily maximum was underestimated by 1.0^{o}C. A bed conductivity of 100 J/m/s/^{o}C matched observations to within 0.5^{o}C.

Table 9: Parameters used during WAIORA calibration: Site 1-2, 8–9 February 2003.

Parameter	Source	Data Value
Upstream site		Site 1
Downstream site		Site 2
Date		8–9 February 2003
Flow [L/s]		1800
Reach length [m]		6900
Mean daily air temperature [°C]	Measured	19.6
Maximum daily air temperature [°C]	Measured	24.5
Mean relative humidity [%]	Measured	66
Mean daily total solar radiation [MJ/m²/d]	Measured	27.2
Elevation [m]	Default	50
Latitude [°]		40
Day number		40
Time of max temp [h]	Estimated	12
% possible sun hours [%]	Observed	50
Wind velocity [m/s]	Observed	4.1
Daylight hours	Observed	12
US mean water temperature [°C]	Observed	18.7
US max water temperature [°C]	Observed	21.7
Depth [m]		0.32
Width [m]	Predicted	12.0
Velocity [m/s]		0.50
Topographic angle [°]		50
Canopy angle [°]	gives DIFN = 47%	50
Fraction through canopy		0
Bed thickness [m]	*a priori*	1
Bed temperature [°C]	Site 2 mean water	19.8

		Predicted	Observed
Bed conductivity [J/m/s/°C]	75		
Mean Daily Temperature [°C] at Site 2		19.5	19.8
Max Daily Temperature [°C] at Site 2		23.9	24.0
Bed conductivity [J/m/s/°C]	100		
Mean Daily Temperature [°C] at Site 2		19.6	19.8
Max Daily Temperature [°C] at Site 2		23.5	24.0
Bed conductivity [J/m/s/°C]	150		
Mean Daily Temperature [°C] at Site 2		19.7	19.8
Max Daily Temperature [°C] at Site 2		23.0	24.0

Testing

The model was tested by predicting temperature changes from Site 3-4 on 8–9 February (Table 10). Upstream water temperatures were re-set to those observed at Site 3. Topography angle was re-set to give the average DIFN measured from Site 3-4 (0.55 ± 0.11). Meteorology, flow and bed parameters remained unchanged from calibration. Predicted daily mean temperatures at Site 4 were within 0.1°C of the observations. For the calibrated bed conductivity of 100 J/m/s/°C daily maximum temperatures matched within 0.2°C.

Table 10: Parameters used during WAIORA testing. Site 3-4, 8–9 February 2003.

Parameter	Source	Data Value
Upstream site		Site 3
Downstream site		Site 4
Date		8–9 February 2003
Flow [L/s]		1900
Reach length [m]		6000
Meteorological and flow data	as for calibration	see Table 6
US mean water temperature [°C]	Observed	20.2
US max water temperature [°C]	Observed	23.6
Topographic angle [°]		42
Canopy angle [°]	gives DIFN = 55%	42
Fraction through canopy		0
Bed thickness [m]	*a priori*	1
Bed temperature [°C]	Site 4 mean water	20.8

		Predicted	Observed
Bed conductivity [J/m/s/°C]	100		
Mean Daily Temperature [°C] at Site 2		20.7	20.8
Max Daily Temperature [°C] at Site 2		24.5	24.3

Further model testing was done using data from 23 February (Tables 11 and 12) when air and upstream water temperatures were significantly lower than during 8–9 February. Meteorology and upstream water temperatures were reset to the observed values on 23 February. Bed temperature was reset to the observed mean water temperature at the downstream site.

From Site 1-2 the calibrated bed conductivity of 100 J/m/s/°C together with a bed temperature of 15.5°C, the mean water temperature observed at Site 2, gave a predicted daily maximum temperature that matched closely and a daily mean that was under-estimated by 0.3°C.

An attempt was made to test the model from Site 2-3. Lighting in this reach was reset to the observed average (0.54 ± 0.13) and bed temperature was reset to 15.9°C the mean water temperature observed at Site 3. While the observed and predicted daily mean temperatures at Site 3 matched closely, the model over-estimated the daily maximum temperature by 0.6°C. A sensitivity analysis was carried out (details omitted for brevity) which showed that an unrealistically large bed conductivity would be required to match the observed daily maximum temperature at Site 3 given the observed lighting from Site 2-3. As shown in Table 3, temperature changes in the reach Site 2-3 are slightly anomalous in that, on average the daily mean increases (0.4 ± 0.1°C) while the daily maximum remains unchanged (-0.3 ± 0.3°C). On 23 February the daily mean increases by 0.4°C while the daily maximum remains unchanged. This is consistent with a short reach of dense shade in the reach from Site 2-3 that reduces solar radiation near mid-day, thereby reducing daily maximum temperature, but heating of both the water and the stream bed above Site 2 that results in an increase in daily mean and minimum temperature. WAIORA is unable to simulate this complex behaviour and a more complex model such as STREAMLINE (Rutherford *et al*., 1997) would be required.

The observed temperature changes also suggest that lighting measurements from Site 2-3 over-estimate the reach-average value, possibly because measurements were biased to more open locations.

No testing is possible from Site 3-4 on 23 February because the Site 4 thermistor malfunctioned after 18 February.

Table 11: Parameters used during WAIORA testing: Site 1-2, 23 February 2003.

Parameter	Source	Data Value
Upstream site		Site 1
Downstream site		Site 2
Date		23 February 2003
Flow [L/s]		1900
Reach length [m]		6900
Mean daily air temperature [℃]	Measured	14.8
Maximum daily air temperature [℃]	Measured	21.0
Mean relative humidity [%]	Measured	64
Mean daily total solar radiation [MJ/m²/d]	Measured	25.1
Elevation [m]	Default	50
Latitude [°]		40
Day number		40
Time of max temp [h]	Estimated	12
% possible sun hours [%]	Observed	80
Wind velocity [m/s]	Observed	3.8
Daylight hours	Observed	12
US mean water temperature [℃]	Observed	14.3
US max water temperature [℃]	Observed	17.3
Depth [m]		0.32
Width [m]	Predicted	12.0
Velocity [m/s]		0.50
Topographic angle [°]		50
Canopy angle [°]	gives DIFN = 47%	50
Fraction through canopy		0
Bed thickness [m]	*a priori*	1
Bed temperature [℃]	Site 2 mean water	15.5

		Predicted	Observed
Bed conductivity [J/m/s/℃]	100		
Mean Daily Temperature [℃] at Site 2		15.1	15.5
Max Daily Temperature [℃] at Site 2		19.0	18.9

Table 12: Parameters used during WAIORA testing: Site 2-3, 23 February 2003.

Parameter	Source	Data Value
Upstream site		Site 2
Downstream site		Site 3
Date		23 February 2003
Flow [L/s]		1900
Reach length [m]		5600
Meteorology and channel parameters	as in Table 8	
US mean water temperature [°C]	Observed	15.5
US max water temperature [°C]	Observed	18.9
Topographic angle [°]		42
Canopy angle [°]	gives DIFN = 54%	42
Fraction through canopy		0
Bed thickness [m]	*a priori*	1
Bed temperature [°C]	Site 2 mean water	15.9

		Predicted	Observed
Bed conductivity [J/m/s/°C]	100		
Mean Daily Temperature [°C] at Site 2		15.8	15.9
Max Daily Temperature [°C] at Site 2		19.5	18.9

Mangatarere Stream

The unknown exchanges with groundwater and tributary inflows prevent quantitative analysis of the observed temperature changes in the two lower sub-reaches (Chester-Belvedere and Belvedere-SH2). This leaves only the upstream reach (Tea Creek-Chester) amenable to modelling with WAIORA.

Calibration

Bed thickness, bed conductivity and bed temperature are unknown in the Mangatarere Stream. Bed thickness was assumed to be 1 m, based on temperature modelling studies in other gravel bed rivers. Bed temperature and conductivity were calibrated using measurements made on 27 March 2003.

Observed daily mean (17.8^{o}C) and maximum (20.7^{o}C) temperature at Tea Creek Road were specified as the upstream (US) boundary conditions. The reach length is 2.5km and the canopy angle was set to 40^o with a gap-fraction of 0.0 since this gives the observed median shade in the study reach (DIFN = 0.60) (Table 13).

Bed temperature was adjusted by trial and error until observed (18.6^{o}C) and predicted daily mean temperatures at Chester Road on 27 March 2003 matched. This was achieved with a bed temperature of 18.2^{o}C. This exactly matches the average water temperature at Chester Rd over the preceeding 7 days. Bed conductivity was then adjusted until observed and predicted daily maximum temperatures (22.1^{o}C) at Chester Road on 27 March 2003 also matched. This was achieved with a bed conductivity of 130 J/m/s/°C (see Table 14).

A limited sensitivity analysis was performed. As bed thickness was increased to 2 and 3 m it was necessary to increase bed conductivity to 260 and 390 J/m/s/^{o}C to match the observed daily maximum temperature at Chester Rd. Bed temperature remained at 18.2^{o}C.

Figure 10 indicates that the daily maximum water temperature is predicted to approach 23^{o}C in the study reach for the meteorological conditions that prevailed during 27 March 2003, but that at higher flows it is unlikely to exceed 21^{o}C.

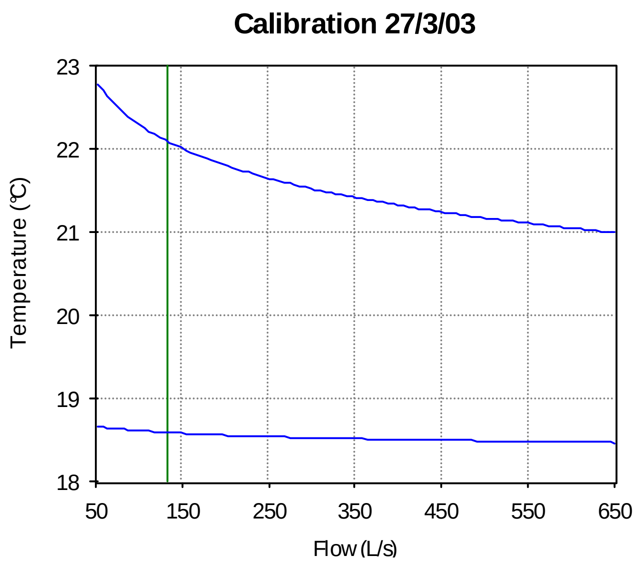


Figure 10: WAIORA calibration. Tea Creek to Chester Rd 27 March 2003.

Table 13: Summary of fixed model parameters.

Parameter	Source	Data Value
Flow 1 [L/s]	rating curve	100
Flow 2 [L/s]	rating curve	600
Depth 1 [m]	rating curve	0.12
Depth 2 [m]	rating curve	0.25
Width 1 [m]	rating curve	5.0
Width 2 [m]	rating curve	6.0
Latitude [°]		40
Elevation [m]		50
Day number		100
Daylight hours		12
Time of max temp [h]		12
Reach length [m]	Measured	2500

Table 14: Summary of parameters values used during model calibration: 27 March 2003.

Parameter	Source	Data Value
Flow [L/s]		128
Mean depth [m]		.133
Mean velocity [m/s]		.188
Width [m]		5.13
Mean daily air temperature [°C]	Measured	19.8
Maximum daily air temperature [°C]	Measured	25.1
Mean relative humidity [%]	Measured	92.2
Mean daily total solar radiation [MJ/m²/d]	Measured	17.2
Topographic angle [°]	To give DIFN = 0.60	40
Canopy angle [°]	To give DIFN = 0.60	40
Fraction through canopy	To give DIFN = 0.60	0
Bed thickness [m]	Calibrated	1
Bed conductivity [J/m/s/°C]	Calibrated	130
Bed temperature [°C]	Calibrated	18.2
% possible sun hours [%]	Measured	33
Wind velocity [m/s]	Measured	1
US mean water temperature [°C]	Measured	17.8
US max water temperature [°C]	Measured	20.7
Tributary flow		Absent
	Predicted	**Observed**
Mean Daily Temperature [°C]	18.5	18.6
Max Daily Temperature [°C]	22.1	22.1

Testing

To check the validity of the calibrated parameters, temperature predictions were made on 6, 14 and 21 March 2003, when flows and/or meteorological conditions were different from the calibration date. Bed conductivity and bed thickness remained unchanged from their calibrated values. Meteorology and flow were changed to the values measured, and bed temperature was changed to the average water temperature at Chester Rd during the preceeding 7 days. Table 15 summarises the results of model testing.

The model predicted daily mean and maximum temperature to within 0.2°C on 6 March, which is within the measurement accuracy of stream temperature. It estimated daily mean temperature on 14 and 21 March to within 0.2-0.3°C, and daily maximum temperature on 21 March to within 0.4°C, which is satisfactory. However, the model underestimated daily maximum temperature on 14 March by 1.4°C. The amplitude of diurnal temperature variations depends strongly on mean water depth, bed conductivity and solar radiation, and less strongly on mean velocity.

There are three possible explanations for the discrepancy on 14 March. First, it is possible that the solar radiation measured at Palmerston North on 21 March underestimated the value at Masterton. Second, the bed conductivity may be lower than the calibrated value of 130 J/m/s/°C at high flows (viz., there may be less exchange between the bed and the overlying water at high flow). Sensitivity analysis indicated that a bed conductivity of 25 J/m/s/°C was required to give a daily maximum temperature on 21 March of 21.8°C (the observed value). However, this resulted in a daily mean temperature (16.2°C) significantly lower than was observed (17.2°C). Because decreasing the bed conductivity did not result in an overall improvement in model fit, it seems unlikely that this parameter alone is the cause of the discrepancy. Third, flow was higher on 21 March (305 L/s) than on the other three dates used during calibration and testing. The depth (0.19 m) and velocity (0.29 m/s) in the model closely matched values measured at the Tea Creek and Anderson's Line gauging sites on 14 March. However, it is conceivable that the reach-average depth and/or velocity are lower than values at these gauging sites. It is common to choose gauging sites for convenience of flow measurement rather than ones that are representative of the channel. Further fieldwork would be required to test this hypothesis.

With the available information it is not possible to explain the discrepancy between observed and predicted daily maximum temperature on 14 March.

Table 15: Summary of parameters values used during model testing.

Parameter	6 Mar.	14 Mar.	21 Mar.	Calibration
Flow [L/s]	253	307	165	128
Mean depth [m]	.176	.190	.147	.133
Mean velocity [m/s]	.262	.288	.213	.188
Width [m]	5.50	5.61	5.26	5.13
Mean air [℃]	14.8	12.7	17.8	19.8
Maximum air [℃]	23.9	21.4	26.7	25.1
Humidity [%]	91.8	94.5	89.5	92.2
Solar radiation [MJ/m²/d]	19.2	18.5	19.8	17.2
Bed thickness [m]		1		
Bed conductivity [J/m/s/℃]		130		
Bed temperature [℃]	17.8	17.4	17.2	18.2
% possible sun [%]		33	33	33
US mean water [℃]	16.9	16.3	16.6	17.8
US max water [℃]	21.5	21.2	21.2	20.7
Wind [m/s]	1	1	1	1
Predicted				
Mean water [℃]	17.5	16.9	17.5	18.5
Max water [℃]	21.4	20.4	21.7	22.1
Observed				
Mean water [℃]	17.5	17.2	17.7	18.6
Max water [℃]	21.6	21.8	22.1	22.1

DISCUSSION AND CONCLUSIONS

Esk River

The observed increase in daily maximum water temperature along the Esk River is to be expected. Water temperatures at Site 1 are low because the water has come from higher elevation where air temperature is low and shade is high. Between Sites 1-4 the river channel is wide, the surrounding topography is less steep and water temperatures are expected to increase as a result of warmer air temperatures and higher inputs of solar and atmospheric radiation.

The Esk River is unusual in exhibiting an increase of daily minimum temperature with distance downstream. In the many small, pasture streams the daily minimum water temperature is unaffected by shade and does not vary significantly downstream (Rutherford *et al*., 1997). Occasionally a reduction in shade results in an increase in heat loss to the atmosphere which causes night time cooling, and hence a reduction in daily minimum temperature (author's, unpubl. data). The likely explanation for the behaviour of the Esk River is a gradual increase in bed temperature with distance downstream. This is plausible since solar radiation causes an increase in water temperature with distance downstream during the day. During the day heat flows from the water to the bed and one might expect to see greater bed warming near Sites 3-4 than Sites 1-2. At night the converse applies and heat flows from the bed back into the water. If bed temperatures are higher at Sites 3-4 then this will result in higher night time water temperatures. Bed temperature measurements and/or more sophisticated modelling (e.g., using the STREAMLINE model, Rutherford *et al*., 1997) would be required to test this hypothesis. The WAIORA model is unable to predict changes in bed temperature.

There was a poor correlation between the water temperature changes observed between adjacent thermistor sites and the measured reach-average lighting level between those sites. This is especially noticeable between Site 2-3 where daily maximum temperature decreased, daily mean and minimum temperature increased and lighting was higher than between Site 1-2. There are three possible reasons. First, because the study reach was 18.5 km long lighting measurements were only made in sub-reaches. Every effort was made to make these measurements along 'representative' sub-reaches but we cannot discount the possibility that our measurements provide 'biased' estimates of the true reach-average lighting. Second, water temperature takes time to respond to changes in shade. Consequently water temperature may be high at a site where lighting is low simply because there is a well-lit reach upstream and water temperature has not yet had time to adjust to the increased shade. Third, heat exchange between the water and the bed further complicates the situation.

Temperatures increased rapidly in the morning everywhere in the study reach but in the afternoon temperatures dropped more rapidly at Site 1 than at Site 2, more rapidly at Site 2 than at Site 3 and so on along the study reach. This is consistent with heating of both the water and the bed in the study reach.

Water and air temperatures were positively correlated. Temperature increases between sites were correlated with solar radiation. In both relationships there was high variability. Shade and bed conduction strongly affect predicted water temperature. Typically shade is known but bed temperature, bed thickness and bed heat conductivity are unknown and must be 'calibrated'.

The model was calibrated over the reach Site 1-2 using data from 8–9 February 2003. It was then tested over the reaches Site 2-3 and Site 3-4 using data from 8-9 and 23 February 2003.

Differences arose from variability and/or bias in our measurements of lighting, depth, velocity and water temperature together with differences in meteorology between the study site and Napier Airport. It is unlikely that the calibration of the WAIORA model can be substantially improved.

Although predictions of water temperature are only accurate to within ± 0.5°C, predictions of temperature change (e.g., resulting from changes of shade or flow) are likely to be significantly more accurate. Flows did not vary significantly during the Esk study and so the available data do not allow us to quantify directly the effects of flow changes or assess the accuracy of model predictions of the effects of flow changes.

Mangatarere Stream

One factor that complicates attempts to predict water temperature in the Mangatarere Stream is the large exchange of water between the stream and the streambed or surrounding groundwater. On 27 February the stream channel was dry for several kilometres in the vicinity of Anderson's Line, and the stream gaugings show a consistent pattern of water loss in this part of the channel.

WAIORA assumes that depth is uniform and so it is not feasible to model temperature accurately in a 'losing' reach in which depth decreases with distance. Similarly WAIORA cannot model in detail a 'gaining' reach in which depth increases with distance. More importantly, in a 'gaining' reach the temperature of emerging groundwater and the location where it emerges must both be known in order to predict water temperature. This information is not available for the Mangatarere Stream.

Consequently, of the three reaches for which measurements were made, the only one where it was feasible to run WAIORA was the reach from Tea Creek Rd to Chester Rd. WAIORA was calibrated by specifying the bed thickness *a priori* and adjusting the bed temperature bed and bed conductivity so that predicted temperatures matched those observed on 26 March 2003.

A conductivity of 130 J/m/s/°C was required to achieve a satisfactory fit. This value is large by comparison with values of 10-50 J/m/s/°C estimated for other New Zealand and Australian rivers. However, in the Mangatarere Stream there is evidence of significant flow into and out of the bed. Adjective flow into and out of the bed is not simulated by WAIORA but the effects of such flow can be mimicked successfully using a high value for the bed conductivity. Calibration also required a bed temperature of 18.2°C. No direct measurements of bed or groundwater temperature are available for comparison with this calibrated value. However, in other studies bed temperature tends to be similar to the long-term average water temperature, which was in the range 17-19°C during the study. The calibrated bed temperature of 18.2°C exactly matched the average water temperature at Chester Rd during the preceding 7 days. Overall the calibrated bed parameters are plausible.

Using the calibrated parameters (viz., bed conductivity = 130 J/m/s/°C and bed temperature = average water temperature during the preceding 7 days), a reasonable match was obtained between predicted temperatures on three separate occasions when flow and/or meteorological conditions were different. The model predicted daily mean temperature to within 0.2-0.3°C, which is satisfactory. In two of the three tests the model predicted daily maximum temperature within 0.2-0.4°C but in one it significantly underestimated daily maximum temperature (by 1.4°C) for reasons that cannot be determined from the available data.

Recommendations

1. Overall, an uncertainty of ± 0.5°C should be ascribed to WAIORA v.2.0 temperature predictions.

2. Predictions of temperature <u>change</u> (e.g., resulting from changes of shade or flow) are likely to be significantly more accurate than predictions of water temperature.

3. Measurements are required of:
    - water temperature at two sites;
    - lighting, depth and velocity between those sites; and
    - meteorology from an adjacent monitoring site.

4. Calibration of WAIORA v.2.0 should be conducted using the following standard protocol
    - specify bed thickness *a priori*
      We recommend using a value of 1 m based on studies in several New Zealand and Australian rivers (author's unpublished data).
    - adjust bed temperature so that the observed and predicted <u>daily mean</u> temperature match at the downstream site.
      We found that this can usually be achieved with a bed temperature equal to the daily mean water temperature at the downstream site. We recommend specifying the bed temperature *a priori* to the measured daily mean water temperature at the downstream site.
    - adjust the bed conductivity so that the observed and predicted <u>daily maximum</u> temperature match at the downstream site.

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REFERENCES

Rutherford, J.C.; Blackest, S.; Blackest, C.; Saito, L. and Davies-Colley, R.J. (1997). Predicting the effects of shade on water temperature in small streams. *New Zealand Journal of Marine and Freshwater Research 31(5)*: 707-721.