

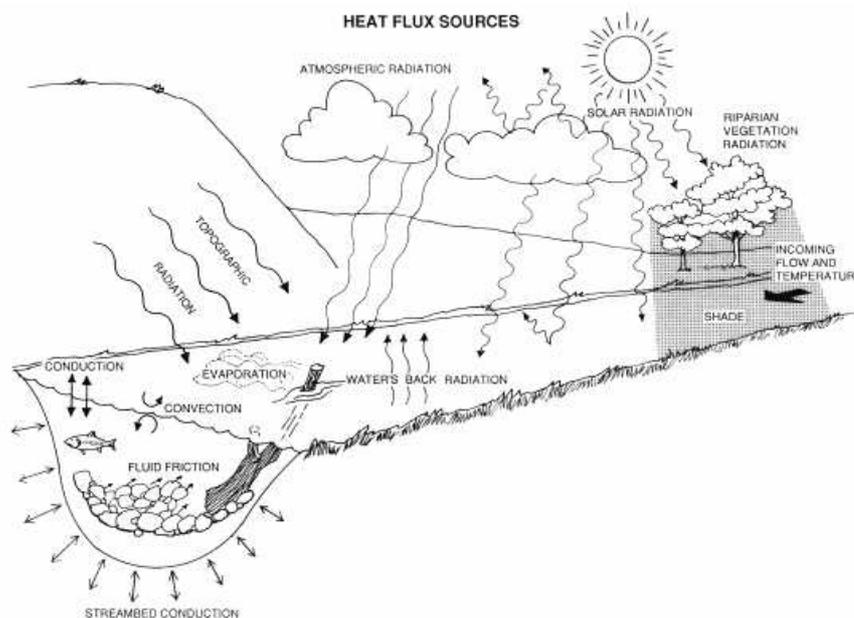
# PROCEDURE FOR CALCULATING WATER TEMPERATURE

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WAIORA version 2.0 uses a dynamic heat transport model to solve the heat flux equations in a downstream direction. This in contrast to the approximate approach used in version 1.0 and 1.1 and provides better estimates of daily extremes than the direct solution used in the SSTEMP model of Bartholow (2002). The heat flux equations used in WAIORA are described in detail in Theurer et al. (1984). Overall, we recommend that temperature predictions be ascribed an uncertainty of  $\pm 0.5^{\circ}\text{C}$  using the WAIORA v.2.0 temperature model, although this is clearly dependent on the quality of the data entered. Relative changes in temperature will be more accurate than absolute predictions.

The water temperature data required for heat budget modelling describe the meteorological, hydrological, shading and streambed conditions. The WAIORA model is a one-dimensional heat transport model that predicts the daily mean and maximum water temperatures as a function of stream distance downstream, and environmental heat flux from the abstraction point. In general terms, WAIORA calculates the heat gained or lost from a parcel of water as it passes through a stream segment. This is accomplished by simulating the various heat flux processes which determine that temperature change (see figure below). These physical processes include convection, conduction, evaporation, as well as heat to or from the air (long wave radiation), direct solar radiation (short wave), and radiation back from the water. WAIORA first calculates the solar radiation and how much is intercepted by shading. This is followed by calculations of the remaining heat flux components for the stream segment.



The heat transport model tracks heat and water fluxes downstream. It assumes that daily temperature and radiation data can be represented by sinusoidal variation about the average, and that other meteorological and hydrological variables can be represented by average values.

Water temperatures are modelled downstream of the abstraction point. The water flowing downstream will then increase or decrease in temperature until a dynamic equilibrium is established between the diurnal pattern of incoming radiation and the diurnal heat losses from the river through radiation and evaporation. This final state, when there is no further change in the diurnal variation of water temperature with distance downstream, is known as the equilibrium condition. The magnitude and rate of change in water temperature will depend on meteorological conditions such as radiation, air temperature, shade and flow.

Limitations and assumptions of the WAIORA temperature model are:

- The characteristics of the selected reach represent the characteristics of a longer section of river and do not change with lateral inflow or distance downstream.
- The model does not handle rapidly fluctuating flows.
- Turbulence is assumed to thoroughly mix the stream vertically and transversely (i.e., no microthermal distributions).

## DATA REQUIREMENTS

### Reach length

The reach length, specified in metres, is the length of the stream that is being evaluated for changes in habitat, water temperature, dissolved oxygen and ammonia concentration. It is assumed that the hydraulic geometry (flow, stream width, depth, and velocity) and other characteristics, such as meteorology, shade, and stream bed conditions, are constant along the reach. Water temperature, dissolved oxygen concentration, and ammonia concentration apply to the end of the reach, whereas habitat conditions apply throughout the length of the reach.

### Air temperature

All temperatures are in degrees Centigrade. Daily means are usually the average of the daily maximum and daily minimum temperatures. The daily maximum/minimum air temperature is usually the maximum/minimum recorded on a max/min thermometer over a 24 h (9am to 9am) period.

Air temperatures should be measured for accurate water temperature model calibration. This and the other meteorological parameters may be obtained from the National Institute of Water and Atmospheric Research for a meteorological station near your site.

The adiabatic lapse rate can be used to correct for elevation differences:

$$T_a = T_o + C_t * (Z - Z_o)$$

where  $T_a$  = air temperature at elevation  $Z$  (°C)

$T_o$  = air temperature at elevation  $Z_o$  (°C)

$Z$  = mean elevation of stream (m)

$Z_o$  = elevation of met. station (m)

$C_t$  = moist-air adiabatic lapse rate (-0.00656 °C /m)

NOTE: Air temperature, radiation, and shade are usually the most important factors in determining water temperature.

## Radiation

The daily total radiation is one of the most important factors affecting water temperature. Daily total radiation is highest in mid-summer and lowest in winter, and is measured in units of megajoules per square metre.

The intensity (or rate) of radiation is usually expressed in ( $\text{W}/\text{m}^2$ ). One watt is equal to one joule of work per second. A megawatt (MW) is the same as 1000000 watts. One langley/min is equivalent to  $697.3 \text{ W}/\text{m}^2$  or  $697.3 \text{ J}/\text{sec}/\text{m}^2$ .

Radiation is usually measured continuously with a pyrometer as a rate in  $\text{MJ}/\text{sec}/\text{m}^2$  or  $\text{MW}/\text{m}^2$ . This is integrated over the day to give the daily total radiation in  $\text{MJ}/\text{m}^2$ .

It is often assumed that about 90% of the ground level solar radiation actually enters the water. Thus, multiply the recorded solar measurements by 0.90 to get the number to be entered.

## Time of maximum temperature

The time of maximum temperature is used to describe the sinusoidal variation in air temperature. It is specified in hours using the 24h clock. This is not a particularly important parameter for water temperature modelling, but can be relevant for calibration of water temperature models. The maximum air temperature usually occurs between 14 and 16 h.

## Wind velocity

The average daily wind velocity over the water surface in m/s. Readings of wind velocity at meteorological stations are often higher than those at water surface level. Adjustment of wind velocity (and shade) can be used to calibrate a water temperature model to known downstream water temperatures. Wind velocity increases evaporative cooling of water as it flows downstream and in some situations can actually result in water temperatures decreasing in a downstream direction.

## Possible sunshine hours

This parameter is an indirect measure of cloud cover. It is expressed as the percentage of maximum possible sunshine hours and is measured with a pyrometer or can be calculated from cloud cover (decimal) as:

$$\text{Percent possible sun hours} = (1 - \text{Cloud}^{(5/3)}) * 100$$

## Relative humidity

The relative humidity is specified as a percentage. The relative humidity increases the rate at which heat is transferred between the air and water and decreases the rate of evaporation, so that an increase in humidity will increase water temperature. Correct for elevation differences by:

$$Rh = Ro * (1.0640^{(To-Ta)}) * ((Ta+273.16)/(To+273.16))$$

where  $Rh$  = relative humidity at the stream for temperature  $Ta$  (decimal)

$Ro$  = relative humidity at meteorology station (decimal)

$Ta$  = air temperature at stream ( $^{\circ}\text{C}$ )

$To$  = air temperature at meteorology station ( $^{\circ}\text{C}$ )

## Day number and latitude

The day number is the Julian day number with 1<sup>st</sup> January being day 1 and 31<sup>st</sup> December day 365. The day number and latitude are used to calculate the sun angle (solar elevation) at different times

of day and hence the times at which the stream is shaded by topography or riparian vegetation. They are also used to calculate the time between sunrise and sunset for the time of year.

### Elevation

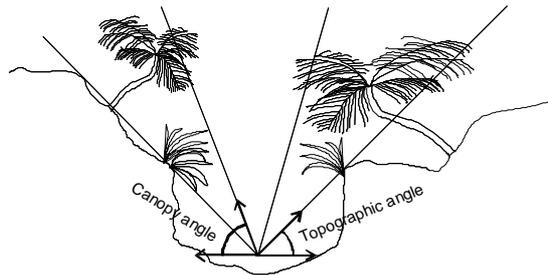
The elevation in metres above sea level at the abstraction point (start of the stream reach to be modelled). This is used to calculate atmospheric pressure for convection heat flux:

$$Pressure = 1013 * ((288 - 0.0065 * Elevation) / 288)^{5.256}$$

### Stream shade

Every stream or river is shaded by the banks and surrounding hills and vegetation. Shade has a large influence on water temperature and it is important to make reliable estimates of it. Shade represents the proportion of the incoming solar radiation that does not reach the water. The amount of shade can be determined either by a trial and error calibration procedure to a known downstream water temperature or by measurement where the elevation angles of the trees, banks and/or hillsides are measured and the fraction of radiation penetrating the canopy estimated. The canopy and topographic shade angles are estimated as the average angle of sky visible around the 360° horizon. For example, a canopy angle of 90° is complete canopy closure.

The topographic angle is the average angle of the tops of hills and other solid objects on the horizon. The canopy angle is the average angle of the tops of riparian vegetation. The fraction penetrating the canopy is the fraction of radiation penetrating the vegetation canopy, as shown below.



The total shade fraction is calculated as topographic shade plus canopy shade.

$$Topographic\ shade = 1 - (Cos(topographic\ angle))^{0.5}$$

$$Canopy\ shade = (1 - Fraction\ penetrating\ canopy) * ((Cos(topographic\ angle))^{0.5} - (Cos(canopy\ angle))^{0.5})$$

The canopy and topographic angles are values between 0 and 90, and the canopy angle must always be equal to (no vegetation) or greater than the topographic angle.

### Stream bed

Heat from the water is lost and gained from the streambed. The streambed acts as a long-term buffer or heat store, effectively damping the response of water temperature to meteorological variations. For this reason, mean monthly air temperatures can be used as bed temperatures if measurements of ground temperature are not available.

In the model, heat is transferred between the streambed and water according to:

$$Heat\ transfer = bed\ conductivity * (bed\ temperature - water\ temperature) / bed\ thickness$$

An estimate of the bed temperature can be obtained from measurements of ground temperature taken at climatological stations. If possible, ground temperatures measured at 1.0 m below ground

level should be used. In such cases, 1 m would be the streambed depth. Measurements at lesser depths can be used if 1 m depth ground temperature measurements are not available. Mean monthly air temperatures can be used as bed temperatures if measurements of ground temperature are not available.

The conductivity of the streambed ( $J/m/sec/^\circ C$ ) is often considered to be 1.65 for water-saturated sands and gravel mixtures. However, the heat transfer process is often more complicated than a simple conductive model because water flows in to and out of the streambed, thus effectively increasing conductivity. For this reason, we suggest a default value of  $10 J/m/sec/^\circ C$ .

Streambed temperatures and bed conductivity can also be used to calibrate water temperature models (see calibration).

### **Initial water temperature**

The initial water temperature is the temperature of the water flowing into the upstream end of the reach. Its units are degrees Centigrade. The initial water temperature at the abstraction point can be either specified directly or calculated from the stream characteristics upstream of the reach by assuming that the water temperature has reached equilibrium temperature. The initial water temperatures and upstream characteristics can be specified in Advanced settings. The default assumption is to use the equilibrium temperature calculated from upstream characteristics that are the same as the reach characteristics. These assumptions can be altered by selecting Advanced settings. The change in water temperature is then calculated as the water flows downstream using the sinusoidally varying water temperature at the abstraction point (beginning of the reach).

By default, the initial water temperature is the equilibrium temperature calculated assuming an infinitely long upstream channel with a flow equal to the existing low flow and the same characteristics as the reach, including shade. If this default assumption is true, there will be little change in temperature with flow and distance downstream. Note that differences in the amount of shade between upstream and downstream reaches will invalidate the default assumption of equilibrium.

### **Lateral and tributary flows**

Inflow (or outflow if negative) can be either uniformly apportioned through the length of the reach (i.e., by selecting lateral inflow) or can flow into the reach at a point (i.e., by selecting tributary inflow). The location of a point tributary inflow is specified by its distance below the abstraction point and that value is entered as the tributary distance. The temperature of the uniformly distributed lateral inflow generally should be the same as groundwater temperature. Groundwater temperature may be approximated by the mean monthly air temperature. Exceptions may arise in areas of geothermal activity. The temperature of tributary inflows is specified in the same way as upstream water temperatures, either an equilibrium water temperature calculated from the tributary stream shade and bed conditions or by specifying the daily mean and maximum water temperature.

## **CALIBRATION OF WATER TEMPERATURE MODEL**

A water temperature model should be calibrated, although this is not necessary in order to get a rough idea of the temperature changes that will be caused by a change in flow. Field measurements of flows, upstream and downstream water temperatures, tributary flows and water temperatures, flow, and meteorological conditions can be used in a trial and error procedure to determine the shade factors and possibly the wind velocity that predict the correct downstream water temperatures. If this procedure does not correctly predict both mean and maximum water temperatures or if the values of shade and wind velocity are unreasonable, the conductivity and temperature of the streambed may need calibration.

Actual meteorological data are required to calibrate a water temperature model. Ideally, these are recorded on site, but at times it is necessary to obtain meteorological data from nearby climate stations. Such data can be obtained from NIWA's National Climate Database. <http://www.niwa.co.nz/services/clidb/>.

To calibrate the model, measurements are required of:

- water temperature at two sites;
- shade, depth and velocity between those sites; and
- meteorology from an adjacent monitoring site (e.g., airport).

The three steps in the calibration protocol are:

1. Specify bed thickness *a priori* (an assumed bed thickness of 1 m is suggested when calibrating bed conditions).

We recommend using a value of 1 m based on studies in several New Zealand and Australian rivers (NIWA unpublished data).

2. Adjust bed temperature so that the observed and predicted daily mean temperature match at the downstream site.

We found that this can usually be achieved with a bed temperature equal to the mean water temperature at the downstream site over one or more days.

3. Adjust the bed conductivity so that the observed and predicted daily maximum temperature match at the downstream site (try a bed conductivity of 10s J/m/s/°C to start with; its value will increase with bed thickness).

If shade has not been measured then it can also be estimated by calibration. The recommended steps are:

1. specify bed thickness *a priori* (an assumed bed thickness of 1 m is suggested when calibrating bed conditions);
2. set the temperature to the average water temperature at the downstream site over one or more days;
3. adjust shade so that the observed and predicted daily mean temperature match at the downstream site;
4. adjust the bed conductivity so that the observed and predicted daily maximum temperature match at the downstream site (try a bed conductivity of 10 J/m/s/°C to start with; its value will increase with bed thickness and could be as high as 100 J/m/s/°C).

## REFERENCES

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