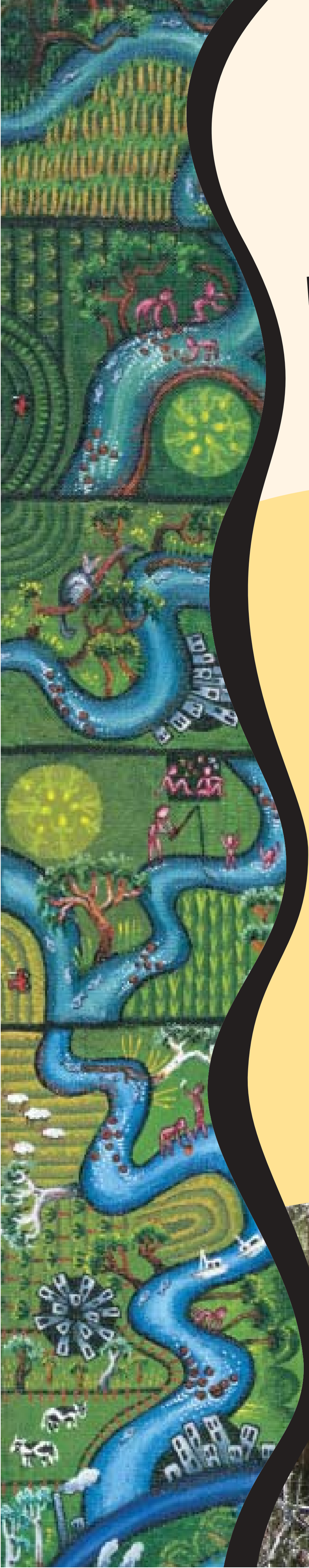

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# Managing high in-stream temperatures using riparian vegetation

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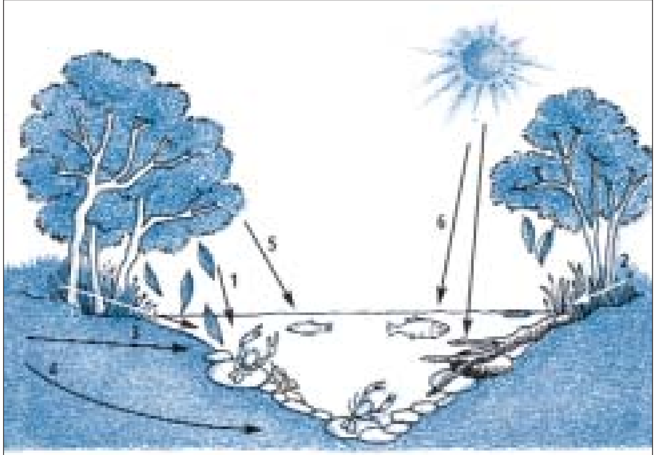
## Summary

- A reduction in water temperature is an ecologically meaningful, tangible and easily measured outcome of riparian replanting. In the absence of shade, water temperatures often exceed thermal tolerances of aquatic fauna. Replanting riparian zones can reduce water temperatures to benefit downstream ecosystems.
- The control of water temperature through riparian shading is an area of restoration where target values can be set and, consequently, the amount of vegetation required to meet these targets can be specified.
- In streams and rivers, particularly those reaches where restoration would normally be attempted, exceedence of lethal temperatures of aquatic fauna is the major issue associated with riparian influences.
- Priority areas for restoration aimed at relieving in-stream thermal stress are to: restore lower order streams before higher order streams; restore streams with woody vegetation before seeking to improve lower density or degraded vegetation; restore streams on north-west aspects before south-east aspects; and preferentially restore reaches where soil properties are most favourable for successful vegetation establishment.
- Stream shade comprises three components — macrotopographic shade provided by nearby hills and other landforms, bank shade and vegetative shade. Methods are provided in this Technical Guideline to estimate these components using Geographic Information Systems and field based approaches.

## Background

Healthy native riparian (streamside) vegetation is known to be a major driver of the ecological health of streams and rivers. Consequently, it should be a primary focus of river restoration in reaches where native vegetation has been cleared extensively or is degraded. Aquatic food webs are supported by the supply of leaves, fruits, twigs, and insects from the riparian zone, and riparian shade regulates the growth of nuisance plants such as algae (Figure 1). In addition, nutrients from adjacent land can be assimilated by riparian vegetation before they are exported into streams where they may degrade local and receiving systems (i.e. estuaries). The multiple roles riparian systems play makes them priority areas for restoration however, it has remained difficult to be prescriptive about the actual amount of vegetation required to achieve ecological goals.



1. Inputs of leaf litter from riparian vegetation.
2. Inputs of logs and branches (important habitat role).
3. Leaves and fine particles of organic matter washed in from surrounding catchment.
4. Dissolved organic matter in sub-surface flow and groundwater.
5. Terrestrial invertebrates falling from riparian vegetation.

Source: S. Bunn, 1998.

**Figure 1**. Schematic representation of the ecological multiple roles of riparian vegetation in controlling river health.

Research has shown that in-stream water temperatures control ecological processes (i.e. ecosystem metabolism) and directly regulate biodiversity when upper lethal limits of resident aquatic fauna are exceeded. Water temperatures can be controlled by adequate riparian shading, and this may have flow-on improvements to lower river systems and estuaries. The control of water temperature through riparian shading, is an area of restoration where target values can be set and consequently the amount of vegetation required to meet these targets can be specified.

In the absence of shade, water temperatures often exceed thermal tolerances of aquatic fauna, leading to loss of biodiversity and changes in ecosystem function. Hence, a reduction in water temperature is an ecologically-meaningful, tangible, and easily measured, outcome of riparian replanting. Replanting riparian zones can also reduce water temperatures to benefit downstream receiving ecosystems.

Water temperature can also indirectly control local biodiversity and ecosystem health though changes to dissolved oxygen concentrations (Figure 2). High water temperatures reduce the solubility of oxygen (the amount of dissolved oxygen in water) and increase rates of ecosystem respiration which also reduces dissolved oxygen, particularly at night when the combined respiration of plants and animals can often result in dissolved oxygen levels approaching anoxia.

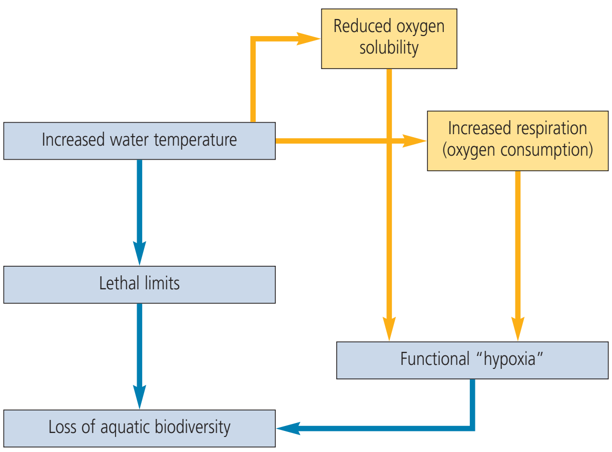



**Figure 2**. Two mechanisms by which water temperature results in a loss of aquatic biodiversity and ecosystem functions.

# Ecological impacts of high water temperatures

## Direct physical influences

Colder waters typically contain a higher oxygen concentration than warm waters. The concentration of oxygen in solution is inversely proportional to temperature (Figure 3) with the solubility of oxygen increasing non-linearly as temperature decreases (Horne & Goldman, 1994). For example, a 10-degree increase in water temperature (a figure commonly recorded in streams as a result of riparian clearing) can reduce dissolved oxygen concentrations by over 2.5 mg/L$^{-1}$.

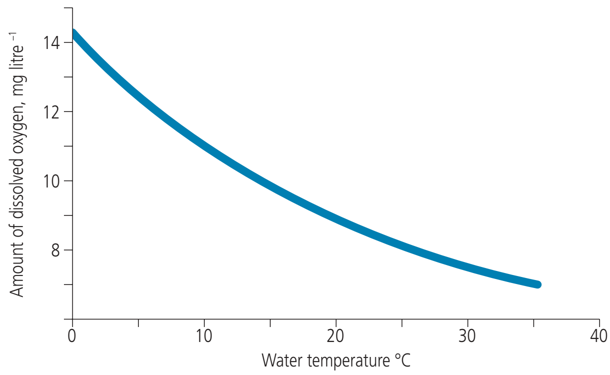



**Figure 3**. The physical relationship between water temperature and dissolved oxygen saturation.

## Effects on ecosystem processes

Ecosystem metabolism, through aerobic respiration, can change the concentration of dissolved oxygen substantially over a 24 hour period. In addition, elevated water temperature can increase the rate of ecosystem respiration and consequently dissolved oxygen consumption. Figure 4 shows a series of

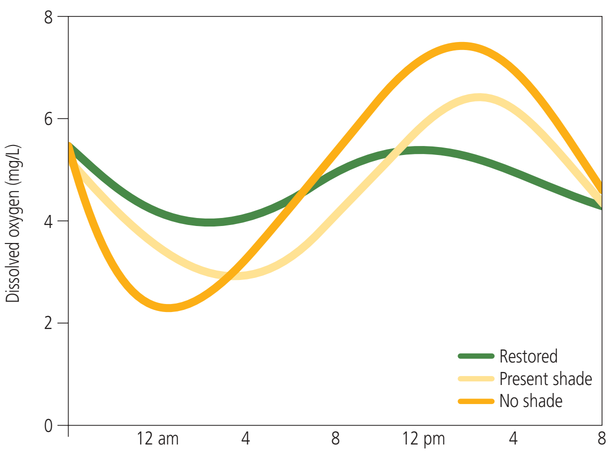



**Figure 4**. The effect of riparian clearing on the amplitude of 24 hour dissolved oxygen concentrations.

**Figure 5**. Metabolism chambers used to test the effects of experimentally raised water temperatures (at top chambers in situ, below prior to use).

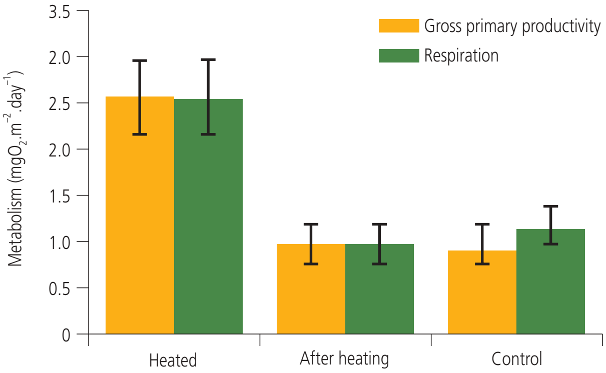



**Figure 6**. Effects on in-stream production and respiration of experimentally raising water temperature by 10°C. Values represent means (SEM) $n$ = 12.

24 hour dissolved oxygen curves for three systems differing in the level of riparian shade and consequently water temperature. The curve for 'no shade' shows dissolved oxygen values close to zero prior to sunrise, largely a consequence of elevated respiration. The amplitude of the dissolved oxygen curve for 'no shade' is more extreme than the sites with increased riparian protection.

To investigate the relationship between water temperature and rates of respiration (and consequently dissolved oxygen), an experiment was conducted at a range of sites, where temperature was elevated within metabolism chambers (using aquarium heaters) and the metabolic response monitored (see Figure 5).

Experimentally raising water temperatures by 10°C more than doubled rates of respiration (see Figure 6). Doubling rates of respiration effectively halved the dissolved oxygen concentration in open water, particularly at night. It is during this period that fish kills are often observed in systems of high dissolved oxygen demand. Riparian clearing increases water temperatures and the occurrence of night-time anoxia, with the metabolic response likely to influence local biodiversity, as well as ecosystem processes and functions.

Extensive metabolism data collected from a range of sites throughout Australia has shown that at dissolved oxygen levels < 2 mg/L, rates of respiration slow down and become a function of oxygen concentration. This indicates that dissolved oxygen concentrations at this low level are impacting on basic ecological processes prior to the levels (i.e close to anoxia) where fish kills can occur. These findings are important in understanding the impact of dissolved oxygen concentrations, however, in the case of river restoration a qualitative sensitivity analysis showed that for streams and rivers which are typical restoration 'targets', direct exceedence of thermal limits of aquatic fauna is the major issue, rather than indirect effects associated with oxygen concentrations.

### Guiding principles for dissolved oxygen effect

- ~ Direct changes in dissolved oxygen solubility in typical streams, due to elevated water temperature, are relatively minor.
- ~ Elevated water temperatures increasing metabolism and consequently dissolved oxygen consumption is likely to be an important issue in large rivers and wetlands particularly in northern Australia.
- ~ Dissolved oxygen levels < 2mg/L are considered harmful to basic ecosystem processes.
- ~ In streams and rivers, particularly those reaches where restoration would normally be attempted, exceedence of lethal temperatures of aquatic fauna is the major issue associated with lack of riparian shade.

## Thermal limits of aquatic fauna

### Measuring upper lethal temperatures in aquatic insects

To determine specific target values for lethal water temperatures, tolerance testing experiments were conducted. Two methodologies are commonly used to determine upper thermal tolerances of stream invertebrates. In the commonly-termed Lethal $Tolerance_{50}$ approach, the temperature at which 50% of test specimens die after 96 hours is recorded as the 'lethal temperature'. The Critical Thermal Maximum procedure is conducted without actually killing the animals. In this procedure, organisms are heated from their acclimation temperature, at a constant rate, until a consistent sublethal endpoint is reached. The temperature at which this endpoint occurs is recorded as the Critical Thermal Maximum. Normally, organisms should be able to regain normal activity when returned to their acclimation temperature. Both procedures have been used to estimate the upper temperature tolerances in aquatic organisms. Neither of these procedures incorporate sub-lethal effects of temperature on crucial life processes such as reproduction, moulting, emergence patterns, feeding rates, or long-term survival of aquatic insects.

Early studies of the upper temperature tolerances of aquatic invertebrates have mainly been centred in the USA. These studies were often initiated due to a concern that the introduction of heated water from steam-electric power generating facilities into local streams would have a detrimental effect on the biota. These studies have covered a number of taxonomic orders, and have shown that some groups, such as mayflies (Ephemeroptera) and stoneflies (Plecoptera) were more sensitive than others. More pertinent to Australia, is work undertaken in New Zealand. The upper thermal tolerances of 12 stream aquatic invertebrates collected from the Waihou River has been assessed (Quinn et al., 1994), and a wide range of upper thermal tolerances have been observed. Again, mayflies and stoneflies were shown to be relatively temperature sensitive.

This present study, which determined the thermal tolerances of selected taxa commonly found in streams of south-western Australia, has provided the first thermal tolerance data for many Australian species. The data generated for four species (representing the insect orders Odonata, Trichoptera and Ephemeroptera: shown to be sensitive in other studies) was in agreement with data obtained for organisms from New Zealand, USA and other parts of the world, and has confirmed that this information can be used

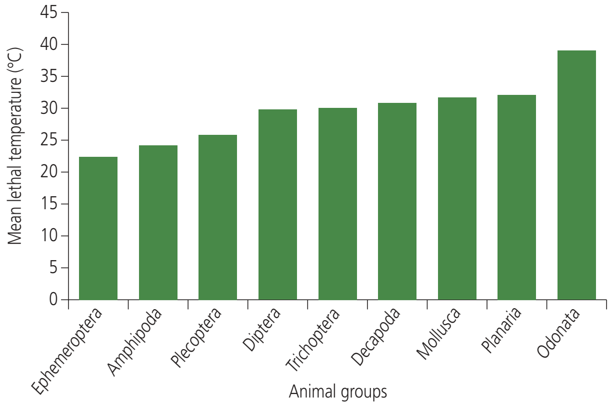



**Figure 7**. Upper lethal temperatures for aquatic organism groups determined from world-wide literature.

to set 'target' temperatures for Australian streams (see Table 1, on following page). Our approach was to investigate if Australian species showed similar temperature tolerances to those measured worldwide. This was necessary due to the taxonomically and geographically limited nature of the assessment of Australian species, where only a few of the many thousands of aquatic groups have been assessed. Being able to show similarities to the global research literature would enable us to use this substantial body of additional information.

### Identifying sensitive taxonomic groups

The calculation of mean upper thermal tolerances across all taxonomic groups found in a variety of geographical locations and habitats, confirmed the sensitivity of certain groups to high temperatures (Figure 7). In particular, mayflies (Ephemeroptera) appeared to be most sensitive to high temperatures, with an average lethal temperature of 22.1°C being recorded for all habitats and geographical areas combined. In contrast, dragonflies (Odonata) appear to be far more tolerant of high temperatures, with an average lethal temperature of 38°C (Figure 7).

Mayflies, stoneflies and caddisflies are important components of invertebrate communities in rivers. Data for these three taxa have been separated into two groups — those characteristic of colder headwaters and those characteristic of warmer streams (Figure 8). An upper lethal temperature of 20.6°C was calculated for mayfly species from 'colder' headwaters, and a temperature of 29.2°C was calculated for those species typical of 'warmer' waters. Species of stoneflies (Plecoptera) typical of cooler waters had an average upper lethal temperature of 21.7°C and those species typical of warmer waters had an upper lethal temperature of 29.1°C. Caddisflies (Trichoptera) were

**Table 1**. Upper lethal temperatures for a variety of aquatic invertebrates occurring in streams worldwide. Highlighted groups designate this study.

| Group | Species | Lethal temperature | Acclimation | Authors |
|---|---|---|---|---|
| Planaria | *Dugesia tigrina* | 31.9 | 5 | Claussen & Walters (1982) |
| | *Dugesia dorotocephala* | 32.4 | 5 | Claussen & Walters (1982) |
| | Average | **32.2** | | |
| Amphipoda | *Paramelita nigroculus* | 34.1 | 13.5 | Buchanan et al. (1988) |
| | *Paracalliope fluviatilis* | 24.1 | 15 | Quinn et al. (1994) |
| | *Gammarus limnaeus* | 14.6 | 6.4 | Gaufin & Hern (1971) |
| | Average | **24.3** | | |
| Decapoda | *Paratya curvirostris* | 25.7 | 15 | Quinn et al. (1994) |
| | *Cambaroides japonicus* | 27.0 | 16 | Nakata Kazuyoshi et al. (2002) |
| | *Pacificastacus leniusculus* | 31.1 | 16 | Nakata Kazuyoshi et al. (2002) |
| | *Orconectes rusticus* | 34.4 | 5 | Claussen (1980) |
| | *Orconectes rusticus* | 35.6 | 15 | Claussen (1980) |
| | Average | **30.8** | | |
| Diptera | *Atherix variegata* | 32.0 | 10 | Nebeker & Lemke (1968) |
| | *Atherix variegata* | 32.4 | 6.4 | Gaufin & Hern (1971) |
| | *Simulium* sp. | 25.1 | 6.4 | Gaufin & Hern (1971) |
| | Average | **29.8** | | |
| Coleoptera | *Hydora* sp. | 32.6 | 15 | Quinn et al. (1994) |
| Ephemeroptera | ***Nyungara* sp.** | **21.9** | **15** | **This study** |
| | ***Centroptilum* sp.** | **20.5** | **15** | **This study** |
| | *Ephemerella subvaria* | 21.5 | 10 | Nebeker & Lemke (1968) |
| | *Deleatidium* sp. | 22.6 | 15 | Quinn et al. (1994) |
| | *Zephlebia dentata* | 23.6 | 15 | Quinn et al. (1994) |
| | *Stenonema ithaca* | 31.8 | 10 | DeKozlowski & Bunting (1981) |
| | *Stenonema tripunctatum* | 25.5 | 10 | Nebeker & Lemke (1968) |
| | *Ephemerella invaria* | 22.9 | 10 | DeKozlowski & Bunting (1981) |
| | *Cinygmula* par | 11.7 | 6.4 | Gaufin & Hern (1971) |
| | *Ephemerella doddsi* | 15.5 | 6.4 | Gaufin & Hern (1971) |
| | *Ephemerella grandis* | 21.5 | 6.4 | Gaufin & Hern (1971) |
| | *Hexagenia limbata* | 26.6 | 6.4 | Gaufin & Hern (1971) |
| | Average | **22.1** | | |
| Plecoptera | *Zelandobius furcillatus* | 25.5 | 15 | Quinn et al. (1994) |
| | *Taeniopteryx maura* | 21.0 | 10 | Nebeker & Lemke (1968) |
| | *Isogenus frontalis* | 22.5 | 10 | Nebeker & Lemke (1968) |
| | *Allocapnia granulata* | 23.0 | 10 | Nebeker & Lemke (1968) |
| | *Pteronarcys dorsata* | 29.5 | 10 | Nebeker & Lemke (1968) |
| | *Acroneuria lycorias* | 30.0 | 10 | Nebeker & Lemke (1968) |
| | *Paragnetina media* | 30.5 | 10 | Nebeker & Lemke (1968) |
| | *Paragnetina media* | 33.0 | 10 | Heiman & Knight (1972) |
| | *Isogenus aestivalis* | 16.5 | 6.4 | Gaufin & Hern (1971) |
| | *Pteronarcella badia* | 24.4 | 6.4 | Gaufin & Hern (1971) |
| | *Pteronarcys californica* | 27.0 | 6.4 | Gaufin & Hern (1971) |
| | Average | **25.7** | | |

| Group | Species | Lethal temperature | Acclimation | Authors |
|---|---|---|---|---|
| Odonata | ***Austroaeschna anacantha*** | **33.8** | **15** | **This study** |
| | *Boyeria vinosa* | 32.5 | 10 | Nebeker & Lemke (1968) |
| | *Ophiogomphus rupinsulensis* | 33.0 | 10 | Nebeker & Lemke (1968) |
| | *Libellula* sp. | 42.8 | 15 | Martin & Gentry (1974) |
| | *Macromia illinoiensis* | 43.1 | 12 to 32 | Garten & Gentry (1976) |
| | *Neurocordulia alabamensis* | 42.6 | 12 to 32 | Garten & Gentry (1976) |
| | Average | 38.0 | | |
| Trichoptera | ***Cheumatopsyche* sp. AV2** | **30.7** | **14** | **This study** |
| | *Parapsyche elsis* | 21.7 | 6.5 | Gaufin & Hern (1971) |
| | *Limnephilus ornatus* | 24.8 | 6.4 | Gaufin & Hern (1971) |
| | *Neothrema alicia* | 25.9 | 6.4 | Gaufin & Hern (1971) |
| | *Drusinus* sp. | 27.3 | 6.4 | Gaufin & Hern (1971) |
| | *Brachycentrus occidentalis* | 29.7 | 6.4 | Gaufin & Hern (1971) |
| | *Brachycentrus americanus* | 29.0 | 10 | Nebeker & Lemke (1968) |
| | *Aoteapsyche colonica* | 25.9 | 15 | Quinn et al. (1994) |
| | *Pycnocentrodes aureola* | 32.4 | 15 | Quinn et al. (1994) |
| | *Pyconocentria evecta* | 25.0 | 15 | Quinn et al. (1994) |
| | *Symphitopsyche morosa* | 30.4 | 10 | DeKozlowski & Bunting (1981) |
| | *Brachycentrus lateralis* | 32.8 | 10 | DeKozlowski & Bunting (1981) |
| | *Hydropsyche* sp. | 30.3 | 6.4 | Gaufin & Hern (1971) |
| | *Chimarra obscura* | 36.5 | 19 | Moulton et al. (1993) |
| | *Chimarra obscura* | 31.4 | 12 | Moulton et al. (1993) |
| | *Chimarra aterrima* | 33.6 | 19 | Moulton et al. (1993) |
| | *Hydropsyche simulans* | 35.6 | 19 | Moulton et al. (1993) |
| | *Hydropsyche simulans* | 34.4 | 12 | Moulton et al. (1993) |
| | *Ceratopsyche morosa* | 34.2 | 19 | Moulton et al. (1993) |
| | Average | 30.1 | | |
| Mollusca | *Potamopyrgus antipodarum* | 32.0 | 10, 16 & 24 | Winterbourn (1969) |
| | *Potamopyrgus antipodarum* | 32.4 | 15 | Quinn et al. (1994) |
| | *Sphaerium novaezelandiae* | 30.5 | 15 | Quinn et al. (1994) |
| | Average | 31.6 | | |
| Oligochaeta | *Lumbriculus variegatus* | 26.7 | 15 | Quinn et al. (1994) |

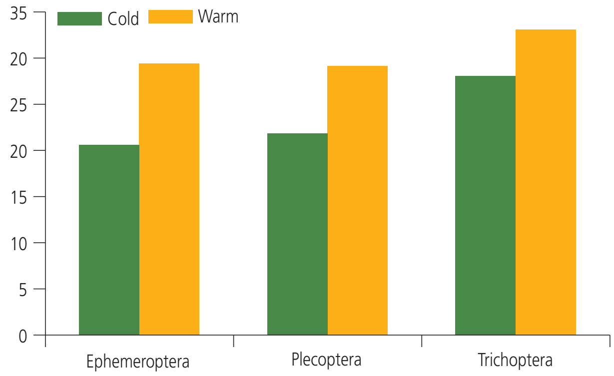



**Figure 8**. Upper lethal temperatures for mayflies (Ephemeroptera), stoneflies (Plecoptera) and caddisflies (Trichoptera) typical of cold and warmer waters.

far more hardy, with species typical of cooler waters having an upper lethal temperature of 28.1°C, and species typical of warmer waters having an upper lethal temperature of 33.1°C.

### Toward setting target temperatures for Australian systems

To ensure the survival of mayflies, the most sensitive group to elevated temperatures, 'target' temperatures of 21°C (cold water species) and 29°C (warm water species) are recommended. However, these values have been calculated using laboratory experiments conducted at constant temperatures. Cox & Rutherford (2000) showed that when temperature varied diurnally by ±5°C, 50% mortality could be expected when the daily maximum was about 2.5°C higher, or the daily mean was about 2.5°C less, than the 96-hour Lethal Tolerance$_{50}$ measured at constant temperature. Based on the work of Quinn et al. (1994), and with the adoption of a 'safety margin' of 3°C below the measured lethal limit of the most sensitive taxa, Rutherford et al. (1997) adopted a 'conservative', upper limit target stream temperature of 20°C for the restoration of New Zealand streams.

An alternative approach to applying a 3°C safety margin would be to limit the exposure time of organisms to high temperatures. This approach is described further in this Technical Guideline (page 9 biogeographic variation). As discussed earlier, the calculation of upper lethal temperatures does not take into account the sub-lethal effects of temperature on reproduction, moulting, emergence patterns, feeding rates, or long-term survival of aquatic insects, hence the need to use a 'safety margin' to account for some of these sublethal effects. The adoption of these recommended targets should ensure the long term survival of the more sensitive components of the macroinvertebrate fauna.

## Targets and priorities for riparian restoration

The temperature of an individual stream reach will depend on a number of factors, including:

~ meteorological conditions,
~ channel morphology,
~ flow,
~ the amount of vegetative and topographic shade, and
~ upstream meteorological, channel morphology, flow and shade conditions.

Elevated in-stream temperature is a highly variable environmental stressor in space and time. Contrasts between Australian bioregions and catchments depend largely on seasonal effects of air temperature and rainfall. Summer stress will be relatively more exaggerated where high air temperatures co-occur with times of low flow, as is the case in regions with a Mediterranean climate. In the tropics, where high flows occur in summer, in-stream temperatures will exhibit less diurnal variation. An illustration of this biogeographic contrast is provided in Figure 9, where average weather and flow conditions for summer and winter are used to simulate the daily change in in-stream temperature for a first order stream located in south-west Western Australia and in the Top End of the Northern Territory.

Because *average* monthly weather and flow conditions are used, the curves in Figure 9 under-represent the magnitude of day to day variation in in-stream temperature. Individual rainfall events and extreme weather conditions within any one month

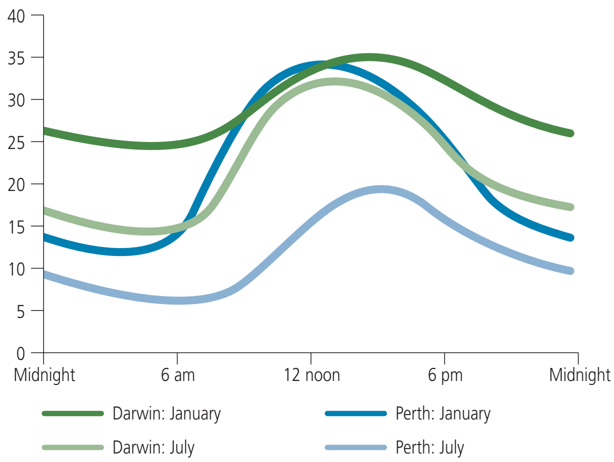



**Figure 9**. Biogeographic and seasonal contrasts in diurnal in-stream temperature. The curves are model simulations representing first order streams having zero shade under flow and weather conditions typical of summer and winter in Darwin and Perth. Note that Darwin's summer curve is considerably flatter than Perth's summer curve because of the higher summer flow in the tropics relative to Mediterranean climates.

can have a strong influence on in-stream temperature, even within higher-order streams. Figure 10 shows in-stream temperature and flow fluctuations for the Tyenna River in Tasmania for the month of December, 2002.

Under natural conditions, the interplay of climate and flow would sometimes result in the transient loss of habitat and the imposition of thermal barriers to effective dispersal. However, with the widespread removal or degradation of riparian vegetation, the problem today is that what was once a localised and transient loss of habitat has become a common and continuous feature in space and time throughout many catchments.

Riparian vegetation has benefits for many different aspects of river structure, composition and function. While the river manager needs to be mindful of the broad range of benefits, one advantage of a focus for restoration effort on temperature targets is that the results of on-ground action may be more easily predicted, measured and demonstrated than for other stressors such as nutrient pollution or sedimentation.

The method to predict stream temperature used here builds on the model 'STREAMLINE' developed by New Zealand's National Institute of Water and Atmospheric Research (Rutherford et al. 1997, Rutherford et al. 1999). STREAMLINE has been shown to be a good predictor of absolute in-stream temperature where detailed information describing meteorology, channel morphology, vegetative shade and stream bank shade has been collated. However, river managers typically require tools at a catchment or subcatchment scale. For this Guideline a simplified version of the STREAMLINE model (Simp-STREAMLINE) was developed to meet the needs of managers at larger scales and under circumstances of coarse data resolution. The simplified model assumes that streamflow, depth and shade are uniform. This enables the further simplifying assumption that stream temperature reaches equilibrium with the prevailing meteorology for the given depth and shade. These assumptions are invalid where there are alternate patches of dense and negligible shade, or where there is a distinct pool-riffle pattern. Minor longitudinal variations of shade or depth are of little consequence.

## Biogeographic variation

Although a range of factors affect in-stream temperature, the predisposition of a stream reach to thermal stress is essentially related to the surface area to volume ratio of the water it carries. Smaller streams cool and heat quicker than larger streams because a greater proportion of their water volume is exposed to weather conditions and any conduction effects of the stream bed. In this part of our research, the average seasonal and diurnal in-stream temperature fluctuations of a first order stream were modelled for 14 locations around Australia (Figure 11).

Developed in New Zealand, STREAMLINE is a physical model that describes heat fluxes in and out of stream water. Although a number of simplifying assumptions are necessarily made, the model can be transported and applied to other parts of the world. In its development phase, the output of

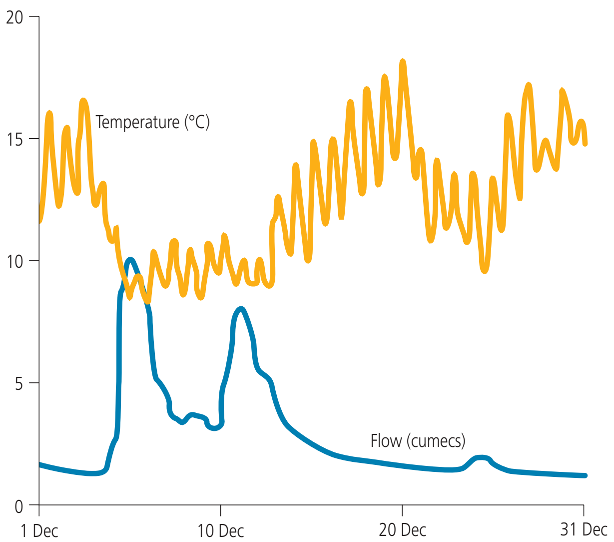



**Figure 10**. Measured in-stream temperature and flow data from the Tyenna River, Tasmania, December 2002.


**Figure 11**. Locations used to characterise biogeographic variation in thermal stress.

STREAMLINE was validated using field observations made at Hamilton, New Zealand (Rutherford et al. 1999), south-east Queensland (Rutherford 2003) and south-west Western Australia (Rutherford et al., in prep). Validation exercises showed no systematic bias in model predictions. Where intensive field reconnaissance of channel morphology and shade description was undertaken, simulation results were found to be within 1°C of stream temperatures measured in the field. In this project, we informally validated SimpSTREAMLINE output for simulation results reported for Albany, Hobart and Cairns on the basis of minimal field description of shade and channel morphology. Again, no bias in model output was evident and accuracy was estimated to be within ±3°C.

It is important to note that all modelling results refer to equilibrium in-stream temperatures. That is, no effect of upstream conditions is taken into account such that the temperatures reported refer to an infinitely long stream reach experiencing the same meteorological conditions and having the same flow and channel morphology characteristics. The approach of the modelling undertaken was to:

1. identify temperature thresholds for sensitive invertebrates at each of the 14 locations, then
2. simulate in-stream temperatures for the 14 locations under conditions of zero shade, then
3. identify the level of shade required to satisfy temperature thresholds at each location.

### What temperature thresholds should apply?

Ideally, thresholds would be based on a detailed biogeographic-specific understanding of the response of biota and underlying ecological processes to thermal stress. Although such detailed knowledge is beyond our current level of understanding, the results from the work discussed previously on measuring lethal temperature tolerances for aquatic insects provides coarse guidance.

Lethal Tolerance$_{50}$ tests over 96 hours indicated thresholds of about 21°C and 29°C for the most sensitive macroinvertebrates occurring in cool and hot climates, respectively. Of the 14 locations examined in this section, we define 'hot climates' as any site having a latitude more extreme than –18°. These locations (Broome, Cairns and Darwin) are assigned temperature thresholds of 29°C. 'Cool climate' locations assigned temperature thresholds of 21°C are those with latitudes more extreme than –35° (Adelaide, Albany, Hobart and Melbourne). The remaining seven locations could be said to have 'intermediate climates'. For these places, the temperature threshold is calculated as a linear interpolation between 21°C and 29°C based on latitude. Thresholds for all locations are shown in Table 2.

In reporting lethal effects, Lethal Tolerance$_{50}$ tests comprise two components — temperature and the time duration of exposure to that temperature. The 21°C and 29°C thresholds for cool and hot climates refer to exposure times of 96 hours. Sub-lethal effects will be observed at lower temperatures or lesser exposures. To account for sub-lethal effects it is desirable to include a safety buffer in either the temperature threshold or the exposure time. The approach adopted here is to define 8 hours as the daily window of time beyond which temperatures in excess of the threshold are regarded as intolerable. For example, in Carnarvon, in-stream temperatures in excess of 25.8°C (Table 2) can be tolerated for up to 8 hours per day. If temperatures exceed 25.8°C for more than 8 hours, the risk to stream ecosystem health is considered intolerable and management intervention through riparian restoration is needed.

This approach acknowledges that, even where riparian vegetation is intact, the ecology and physiology of temperature sensitive biota will be occasionally compromised under summer or low flow conditions. In defining a time window of 8 hours, it is implicitly assumed that this level of exposure represents a low level of risk for the longer term integrity of a stream ecosystem's structure, function and composition. By necessity, this is a working assumption and more detailed ecological and physiological studies are needed to substantiate its validity.

### How was SimpSTREAMLINE used to simulate in-stream temperatures for the 14 locations?

The input variables for the SimpSTREAMLINE model relate to weather conditions, flow and channel morphology. The output of a single simulation run is the diurnal trend in in-stream temperature over 24 hours. The curves in Figure 9 show the output for four individual simulation runs having input data corresponding to summer and winter conditions in Darwin and Perth. Here, 12 simulations for each of the 14 locations were run under conditions of zero shade, with each of the 12 simulations representing average monthly flow and weather conditions. The way input data was derived for (a) flow and channel attributes, and (b) weather conditions are summarised in Boxes 1 and 2, respectively. River managers with access to measured stream data will be able to improve on the assumptions implicit in this method.

**Table 2**. Calculated in-stream 8-hour temperature thresholds for the 14 locations.

| Location | Mean annual rainfall (mm) | Mean annual maximum air temperature (°C) | Latitude (degrees) | In-stream temperature threshold (°C) |
|---|---|---|---|---|
| Adelaide | 455 | 21.3 | –35.0 | 21.0 |
| Albany | 797 | 20.2 | –35.0 | 21.0 |
| Alice Springs | 286 | 28.6 | –23.8 | 26.3 |
| Broome | 594 | 32.2 | –18.0 | 29.0 |
| Cairns | 1992 | 28.9 | –16.9 | 29.0 |
| Carnarvon | 227 | 27.1 | –24.9 | 25.8 |
| Darwin | 1702 | 31.9 | –12.4 | 29.0 |
| Forrest | 188 | 25.4 | –30.8 | 23.0 |
| Hobart | 509 | 17.4 | –42.8 | 21.0 |
| Melbourne | 654 | 19.8 | –37.8 | 21.0 |
| Perth | 788 | 24.3 | –31.9 | 22.5 |
| Rockhampton | 810 | 28.3 | –23.4 | 26.5 |
| Sydney | 1099 | 22.1 | –33.9 | 21.5 |
| Townsville | 1126 | 28.8 | –19.3 | 28.4 |

**BOX 1. The derivation of flow and channel attributes for model input**

Flow of the simulated first order stream was derived for each month and each location on the basis of long term average monthly rainfall records, whereby rainfall (mm) = flow (L/s). For example, Bureau of Meteorology statistics report an average May rainfall of 50 mm for Townsville. The May simulation run for Townsville was therefore assigned a flow of 50 L/s.

Channel attributes other than flow can be summarised by description of depth, velocity and width. Depth and velocity for each month and each location were derived using the power relations described by Griffiths (1980). Fitting data obtained from gravel bed rivers in New Zealand, Griffiths (1980) related flow and depth by the formula, $depth = 0.21F^{0.43}$ where depth is measured in metres and flow ($F$) in $m^3/s$.

Flow and velocity are related by the formula, $velocity = 0.61F^{0.11}$ where velocity is measured in m/s and flow (F) in $m^3/s$. SimpSTREAMLINE assumes the channel shape to be a right angled ditch, such that width is derived after inputting flow, depth and velocity using the formula below, where flow is measured in m3/s, velocity in m/s and depth in metres.

$$width = \frac{flow}{velocity \ x \ depth}$$

It is important to note that another channel attribute that can affect in-stream temperature is the conductivity of the stream bed's substrate. In all simulations the value for bed conduction in the SimpSTREAMLINE model was set to zero because of the highly variable nature of bed substrates within and between Australian bioregions.

**BOX 2. The derivation of weather conditions for model input**

For any one simulation run, the SimpSTREAMLINE model assumes constant flow but allows meteorological conditions to vary throughout the 24 hour day. A range of meteorological parameters are required by SimpSTREAMLINE. Long term records from the Bureau of Meteorology were used to describe the mean, amplitude and time of maximum for air temperature, cloud cover, wind speed, air pressure and humidity for each month and each location. SimpSTREAMLINE also allows the solar radiation a site receives to vary throughout the simulated day. Again, Bureau of Meteorology data was used to estimate the average daily Global Solar Radiation received at each location for each month. Global Solar Radiation is measured in $MJ/m^2/day$ and comprises direct and diffuse components. SimpSTREAMLINE assumes the ratio of direct and diffuse radiation to be 80:20. The amount of radiation received at any single time step within a simulation run is determined by the trajectory of the sun, so SimpSTREAMLINE also requires input for the location's latitude, average monthly daylength, and Julian day. Full details describing the STREAMLINE model are provided by Rutherford et al. (1997) and Rutherford et al. (1999).

L/s = litres per second (velocity)

m3/s = cubic metres per second (volume)

$MJ/m^2/day$ = mega joules/square metres/day

The average monthly maximum in-stream temperatures for the 14 locations are shown in Figure 12. As a result of the moderating effect of high flows in summer, the tropical locations of Broome, Cairns, Darwin and Townsville show relatively less month to month variation in maximum temperature when compared to southern locations having a more Mediterranean climate.

Maximum temperatures are a coarse descriptor of thermal stress. Greater insight is offered by considering the amount of time (both monthly and daily) a site 'experiences' in-stream temperatures in excess of the thresholds shown in Table 2. Figure 13 illustrates the average effects of seasonality on diurnal in-stream temperatures for each location as a three-dimensional surface chart. The areas marked red on the surface charts are times where in-stream temperature exceeds the threshold associated with each location. Examination of these charts reveals that, of the locations modelled, thermal stress in first order streams is likely to occur throughout the year at Broome, Cairns, Carnarvon, Darwin, Rockhampton and Townsville. At all other locations, thermal stress is restricted to the warmer months.

The simulated data used to produce the three-dimensional surface charts in Figure 13 are summarised in Table 3 (overleaf), where the average daily time window in which temperature thresholds are exceeded are provided for each location and month. Although Broome, Cairns, Carnarvon, Darwin, Rockhampton and Townsville all experience in-stream temperatures beyond their associated threshold throughout the 12 months of the year, the exposure time during cooler months is tolerable, being less than 8 hours.

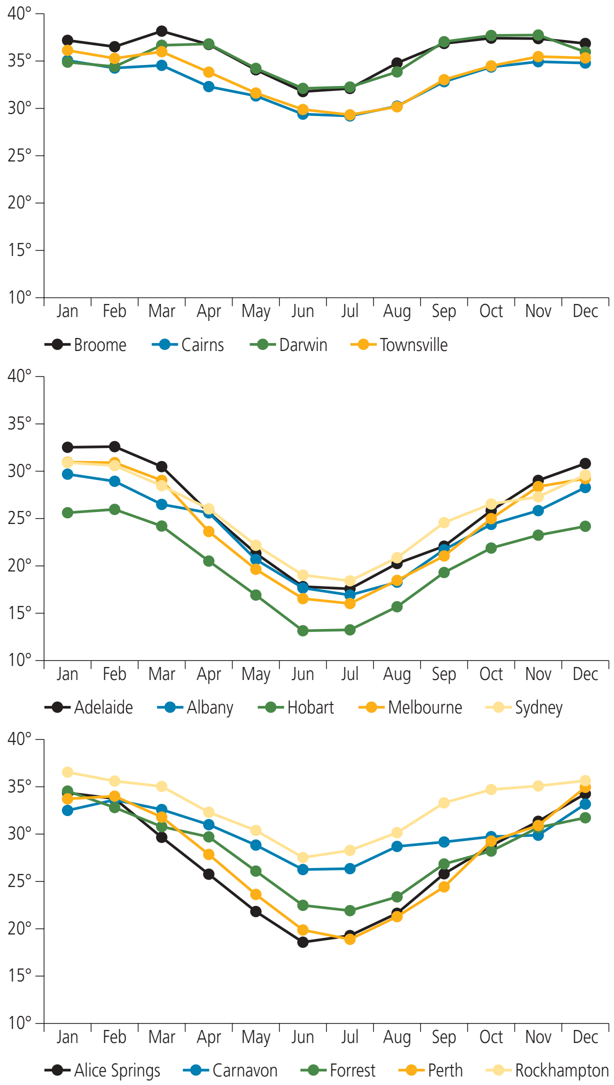



**Figure 12**. Predicted monthly-average maximum daily in-stream temperatures at 14 locations for a hypothetical first-order stream having zero shade.

## How much shade is needed to alleviate thermal stress to tolerable levels?

The simulation output shown in Figure 13 and Table 3 are for lower order streams having no shade. For each location, simulations were re-run with varying shade levels to work out the shade required to reduce the average daily exposure time to 8 hours or less within each month. Results are shown in Table 4. Examination of Tables 3 and 4 suggests there is no simple pattern in the shade requirements for different biogeographic regions of Australia. While the shade targets reported in Table 4 provide rough guidance, the location-specific interactive effects of seasonal variation in meteorological variables and flow, mean that the targets need to be used with caution when applied to locations other than those modelled here.

Shade can be provided in three ways — bank shade, vegetative shade from riparian vegetation, and macro-topographic shade from surrounding hills and landforms. The percentage targets shown in Table 4 do not discriminate between these three components. A method to estimate the relative shade provided by macro-topography is provided later in this Technical Guideline. Field observations are needed to estimate the individual and cumulative effect of bank and vegetative shade.

Shade targets provided in Table 4 refer to first order streams. River managers need to know whether these shade targets are adequate for higher order streams. The lower surface area to volume ratio of higher order streams means that, generally, achievement of the targets provided in Table 4 will

**Figure 13**. Three-dimensional surface charts showing predicted monthly and diurnal trends in average in-stream temperature for a hypothetical first order stream, with zero shade, at each of the 14 locations modelled. The three axes represent time of day, (*x*-axis) with 0 and 24 hours = midnight, 8 hours = 8 am and 16 hours = 4pm; month of year (*y*-axis) with 4 = April, 8 = August and 12 = December; and in-stream temperature (z-axis) ranging from –5°C to 40°C.

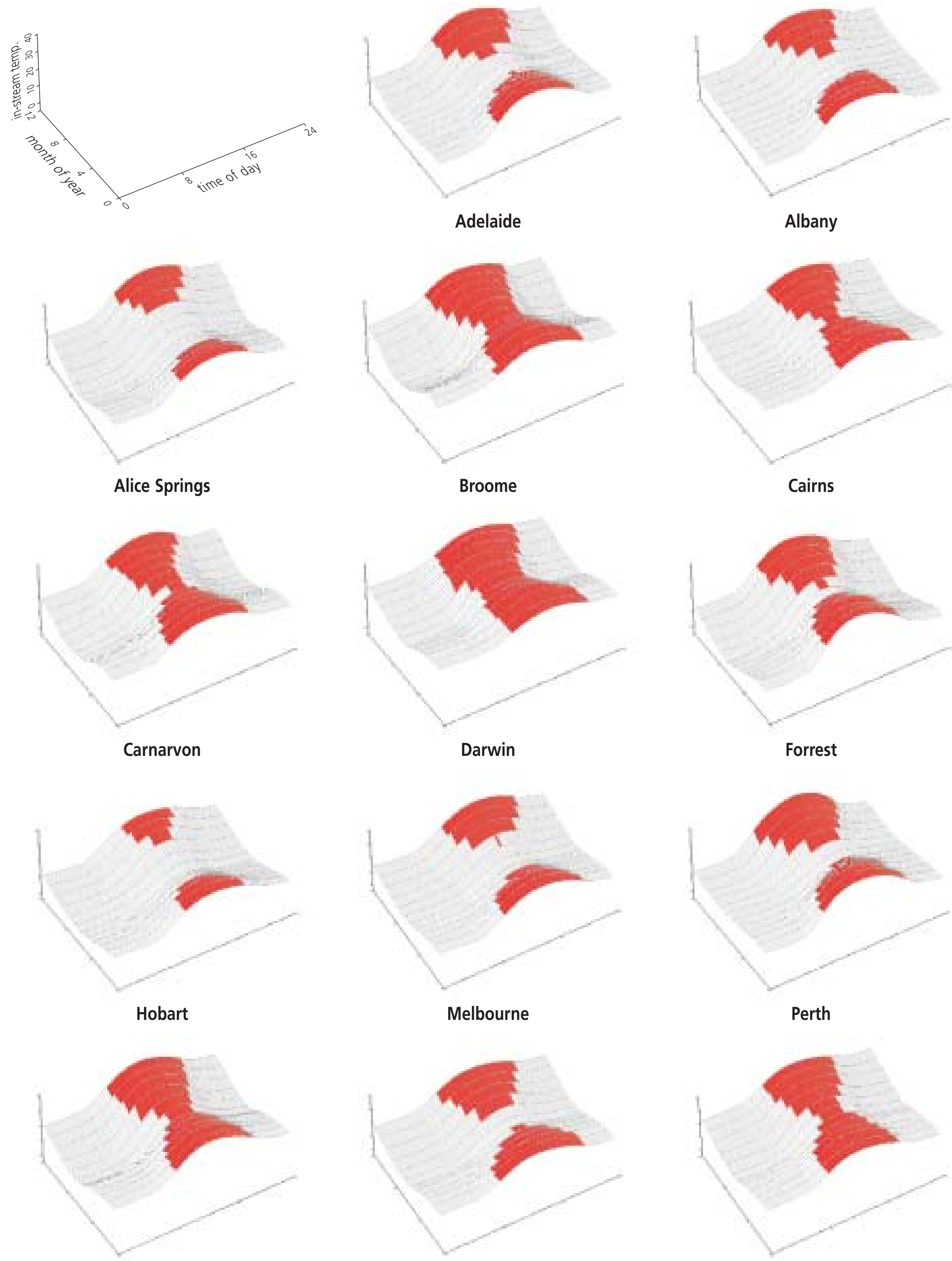


**Table 3**. Average daily hours of threshold exceedence by month and location, under conditions of zero shade. Cells coloured red represent months and locations where average conditions under zero shade result in intolerable exposure to high in-stream temperatures. Yellow cells indicate where temperatures are high but exposure times are within a tolerable limit. Green cells show months and locations where high in-stream temperatures are not considered to be ecologically important.

| Location | Threshold | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Darwin | 29.0°C | 10.5 | 9.75 | 10.25 | 9.25 | 7.5 | 5.75 | 6.0 | 7.0 | 8.75 | 9.75 | 10.25 | 10.5 |
| Cairns | 29.0°C | 9.5 | 9.25 | 8.25 | 6.25 | 5.0 | 2.25 | 1.25 | 3.5 | 6.25 | 7.5 | 8.5 | 9.0 |
| Broome | 29.0°C | 11.0 | 10.75 | 10.5 | 8.75 | 6.5 | 4.5 | 4.75 | 6.25 | 7.75 | 9.0 | 10.0 | 10.5 |
| Townsville | 28.4°C | 10.0 | 9.5 | 9.0 | 7.25 | 5.5 | 3.25 | 2.5 | 4.0 | 6.5 | 8.0 | 9.0 | 9.75 |
| Rockhampton | 26.5°C | 10.75 | 10.25 | 9.25 | 7.5 | 5.75 | 2.5 | 3.5 | 5.0 | 7.0 | 8.75 | 9.5 | 10.25 |
| Alice Springs | 26.3°C | 9.5 | 9.0 | 6.0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.0 | 7.5 | 9.25 |
| Carnarvon | 25.8°C | 10.25 | 10.5 | 9.0 | 7.5 | 5.0 | 2.0 | 1.75 | 4.25 | 5.5 | 6.5 | 7.75 | 9.5 |
| Forrest | 23.0°C | 9.75 | 9.75 | 8.75 | 7.5 | 4.75 | 0 | 0 | 1.5 | 5.75 | 7.25 | 8.75 | 9.5 |
| Perth | 22.5°C | 11.0 | 10.5 | 9.0 | 7.5 | 3.25 | 0 | 0 | 0 | 4.25 | 7.5 | 9.25 | 11.0 |
| Sydney | 21.5°C | 11.5 | 11.5 | 9.25 | 6.75 | 2.0 | 0 | 0 | 0 | 5.0 | 7.5 | 8.75 | 10.75 |
| Adelaide | 21.0°C | 10.75 | 10.5 | 9.0 | 6.25 | 1.0 | 0 | 0 | 0 | 2.75 | 7.0 | 9.5 | 10.25 |
| Albany | 21.0°C | 10.0 | 9.75 | 8.25 | 6.25 | 0 | 0 | 0 | 0 | 2.5 | 5.75 | 7.5 | 9.5 |
| Melbourne | 21.0°C | 11.0 | 10.25 | 8.5 | 4.75 | 0 | 0 | 0 | 0 | 0.5 | 6.5 | 9.0 | 10.25 |
| Hobart | 21.0°C | 8.0 | 7.75 | 5.5 | 0 | 0 | 0 | 0 | 0 | 0 | 2.75 | 5.25 | 6.75 |

**Table 4**. Shade targets for each of the 14 locations modelled. The targets refer to the level of shade required to reduce the average daily time of exposure to in-stream temperatures in excess of the location-specific threshold to 8 hours or less, for all months of the year.

| Location | In-stream temperature threshold (°C) | Shade target (%) |
|---|---|---|
| Darwin | 29.0 | 45 |
| Cairns | 29.0 | 30 |
| Broome | 29.0 | 60 |
| Townsville | 28.4 | 50 |
| Rockhampton | 26.5 | 65 |
| Alice Springs | 26.3 | 30 |
| Carnarvon | 25.8 | 70 |
| Forrest | 23.0 | 50 |
| Perth | 22.5 | 70 |
| Sydney | 21.5 | 75 |
| Adelaide | 21.0 | 60 |
| Albany | 21.0 | 50 |
| Melbourne | 21.0 | 55 |
| Hobart | 21.0 | 5 |

result in tolerable thermal stress. For example, Table 5 gives SimpSTREAMLINE results for the average daily hours above temperature thresholds for Albany, Cairns and Sydney in January. In all cases, the shade target prescribed for first order streams provides times of exposure comfortably within the 8 hour limit for higher order streams. However, it is important to note that if a 30% shade target established for a lower order stream is transferred to a higher-order stream, vegetation of a greater density and/or greater height to counter the effect of the greater stream width may be required (see section on estimating stream shade page 19).

### How much stream bank needs to be revegetated?

It was noted earlier that all results obtained from the SimpSTREAMLINE model are for 'equilibrium' conditions, whereby in-stream temperatures are reported for an infinite length of stream having the same channel attributes and shade. An important question is what distance of stream bank needs to be revegetated to realise the temperature alleviation benefits of riparian restoration.

Although slower streams will cool and heat over shorter distances than faster streams, a useful rule of thumb is that the rate small streams cool and heat is about 30% per 100 metres, where the 'rate' refers to geometric change in stream temperature

**Table 5**. Are shade targets adequate for higher order streams? Average daily hours of temperature threshold exceedence for varying stream orders at three locations in January, using shade targets prescribed for first order streams.

| | | Channel attributes | | | Shade | Temperature | Average daily |
|---|---|---|---|---|---|---|---|
| | Flow (L/s) | Width (m) | Depth (m) | Velocity (m/s) | target (%) | threshold (°C) | hours of exceedence |
| Albany | | | | | | | |
| 1st order | 20 | 1.3 | 0.04 | 0.40 | 50 | 21.0 | 8.0 |
| 3rd order | 120 | 2.9 | 0.08 | 0.48 | 50 | 21.0 | 7.5 |
| 5th order | 400 | 5.1 | 0.14 | 0.55 | 50 | 21.0 | 6.75 |
| Cairns | | | | | | | |
| 1st order | 300 | 4.5 | 0.13 | 0.53 | 30 | 29.0 | 8.0 |
| 3rd order | 1800 | 10.2 | 0.27 | 0.65 | 30 | 29.0 | 6.5 |
| 5th order | 6000 | 17.8 | 0.45 | 0.74 | 30 | 29.0 | 4.0 |
| Sydney | | | | | | | |
| 1st order | 90 | 2.6 | 0.07 | 0.47 | 75 | 21.5 | 8.0 |
| 3rd order | 540 | 5.9 | 0.16 | 0.57 | 75 | 21.5 | 7.0 |
| 5th order | 1800 | 10.2 | 0.27 | 0.65 | 75 | 21.5 | 5.25 |

from a defined upstream starting point, to specified distances downstream in a channel having more or less consistent morphology and shade characteristics. That is:

$$T_d = T_0 - \left\{ (T_0 - T_e)\left(1 - e^{\frac{-rd}{10}}\right) \right\}$$

where $T_0$ and $T_d$ are the in-stream temperatures (°C) at the starting point and a point distance $d$ (measured in km) downstream, respectively, $r$ is the 30% constant rate of change, and $T_e$ is the equilibrium temperature reported by SimpSTREAMLINE for a channel of known morphology and shade experiencing known meteorological conditions.

An example of what this rule of thumb means in practice is illustrated in Figure 14. Suppose that the in-stream temperature of a reach in a paddock offering no shade is 27°C at the property boundary. The river manager seeks to restore riparian vegetation downstream from the property boundary and estimates that 60% shade is needed for a tolerable level of thermal stress, equating to an equilibrium temperature of 22°C. The distance downstream at which the in-stream temperature is within 0.25°C of 22°C is 1 kilometre. The effect of restoration effort using the '30% per 100 metres' rule of thumb is summarised in Table 6.

Figure 14 and Table 6 demonstrate that restoration aimed at addressing in-stream thermal stress is most appropriately undertaken at the scale of entire subcatchments or catchments rather than individual stream reaches.

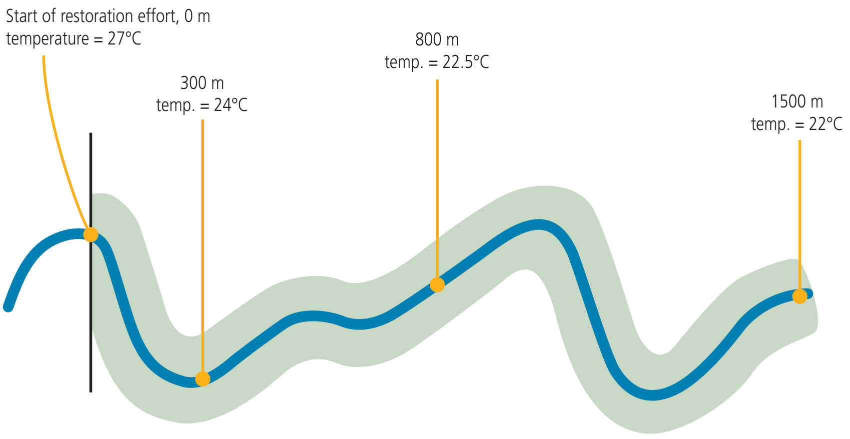



**Figure 14**. Change in in-stream temperature with distance of restoration effort for a hypothetical stream using the 30% per 100 metres rule of thumb. See text for details.

**Table 6**. What distance of riparian restoration do I need? The proportional effect of restoration effort on in-stream temperature as a function of distance in small streams.

| Distance | Proportional effect of restoration effort |
|---|---|
| 100 m | 25% |
| 200 m | 45% |
| 300 m | 60% |
| 800 m | 90% |
| 1000 m | 95% |
| 1500 m | 99% |

## Local variation

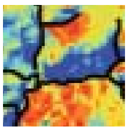
Beyond identifying what level of shade is required to reduce thermal stress to tolerable levels, river managers need to know which parts of a catchment or sub-catchment will most benefit from restoration effort using finite resources. The SimpSTREAMLINE simulation modelling discussed previously, ignored local effects associated with surrounding topography and stream orientation. That is, stream shade was set to zero and the global solar radiation received by a flat horizontal plane was used for model input. Because local macro-topographic conditions have a large influence on the amount of solar radiation a given location in the landscape receives, no simple rules of thumb can be applied.

This section describes a method for identifying relative priorities at the scale of a sub-catchment or catchment. Essentially, the method involves overlaying a map of existing stream vegetation with a map of solar radiation to identify areas of relatively high and low priority. Six steps are involved in identifying priorities:

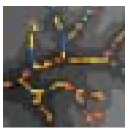
Step 1. Obtain aerial photo to be used in vegetation mapping

Step 2. Obtain Digital Elevation Model for mapping solar radiation

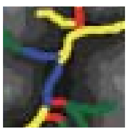
Step 3. Map riparian vegetation using ordinal classes



Step 4. Map solar radiation using index algorithm



Step 5. Use a GIS to extract solar radiation for streams



Step 6. Identify priorities by overlaying radiation and vegetation maps

Each step is illustrated here using Burns Creek as an example, a small catchment located in south-east Tasmania (Figure 15).

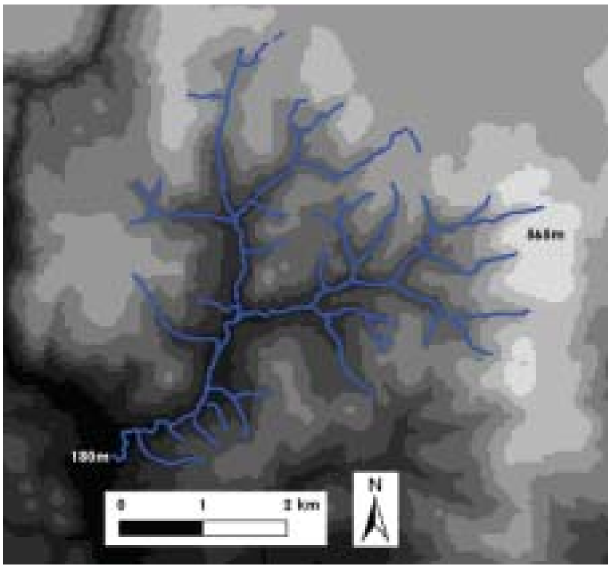
**Figure 15**. Burns Creek catchment, south-east Tasmania.

### Step 1. Obtain aerial photo to be used in vegetation mapping

Most areas around Australia have recent aerial photos flown for topographic mapping at a 1:25,000 to 1:100,000 scale. Larger scale photos will make vegetation mapping easier, but a trade-off may need to be made between photo scale and age. The photograph shown below for Burns Creek is a 1:42,000 shot flown in 1999.

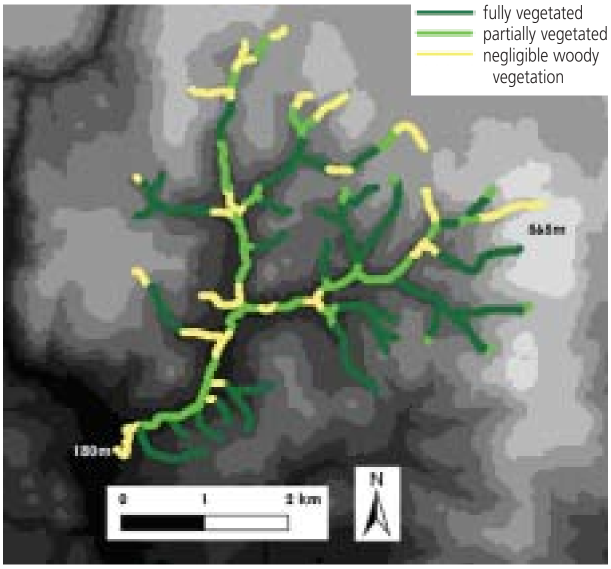
### Step 2. Obtain Digital Elevation Model for mapping solar radiation

Digital Elevation Models (DEMs) are electronic topographic maps that can be read using a Geographic Information System (GIS). The availability, quality and resolution of DEMs vary throughout different regions of Australia. Contact your local State Government Lands or Mapping agency to see what is available. For Burns Creek, the Tasmanian Department of Primary Industries Water & Environment was able to provide the DEM shown below at a resolution of 25 m pixel size.



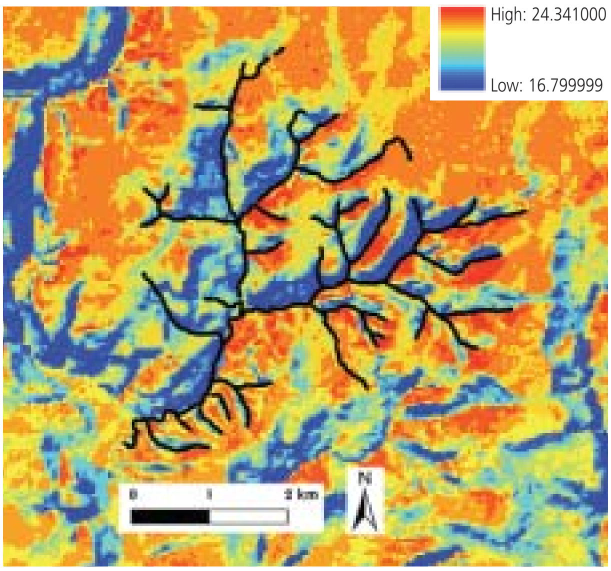

### Step 3. Map riparian vegetation using ordinal classes

Mapping riparian vegetation will be more accurate using a stereoscope and paired aerial photos. However, where the photo scale is large, a single image will probably be sufficient. The number of ordinal classes used will depend on the level of detail sought and the scale of the photograph. In the Burns Creek example, we've used three classes.



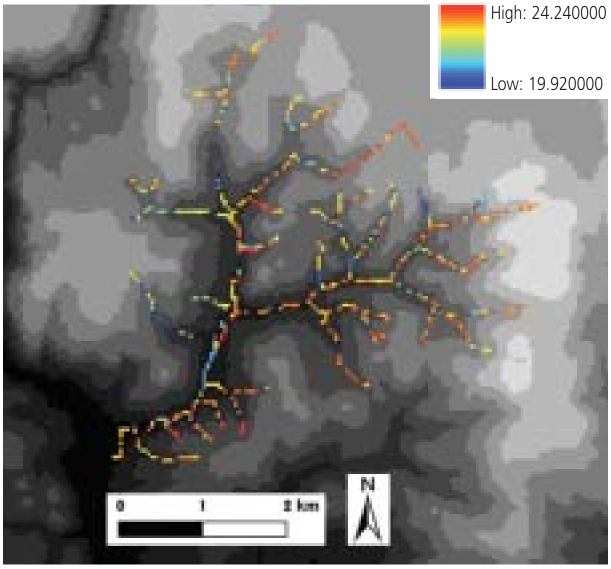

### Step 4. Map solar radiation using index algorithm

This step will require expertise in GIS. It uses an algorithm developed by the NSW Department of Environment and Conservation with the DEM. The algorithm 'tracks' the trajectory of the sun for a given month and outputs the relative solar radiation received at each pixel in the DEM, taking into account topography. Relative index values for each pixel can be converted to absolute global solar radiation values (MJ/m$^2$/day) using flat surface global radiation data available from the Bureau of Meteorology (2002). Because it is generally the time where in-stream temperature stress is most extreme, the algorithm should be applied using the month of January. The output for Burns Creek for January clearly shows the variation in global radiation associated with aspect and slope.



**Step 5. Use a GIS to extract solar radiation for streams**

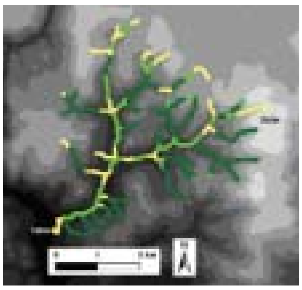
Only the pixels from the radiation algorithm output that coincide with streams are of interest. Assuming hydrographic data are available, it is a simple operation using GIS to extract the relevant pixels. For the Burns Creek catchment it can be seen that while westerly and northerly flowing stream reaches generally receive more solar energy than southerly and easterly flowing reaches, there is considerable variation caused by local topographic effects.

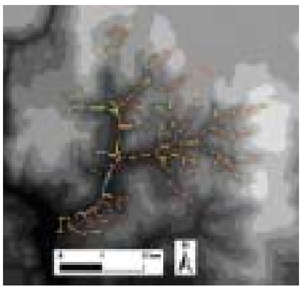


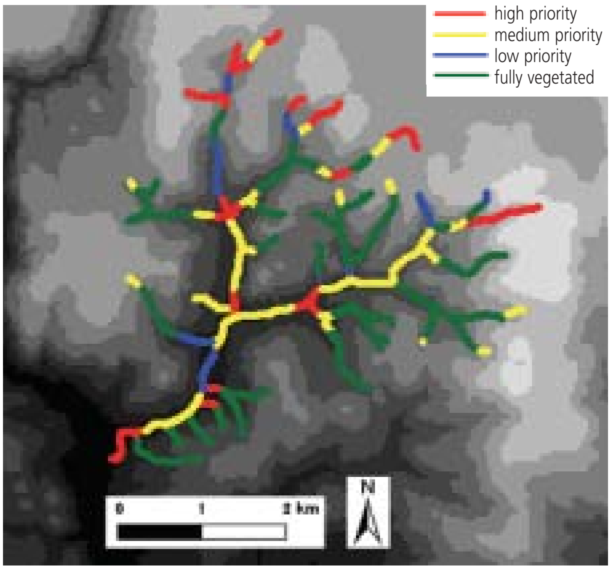

**Step 6. Identify priorities by overlaying radiation and vegetation maps**

Specific areas to be targeted as high, medium and low priority for restoration can now be mapped through simultaneous consideration of the spatial pattern of solar radiation and vegetation. In the Burns Creek example, stream reaches with high radiation and negligible vegetation have been assigned high priority. Reaches receiving intermediate radiation or having partial vegetation are of medium priority. The lowest priority class is assigned to those reaches where radiation is relatively low and some level of vegetation cover is already present.

Vegetation mapping + Radiation mapping = Priority map








## General principles

While the method illustrated in this section will provide a sound basis for identifying priority areas, we recognise that it has substantial technical and data demands that will not be available to all river managers. As concluding comments, we offer the following points as general principles to use in the identification of priority areas for restoration aimed at relieving in-stream thermal stress:

- *Restore lower order streams before higher order streams.*
- *Restore stream reaches with negligible woody vegetation before seeking to improve lower density or degraded vegetation.*
- *Restore streams on north-west aspects before south-east aspects.*
- *Preferentially restore reaches where soil properties are most favourable for successful vegetation establishment.*

## Estimating stream shade

Stream shade comprises three components — macrotopographic shade provided by nearby hills and other landforms, bank shade, and vegetative shade. The contribution of macrotopographic shade can be worked out from the method presented on page 16. In this section, a field-based method for estimating the individual and cumulative contribution of bank and vegetative shade is provided, together with photographic examples of varying shade levels.

A general index of exposure to light is diffuse non-interceptance (DIFN), defined as the diffuse radiation received at a partially shaded site as a proportion of that received at an open site. Shade is the complement of DIFN such that shade = 1 – DIFN. DIFN can be estimated directly using a pair of ceptometers under uniformly overcast skies, where measurements from one ceptometer placed at the site of interest (in this context, the centreline of a stream) are compared to simultaneous measurements made from a second ceptometer at a nearby open site. A ceptometer is a specialised scientific instrument that is unlikely to be available to most river managers.

An alternative field-based method for shade estimation at a point in a stream has been developed and described by Davies-Colley & Rutherford (2001). The method is based on measurement of three parameters:

1. the angle to the top of the stream bank measured from the centreline of the stream, $\theta_b$
2. the angle to the top of the riparian vegetation canopy, $\theta_c$ and
3. the average 'shade factor' of riparian vegetation.

The method requires access to a clinometer to measure $\theta_b$ and $\theta_c$ , a compass, and an understanding of the shade factor provided by different vegetation types. It is also a good idea to have a measuring tape to measure stream width so that an appreciation can be gained of the importance of the ratio of stream width to $\theta_b$ and $\theta_c$. Here, we recommend the use of Specht et al.'s (1995) structural classification of Australian vegetation types to approximate shade factor (Table 7). It is important to note that the classification of Specht et al. (1995) refers to the tallest stratum, and that when considering riparian vegetation, the higher foliage density of the understorey may need to be taken into account (see Example 2, overleaf).

Davies-Colley & Rutherford (2001) relate DIFN to the three parameters using the formula,

$$\text{DIFN} = \cos^2\theta_b + [\text{shade factor}(\cos^2\theta_c - \cos^2\theta_b)].$$

The average of eight estimates of DIFN is recommended, using $\theta_b$ and $\theta_c$ observations made looking to the north, north-east, east, south-east, south, south-west, west and north-west from the centreline of the stream.

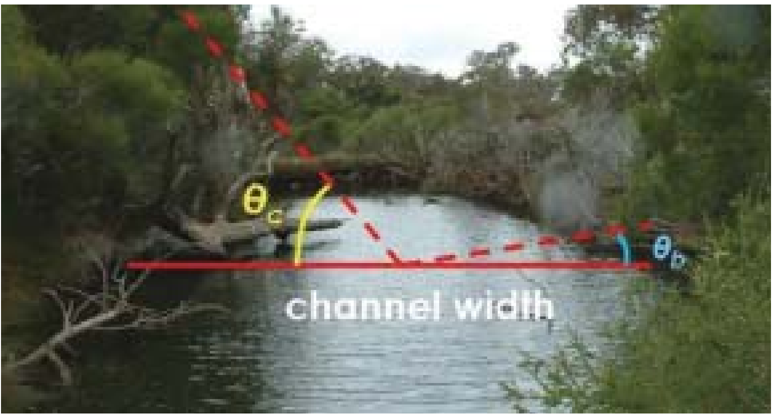
The total shade provided by a stream's bank and riparian vegetation is therefore,

$$\text{Shade} = 1 - \{\cos^2\theta_b + [\text{shade factor}(\cos^2\theta_c - \cos^2\theta_b)]\}.$$

Two examples of shade calculation are provided overleaf, followed by photographic illustration of varying shade levels.

**Table 7**. Structural formations of Australian vegetation (adapted from Specht et al., 1995).

| Life form and height | Foliage cover of tallest stratum (%) | | | |
|---|---|---|---|---|
| of tallest stratum | 100–70 | 70–30 | 30–10 | < 10 |
| Trees > 30 m | Tall closed-forest | Tall open-forest | Tall woodland | |
| Trees 10–30 m | Closed-forest | Open-forest | Woodland | Open-woodland |
| Trees 5–10 m | Low closed-forest | Low open-forest | Low woodland | Low open-woodland |
| Trees < 5 m | Very low closed-forest | Very low open-forest | Very low woodland | Very low open-woodland |
| Shrubs > 2 m | Closed-scrub | Open-scrub | Tall shrubland | Tall open-shrubland |
| Shrubs 0.25–2 m | Low closed-scrub | Low open-scrub | Low shrubland | Low open-shrubland |
| Shrubs < 0.25 m | | | Dwarf open-shrubland | Dwarf sparse-shrubland |
| Hummock grasses | | Dense hummock grassland | Hummock grassland | Open hummock grassland |
| Herbaceous layer | Closed grassland | Grassland | Open grassland | Sparse grassland |
| Sedges | Closed-sedgeland | Sedgeland | Open-sedgeland | Sparse-sedgeland |
| Herbs | Closed-herbland | Herbland | Open herbland | Sparse-herbland |
| Ferns | Closed-fernland | Fernland | | |
| Reeds/rushes | Closed-reedland | Reedland | | |





**Example 1**

The riparian vegetation at this reach comprises a high density Melaleuca thicket that can be structurally described as a (low) closed forest having a shade factor of about 0.75. The bank and canopy angles ($\theta_b$ and $\theta_c$) are measured in 8 equally spaced directions (north, north east, east, etc.) from the centreline of the stream and DIFN calculated for each pair of measurements.

As an indication of the photo's scale, the channel width = 6 m. Note that at greater stream widths the values of $\theta_b$ and $\theta_c$ for the same bank and vegetation heights would be less. This means that for an equivalent level of shade, wide streams need taller and/or denser vegetation than narrow streams. Using the formula,

$$\text{Shade} = 1 - \{\cos^2\theta_b + [\text{shade factor}(\cos^2\theta_c - \cos^2\theta_b)]\},$$

the bank was found to provide 1% shade and the canopy 23% shade, with a total of 24% shade.

**Example 2**

The riparian vegetation in this photo comprises two distinct strata — a medium density Melaleuca dominated understorey with a sparser Mallee eucalypt overstorey. The understorey (c1) can be structurally described as a (very low) open forest with a shade factor of about 0.6. The overstorey (c2) is a woodland with a shade factor of about 0.2. The channel width = 13 m.

Adjusting Davies-Colley & Rutherford's (2001) formula to account for two canopies, the bank was found to provide 2% shade, the understorey (c1) provides 6% shade, and the overstorey (c2) provides 9% shade. Total shade = 17%.

## Photographic examples of varying shade levels

Channel width = 1.7 m    Canopy shade = 1%
Bank shade = < 1%    Total shade = 1%

Channel width = 5 m    Canopy shade = 4%
Bank shade = 1%    Total shade = 5%

Channel width = 6 m
Bank shade = 4%
Canopy shade = 18%
Total shade = 22%

Channel width = 25 m
Bank shade = 2%
Canopy shade = 34%
Total shade = 36%

Channel width = 8 m
Bank shade = 6%
Canopy shade = 18%
Total shade = 24%

Channel width = 4 m
Bank shade = 10%
Canopy shade = 39%
Total shade = 49%

Channel width = 8 m
Bank shade = 8%
Canopy shade = 41%
Total shade = 49%

Channel width = 22 m
Bank shade = 8%
Canopy shade = 51%
Total shade = 59%

Channel width = 5 m
Bank shade = 12%
Canopy shade = 38%
Total shade = 50%

Channel width = 8 m
Bank shade = 4%
Canopy shade = 57%
Total shade = 61%

Channel width = 6 m
Bank shade = 14%
Canopy shade = 49%
Total shade = 63%

Channel width = 6 m
Bank shade = 3%
Canopy shade = 80%
Total shade = 83%

Channel width = 11 m
Bank shade = 2%
Canopy shade = 74%
Total shade = 76%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Louise Everett (CENRM) conducted initial simulations using SimpSTREAMLINE. Michael Drielsma (NSW Department of Environment and Conservation) made available the solar radiation index algorithm referred to on page 17 and Jane Elith (University of Melbourne) produced solar radiation maps. Robert Musk (University of Tasmania) ably provided technical assistance in field work. The following organisations made data and expertise available for the project: the Western Australian Department of Environment, Tasmanian Department of Primary Industries Water and Environment, Commonwealth Bureau of Meteorology, Queensland Department of Natural Resources and Mines, and the Wet Tropics Management Authority. The production of maps and figures for the project has benefited from the editorial expertise of Leisha Richards (CENRM). We are especially grateful to all landholders who allowed access to their properties in the capture of field data.

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