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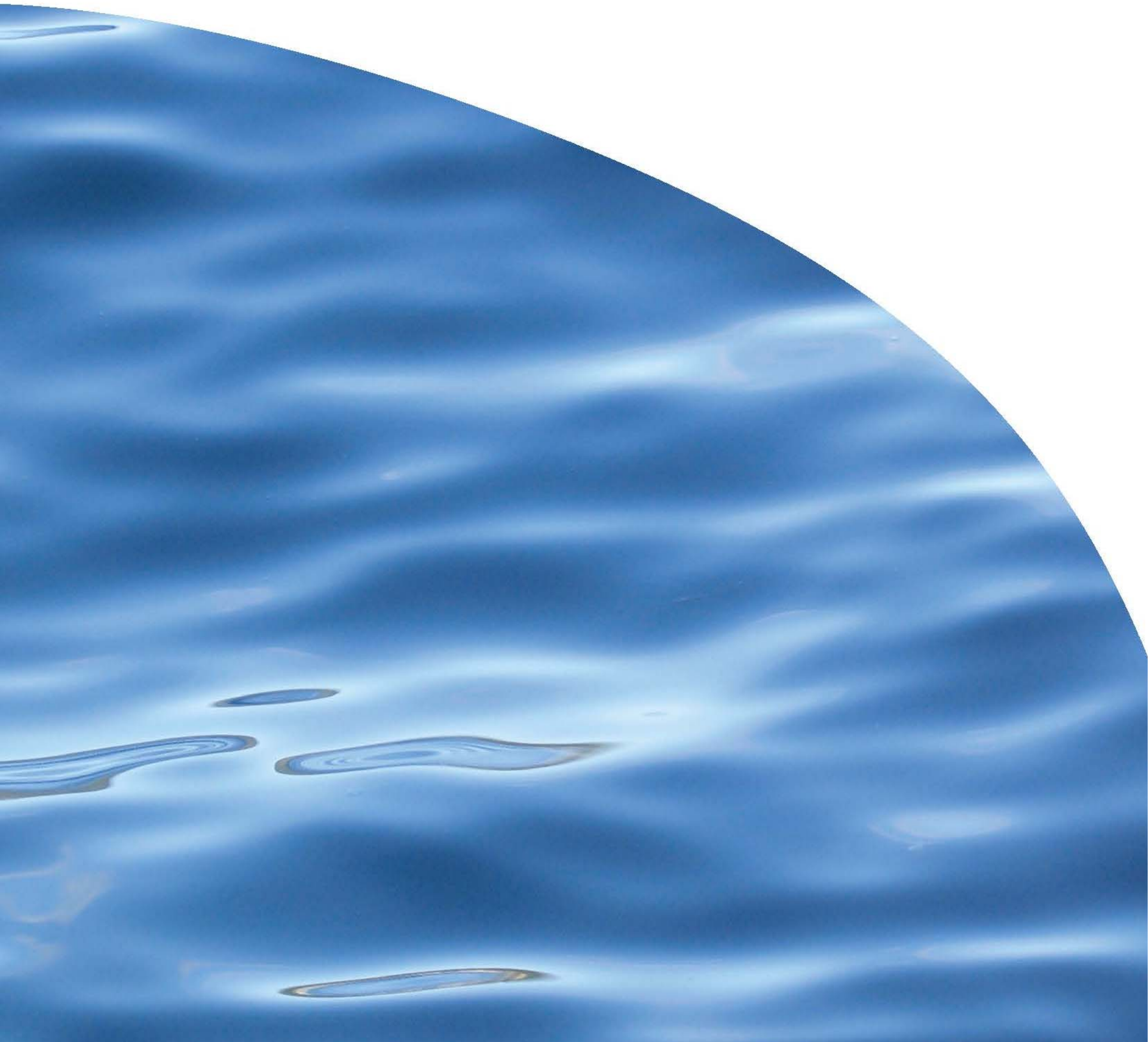
MANAGING POTENTIAL WATER TEMPERATURE EFFECTS OF DISCHARGES FROM THE MAITAI RESERVOIR



MANAGING POTENTIAL WATER TEMPERATURE EFFECTS OF DISCHARGES FROM THE MAITAI RESERVOIR

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Prepared for Nelson City Council

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EXECUTIVE SUMMARY

Poor quality water sometimes discharged from the Maitai Reservoir is known to have detrimental effects on water quality in the Maitai River, as evidenced by declines in biotic river health indicators below the reservoir discharge observed during annual monitoring. This report examines the influence of discharges from the Maitai Dam on water temperature in the Maitai River. It was commissioned by Nelson City Council to examine the temperature effects of the current dam discharge regime and explore the potential river temperature implications of discharging water from different depths in the Maitai Reservoir.

Water for Nelson's municipal supply is commonly abstracted from the South Branch weir and replaced with water from the reservoir on the North Branch of the Maitai, via a pipe discharging below the weir, referred to as the back-feed. During summer the reservoir water commonly stratifies. The cooler bottom water becomes deoxygenated, with an associated decline in water quality. Back-feed water can be sourced from three different intake levels the intake tower in the reservoir, at depths of 6 m, 15 m and 24 m respectively, as well as from a scour valve at approximately 25 m. Because water temperature varies with depth in the reservoir's water column it is possible to selectively control the temperature, and water quality, of the back-feed discharge.

Existing resource consent conditions require that the back-feed discharge at the South Branch weir must not alter the water temperature in the river by more than 3 °C, and must not cause water temperature to alter beyond certain bounds (maximum 20 °C and minimum 6 °C). However, the thermal stratification, with its associated poor water quality, means the selection of back-feed water is a trade-off between water temperature and other water quality parameters. Releasing cool water from the lower intakes may comply with temperature related consent conditions, but in summer this bottom water is deoxygenated and has poor water quality. On the other hand, releasing better quality water from nearer the surface may breach temperature conditions.

There is a sound ecological basis for the existing consent conditions prohibiting the back-feed discharge from raising the temperature of the river above 20 °C and the 3 °C maximum permitted increase in temperature downstream of the reservoir compared with upstream. However, reductions in temperature of more than 3 °C seem less likely to incur adverse effects than temperature increases of similar magnitude. Furthermore, short term breaches of the 3 °C maximum permitted change might be expected to have less significant adverse effects than breaches of the 20 °C maximum temperature threshold. The rationale for the minimum temperature threshold of 6 °C is unclear, although it seems unlikely to ever cause problems for operation of the water supply scheme during summer stratification events.

While the operation of the back-feed largely complied with the temperature related consent conditions during summer 2014/15, for much of the summer bottom water from the reservoir scour valve was discharged through the back-feed. Records show that from 2 February onward back-feed water was sourced either from a combination of the upper intake and the

scour valve, or from the scour valve alone (from early April onward). This resulted in anoxic water from the bottom of the dam being discharged for much of the summer, with potential adverse effects on the river ecology as well as adverse aesthetic effects (including reddish-brown flocculate on the stream bed and an objectionable smell of hydrogen sulphide within the valley at times). This appears inconsistent with the intent of conditions governing the discharge of scour water from the reservoir, which state that "*Other than in emergencies, the discharge of scour water shall only occur when the river is in fresh and naturally discoloured...*" Although there were some fresh events during the summer, for most of the time the flow was reasonably stable and low. Therefore, under this condition scour water should not have been being discharged to the river for most of this period. However, it appears that this condition does not explicitly apply to discharge via the back-feed. Nevertheless, given the observed declines in biotic indicators downstream of the back-feed (relative to an upstream control site) and the possibility that discharge of anoxic scour water is contributing to these trends, we recommend that NCC seek legal advice on interpretation of this condition of consent and consider initiating a review of conditions, or at least a review of operating procedures in the interim.

Water at the top intake reservoir level (6 m) was below the 20 °C temperature threshold for most of the 2014/15 summer and temperatures at the middle (15 m) and bottom (24 m) intake levels were below this threshold for the entire summer. This demonstrates that it was not necessary to source back-feed discharge water from the scour valve in order to comply with the 20 °C maximum temperature threshold. Furthermore, compliance with the 3 °C maximum change in water temperature below the back-feed would have been possible by drawing water from a combination of the upper and middle intakes for most of the summer, at least up until early April.

Installing water temperature sensors at each reservoir intake level would allow back-feed water to be sourced to match ambient temperatures in the South Branch. With real time data from these sensors, along with data that is already collected (*e.g.* South Branch flow and temperature, abstraction rate at the weir and required back-feed discharge rate), it would be a relatively simple task to derive an algorithm that would calculate the mix of water from the intake valves required to match the temperature in the South Branch. Sourcing water from the top and middle valves could be prioritised over the summer, to avoid releasing the low quality anoxic bottom water during thermal stratification events. We recommend that this approach should be pursued.

Despite operation of the back-feed discharge complying with temperature related conditions most of the time, river water temperatures increased rapidly downstream during the warm settled period in late January 2015. Consequently, daily maximum temperatures from the site immediately upstream of the spillway discharge pool on downstream were often above 20 °C throughout much of this settled fine weather. Temperatures observed downstream of the Maitai Forks flow recorder site, in particular, during late January would be expected to induce thermal stress in a range of aquatic organisms, with the likely elimination of some sensitive species.

It is possible that the cooler water of the South Branch could provide a thermal refuge for mobile species, such as fish, during periods when the lower Maitai River experiences potentially stressful water temperatures. However, the South Branch upstream of the weir may be inaccessible, due to the weir impeding passage for fish attempting to access this habitat during low flows (notwithstanding recent fish passage remediation work). Temperature modelling, predicting longitudinal profiles of daily mean and maximum water temperatures through the upper Maitai River, shows that the back-feed discharge can alter the length of potential thermal refuge habitat available. Releasing warm water from the reservoir can reduce the length of river remaining below 20 °C, which potentially acts as a thermal refuge, while releasing cooler water can extend this potential refuge habitat.

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1. INTRODUCTION

This report examines the influence on river water temperature of discharges from the Maitai Reservoir into the Maitai River. It was commissioned by Nelson City Council (NCC) to help inform options for dam operation in the future.

The Maitai Dam was built in 1987 on the North Branch of the Maitai River, immediately upstream of the confluence with the South Branch (Figure 1). It is 36 m high and retains a reservoir that covers an area of 32 hectares. Water for Nelson's municipal supply is sourced from either the reservoir or from the South Branch, approximately 1.7 km upstream of the dam, at the South Branch weir. To minimise water treatment requirements, water tends to be sourced mainly from the South Branch except during high flow events, when the river water becomes turbid. When water is abstracted from the South Branch weir it is replaced with water from the reservoir via a pipe discharging below the weir, referred to as the back-feed. Existing resource consent conditions require that the back-feed discharge at the South Branch weir must not alter the water temperature in the river by more than 3 °C, and must not cause water temperature to alter beyond certain thresholds (see section 1.1).

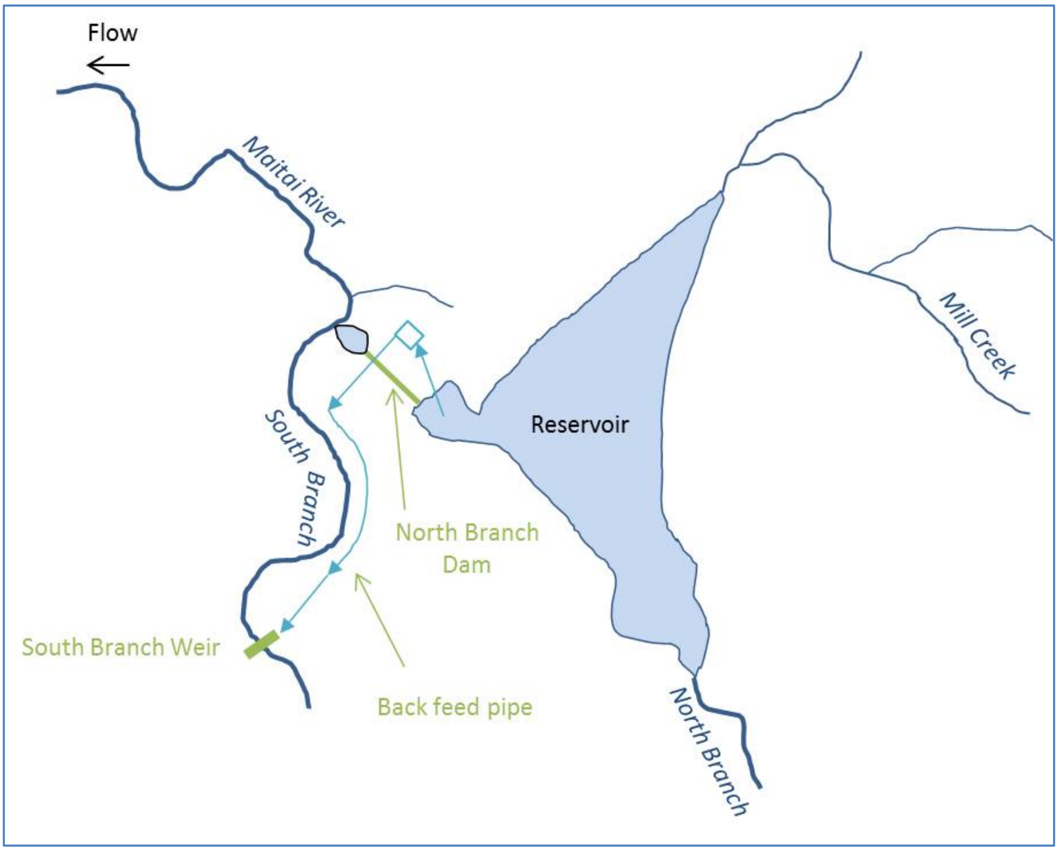

Figure 1. Schematic diagram of the Maitai Water Supply Scheme showing the locations of the Maitai Dam, the South Branch weir and the back-feed pipe in relation to the reservoir (not to scale).

During summer the reservoir water commonly stratifies, with the cooler bottom water becoming deoxygenated, with an associated decline in water quality. In particular the deoxygenated bottom water takes on elevated levels of iron, manganese, and nickel, and water from the back-feed discharge tends to also have slightly elevated concentrations of nitrogen and phosphorus (Allen *et al*. 2014).

The back-feed water can be sourced from three different intake levels on the intake tower in the reservoir (at depths of 6 m, 15 m and 24 m, respectively, as well as a scour valve at approximately 25 m), which provides some ability to selectively control the temperature and water quality of back-feed water. However, the combination of the temperature restrictions and thermal stratification, with its associated poor water quality, can make selection of back-feed water a trade-off between water temperature and other water quality parameters. Releasing cool water from the lower intakes may comply with temperature related consent conditions, but in summer this bottom water is deoxygenated and has poor water quality. On the other hand, releasing better quality water from nearer the surface may breach temperature conditions.

Water discharged from the reservoir via the back-feed, as it is currently operated, is known to have detrimental effects on water quality in the Maitai River, as evidenced by declines in biotic river health indicators below the back-feed observed during annual monitoring (Allen *et al.* 2013, Allen *et al.* 2014).

In reviewing temperature and water quality data from the Maitai Reservoir, Kelly (2014) suggested sourcing back-feed water from progressively higher levels in the reservoir as thermal stratification and deoxygenation of bottom water proceeds during summer, to avoid releasing anoxic water with its associated poor water quality from the lower levels of the dam. He recognised that releasing water from the upper (6 m) intake could result in warming of the river during mid-summer, but suggested that the warming would likely be modest, on the basis of temperature data from the upper (6 m) intake level, which never exceeded 19 °C during the 2013/14 summer. These contentions are largely supported by the analyses discussed in Section 3 below.

Kelly (2014) suggested that the consent condition permitting no more than a 3 °C change in water temperature in the South Branch may have to be reviewed to facilitate this change in sourcing back-feed water. He recommended further investigation, including temperature modelling, to better understand the potential effects of sourcing back-feed water from different valve levels during periods of anoxia in the reservoir. This report was commissioned to examine the temperature effects of current dam operation and explore whether there may be scope to achieve better ecological outcomes through different operating regimes.

1.1. Existing water temperature conditions

The existing water temperature consent conditions associated with the operation of the South Branch intake and the back-feed[1] are:

(a) When the water temperature prevailing immediately above the intake is between 8 °C and 18 °C inclusive, the discharge shall not change the temperature of the river water by more than 3 °C.

(b) When the water temperature prevailing immediately above the intake is greater than 18 °C, the discharge shall not reduce the temperature of the river water below 15 °C.

(c) When the water temperature prevailing immediately above the intake is less than 8 °C, the discharge shall not increase the temperature of the river water above 11 °C.

(d) When Conditions (b) and (c) are in force, the discharge shall only be turned off at an even rate over a minimum period of two hours.

(e) At no time shall the discharge increase the temperature of the river above 20 °C or reduce it below 6 °C.

These conditions were confirmed when Water Rights 825020 and 831560 were renewed as Resource Consent 960396 in March 1997.

2. ECOLOGICAL SIGNIFICANCE OF WATER TEMPERATURE

Water temperature affects all aspects of freshwater ecosystems, from its influence on the solubility of oxygen through to regulating metabolic rates (and therefore the growth and activity) of most aquatic organisms (Davies-Colley *et al.* 2013). Consequently, it is critical to correctly manage this aspect of freshwater systems. Management of water temperatures for the protection of aquatic species should consider more than just their critical thermal limits and should be based on the thermal requirements of all life stages of the species in question.

Water temperature varies naturally on daily and seasonal cycles, largely driven by solar inputs. However, it can be influenced by discharges of water that is either warmer (*e.g.* industrial cooling water, or surface water from thermally stratified reservoirs) or cooler (*e.g.* bottom release from dams, or groundwater) than ambient conditions in the river.

[1] Consent number 960396, Condition 8.

As alluded to above, the metabolic demands (and therefore the growth and activity) of most aquatic organisms are regulated by water temperature. This is because most are poikilotherms (commonly known as cold-blooded in animals), meaning that their internal temperature follows that of the environment (with some lag). Consequently, they are highly susceptible to changes in the ambient river water temperatures caused by discharges.

Olsen *et al.* (2011) recently reviewed the thermal requirements of native freshwater biota and this review subsequently helped inform thermal criteria recommended for the National Objectives Framework (NOF) (Davies-Colley *et al.* 2013). Avoiding excessive elevation of temperature is the key management concern, because lethal temperatures for many species are only slightly above their optimal temperatures for growth (perhaps as little at 5 °C above), (Davies-Colley *et al.* 2013) and are close to the temperature range commonly experienced in New Zealand streams during summer. While temperature reductions below optimal conditions tend to produce a gradual decline in growth and activity rates, temperatures above the growth optimum become increasingly stressful comparatively rapidly, because of effects on cellular function, with enzymes becoming denatured (Davies-Colley *et al.* 2013).

The following review of ecological influences of water temperature and thermal limits for New Zealand aquatic biota are based on these two recent reviews (Olsen *et al.* 2011, Davies-Colley *et al.* 2013).

2.1.1. Sub-lethal effects

Even if temperatures do not encroach into the lethal range for a given species, this does not imply that there is no consequence. Aquatic organisms will display behavioural and physiological changes as temperatures diverge from their thermal optima. These are likely to include changes in activity, feeding and growth rates, with potential consequences for evolutionary fitness (*i.e.* the reproductive capacity of individuals) and for productivity (*e.g.* of fisheries). Reduced growth is an important sub-lethal response to temperature, because body size is directly related to fecundity in many species and large size often also confers competitive advantages over smaller individuals (Olsen *et al.* 2011).

2.1.2. Defining thermal tolerance limits

The thermal tolerance of a given species can vary with preceding thermal conditions (due to acclimation), food availability and quality, and may change over the life-cycle of the species.

The thermal tolerances and requirements of a species across a range of different acclimation temperatures can be represented as a thermal tolerance polygon (Figure 2). The thermal tolerance polygon for brown trout (*Salmo trutta* L.) is shown in Figure

2 to illustrate the various critical temperatures discussed below. To date, sufficient information has not been collected to present such information for any New Zealand native species. Gathering the data required to define a thermal tolerance polygon of this sort requires a concerted experimental effort. The brown trout is highly valued nationally and internationally for the fisheries it supports, and largely as a consequence of this detailed scientific information about its thermal requirements are available (see review in Elliott 1994). Furthermore, brown trout rank among the most sensitive to warm river conditions of fish found in New Zealand Rivers. Therefore, the thermal requirements of trout are often considered to provide a conservative objective for temperature management in New Zealand Rivers.

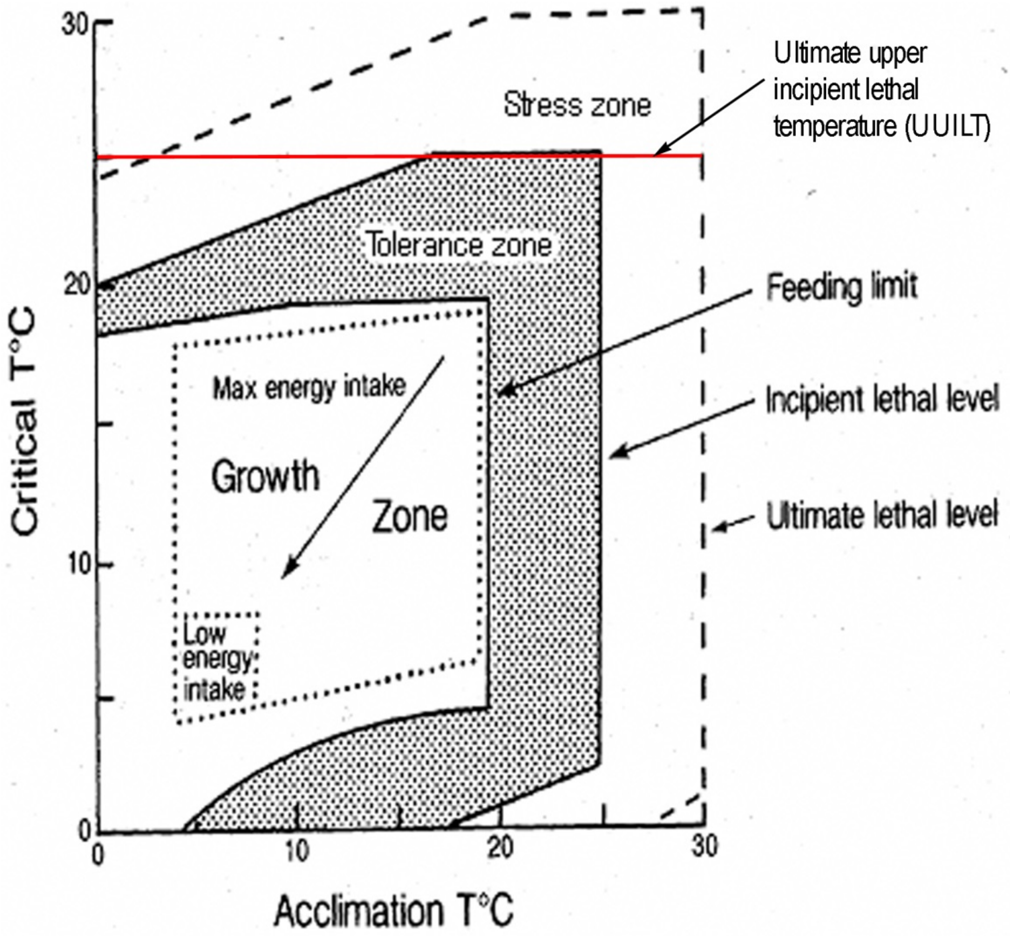

Figure 2. Thermal tolerance polygon for brown trout from Elliott (1994).

The growth zone is the temperature range over which growth can occur, given sufficient availability of food. For brown trout the upper bound of this zone is 19 °C, regardless of acclimation temperature. Above this temperature brown trout cease feeding. Within the growth zone there is a thermal growth optimum (T_{opt}), the thermal range over which the greatest rate of growth occurs. The bounds of the growth zone also depend on food availability and the relative energy content of available food. If trout are not able to attain maximum rations, the growth optimum shifts to cooler temperatures. The optimal temperature for growth of brown trout fed on an invertebrate diet is 14 °C while this increases to 17 °C in trout fed on a fish diet (Elliott & Hurley 1998; 1999; 2000).

Beyond the growth zone is a tolerance zone. This is the thermal range over which the animal will not grow but will still survive for significant periods of time. The upper and lower limits of the tolerance zone are defined by the upper and lower incipient lethal temperatures (UILT and LILT, respectively). The incipient lethal temperature is usually defined as the temperature at which 50% mortality occurs in experiments conducted over a set period of time. The UILT varies with acclimation temperature (Figure 2) and for brown trout increases with acclimation to a plateau at 24.7 °C. This ultimate upper incipient lethal temperature (UUILT), the point at which the upper incipient lethal temperature no longer increases with acclimation temperature (Figure 2), is often used to estimate the temperature at which significant mortality is expected to occur.

It is worth noting that the incipient lethal temperature is dependent on the exposure time. Consequently, for a given organism a higher incipient lethal temperature would be derived from an experiment conducted over a short time period rather than a long one.

The stress zone lies between the incipient lethal temperature and the ultimate lethal temperature (the temperature at which death occurs almost instantaneously). For brown trout the ultimate lethal temperature reaches a plateau at 29.7 °C (Elliott 1981; Elliott 1994; Elliott & Elliott 1995). The stress zone is where thermal stress occurs that will ultimately kill the animal, with the time until death being a function of exposure time to the thermal stress. Trout deaths have been reported in New Zealand rivers when water temperatures have equalled or exceeded 26 °C (Jowett 1997). Interestingly, brown trout do not appear to have reached their lower ultimate lethal temperature at 0 °C, as long as they do not become entombed in ice (Figure 2, Elliott 1994).

In reality sub-lethal population effects can occur at lower temperatures than those defined by thermal tolerance laboratory experiments. The impacts of 'sub-lethal' high water temperatures are expressed not only in fish behaviour and growth rate but also in survival rates and population production. For example, in trout, mortality increases as water temperature rises above the growth optima (14 °C – 17 °C for brown trout, 16 °C – 18 °C for rainbow trout). Reasons for increased mortality with increasing 'sub-lethal' temperatures include, stress, increased risk of disease, and greater activity of some predators. A study on rainbow trout found that the maximum temperature at which a population can be expected to maintain its weight (biomass) was a constant temperature of 23 °C and a fluctuating mean temperature of 21 °C (Hokanson *et al.* 1977) (*i.e*. the temperature at which population production is zero). Given the differences in temperature preference between rainbow and brown trout, an equivalent zero production temperature for brown trout is likely to be 19 °C. These maximum temperatures apply to fish on maximum rations; they will be even lower for food-limited populations (Hokanson *et al*. 1977).

2.2. Thermal thresholds of native fauna

Theoretically, the optimum temperature for growth (T_{opt}) of keystone species provides a better criterion for temperature management than lethal temperatures, as suggested by Davies-Colley *et al*. (2013). This is because for long term (chronic) management the aim ought to be to avoid temperatures going into the 'stress zone' for organisms, or even the 'tolerance zone', let alone approaching acutely lethal temperatures.

Unfortunately, as mentioned above, because defining growth curves requires substantial experimental effort for individual species (Olsen *et al.* 2011), less information is available on growth curves, from which to define T_{opt}, than for lethal temperatures. In fact, no such growth curve data has been developed for any native New Zealand aquatic organisms. Consequently, temperature guideline values are generally based on incipient lethal temperatures and incorporate a safety margin.

Two main experimental approaches have generally been used to define thermal limits for New Zealand fish and invertebrates, the critical thermal maximum (CTM) method and the incipient lethal temperature (ILT) method (Olsen *et al.* 2011). The CTM method involves placing acclimated individuals in an experimental apparatus then increasing the water temperature at a constant rate until the CTM is reach. This is usually defined as the temperature at which the animal's movement becomes disorganised and the animal would be unable to actively escape the warm water (Olsen *et al.* 2011). This method has commonly been employed for native fish species in New Zealand.

The incipient lethal temperature (ILT) approach generally involves transferring experimental organisms from an acclimation tank to a tank held at a given temperature. The ILT is usually calculated as the temperature at which 50% mortality occurs over a set time period, often referred to as the LT_{50}. The duration of such experiments has varied widely, ranging from 10 minutes to 14 days. In the case of Richardson et al. (1994), fish were transferred from a tank held at the acclimation temperature to a water bath heated to the experimental temperature where they were immersed for 10 minutes before being returned to the acclimation tank. A disadvantage of this approach is that the test animals are subjected to a rapid change in temperature, which may elicit a shock response. It is also open to the criticism that it does not replicate rates of temperature change likely to be experienced naturally. The ILT approach has commonly been used for invertebrates in New Zealand. Obviously values derived by either method will vary according to the duration of exposure, as well as acclimation temperature.

Figure 3 summarises thermal preferences and incipient lethal temperatures for some native species (from Olsen *et al.* 2011). Much of the experimental findings for New Zealand native species are arguably more relevant to acute exposure to high temperatures, rather than tolerance of more chronic exposure (Olsen *et al.* 2011).

Eels appear to have among the highest thermal preferences (and CTM) of New Zealand native species tested (Figure 3), while banded kokopu and koaro exhibit lower thermal preferences, in the mid to high teens. Notably though, the temperature preferences shown in this figure for longfin (LFE) and shortfin (SFE) eels are within < 1 °C of their, respective, incipient lethal temperatures (shown below), suggesting a very narrow 'tolerance zone' for these species.

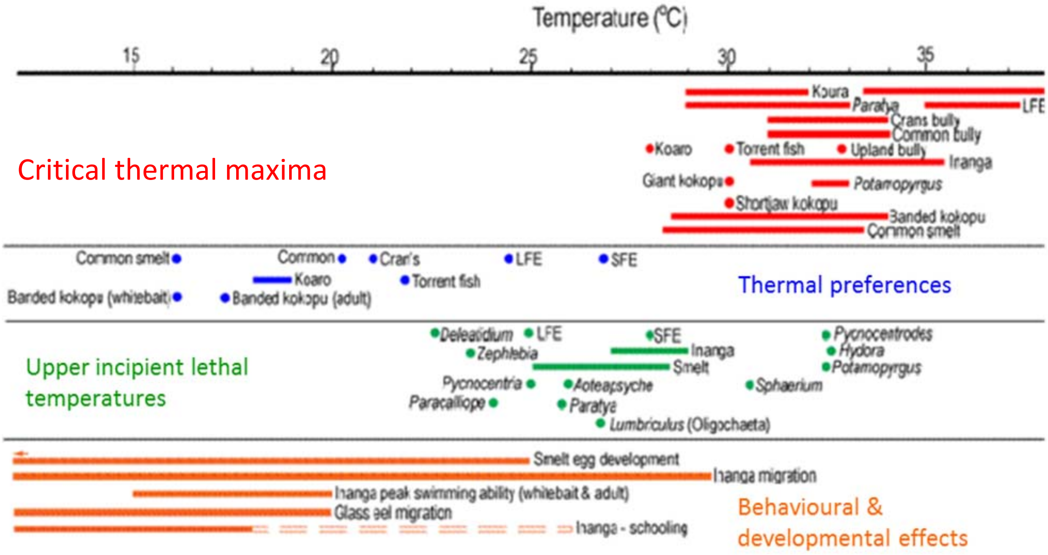

Figure 3. Summary of thermal tolerance of native fish and macroinvertebrates as defined by critical thermal maxima (CTM - red), thermal preferences (blue), upper incipient lethal temperature (UILT — green) and behavioural and developmental effects (orange). Where CTM or UILT have been determined for multiple acclimation temperatures, the range is shown as a bar. Behavioural and developmental effects are shown as bars representing the range of temperatures when normal behaviour/development is apparent. Inanga schooling is dependent on acclimation temperature (from Olsen *et al.* 2011).

For most native fish species tested, data are only available for a single life stage (Olsen *et al.* 2011). Exceptions to this include eels (with adults having higher ultimate lethal temperatures than elvers) and inanga (with adults and juveniles having similar thermal preferences and CTM to adults).

Graynoth & Taylor (2000) reported that growth of shortfin eels ceased below 8.9 °C for fish fed on maximum rations. This appears to be the sole estimate of a thermal minimum for growth for a New Zealand native fish species.

Of the invertebrate species for which data are available mayflies (Ephemeroptera) and stoneflies (Plecoptera) seem to be most sensitive to high temperatures. In a study of the effects of environmental variables on macroinvertebrate communities in 88 New Zealand Rivers, Quinn & Hickey (1990) found that stoneflies were largely restricted to rivers with a mean annual water temperature of less than 13 °C and annual maximum temperature of less than 19 °C (Quinn & Hickey 1990). Similarly, mayflies were largely restricted to rivers with an annual maximum temperature of less than 21.5 °C (Quinn & Hickey 1990). Strong relationships between temperature and abundance were not evident for other macroinvertebrate families. The incipient lethal temperatures of the two mayfly taxa *Deleatidium* and *Zephlebia* in Figure 3 are about 21– 23 °C. In developing their recommendations for water temperature limits for the NOF, Davies-Colley *et al.* (2013) appeared to put quite strong emphasis on the findings of Quinn & Hickey (1990).

2.3. Fish spawning

For spawning and incubation the main issues for trout fisheries are temperature and dissolved oxygen, as well as maintaining a relatively low fine sediment fraction in the substrate (Hay *et al.* 2006). These three key water quality factors are probably also relevant to many native fish species, although the parameter levels required are not as well studied. The eggs of some native fish species are known to incubate out of the water column (*e.g.* inanga and kōaro). Consequently, water quality parameters may be of limited relevance to spawning success for these species.

Winter water temperature was one of the main predictive factors in Jowett's (1992) "100 rivers models" predicting brown trout abundance in New Zealand rivers. Jowett's study indicated that rivers with winter water temperatures > 10 °C contained very few, or no, brown trout. It appears from this that high water temperatures in winter (the spawning and incubation period) may limit brown trout recruitment in New Zealand rivers.

Hay et al. (2006) suggested that water temperature in streams managed for trout spawning be maintained at < 11 °C during the spawning and incubation period, on the basis of thermal optima and tolerance limits in the literature.

The spawning season for brown trout is generally between May-October, but extends into November and December for native fish including bullies and kōaro.

Consequently, thermal requirements for spawning are not particularly relevant to consideration of the discharge of thermally stratified water from the Maitai Reservoir.

2.4. Periphyton

The review undertaken by Olsen *et al.* (2011) focused mainly on the thermal requirements of fish and invertebrates, but also included a brief discussion of upper temperature limits for some periphyton taxa. The temperature limits recommended for the NOF did not consider periphyton, because they generally have substantially broader temperature tolerance than fish and invertebrates (Davies-Colley *et al.* 2013). Nevertheless, water temperature is an important factor influencing periphyton growth rates. Key factors controlling periphyton cover and biomass on river beds include sunlight, nutrient concentration, temperature, grazing by invertebrates and flow history (*i.e.* the history of bed disturbance). If sufficient nutrients and light are available, temperature becomes the next most important controller of how fast cells divide and algal biomass can develop (Biggs 2000). Consequently, elevating stream temperatures may exacerbate periphyton proliferation to some extent, by hastening growth to nuisance levels.

2.5. Influence on other water quality parameters

2.5.1. Dissolved Oxygen

The potential impacts of reduced dissolved oxygen (DO) are influenced by temperature. Water temperature controls the solubility of oxygen, with cooler water able to hold more oxygen, and also controls the metabolic demands of most aquatic organisms. So with elevated water temperatures biological oxygen demands tend to be higher, but DO concentrations tend to be lower.

2.5.2. Ammonia

When in solution in the water, ammonia occurs as two main chemical forms: the ammonium cation (NH_4^+) and unionised ammonia (NH_3). The relative proportion of these two forms is determined by a chemical equilibrium, which is controlled by pH and temperature. Higher pH and temperature result in a higher proportion of unionised ammonia. Unionised ammonia is much more toxic to aquatic life than ionised ammonia, thus the toxicity of total ammonia (being the sum of unionised and ionised forms) increases with pH and / or temperature (Ausseil 2013a).

2.6. Temperature thresholds for ecological protection

From the discussion above it can be seen that maintaining river water temperatures below about 19 °C is likely to largely avoid adverse effects on sensitive native fish and invertebrate species, as well as brown trout. Maintaining water temperatures below the low 20s °C is likely to incur some thermal stress on sensitive species, while temperatures over about 25 °C are likely to result in some degree of stress for a range of species and may result in the loss of particularly sensitive fish and invertebrate species from the local community.

These thresholds align well with the water temperature limits recommended for the NOF by Davies-Colley *et al.* (2013). While temperature limits were not ultimately adopted in the NOF, their recommended temperature limits provide a useful basis of comparison for river water temperatures, giving an indication of the likely level of ecological impacts. Their recommendations for the upper bounds of A, B and C band stream sites for 'Eastern Dry' regions (including Nelson) were ≤ 19 °C, ≤ 21 °C and ≤ 25 °C, respectively. These bands were intended to result in:

A band. No thermal stress on any aquatic organisms that are present at matched reference (near-pristine) sites.

B band. Minor thermal stress on occasion (clear days in summer) on particularly sensitive organisms such as certain insects and fish.

C band. Some thermal stress on occasion, with elimination of certain sensitive insects and absence of certain sensitive fish.

The temperature thresholds were intended to be assessed against the summer period measurement of the Cox-Rutherford Index (the average of the daily mean and maximum temperature), averaged over the five hottest days from a continuous temperature record.

These A and B band limits align reasonably closely with daily maximum temperature criteria suggested by Hay *et al.* (2006) for protection of trout fisheries values in Horizons One Plan (19 °C for 'Outstanding' or 'Regionally significant' trout fisheries, and 24 °C for 'other significant trout fisheries'), bearing in mind that the band limits recommended by Davies-Colley *et al.* (2013) are for the average of the daily mean and maximum temperature.

2.6.1. Consideration of existing temperature consent conditions

In light of the discussion above there appears to be a reasonably sound ecological basis for the existing consent condition 'At no time shall the discharge increase the temperature of the river above 20 °C'. The rationale for the minimum temperature threshold of 6 °C is less clear, although it seems unlikely to ever cause problems for operation of the water supply scheme.

The 3 °C maximum change in temperature has most likely been adopted directly from the Resource Management Act (RMA 1991). This degree of change appears to be fairly arbitrary, but has been widely adopted as an acceptable threshold of change since it was put forward in the RMA (1991), see Table 1. Having a maximum degree of change like this has the advantage of avoiding large deviations from natural seasonal and diurnal patterns in temperature, which may trigger behavioural responses in some aquatic biota. As discussed by Davies-Colley *et al.* (2013), lethal temperatures for many species are only slightly above their optimal temperatures for growth, perhaps as little as 5 °C above, and are close to the temperature range commonly experienced in New Zealand streams during summer. Even below the stress range relatively moderate changes in water temperature may have adverse effects. For example, a temperature increase of as little as 5 °C, is the difference between their optimal temperature for growth for brown trout (14 °C) and the temperature at which they cease feeding and growth ceases (19 °C). In light of these considerations, the existing 3 °C maximum change in water temperature also appears to have merit, although short term breaches might have less significant adverse effects than breaches of the 20 °C maximum temperature threshold. Also, reductions in temperature of more than 3 °C seem less likely to incur adverse effects than temperature increases of similar magnitude, on the basis of the literature review above.

The existing consent condition requiring the back-feed discharge to be turned on or off progressively at an even rate over two hours also appears to have merit. Abrupt changes in temperature preclude acclimation and may cause shock (Olsen *et al.* 2011). However, is not possible to specify an appropriate rate of change on the basis of existing data.

Table 1. Examples of temperature guidelines to protect aquatic ecosystem values from selected regional and national policy documents.

Source	**Parameter**	**Standard**	**Comment**
Horizons One Plan (2013)	Temperature (max daily)	19 °C–24 °C	Applies at all times. Water management zone-specific target.
Canterbury Natural Resources Regional Plan (2010); Canterbury Land & Water Regional Plan (2014)	Temperature (max daily)	20 °C	This is an objective, rather than a limit or standard
	Temperature (change)	2 °C	Standard, applicable to consented activities

Source	Parameter	Standard	Comment
Waikato Regional Plan (2007)	Temperature (change)	3 °C	General "Surface Water Class". The Waikato Regional Plan also defines a number of narrative standards relative to changes in pH, water clarity, DO, deposited sediment and biological growths "if they have any significant adverse effects on aquatic ecosystems"
Ausseil 2013a recommendations to Greater Wellington Regional Council	Temperature (daily max)	19 °C to 23 °C	Applies at all times. FWENZ class dependent.
	Temperature change	±2 °C to ±3 °C	Applies at all times. FWENZ class dependent.
Davies-Colley *et al.* 2013 NOF proposed thresholds (Rivers in Eastern Dry Climates)	Temperature (Cox-Rutherford Index[2])	≤ 19 °C Band A ≤ 21 °C Band B ≤ 25 °C Band C >25 °C Band D	Summer period measurement of the Cox-Rutherford Index (CRI), averaged over the five (5) hottest days (from inspection of a continuous temperature record). Band A no thermal stress, Band B occasional thermal stress, particularly for sensitive species, Band C some thermal stress on occasions, with risk of sensitive species being lost Band D significant stress, loss of ecological integrity

3. OBSERVED WATER TEMPERATURE PATTERNS

Several sources of water temperature and flow data were explored in the analyses in the following section (Figure 4). These included:

- Data detailing the operation of the back-feed including: which intake valve in the reservoir back-feed water was drawn from, back-feed flow rates, and water temperatures in the back-feed and the South Branch both upstream and downstream of the back-feed; as well as flow data for the Maitai Forks recorder site. These data were provided by Alex Miller (NCC),
- Records from seven water temperature loggers deployed by Cawthron (from December 2014 to May 2015) in the Maitai River, between 100 m downstream of the back-feed and immediately downstream of the Maitai campground.
- Data from the thermistor chain deployed by Cawthron in the reservoir, providing water temperature at 3 m, 6 m, 15 m, and 24 m depths within the reservoir.
- Flow data for the Maitai South Branch upstream of the water supply weir and for the Maitai Forks recorder site, provided by Martin Doyle (Tasman District Council).

[2] The average of the mean daily and daily maximum temperatures is a valuable metric because it permits direct application of constant temperature criteria from laboratory experiments. Animals respond to diurnally fluctuating temperatures in much the same way as if exposed to a constant temperature equal to the CRI.

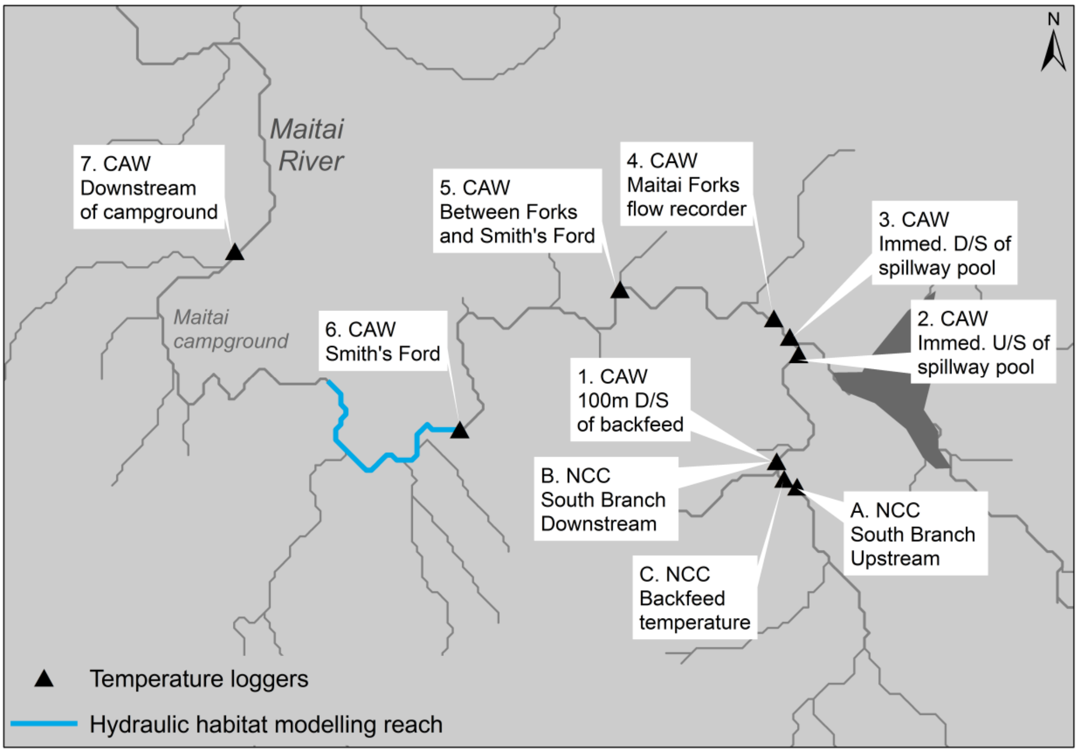

Figure 4. The upper Maitai River catchment, showing the locations of temperature loggers used in this study, as well as the location of the hydraulic modelling reach used for temperature modelling.

3.1. Back-feed operation

Temperature monitoring data show that the water temperature consent conditions were met most of the time during this summer (2014/15). Water temperature downstream of the back-feed discharge was kept within the maximum and minimum thresholds of 6 °C and 20 °C as stipulated in consent conditions (Figure 5). This was despite temperatures in the South Branch upstream of the weir briefly exceeding 20 °C naturally, during a warm period in late January 2015.

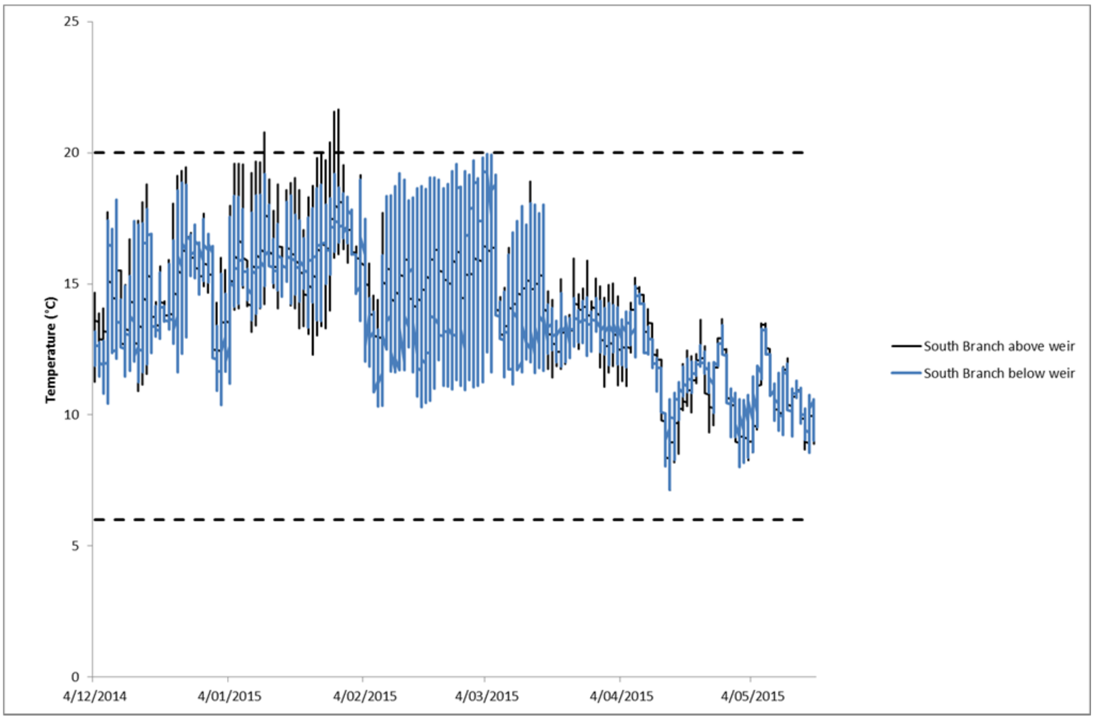

Figure 5. Time series of the water temperature in the Maitai South Branch upstream and downstream of the back-feed discharge, at the South Branch weir. Dashed horizontal lines indicate the maximum and minimum permissible temperature thresholds of 6 °C and 20 °C stipulated in consent conditions.

The condition stipulating no more than a 3 °C change in river water temperature downstream, compared to upstream, of the South Branch intake weir was also complied with for more than 99% of the time (Figure 6). There were several brief periods of non-compliance with this condition, mainly excessive cooling during summer, switching to mainly excessive warming during autumn.

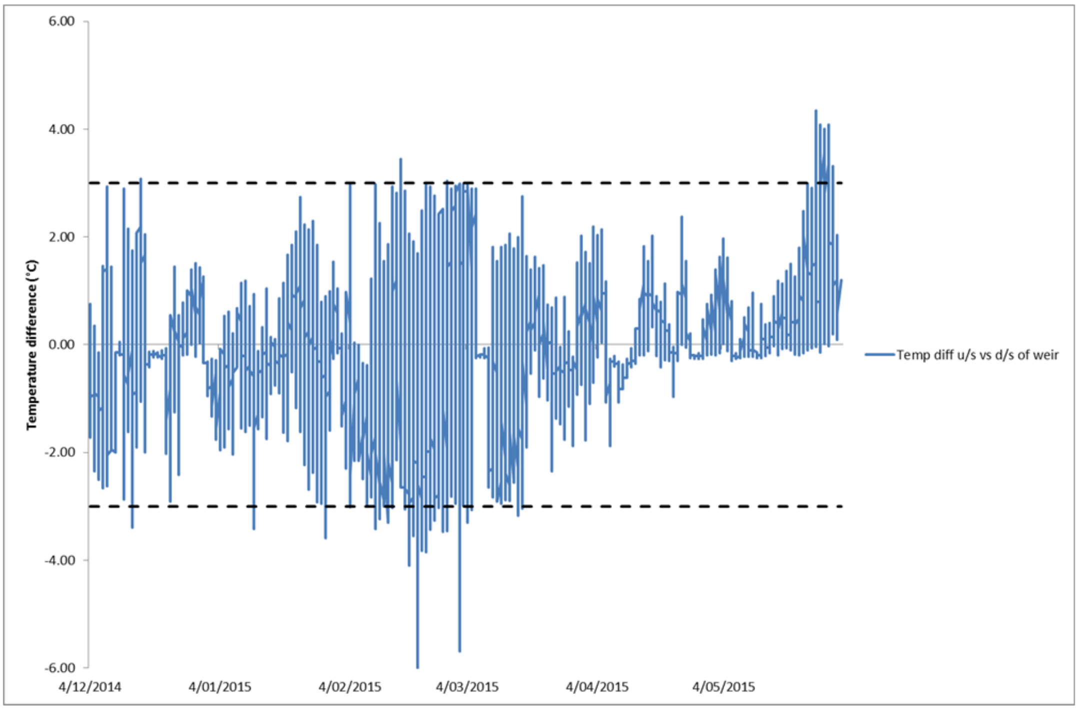

Figure 6. Time series of the difference in water temperature in the Maitai South Branch upstream versus downstream of the back-feed discharge, at the South Branch weir. Negative values indicate downstream is cooler than upstream. Dashed horizontal lines indicate the threshold maximum permissible temperature change of 3 °C stipulated in consent conditions.

However, while the operation of the back-feed largely complied with the temperature related consent conditions, for much of the summer the back-feed discharge was sourced from the lower levels of the reservoir, potentially contributing to adverse effects on the river. Figure 7 shows where in the reservoir the back-feed water was sourced from, as well as the water temperatures at the three intake levels compared with that in the South Branch upstream of the weir. This figure indicates that for most of the summer (from 2 February 2015 onward) back-feed water was sourced either from a combination of the upper intake and the scour valve, or from the scour valve alone (from early April 2015 onward). This resulted in anoxic scour water from the bottom of the dam being discharged for much of the summer, with potential adverse effects on the river ecology as well as adverse aesthetic effects (including reddish-brown flocculate on the stream bed and an objectionable smell of hydrogen sulphide at times [pers. obs.]).

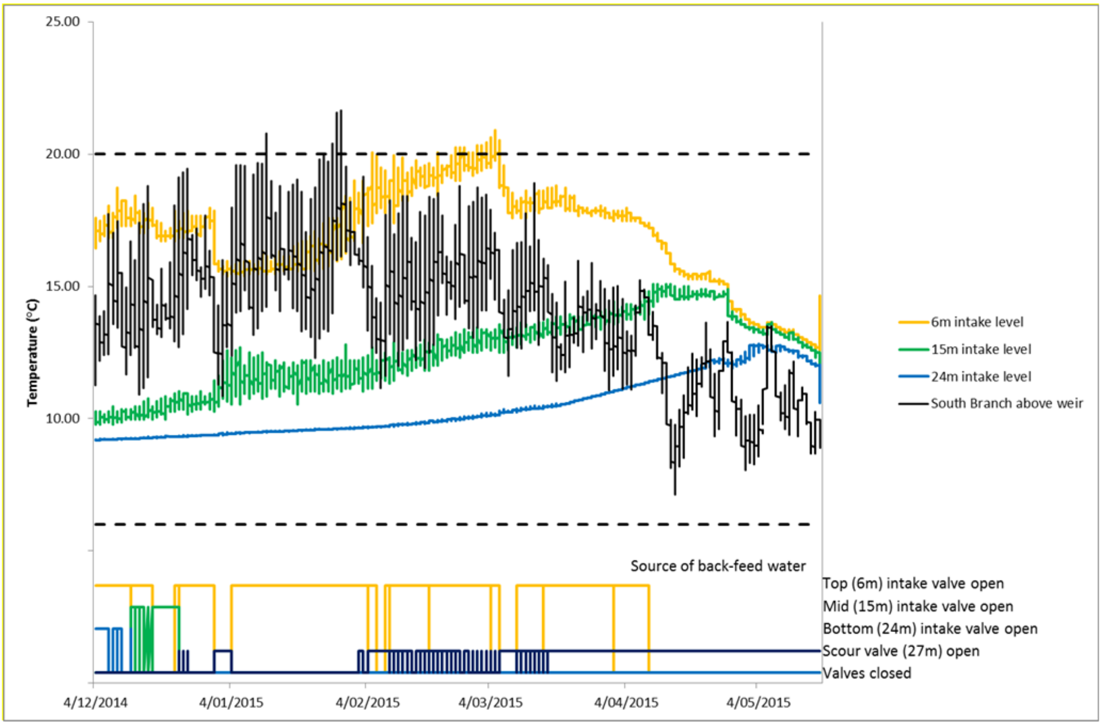

Figure 7. Time series of the water temperature in the Maitai South Branch upstream of the back-feed discharge, at the South Branch weir, compared with that at the three intake valves in the Maitai Reservoir. Dashed horizontal lines indicate the maximum and minimum permissible temperature thresholds of 6 °C and 20 °C stipulated in consent conditions. Time series at the bottom of the figure shows which valves the back-feed water was being sourced from.

While this approach achieved compliance with the water temperature consent conditions, it does not appear to be consistent with the intent of consent conditions governing the timing of scour water discharge. Conditions governing the discharge of scour water from the reservoir[3] state that "*Other than in emergencies, the discharge of scour water shall only occur when the river is in fresh and naturally discoloured...*" This condition appears to recognise the potential for adverse effects if scour water is released under base-flow conditions. There were some fresh events during the summer (Figure 8), but for most of the time the flow was reasonably stable and low. Consequently, under this condition scour water should not have been discharged from the reservoir for the majority of this period. However, as it is written, this condition does not seem to explicitly apply to discharge of scour water via the back-feed. Therefore, the routine discharge of scour water via the back-feed does not appear to be prohibited, despite potential adverse effects.

[3] Consent No: RM025151/3 (Ex-Water Right No: 820510) Condition 2.

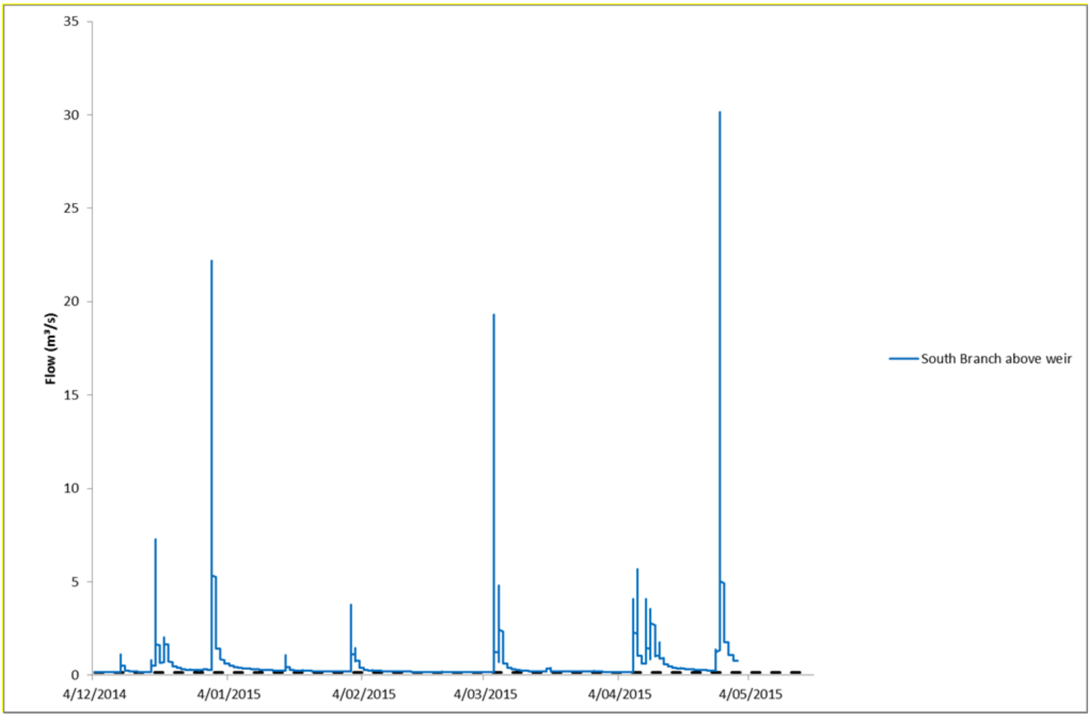

Figure 8. Hydrograph showing flow in the Maitai South Branch upstream of the water supply weir for summer 2014/15. The dashed black line indicates the seven day mean annual low flow (7 day MALF) for this site of approximately 0.16 m^3/s.

It was not necessary to source back-feed discharge water from the scour valve in order to comply with the 20 °C maximum temperature threshold. As shown in Figure 7, water temperatures at the level of the upper intake valve in the reservoir were less than the 20 °C threshold almost all summer, and the temperature at the middle and bottom intake valves was constantly within the permissible temperature range.

Neither was discharge of this scour water necessary to achieve compliance with consent conditions governing permissible temperature change in the South Branch below the weir, compared with upstream of the weir. Figure 9 is similar to Figure 7, but it shows the difference between the water temperatures at each of the three reservoir intake levels compared with those of the South Branch upstream of the weir. Figure 9 suggests that to comply with the 3 °C maximum change in water temperature below the back-feed it would have been possible to draw water from a combination of the upper and middle intakes for most of the summer, at least up until early April 2015.

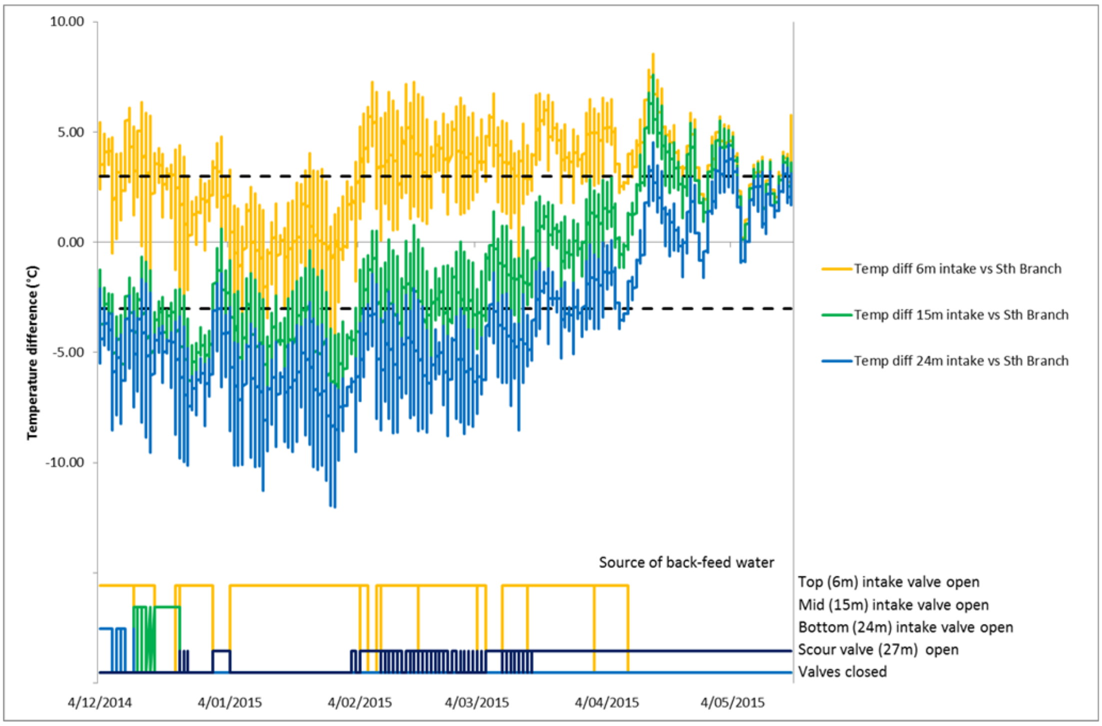

Figure 9. Time series of the difference in water temperature in the Maitai South Branch upstream of the back-feed discharge, at the South Branch weir, compared with the three intake valves in the Maitai Reservoir. Negative values indicate the intake valve level is cooler than the South Branch upstream of the weir. Dashed horizontal lines indicate the threshold maximum permissible temperature change of 3 °C stipulated in consent conditions. Time series at the bottom of the figure shows which valves the back-feed water was being sourced from.

It is worth noting that discharging water from the back-feed that is more than 3 °C different from the ambient water temperature in the South Branch would not necessarily result in a breach of the 3 °C maximum allowable temperature change condition, since the rate of discharge relative to the South Branch flow passing over the weir would also influence the resultant water temperature following mixing. The resultant temperature from mixing two volumes of water of different temperatures can be calculated by the following formula:

Equation 1. Calculation of the resultant temperature from mixing two volumes of water of differing temperatures.

$$T_{final} = \frac{m_1(T_1) + m_2\,(T_2)}{m_1 + \,m_2}$$

Where:

m_1 and m_2 are the masses of the respective volumes of water to be mixed, with temperatures of T_1 and T_2. Although the density of water changes with temperature, over the range of temperatures considered here this density change is negligible and consequently, mass is taken to be equivalent to volume.

After early April 2015, even water taken from the bottom intake would have been more than 3 °C warmer than the South Branch (Figure 9), potentially constraining the volume of water that could be discharged via the back-feed during this period. Water released from the scour valve would have been a similar temperature to that at the 24 m bottom intake valve during this period. Consequently, releasing water from the scour valve would also breach the 3 °C temperature change condition during this period. In fact, this appears to have happened some of the time (Figure 6).

Kelly (2014) suggested that the greatest potential warming effect of sourcing back-feed water from the upper valve would probably occur immediately after floods, due to substantial declines in river temperature at these times. However, the back-feed discharge tends to be reduced during high flow events (although scour water is sometimes still released), presumably because water for municipal supply is being sourced from the reservoir at these times to avoid elevated suspended sediment loads in the river. Furthermore, increased river discharge rates during these events are likely to overwhelm any temperature influence from the back-feed. For example, following a fresh event on 6 March 2015 water temperature in the South Branch fell to about 11.7 °C (on 8 March 2015), while the temperature at the 6 m reservoir intake level remained at about 18.4 °C, producing a potential 6.7 °C temperature difference. However, the discharge in the South Branch at this time was about 1.233 m^3/s, while the back-feed discharge was only 0.163 m^3/s. Consequently, based on Equation 1[4], even if the entire back-feed discharge had been sourced from the 6m intake valve the temperature below the back-feed would have been only 12.6 °C (*i.e.* 0.9 °C warmer than upstream). If the back-feed discharge had been higher at the time, say 0.317[5] m^3/s (which was the maximum back-feed discharge during summer 2014/15) the resulting temperature downstream of the back-feed would still be only 13.4 °C (*i.e.* 1.7 °C warmer than upstream).

Another factor to take into consideration with sourcing of back-feed water is the dissolved oxygen status of water at the 15 m (middle intake) level. In early February, when water temperatures at the level of the 6 m (top) intake began to exceed South Branch temperatures by more than 3 °C (Figure 9), the cooler water at the 15 m level was still at about 50% DO saturation. However, DO levels continued to track down over time. By early April it would have been about 13% saturation at the 15 m intake level, and remained low until the thermal stratification of the reservoir broke down in early May. Nevertheless DO levels at the middle intake level were consistently higher than the scour water that was being released during this period, with the bottom water

[4] These calculations assume that a volume equal to the back-feed discharge was being abstracted at the weir, i.e. the South Branch flow contribution to flow below the weir was reduced by a volume equivalent to the back-feed, before the back-feed water was added to it.

[5] The maximum rate of discharge from the back-feed is nominally 0.3 m^3/s, and equal to the consented abstraction from the South Branch, source (Alex Millar, NCC, pers. comm.).

of the reservoir having been completely anoxic since January. Furthermore, by sourcing back-feed water from a mix of the upper and middle intake valves the, low DO and potentially low water quality of water sourced from the middle intake would be mitigated by dilution with the well oxygenated water from the upper intake.

These observations raise the obvious question, why was poor quality water being discharged from the scour valve during this period, when this was not necessary in order to comply with water temperature consent conditions? One possible reason for discharging from the scour valve would be to prevent sediment from building up in the vicinity of the valve. However, this is unlikely to occur during periods of low flow, when sediment inputs to the reservoir would be low. Periodic opening of the scour valve during high flow events, as provided for in consent conditions, ought to be sufficient to keep the valve clear of sediment.

Another possible reason for sourcing water from the scour valve could be a lack of knowledge of the temperatures at each intake level. Without information on water temperatures at each intake level it may be tempting to simply use a mix of top and scour valves (*i.e.* the warmest and coldest water available to you) to attempt to match temperatures in the river. This issue could easily be addressed by installing water temperature sensors at each intake level. With real time data from these sensors, along with data that is already collected (*e.g.* South Branch flow and temperature, abstraction rate at the weir and required back-feed discharge rate), it would be a relatively simple task to derive an algorithm based on Equation 1 (above) that would calculate the mix of water from the intake valves required to match the temperature in the South Branch. Sourcing water from the top and middle valves could be prioritised over the summer, to avoid releasing the low quality anoxic bottom water during thermal stratification events. The temperature of water discharged from the back-feed may also be moderated to some extent by heat exchange with the ground, during transit through the back-feed pipe (which is predominantly underground). The magnitude of any such effect could be determined empirically and used to adjust the algorithm suggested above, if necessary.

Discharge of this poor quality scour water from the lower reservoir levels has been implicated in the observed adverse ecological impacts in the river (Allen *et al.* 2013, Allen *et al*. 2014), as well as adverse aesthetic impacts (Kelly 2014 and pers. obs.). Most of these adverse effects could potentially be avoided by sourcing water from the upper and middle intake valves. Furthermore, this could be done without breaching existing temperature related consent conditions. Sourcing back-feed water from the scour valve when the river is not in fresh, as is currently done, appears to be inconsistent with the intent of consent conditions governing the discharge of scour water. Consent conditions governing operation of the back-feed provide for the consent authority to review the conditions in light of any adverse effect on the environment arising from exercise of the consent, or new information suggesting that an adverse effect on the environment is likely to occur[6]. Given the adverse effects on the environment downstream of the back-feed discharge observed through routine monitoring (*e.g.* Allen *et al.* 2013, Allen *et al*. 2014), there appears to be justification for initiating such a review. It is highly likely that the routine discharge of scour water via the back-feed is contributing to the adverse effects observed, and this practice seems inconsistent with the intent of conditions governing release of scour water from the reservoir. Consequently, we suggest NCC should seek legal advice on interpretation of these conditions and either initiate a review of consent conditions, or review operational procedures around where back-feed water is sourced within the reservoir and when it is discharged into the Maitai River.

3.2. Water temperature downstream of the weir

3.2.1. Back-feed to spillway

As discussed above, water temperature below the South Branch weir during summer 2014/15 was consistently maintained below the 20 °C maximum threshold and mostly within the 3 °C maximum permissible temperature change (relative to upstream of the weir) stipulated in consent conditions. Despite this, water temperature increases quite rapidly downstream during warm periods in summer, with daily maxima in the stress range for many aquatic fauna at sites downstream (*e.g.* up to 26.4 °C at the Maitai Campground site).

The initial rate of warming was sometimes rapid in the reach of river between the back-feed discharges and immediately upstream of the spillway. Daily average temperatures over December, January and February were on average 0.6 °C warmer immediately upstream of the spillway discharge compared with the site 100m downstream of the back-feed. However, daily maximum temperatures frequently increased by 1.5-2 °C (or more) between these sites during December and January, and again in late March. Consequently, daily maximum temperatures immediately upstream of the spillway discharge were often above 20 °C throughout much of the settled fine weather period in January 2015 (Figure 10). Daily maximum temperatures downstream of the spillway discharge pool were often another 1.5-2 °C warmer during this period, regardless of whether the spillway was discharging. Similar rates of warming through this reach were recorded in spot measurements reported by Allen *et al.* 2014 (see their table 4).

[6] Consent No. 960396 Condition 3.

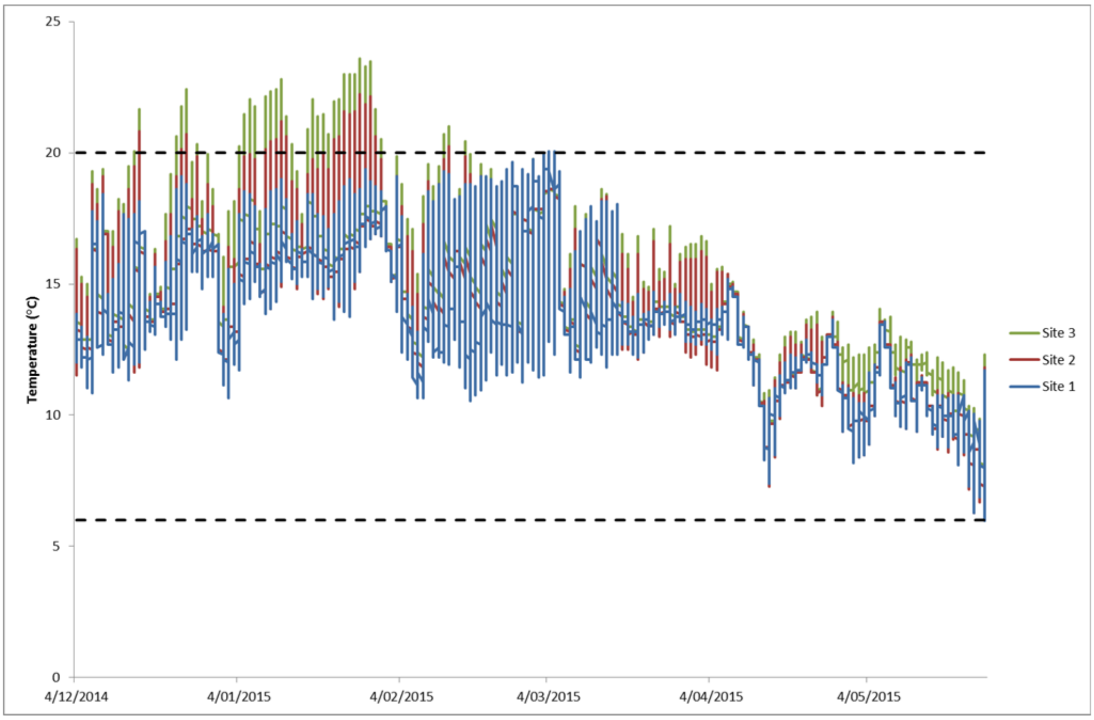

Figure 10. Time series of the water temperature in the Maitai at three sites in the vicinity of the Maitai Dam: 100 m downstream of the back-feed discharge (Site 1), immediately upstream and downstream of the spillway discharge pool (Site 2 and Site 3, respectively). Dashed horizontal lines indicate the maximum and minimum permissible temperature change thresholds of 6 °C and 20 °C stipulated in consent conditions.

The existing consent conditions stipulate that water temperature conditions should be monitored and met at 'Site B' (a monitoring site approximately 200 m upstream of the spillway discharge pool). However, water temperatures are actually monitored approximately 100 m downstream of the back-feed discharge instead (*i.e.* approximately 1.2 km upstream of 'Site B'). Monitoring temperature at 'Site B' would make it difficult to assess whether temperature breaches (i.e. temperatures differences downstream of the back-feed, relative to those upstream, exceeding consented thresholds) are caused by the back-feed discharge or by natural warming (or cooling) through this reach. This clause should be re-examined during the next consent review.

3.2.2. Spillway influence

Notwithstanding the consent conditions controlling the temperature of water released via the back-feed, discharge of surface water via the spillway theoretically provides an uncontrolled release of warm surface water. Intuitively, this has the potential to increase water temperatures below the spillway by more than the 3 °C maximum change allowed in consent conditions. While this did not occur during the period of monitoring (4 December 2014 to 26 May 2015), data from the temperature loggers upstream and downstream of the spillway discharge pool do illustrate the potential for this discharge to enhance warming of the river water (Figure 11). The step up in water temperature downstream of the spillway discharge pool is clearly evident in the longitudinal profiles of average daily temperatures recorded through this reach. As mentioned above this warming influence occurs even when the spillway is not operating (presumably because warm surface water from the plunge pool below the spillway is entrained into the river flow), although it is more pronounced when the spillway is operating (as it was in the temperature profiles for 29 December 2014, 29 April and 25 May 2015 depicted on this figure).

The maximum water temperature difference between the loggers upstream and downstream of the spillway discharge pool, for periods when the spillway was operating, was 2.87 °C[7], compared with 1.82 °C when it was not. On average the temperature downstream of the spillway discharge pool was 1.11 °C warmer than that immediately upstream during periods when the spillway was operating, compared with 0.28 °C when it was not.

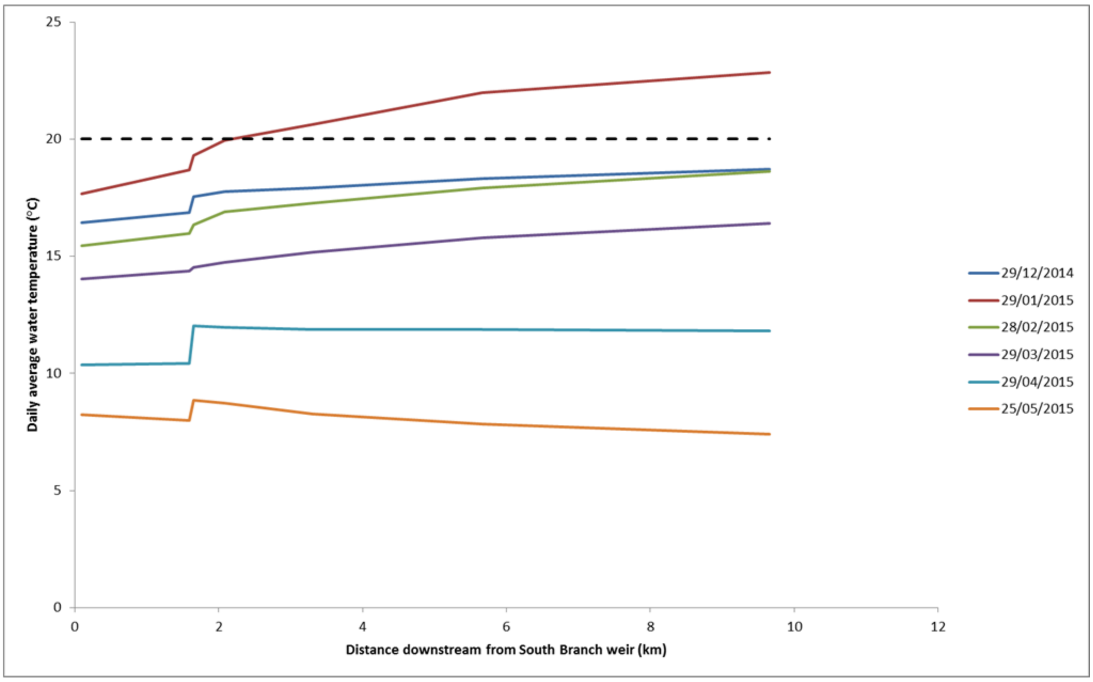

Figure 11. Daily temperatures records from seven temperature loggers located sequentially down the upper Maitai River, below the South Branch water supply weir, for six selected days over the summer of 2014/15. Dashed horizontal line indicates the maximum permissible temperature threshold of 20 °C stipulated in consent conditions.

The spillway was not spilling for a large proportion of the summer (Figure 12), so it is possible that its influence could be greater in years when the spillway flows more consistently.

[7] This occurred during a high flow event on 3 Jan 2015.

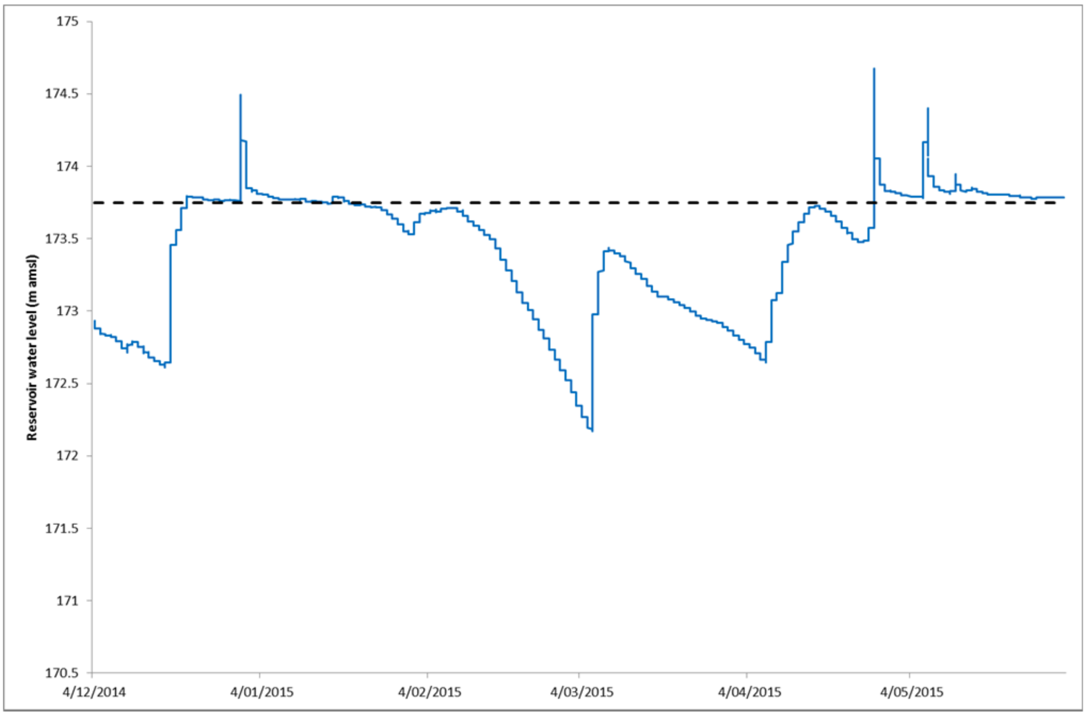

Figure 12. Time series of variation in the Maitai Reservoir water level during summer 2014/15, with the dashed horizontal line indicating the level of the spillway crest (*i.e*. the level above which water would begin to flow down the spillway).

3.2.3. Downstream of the spillway

Below the spillway discharge pool, water temperature generally continued to increase gradually downstream, over the December to March period (Figure 11), at least as far downstream as the lowest logger site, below the Maitai campground.

Later in the season the temperature was either stable downstream or even declined slightly (Figure 11). During this latter period it appears discharges from the back-feed and/or the dam spillway had elevated the river temperature above equilibrium with the atmosphere and stream bed. Consequently, the river was losing heat as it travelled downstream, although the influence of cooler tributaries may also have contributed to this pattern.

3.2.4. Comparison with ecological temperature criteria

As shown in Figure 11, the water temperature can enter the stress range for many species during warm periods in summer (see temperature profile for 29 January 2015). As discussed in section 2.6, sensitive species are likely to experience stress as temperatures exceed about 19-20 °C. The temperature profiles depicted in Figure 11 are daily average values. Recorded daily maximum temperatures were higher still, and at times were in the lethal range for some species.

Table 2 shows average Cox-Rutherford index values (average of the daily mean and daily maximum) for the five hottest days during the summer (hottest water temperatures were recorded 24-29 Jan 2015). These values can be compared with the temperature limits recommended by Davies-Colley *et al.* (2013) for the NOF. This shows that, although the back-feed discharge does not increase temperatures above 20 °C, or alter ambient river temperature by more than the 3 °C (as required by consent conditions), rapid warming downstream means that river water temperatures soon exceed recommended limits for pristine sites regardless of the influence of the discharge. The Cox-Rutherford index value for the site 100 m downstream of the back-feed places this site in the A band (< 19 °C). However, by the time water reaches the spillway discharge pool (only ~1.6 km downstream of the back-feed) it is already in the suggested B band range (19-21 °C), and by the flow recorder site (a further 400 m downstream) it also exceeds the limit for this band. Thus, from this point on downstream the Maitai River would be placed in the suggested C band, which is expected to experience "*some thermal stress on occasion, with elimination of certain sensitive insects and absence of certain sensitive fish*". Table 2 includes data as far downstream as the Maitai Campground only. It is probable that Cox-Rutherford Index scores for sites further downstream would be higher still, and possibly even enter the D band (≥ 25 °C), with expected "*significant stress, loss of ecological integrity*".

Table 2. Cox-Rutherford Index values for seven locations located sequentially down the Maitai River below the South Branch water supply weir. Cox-Rutherford index values are calculated as the average of the daily means and maxima for the five hottest days of summer.

Site	Distance below Sth Branch weir (km)	Location	Cox-Rutherford Index (24-29 Jan 2015)
Site 1	0.1	100m d/s Back-feed	17.92
Site 2	1.59	Immediately u/s spillway pool	19.86
Site 3	1.65	Immediately d/s spillway pool	20.87
Site 4	2.08	Flow recorder site	21.82
Site 5	3.31	Btwn Flow recorder & Smith's Ford	21.78
Site 6	5.66	Smith's Ford	22.95
Site 7	9.66	d/s Campground	23.51

These ecologically stressful temperatures during January were not caused by the operation of the back-feed. Rather they occurred despite the back-feed being operated in accordance with consent conditions. At this time the back-feed water was being sourced exclusively from the top (6 m) intake valve (Figure 9). The water from this level was well within the 20 °C maximum temperature threshold, averaging 17.8 °C (24-29 January). On average it was slightly more than 3 °C warmer than the South Branch above the weir (which averaged 13.9 °C, over the same period). However, release of this water through the back-feed did not breach the 3 °C maximum temperature change consent condition (Figure 6). As discussed in section 3.1, if the water temperature at this level had been warmer, water would have been able to be sourced from the middle or bottom intake levels.

During this period in late January the spillway was not operating. If it had been, the temperature increase downstream of the spillway pool may have been slightly more pronounced. The temperature of the surface water (3 m depth) of the reservoir during this time averaged about 21 °C. However, the overall pattern is likely to have remained similar.

3.2.5. Potential ecological importance of thermal refugia

As discussed in section 2.6 there is a reasonably sound basis for the 20 °C maximum water temperature threshold in consent conditions. As water temperatures increase above this level they begin to enter the stress range for sensitive aquatic organisms. It may seem that the 20 °C maximum threshold downstream of the back-feed discharge is somewhat irrelevant, since water temperatures already exceed this threshold further downstream, despite the operation of the back-feed complying with conditions. However, while the water temperature may be maintained below this threshold for a relatively short length of river during hot periods in summer, this section of the river may be important to maintaining aquatic populations in the wider catchment.

While most aquatic fauna are cold-blooded and, consequently, ambient water temperatures directly influence their body temperatures, they can nevertheless influence their body temperature through behaviour. Mobile organisms can thermoregulate by selecting areas with suitable temperatures. For behavioural thermoregulation to be effective, the environment must vary thermally at an appropriate scale. Longitudinal changes in water temperature, due to altitude or differences in shading, may offer thermal refuge habitat for mobile species during periods of thermal stress, although this may require large-scale migration to reach these refuges. Whilst such migrations do occur, smaller-scale thermal heterogeneity may also provide resident fish with the opportunity to behaviourally thermoregulate without the large energetic investment and risk associated with long-distance migrations. Sources of such smaller-scale heterogeneity include tributary inflows and groundwater inputs (such as springs) (*e.g.* Olsen & Young 2009), as well as thermal stratification in lakes. Some macroinvertebrates may also be able to take refuge in the hyporheic zone.

It is possible that the cooler water of the South Branch could provide a thermal refuge for mobile species, such as fish, during periods when the lower Maitai River experiences high water temperatures. There is little monitoring data available to reveal whether this may occur, since biological monitoring in the vicinity of the dam usually occurs during spring and autumn. However, a longitudinal study downstream of the back-feed discharge during February 2014 reported higher densities of eels and trout in the reach immediately below the back-feed than further downstream (Allen *et* *al.* 2014). Spot water temperatures recorded during that study were approaching 20 °C at the most downstream sites, but were cooler (~14-16 °C) upstream of the spillway discharge pool.

The South Branch upstream of the weir also has the potential to provide thermal refuge habitat. However, notwithstanding recent fish passage remediation work, the weir is likely to present an impediment to passage for fish attempting to access this habitat during low flow periods (Doehring and Hay 2014, Hay *et al.* 2015).

It is possible to predict the potential impact of releasing warmer water from the reservoir on water temperature profiles downstream, and how this influences the extent of the thermal refuge that may be provided for mobile aquatic organisms. The following section explores some alternative scenarios with reach scale water temperature modelling.

4. MODELLED WATER TEMPERATURE PATTERNS

The software package SEFA (System for Environmental Flow Analysis; I Jowett, B Milhous, T Payne, JM Diez Hernández; www.sefa.co.nz) has a module for predicting longitudinal profiles of daily mean and maximum water temperatures down a modelled reach, over a specified flow range. This module builds on the temperature modelling capability previously available in RHYHABSIM (River Hydraulics and Habitat SIMulation; Jowett Consulting).

The model is a mechanistic, one-dimensional heat transport model that predicts the daily mean and maximum water temperatures as a function of stream distance and environmental heat flux. Net heat flux is calculated on the basis of heat gain or loss through long-wave atmospheric radiation, direct short-wave solar radiation, convection, conduction, evaporation, accounting for streamside vegetation (shading), streambed fluid friction, and back radiation from the water to the atmosphere. The heat flux model can also account for groundwater influx. Water flowing downstream will increase or decrease in temperature until the incoming radiation equals the heat lost from the river through radiation and evaporation. The temperature at which incoming energy equals the outgoing energy, resulting in no further increase in water temperature, is known as the equilibrium temperature.

There are two calculation options available within the module. The Lagrangian heat transport model tracks heat and water fluxes downstream, based on the differential heat balance equations described in Rutherford *et al.* (1997), whereas the Theurer model uses numerical solutions to the heat flux and transport equations as described in Theurer *et al.* (1987).

This temperature modelling module was used to predict water temperatures in the upper Maitai River for alternative scenarios of back-feed discharge temperature.

4.1. Temperature modelling methods

Input data for the temperature model were sourced from the water temperature and discharge data recorded from the Maitai in the vicinity of the dam along with meteorological data from local weather and air quality monitoring stations (Appendix 1).

The hydraulic modelling dataset originally produced by Hayes (2003) to model physical instream habitat in the vicinity of Smith's Ford was used for this modelling. This dataset was imported from RHYHABSIM. The field data collection methods and data checking procedures are described by Hayes (2003). This dataset was primarily collected to assess minimum flow requirements, and the data were collected over a relatively low flow range (0.404 m^3/s – 0.503 m^3/s in the Smith's Ford reach *c.f.* median flow at the Maitai Forks recorder site of 0.524 m^3/s, equivalent to 0.527 m^3/s in the Smith's Ford reach). Consequently, this data set should be fairly well suited to modelling temperature in the low flow range. The channel profile in this modelled reach ought to be representative of the Maitai River channel at least as far upstream as the spillway discharge. It may not be as representative of the channel upstream of the spillway pool, since the channel forming flood flows experienced in the South Branch will be smaller in magnitude than those in the modelled reach downstream of the spillway discharge. Also the topographic shading characteristics differ between these sub-reaches, with the lower South Branch valley oriented relatively North-South, while most of the rest of the modelled reach has a predominantly East-West orientation. However, the South Branch comprises a relatively small proportion of the overall modelled reach (*i.e* ~1.6 km of ~9.6 km modelled), and the model reproduced observed longitudinal temperature profiles downstream reasonably well, see below.

The model was calibrated by manipulating the shade, wind speed and bed conductivity parameters to optimise predictions of mean and maximum water temperature relative to observed data at a given location downstream (*i.e.* minimise the root-mean-squared error of prediction of these two parameters). The recorded daily mean and maximum water temperature downstream of the South Branch weir were used as input for the top of the reach, while data from the Smith's Ford temperature logger (approximately 5.66 km downstream of the South Branch weir) were used as input for the bottom of the reach during calibration. The time of maximum daily air temperature was also adjusted to improve the prediction of maximum water temperatures.

Calibration was undertaken to represent two periods:

1. The hot period with maximum recorded river temperatures in the South Branch, in late January 2015. Represented by daily averages for 29 January 2015.
2. The period with maximum differences between temperatures recorded in the South Branch and reservoir temperatures at the 6 m (top) intake level, in mid-April 2015. Represented by daily averages for 15 April 2015.

Model calibration was undertaken using both the Lagrangian and Theurer calculation methods. Both approaches reproduced observed patterns of mean daily water temperature reasonably well (generally within about 0.3 °C). Unfortunately, the Lagrangian calculation method, as currently implemented in SEFA, has a computation instability which affects predictions of daily maximum temperatures for the first few km downstream. (*e.g*. Figure 13). While this may not be a problem for some applications, it is these first few km downstream that are of most interest in this study. Consequently, only modelling results from the Theurer calculation method are shown below. Although these results tend to underestimate daily maximum temperatures (*e.g.* Figure 13), they still provide a basis for comparison of the influence downstream of varying the temperature of the back-feed.

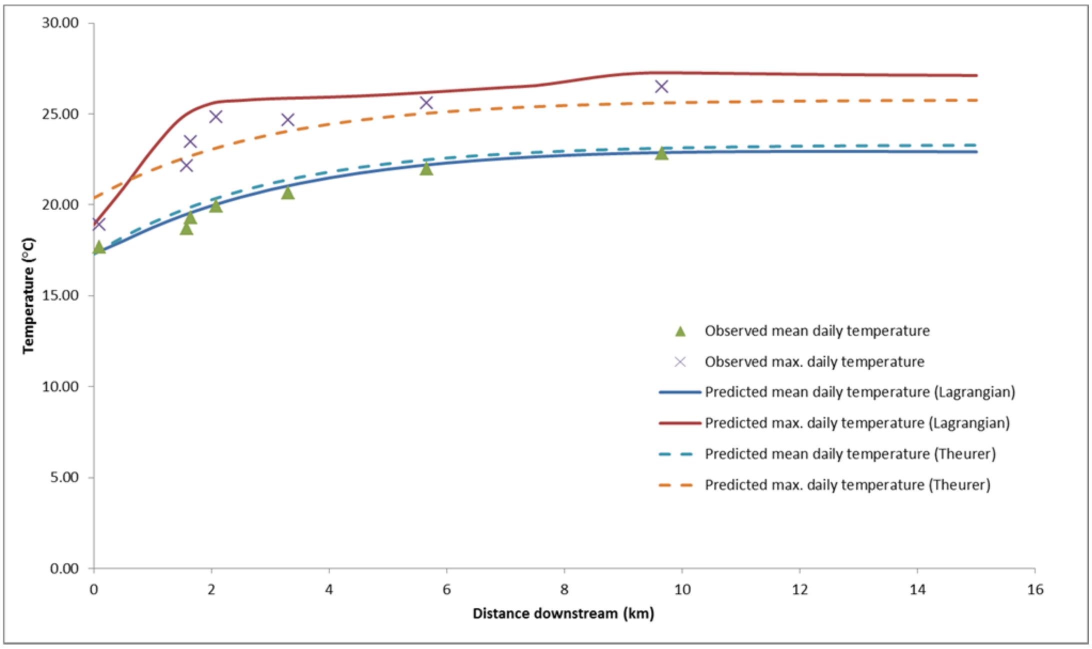

Figure 13. Observed and modelled longitudinal water temperature profiles downstream of the Maitai water supply weir on the South Branch for the 29 January 2015, using two alternative calculation methods (described in the text).

4.2. Temperature modelling results and discussion

The influence of releasing water of different temperatures from the back-feed was modelled by calculating the temperature downstream of the back-feed for a given back-feed temperature and discharge rate, and a given South Branch temperature and discharge rate (using Equation 1 shown in section 3.1). The combined temperature and discharge were then used to initiate the reach model, along with the same meteorological and reach parameters used in the calibration process.

4.2.1. Influence of varying back-feed temperature during peak summer river temperatures

Figure 14 shows model predictions of longitudinal water temperature profiles for three back-feed source temperature scenarios, during the period of maximum recorded water temperature in the Maitai River over the summer of 2014/15.

The first scenario used the actual back-feed discharge temperature on 29 January 2015 (mean = 17.1 °C, max = 18.1 °C).

The second scenario assumed a constant back-feed discharge temperature on that day of 22 °C. This is 1.1 °C warmer than the maximum temperature recorded at the 6m (top) intake level in the reservoir during the 2014/15 summer, and is equivalent to the maximum temperature recorded at the 3 m (surface) level. This was intended to illustrate an extreme worst case scenario of releasing warm water from the top intake.

The third scenario assumes back-feed water was being sourced from the middle (15 m) intake from the reservoir, and uses the mean and maximum temperatures recorded at that level in the reservoir on 29 January 2015 (13.1 °C and 14.3 °C, respectively). This was intended to illustrate the extent to which there is potential to mitigate temperature effects downstream by releasing cooler water from the middle intake.

The modelled flow was 0.260 m^3/s (based on the daily mean flow for that date at the Forks recorder), with 0.201 m^3/s of this coming from the back-feed discharge (based on the daily mean back-feed discharge rate for that date) and the balance (0.059 m^3/s) from the South Branch above the weir. The back-feed discharge rate on this date was relatively high, compared with the median and maximum over summer 2014/15 (0.151 m^3/s and 317 m^3/s, respectively). The spillway was not discharging on this date.

Figure 14 illustrates that although release of warmer water from the back feed would initially increase river water temperatures downstream, the magnitude of this effect diminishes with distance downstream, as equilibrium temperature is approached. Once equilibrium temperature is reached the back-feed discharge no longer influences temperatures further down the catchment. Likewise, the influence of releasing cooler water from the back-feed is most pronounced immediately below the discharge and diminishes downstream.

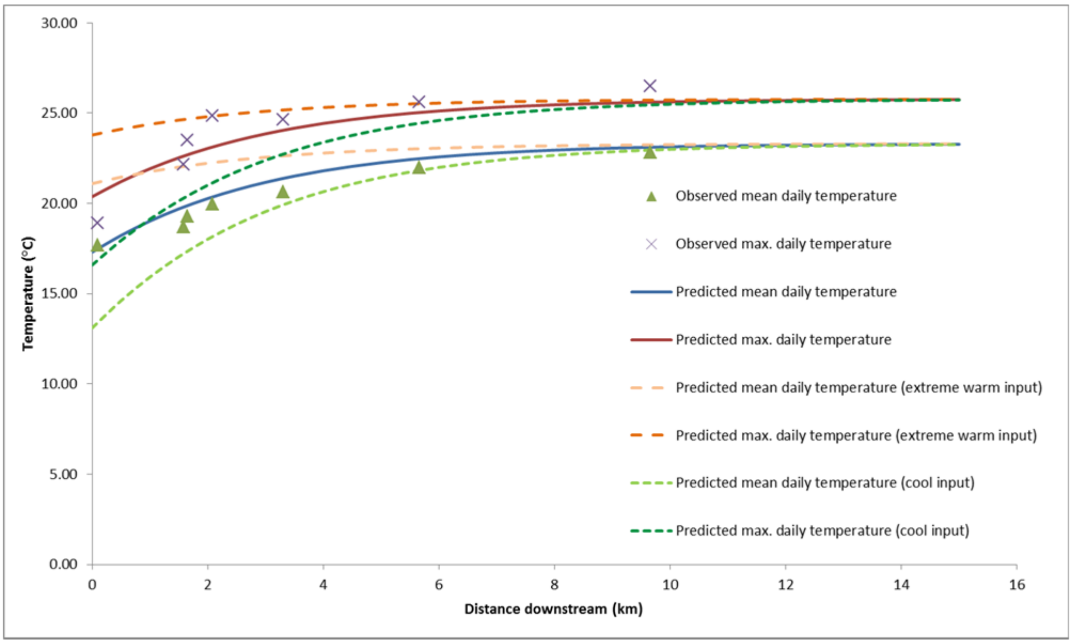

Figure 14. Observed and modelled longitudinal water temperature profiles downstream of the Maitai water supply weir on the South Branch for the 29 January 2015, for three alternative back-feed temperature scenarios: 1) the recorded back-feed temperatures for that date, 2) a warmer back-feed discharge based on the maximum recorded reservoir surface temperature for this summer (22 °C), and 3) a cool back-feed discharge based on recorded temperatures at the middle (15 m) reservoir intake level for that date.

The warm input scenario depicted in Figure 14 would represent non-compliance with existing consent conditions, since increasing river water temperatures above 20 °C is currently not permitted. As discussed in section 3.2.5, the section of river where this temperature guideline is complied with has the potential to act as a thermal refuge for sensitive species. The observed daily maxima in Figure 14 suggest that during this very warm period in late January the extent of this potential refuge habitat was in the order of only 1 km downstream of the back-feed. Under the warm input scenario this short section of potential refuge would be lost. Conversely, releasing cooler water from the back-feed (of the temperature recorded at the 15 m middle intake level) could lengthen the extent of this refuge habitat where daily maximum temperatures were below 20 °C by about 1km (from ~1 km out to ~2 km).

These scenarios demonstrate that while the influence of back-feed discharge on river water temperatures diminishes downstream, there may still be localised ecological effects in the first few km below the discharge. It should be remembered that these scenarios represent an extreme case of ambient river water temperatures. Daily maximum water temperatures over this extreme warm period of late January were in excess of 20 °C upstream of the South Branch weir, and the back-feed discharge was actually cooling the river slightly already. For most of the rest of the summer longitudinal daily average temperature profiles remained below 20 °C, at least as far downstream as the Maitai Camp (Figure 11), although daily maximum temperatures often exceeded this threshold for much of December to February, inclusive, from the Maitai Forks recorder site downstream.

However, the concept still holds that releasing warm water from the reservoir has the potential to reduce the length of river remaining below 20 °C, that potentially acts as a thermal refuge, while releasing cooler water can extend this potential refuge habitat. But releasing cooler water during reservoir stratification events comes with the risk of impacting water quality. Consequently, the situation remains a trade-off. However, as discussed in section 3.1, it should be feasible to closely match ambient river temperatures most of the time, if temperature sensors are installed at the intake valves, allowing calculation of the required mix of water from the upper and middle intake levels. This solution should minimise temperature alteration and reduce the potential for releasing poor quality, deoxygenated bottom water from the reservoir.

4.2.2. Influence of varying back-feed temperature during peak differences between reservoir surface temperatures and river temperatures

Figure 15 shows model predictions of longitudinal water temperature profiles for three back-feed source temperature scenarios, during the period of maximum recorded difference in water temperature between the 6 m (top) reservoir intake level and the Maitai South Branch over the summer of 2014/15. These scenarios illustrate the influence of releasing water from the back-feed that is warmer than the equilibrium temperature in the river. During this period the water available for discharge from the top and middle intake valves was warmer than the South Branch.

The first scenario used the actual back-feed discharge temperature on the 15 April 2015 (mean = 11.3 °C, max = 11.5 °C).

The second scenario assumes back-feed water was being sourced from the top (6 m) intake from the reservoir, and uses the mean and maximum temperatures recorded at that level in the reservoir on 15 April 2015 (15.7 °C and 15.86 °C, respectively).

The third scenario assumes a constant back-feed discharge temperature on that day of 22 °C[8].

The modelled flow was 0.510 m^3/s (based on the daily mean flow for that date at the Forks recorder), with 0.121 m^3/s of this coming from the back-feed discharge (based on the daily mean back-feed discharge rate for that date) and the balance (0.389 m^3/s) from the South Branch above the weir. The back-feed discharge rate on this date was relatively low, compared with the median and maximum over summer 2014/15 (0.151 m^3/s and 317 m^3/s, respectively). The spillway was not discharging on this date.

[8] As discussed above, this is 1.1 °C warmer than the maximum temperature recorded at the 6 m (top) intake level in the reservoir during the 2014/15 summer, and is equivalent to the maximum temperature recorded at the 3 m (surface) level

Figure 15 demonstrates that although release of warmer water would initially increase river water temperatures, the magnitude of this effect would diminish with distance downstream, as heat is lost from the river and equilibrium temperature is approached.

The low back-feed discharge rate, relative to the South Branch flow on this date, means that the temperature of the water released from the back-feed has only a moderate influence on river temperatures. This reinforces the point that both the volume and temperature of the back-feed, relative to the South Branch contribution, together control the degree of influence on temperatures downstream. Even the extreme worst case scenario of releasing 22 °C water from the back-feed (scenario three), would increase average daily temperatures immediately below the back-feed by only about 3.2 °C, with this ratio of back-feed to river discharge rates. However, the influence of this extreme scenario of warm back-feed input water was predicted to extend a considerable distance downstream. Under this scenario equilibrium temperatures had not been reached even by the most downstream temperature logger site (downstream of the Maitai Campground).

Sourcing back-feed water from the top (6 m) reservoir intake during this period would also have resulted in an increase in average daily temperatures immediately below the back-feed (compared with upstream) by only about 1.7 °C, and maximum daily temperature would be increased by about 1.4 °C. This relatively small influence on river water temperature was predicted to have attenuated substantially by the sixth temperature logger site, at Smiths Ford. It is possible that a slight warming of this section of river at this time could have increased productivity slightly, though this is not likely to have been a significant effect. Instead, back-feed water was being sourced from the scour valve on this date (as discussed in section 3.1), resulting in poor quality anoxic water being released into the river.

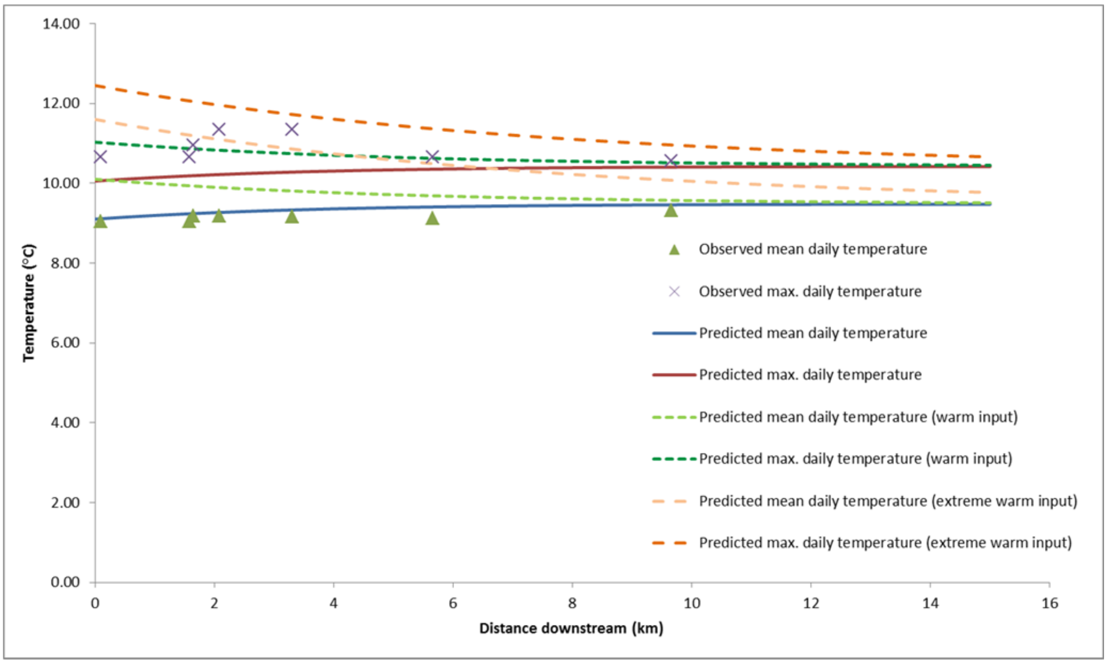

Figure 15. Observed and modelled longitudinal water temperature profiles downstream of the Maitai water supply weir on the South Branch for 15 April 2015, for three alternative back-feed temperature scenarios: 1) the recorded back-feed temperatures for that date, 2) a slightly warmer back-feed discharge based on recorded temperatures at the top (6 m) reservoir intake level for that date, and 3) a warmer back-feed discharge based on the maximum recorded reservoir surface temperature for this summer (22 °C).

Rates of warming or cooling downstream are also influenced by river discharge rates, with temperatures more rapidly reaching equilibrium during low flows. Consequently, the length of river where the temperature influence of the back-feed discharge is detectable will tend to be shorter during low river flows. Conversely though, the potential for the back-feed discharge to influence the temperature of the river is diminished at higher river flows, because it makes a smaller proportional contribution to the flow in the river.

5. SUMMARY AND RECOMMENDATIONS

There appears to be a sound ecological basis for the existing consent conditions prohibiting the back-feed discharge from raising the temperature of the river above 20 °C and the 3 °C maximum permitted increase in temperature downstream of the back-feed compared with upstream. However, reductions in temperature of more than 3 °C seem less likely to incur adverse effects than temperature increases of similar magnitude, and short term breaches of the 3 °C maximum permitted change might be expected to have less significant adverse effects than breaches of the 20 °C maximum temperature threshold. The rationale for the minimum temperature threshold of 6 °C is unclear, although it seems unlikely to ever cause problems for operation of the water supply scheme during summer stratification events.

While the operation of the back-feed largely complied with the temperature related consent conditions during summer 2014/15, for much of the summer the scour water from the reservoir was discharged through the back-feed. This appears inconsistent with the intent of conditions governing the discharge of scour water from the reservoir[9], which state that "*Other than in emergencies, the discharge of scour water shall only occur when the river is in fresh and naturally discoloured...*" Although there were some fresh events during the summer, for most of the time the flow was reasonably stable and low. Consequently, according to this condition it appears that scour water should not have been discharged for most of this period. However, records show that for most of the summer (from 2 February 2015 onward) back-feed water was sourced either from a combination of the upper intake and the scour valve, or from the scour valve alone (from early April 2015 onward). This resulted in anoxic water from the bottom of the dam being discharged for much of the summer, with potential adverse effects on the river ecology as well as adverse aesthetic effects (including reddish-brown flocculate on the stream bed and an obnoxious smell of hydrogen sulphide at times. Declining trends in biotic indicators have been observed in the river downstream of the back-feed discharge (Allen *et al.* 2013, Allen *et al.* 2014), and it is likely that discharge of poor quality water from the lower reservoir levels has contributed to these adverse ecological impacts. We recommend that NCC seek legal advice on interpretation of consent conditions governing discharge of scour water and consider initiating a review of conditions, or at least a review of operating procedures in the interim, in light of the observed adverse effects on the environment. .

It was not necessary to source back-feed discharge water from the scour valve in order to comply with the 20 °C maximum temperature threshold, since water at the top intake reservoir level (6 m) was below this temperature threshold for most of the summer and temperatures at the middle (15 m) and bottom (24 m) intake levels were consistently well below this threshold for the entire summer. Compliance with the 3 °C maximum change in water temperature below the back-feed would have been possible by drawing water from a combination of the upper and middle intakes for most of the summer, at least up until early April 2015.

The issue of sourcing back-feed water to match ambient temperatures in the South Branch could be addressed by installing water temperature sensors at each intake level. With real time data from these sensors, along with data that is already collected (*e.g.* South Branch flow and temperature, abstraction rate at the weir and required back-feed discharge rate), it would be a relatively simple task to derive an algorithm based on Equation 1 (above) that would calculate the mix of water from the intake

[9] Consent No: RM025151/3 (Ex-Water Right No: 820510) Condition 2.

valves required to match the temperature in the South Branch. Sourcing water from the top and middle valves could be prioritised over the summer, to avoid releasing the low quality anoxic bottom water during thermal stratification events. We recommend that this approach be pursued.

Even though operation of the back-feed discharge complied with temperature related conditions most of the time, river water temperatures increased rapidly downstream during the warm settled period in late January. Consequently, daily maximum temperatures immediately upstream of the spillway discharge pool were often above 20 °C throughout much of this settled fine weather and a further 1.5-2 °C warmer downstream of this point. This occurred despite the fact that the spillway was not operating at this time.

The warm daily average and daily maximum temperatures observed during late January 2015 would place the Maitai River downstream of the Forks recorder site in the C band recommended for inclusion in the NOF by Davies-Colley *et al*. (2013). This band was expected to experience "*some thermal stress on occasion, with elimination of certain sensitive insects and absence of certain sensitive fish*".

Notwithstanding the consent conditions controlling the temperature of water released via the back-feed, discharge of surface water via the spillway theoretically provides an uncontrolled release of warm surface water. While this discharge did not increase river water temperatures by more than 3 °C in Summer 2014/15, the spillway was not spilling for much of the summer so it is possible that its influence could be greater in years when the spillway flows more consistently.

It is possible that the cooler water of the South Branch could provide a thermal refuge for mobile species, such as fish, during periods when the lower Maitai River experiences potentially stressful water temperatures. The South Branch upstream of the weir may be inaccessible, due to the weir impeding passage for fish attempting to access this habitat.

Temperature modelling undertaken to predict longitudinal profiles of daily mean and maximum water temperatures down the upper Maitai River, shows that the back-feed discharge can alter the length of potential thermal refuge habitat available. Releasing warm water from the reservoir can reduce the length of river remaining below 20 °C that potentially acts as a thermal refuge, while releasing cooler water can extend this potential refuge habitat. However, releasing cooler water during reservoir stratification events comes with the risk of impacting water quality. Consequently, the situation remains a trade-off between releasing cooler, but low quality mid-bottom water, or releasing warmer surface-mid level water, with better water quality. However, as discussed above, we recommend that temperature sensors should be installed at the intake valves to allow calculation of the mix of water, predominantly from the upper and middle intake levels, required to closely match ambient river temperatures most of the time. This solution should minimise temperature alteration and reduce the potential for releasing poor quality, deoxygenated bottom water from the reservoir.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Allen C, Holmes R, Shearer K 2013. The Impact of the Maitai Dam on River Health Relative to Other Catchment Pressures: A Review. Prepared for Nelson City Council. Cawthron Report No. 2371. 31 p. plus appendices.

Allen C, Kelly D, Holmes R, Jiang W 2014. Longitudinal assessment of the health of the Maitai River: The influence of the Maitai Reservoir. Prepared for Nelson City Council. Cawthron Report No 2552.

Biggs BJF 2000. New Zealand periphyton guidelines: Detecting, monitoring and managing enrichment of streams. Ministry for the Environment, Wellington. 122 p.

Davies-Colley R, Franklin P, Wilcock B, Clearwater S, Hickey C 2013. National Objectives Framework - Temperature, Dissolved Oxygen & pH, Proposed thresholds for discussion. Prepared for Ministry for the Environment. NIWA Client Report No: HAM2013-056.

Doehring K, Hay J 2014. Fish passage assessment of the Maitai River North Branch Dam and South Branch weir. Prepared for Nelson City Council. Cawthron Report No. 2601. 38 p. plus appendices.

Elliott JM 1981. Some aspects of thermal stress in teleosts. In: Pickering AD ed. Stress and fish. Academic Press, London. Pp 209-245.

Elliott JM 1994. Quantitative ecology and the brown trout. Oxford University Press, Oxford.

Elliott JM, Elliott JA 1995. The effect of the rate of temperature increase on the critical thermal maximum for parr of Atlantic salmon and brown trout. Journal of fish biology 47: 917-919.

Elliott JM, Hurley MA 1998. A new functional model for estimating the maximum amount of invertebrate food consumed per day by brown trout, Salmo trutta. Freshwater Biology 39 (2): 339-349.

Elliott JM, Hurley MA 1999. A new energetics model for brown trout, Salmo trutta. Freshwater Biology 42: 235-246.

Elliott JM, Hurley MA 2000. Daily energy intake and growth of piscivorous brown trout, Salmo trutta. Freshwater Biology 44 (2): 237-245.

Graynoth E, Taylor MJ 2000. Influence of different rations and water temperatures on the growth rates of shortfinned eels and longfinned eels. J Fish Biol 57 (3): 681-699.

Hay J, Hayes J, Young R 2006. Water quality guidelines to maintain trout fishery values. Prepared for Horizons Regional Council. Cawthron Report No. 1205. 17p.

Hay J, Chandler M, Kelly D 2015. Maitai South Branch weir fish passage remediation efficacy monitoring. Prepared for Type in client name. Cawthron Report No. 2730. 17 p.

Hayes JW 2003. Maitai river instream habitat flow analysis. Cawthron Report No. 795. Prepared for Nelson City Council.

Hokanson KEF, Kleiner CF, Thorslund TW 1977. Effects of constant temperatures and diel temperature fluctuations on specific growth and mortality rates and yield of juvenile rainbow trout, Salmo gairdneri. J Fish Res Board Can 34: 639-648.

Jowett IG 1992. Models of the abundance of large brown trout in New Zealand rivers. North American Journal of Fisheries Management 12: 417-432.

Jowett IG 1997. Environmental effects of extreme flows. In: Mosley, MP, Pearson, CP (Eds) Floods and droughts: the New Zealand experience. New Zealand Hydrological Society, Caxton Press, Christchurch. Pp. 103-116.

Kelly D 2014. Maitai Reservoir water and sediment quality: 2014. Prepared for Nelson City Council. Cawthron Report No. 2613. 30p. plus appendix.

Olsen DA, Young RG 2009. Significance of river-aquifer interactions for reach-scale thermal patterns and trout growth potential in the Motueka River, New Zealand. Hydrogeology Journal 17 (1): 175-183.

Olsen DA, Tremblay L, Clapcott J, Holmes R 2011. Water temperature criteria or aquatic biota. Prepared for Auckland Council, Environment Waikato and Hawkes Bay Regional Council. Cawthron Report No. 2024. Cawthron Institute, Nelson.

Quinn JM, Hickey CW 1990. Characterisation and classification of benthic invertebrate communities in 88 New Zealand rivers in relation to environmental factors. New Zealand Journal of Marine and Freshwater Research 24: 387-409.

Richardson J, Boubee JA, West DW 1994. Thermal tolerance and preference of some native New Zealand freshwater fish. N Z J Mar Freshwater Res 28 (4): 399-407.

Rutherford JC, Blackett S, Blackett C, Saito L, Davies-Colley RJ 1997. Predicting the effects of shade on water temperature in small streams, New Zealand Journal of Marine and Freshwater Research, 31:5, 707-721.

Theurer FD, Voos KA, Miller WJ 1984. Instream Water Temperature Model. Instream Flow Information paper 16. U.S. Fish and Wildlife Service FWS/OBS-84/15

8. APPENDICES

Appendix 1. Parameters used in water temperature modelling.

Model parameters			Source
Date	29-Jan-15	15-Apr-15	
Mean air temperature (°C)	21.82	8.86	From NCC St Vincent St (air sensor) (adjusted for elevation difference, 18 mASL to 130 mASL)
Maximum air temperature (°C)	26.14	17.1	From NCC St Vincent St (air sensor) (adjusted for elevation difference, 18 mASL to 130 mASL)
Time of maximum air temperature (h)	14:00	12:00	From NCC St Vincent St (air sensor)
Radiation ($J/m^2/s$)	384.7	200.2	From Niwa Cliflo database (Appleby site)
Relative humidity (fraction)	0.65	0.67	From Niwa Cliflo database (Appleby site) (adjusted for elevation difference, 18 mASL to 130 mASL)
Wind velocity m/s	2	3.3	From Calibration process
Sunshine hours (h)	12.8	10	From Niwa Cliflo database (Appleby site)
Hours of daylight (h)	14.2	10.9	Calculated internally
Latitude (degrees)	41.2	41.2	From MemoryMap topographical map
Reach topography angle (degrees)	37.9	62	From Calibration process
Reach canopy angle (degrees)	37.9	62	From Calibration process
Reach fraction of radiation through canopy (fraction)	0.5	0.5	From Calibration process
Reach shade factor	0.38	0.78	From Calibration process
Reach bed temperature (°C)	18.88	15.27	Estimated as monthly average air temp from NCC St Vincent St (air sensor), as recommended in WAIORA 2.0 Manual.
Reach bed thickness (m)	1	1	Default
Reach bed conductivity (J/m/s/°C)	12.58	7.84	From Calibration process
Reach elevation (top of reach) (m)	170	170	From MemoryMap topographical map, approximate elevation of South Branch weir
Reach slope (m/m)	0.0107	0.0107	From MemoryMap topographical map, inter-contour slope in upper Maitai between Forks and Poleford Bridge

Model parameters			Source
Mean daily water temperature at top of reach (°C)	17.33	9.06	Calculated from the data below
Max. daily water temperature at top of reach (°C)	18.91	10.16	Calculated from the data below
Daily average discharge Maitai Forks (m^3/s)	0.26	0.51	From NCC records
Daily average back-feed discharge (m^3/s)	0.201	0.121	From NCC records
Daily average Sth Branch flow contribution (m^3/s)	0.059	0.389	difference between the above
Mean daily water back-feed temperature (°C)	17.08	11.29	From NCC records
Max. daily water back-feed temperature (°C)	18.11	11.46	From NCC records
Mean daily water temperature of Sth Branch u/s of weir (°C)	18.18	8.36	From NCC records
Max. daily water temperature of Sth Branch u/s of weir (°C)	21.63	9.76	From NCC records