

TEMPERATURE AS A CONTAMINANT IN STREAMS IN THE AUCKLAND REGION, STORMWATER ISSUES AND MANAGEMENT OPTIONS

Emily Afoa (PhD), Morphum Environmental Ltd
Damian Young (BEng), Morphum Environmental Ltd
Wolfgang Kanz (MSc), Auckland Council

ABSTRACT

Elevated discharge water temperature is gaining international recognition as a contaminant of concern to receiving waterways. Maintaining suitable thermal conditions in waterways is critical to stream health, and guidance is required for the assessment and management of stormwater temperature effects on freshwater receiving environments.

Reference catchments representative of bush (pre-development state), pastoral, and urban catchments were studied to provide data on baseline temperature regimes in Auckland. Based on an ideal management scenario to prevent additional thermal enrichment and reduce existing background thermal enrichment levels in Auckland streams, where possible, a conservative maximum temperature criterion of 20°C is recommended for all streams where the protection of stream ecological value is a management concern.

A water sensitive pathway applicable to retrofit, new development, and re-development scenarios is proposed to address temperature effects: firstly, by reducing effective impervious areas to avoid thermal enrichment; secondly, by shading existing at risk areas to mitigate thermal effects; and thirdly, by integrating temperature moderating stormwater practices to prevent or mitigate discharge of thermally enriched water directly into Auckland freshwater streams.

KEYWORDS

Temperature, Thermal Enrichment, Stormwater, Water Sensitive Design

PRESENTER PROFILE

Dr. Afoa is an Environmental Engineer specialising in Stormwater Management with interests in water sensitive design and the suite of green infrastructure technologies available for receiving water protection. She promotes solutions that incorporate both conventional and innovative low impact design systems.

1 INTRODUCTION

There is growing international recognition that elevated discharge water temperature is a contaminant of concern, in addition to typically recognised stormwater contaminants. The effects of heated water on receiving environments are known as 'thermal pollution', or 'thermal enrichment', defined as "the degradation of water quality by any process which changes its ambient water temperature". Water temperature influences all aspects of

freshwater ecosystem function. Modified water temperature regimes can alter habitat conditions (e.g. promote algal blooms) and cause a wide variety of behavioural and physiological responses including death (Olsen et al., 2011). Consequently, maintaining suitable thermal conditions is critical to stream health and guidance is required for the assessment and management of stormwater temperature effects on freshwater receiving environments.

2 TEMPERATURE AS A 'CONTAMINANT'

In urban catchments, heated discharges can result from a wide range of anthropogenic processes such as: cooling water discharges from industrial plants; drainage network alteration; riparian vegetation removal; increased imperviousness leading to runoff from warm surfaces such as pavement, roofs, and roads; and a reduction in groundwater infiltration (Shanahan, 1984; Galli, 1990; Arrington, 2003; Roa-Espinosa et al., 2003; Mills, 2008; Herb et al., 2009). Groundwater recharge (i.e. infiltration) is required to maintain baseflows and mitigate higher water temperatures during low flows, when rains are absent. The shallow waters associated with low baseflows are generally more prone to thermal effects than deeper waters. This is particularly relevant to Auckland, which has a high proportion of first and second order streams which are relatively small and usually less than a few metres wide, making them susceptible to the effects of reduced baseflows, lack of shading, and stormwater runoff from heated surfaces (Storey & Wadhwa, 2009; ARC, 2010).

Although water temperatures exhibit natural daily and seasonal temperature fluctuations, heat from anthropogenic discharges can have a substantial impact on aquatic ecosystems. The degree to which temperature impacts stream biota is generally dependent on the following (Arseneau et al., 2010):

- Magnitude (maximum and range) of the temperature organisms are exposed to;
- Duration of exposure;
- Frequency of exposure; and
- Spatial extent of temperature effects (opportunity for behavioural avoidance – possibly limited in urban streams with reduced heterogeneity due to artificial straightening or altered flow regimes).

It is for these reasons that aquatic temperature criteria are divided into 'acute' and 'chronic' exposure patterns (Olsen et al., 2011):

- Acute criteria address short duration changes in temperature i.e. intermittent discharge, point source inputs, or daily high temperatures that lead to sudden death. Typically expressed as a daily maximum temperature.
- Chronic criteria protect against the effects of prolonged exposure to raised (sub-lethal) temperatures that will negatively affect behaviour, metabolism, growth, and reproduction. Typically expressed as the maximum weekly average temperature.

New Zealand aquatic freshwater fauna have evolved with a high level of tree shading (Maxted et al., 2005), little to no urban development, and consequently, lower water temperatures with less diurnal fluctuation than modified urban streams. Water temperature criteria for native aquatic biota in New Zealand have been determined from thermal tolerances of individual native fish and benthic macroinvertebrate species available from the literature (Olsen et al., 2011).

Acute criteria are expressed as the daily maximum water temperature (Olsen et al., 2011):

- For streams with a summer mean water temperature of around 15°C ('upland' streams), acute criteria were calculated for common smelt, shortfin and longfin eels and for 11 macroinvertebrate taxa (ranging from 21 to 32°C); the most sensitive native taxa should be protected provided that maximum temperatures are less than 20°C.
- For streams with a summer mean water temperature of around 20°C ('lowland' streams), acute criteria were calculated for the common smelt only (26°C and 27°C for adult and larval stages, respectively); the most sensitive native taxa should be protected if maximum temperatures are less than 25°C.

The daily mean temperatures are those that the resident organisms are roughly acclimated to, and are an important factor in whether organisms can deal with short-term temperature increases such as those due to heated stormwater inputs.

Due to deficiencies in regional datasets, the majority of the criteria were calculated with a low-to-moderate level of confidence. Because no data was available for further taxa that may be more sensitive than the common smelt, the 'lowland' criterion must be applied with caution. The chronic criteria provided in Olsen et al. (2011) were not considered due to the low level of confidence in the data. However, the potential sub-lethal effects of observed elevated temperatures are discussed.

3 AUCKLAND RIVER ENVIRONMENT

The Auckland region has an estimated 16,650 km of permanently flowing rivers, 4480 km of intermittent stream (seasonally flowing within defined stream banks), and 7110 km of ephemeral stream (flow for short periods of time following rain events) (Storey & Wadhwa, 2009). Because no mainland location is more than 20 km from the coast, all rivers have relatively small catchments. The majority of rivers (78% of total stream length) fall into the category of first or second-order streams (Storey & Wadhwa, 2009).

River water temperature is highly correlated with air temperature. In summer the daytime air temperature ranges 22–32°C but rarely reaches 30°C, and in winter the daytime air temperature ranges 12–17°C. However, climate change projections suggest that the Auckland region could experience increased average temperatures, more hot days during summer and a lower average annual rainfall (ARC, 2010).

3.1 TEMPERATURE REGIMES IN AUCKLAND STREAMS

When evaluating the effects of stormwater runoff on stream temperature, it is essential to have an accurate representation of both the optimal temperature regime in natural catchments and the actual temperature regimes found in urbanised catchments. This provides context to the work done by Olsen et al. (2011) and can inform thermal management criteria.

Seven Auckland catchments of different land-use intensities were identified, including streams in bush, pastoral, and urban catchments (summarised in Table 1 and Figure 1). Bush catchments provide information on baseline temperature regimes that are representative of the natural condition. A pastoral catchment represents an impacted channel, typical of rural environments where riparian vegetation has been removed and the stream is predominantly unshaded. Urban catchments are the most heavily impacted, with substantial modifications to channel morphology and flow patterns due to stormwater runoff. Significant bank modifications (concrete lined, earth contoured banks, etc.) have dramatically reduced the available habitat and influenced temperature

regimes. In contrast to less modified bush or pastoral catchments, urban catchments demonstrate significant variation in characteristics between sites.

Continuous water temperature data from 2010-2012, taken at 15 min intervals, were analysed for the period December–March as these months have the warmest water temperatures throughout the year. Three years of data (2010-2012) are presented to show variation in temperature regimes across different years.

Table 2 presents summary statistics of the daily temperature data:

- Daily mean water temperature: The average temperature an organism experiences within a single day (24-hr period).
- Daily maximum water temperature: The maximum temperature an organism experiences within a single day.
- Daily mean temperature fluctuation: The range of temperatures an organism experiences within a single day. Large daily fluctuations in water temperature can result in significantly different impacts than constant temperatures; however, there is a poor understanding of thermal stress in fish in thermally dynamic environments (Bevelhimer & Bennett, 2000).

Table 1: Summary characteristics for each representative catchment

Land Use	Site Name	Size (km ²)	Elevation (m)	Impervious Cover (%)	Channel Shading ¹ (%)	Average MCI ² / SEV ³	Channel Lining / Piping ⁴ (%)
Bush	West Hoe	0.7	40.0	0.0	>80	126.4 / 0.90	0 / 0
	Opanuku	17.6	21.5	2.6	>80	90.7 / 0.80	0 / 0
Pastoral	Kumeu	45.2	20.5	2.0	48.1	65.9 / -	0 / 0
Urban	Days Bridge	11.7	2.5	56.1	39.4	58.1 / -	-
	Alexandra	3.3	15.5	59.5	38.9	- / 0.57	0 / 22
	Taiaotea	3.3	1.5	50.0	19.6	- / 0.47	16 / 24
	Hillcrest	1.8	19.0	67.0	23.4	- / -	38 / 24

1. Average riparian cover calculated using the Stream Walk Dataset 2002-2013 for the urban catchments, extrapolated from 5.7 km of stream walk data for Kumeu (MEL, 2011), and estimated based on knowledge of the catchments for the bush sites.

2. Table 12, Section 4.3, State of the Auckland Region (ARC, 2010), Macroinvertebrate Community Index: >120 = excellent, 100-120 = good, 80-100 = fair, <80 = poor quality (Note: 'Days Bridge' referred to as 'Oteha')

3. Stream Ecological Valuation (SEV): broad indication of stream health ranging 0 –1 (1 indicating highest ecological value), averaged for any reaches assessed in the catchment.

4. The percentage of the total catchment either concrete lined or piped, respectively.

Figure 1: Location map for representative catchment boundaries and monitoring sites

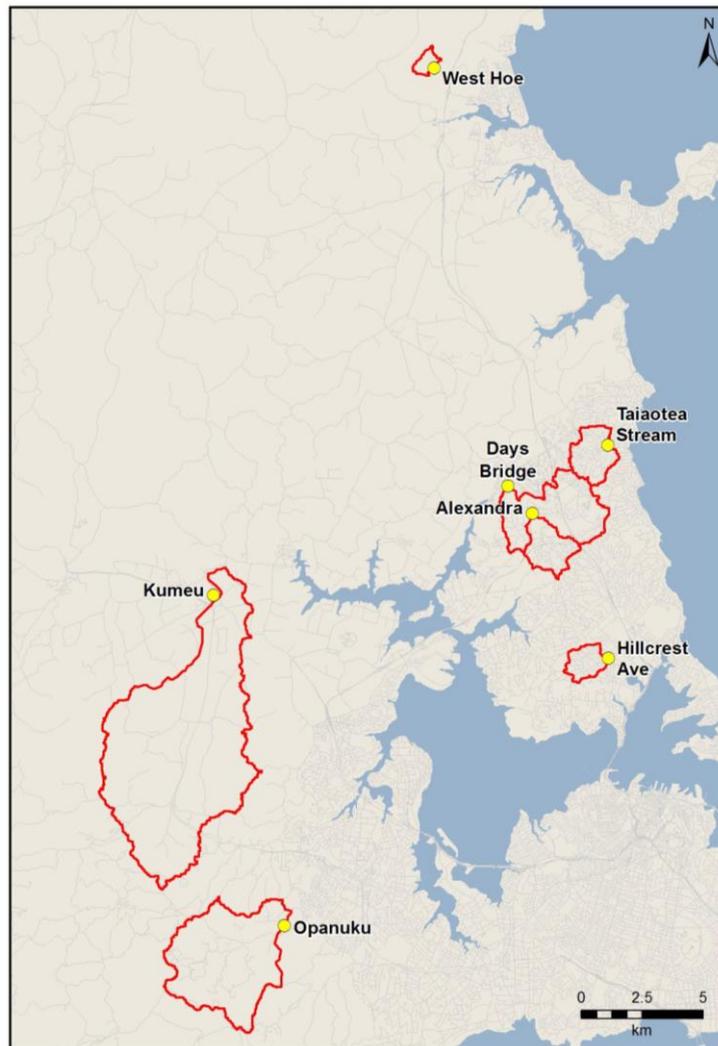


Table 2: Summary statistics of daily water temperature for each catchment

Land Use	Site Name	Mean Water Temperature (°C)	Maximum Water Temperature (°C)	Temperature Fluctuation (°C)
Bush	West Hoe	15.8 (13.1–18.2)	16.2 (13.6–18.6)	0.8 (0.1–2.4)
	Opanuku	16.3 (14.1–18.1)	17.1 (14.5–20.0)	1.6 (0.4–3.7)
Pastoral	Kumeu	18.2 (15.0–21.4)	18.9 (15.6–22.3)	1.4 (0.3–3.5)
Urban	Days Bridge	18.5 (15.5–21.6)	19.1 (15.6–22.3)	1.1 (0.1–3.6)
	Alexandra	17.8 (14.9–21.1)	18.4 (15.4–21.9)	1.1 (0.2–5.2)
	Taiaotea	20.7 (16.6–24.1)	23.2 (17.9–28.3)	4.3 (0.8–8.4)
	Hillcrest	19.7 (16.1–22.9)	24.1 (17.8–30.3)	6.8 (1.1–14.4)

Note: Data presented as Average (Range) for the Dec-Mar period across the three sampled years.

Streams in the bush catchments are well-shaded (>80% channel shading, Table 1) and have natural flow regimes and channel morphologies. Hence, their temperature regime is closest to that in which native biota have evolved. These two sites can be both classified as 'lowland' being located at elevations of 40 m and 21.5 m for West Hoe and Opanuku, respectively. However, water temperature data indicates the catchments are better represented by Olsen et al.'s (2011) 'upland' water temperature criteria; daily mean water temperatures for Dec-Mar were 15.8 and 16.3°C for West Hoe and Opanuku, Water New Zealand Stormwater Conference 2014

respectively (Table 2). However, daily means at these sites were as low as 13.1 and 14.1°C, and as high as 18.1 and 18.2°C, respectively. This is attributed largely to local variation in diurnal air temperature and solar radiation.

As expected, in these bush catchments daily maximum water temperatures never exceeded the acute criteria of 20°C (for an acclimation temperature of ~15°C) given by Olsen et al. (2011), and diurnal temperature fluctuations that organisms are exposed to were typically low (Table 2). Figure 2 provides an example of temperature variation from Dec-Mar for a representative bush catchment.

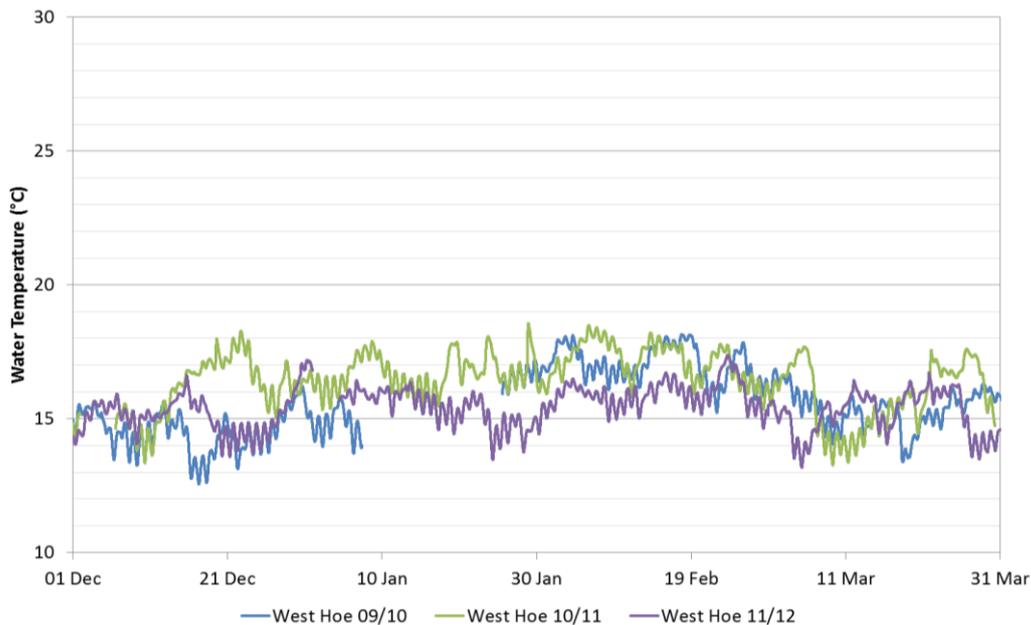


Figure 2: Representative Bush Catchment (3 yrs. data)

Pastoral stream are generally poorly shaded and hence experience higher daily mean and maximum water temperatures as well as higher daily temperature fluctuations. The daily mean water temperature Dec–Mar was 18.2°C but it could be as low as 15.0°C and as high as 21.4°C (Table 2). Daily maxima were only slightly higher than daily averages, averaging 18.9°C, with a maximum of 22.3°C (Table 2). Hence, on multiple days observed water temperatures breached the Olsen et al. (2011) acute criterion of 20°C (to protect the most sensitive native taxa), which are appropriate considering the range of daily mean water temperatures observed. Elevated temperatures up to 22.3°C (Table 2) are unlikely to have caused immediate widespread death among the most thermally sensitive fish (common smelt adults: UILT=23.3 °C) and invertebrates (*Deleatidium*: UILT=22.6°C), for which experimental data is available (Olsen et al., 2011). However, the generally higher temperatures compared to those experienced in bush catchments (likely a consequence of poor shading, 48.1%, Table 1) could potentially have negative sub-lethal effects on the growth and behaviour of sensitive biota. Figure 3 shows a slightly impacted temperature regime in comparison to that of the bush catchments that cannot be related to impervious cover (only 2.0%, Table 1); temperature impacts thus likely result from the reduced riparian.

Daily temperature fluctuations averaged 1.4°C with a maximum of 3.5°C (Table 2, Figure 3)—comparable to the bush sites. The relatively low daily fluctuations, despite poor shading, can probably be attributed to greater stream depths, and consequently higher water volumes (4th order stream with an average flow of 1.0 m³ s⁻¹). The temperature regime at Kumeu is likely to be less impacted than that of streams within smaller pastoral catchments.

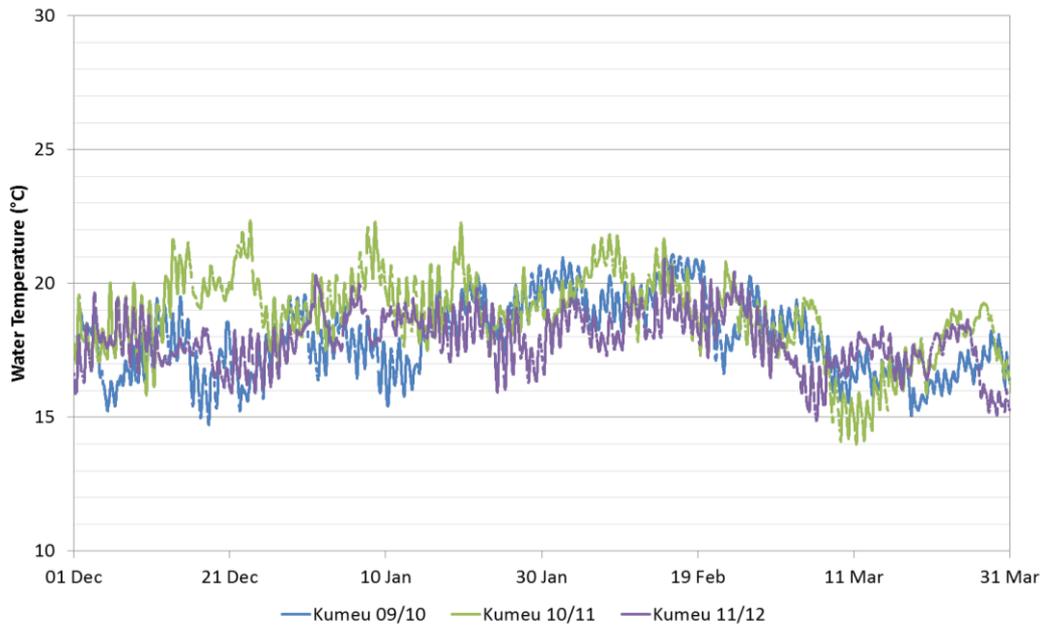


Figure 3: Representative Pastoral Catchment (3 yrs. data)

All four urban sites have $\geq 50\%$ impervious cover in the catchment but varying levels of channel shading and channel modification (Table 1), leading to varying degrees of thermal pollution observed (Table 2). The daily mean and daily maximum water temperatures at the urban sites were notably higher than those at the two bush sites. Based on temperature characteristics, the sites Days Bridge and Alexandra, and the sites Taiaotea and Hillcrest, can be broadly grouped into 'thermally impacted', and 'highly thermally impacted' sites, respectively.

The 'thermally impacted' sites were comparable to the pastoral catchment (Figure 4), while the 'highly thermally impacted' sites showed substantially larger diurnal variation and higher maximum temperatures (Figure 5). The main differences are:

- The highly impacted urban catchment has substantial channel modification and sparse shading (Table 1)
- The impacted urban catchment is downstream of a shaded wetland which may have the effect of moderating stream temperatures.

For the impacted urban catchments, average daily mean temperatures were 17.8 and 18.5°C, but were as low as 14.9 and 15.5°C (Table 2). Hence, application of the acute temperature criterion of 20°C (Olsen et al., 2011) seems most appropriate. This criterion was breached on multiple days with daily maximum temperatures of up to 22.3°C (Table 2, Figure 4). The mean daily temperature fluctuations of 1.1°C at both sites are similar to those of the two bush sites; however temperatures at Alexandra fluctuated up to 5.2°C on more extreme days (Table 2).

The potential negative thermal effects on biota may be of similar magnitude to those expected for the pastoral sites. However, considering that these urban streams have been modified and have higher % impervious cover than the pastoral stream, the thermal impacts are likely to be worse. Organisms exposed to multiple urban stressors may be less resilient to increased temperatures than those exposed to elevated temperature only. Little is known about whether other land-use related stressors impact thermal tolerances of native biota. However, interactive effects between temperature, fine sediment and nutrients on macroinvertebrate communities and ecosystem

processing have been demonstrated in experimental streamside mesocosms (Piggott et al., 2012).

By contrast, the highly impacted urban streams have poor shading and high channel modification (Table 1), and thus experience high temperatures during periods of low flow. The average daily mean temperatures were 19.7 and 20.7°C, but the daily mean peaked at 24.1°C and were as low as 16.1°C (Table 2). With daily mean water temperature around 20°C at both sites, application of the acute temperature criterion of 25°C (for an acclimation temperature of ~20°C; Olsen et al., 2011) seems most appropriate. Daily maxima averaged 23.2 and 24.1°C at these sites, however were as high as 28.3°C and 30.3°C (Table 2, Figure 5). The criterion of 25°C was breached on multiple days during the period Dec–Mar. The daily maximum temperatures on the most extreme days were above the upper incipient lethal temperatures (UILTs) of all fish and most invertebrate species for which data was available (Olsen et al., 2011).

Daily temperature fluctuations were also much higher than those at the other two urban sites; averaging 4.3 and 6.8°C, but on extreme days temperatures fluctuated by up to 8.4 and 14.4°C at these highly impacted locations (Table 2). The acute temperature criterion considers mean summer temperatures in relation to acclimation temperatures. Acclimation may not be achieved when streams demonstrate extremely large diurnal variations, such as the highly impacted streams have exhibited. It may be that fish and other in-stream fauna experience greater stresses as a result of the combined effects of elevated temperatures and large diurnal variations.

Thermal impacts at these highly-modified urban stream sites are likely to exclude a range of fish and invertebrate species that cannot survive these high temperature events, and have sub-lethal effects on the more tolerant species, especially considering the prolonged suboptimal temperatures and the high daily temperature fluctuations (although little information is available on their effects).

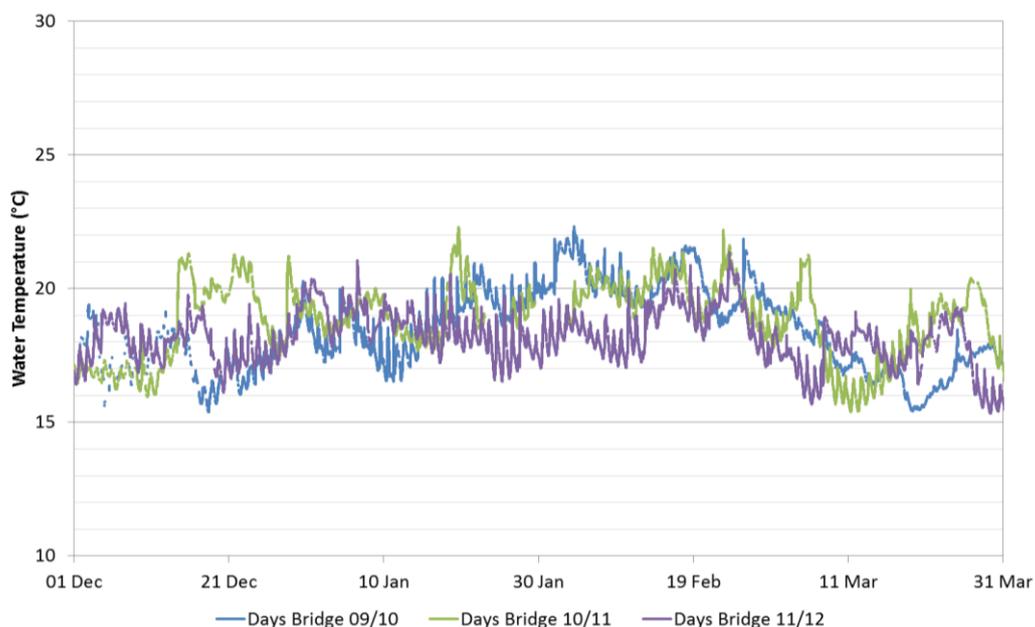


Figure 4: Representative Impacted Urban Catchment (3 yrs. data)

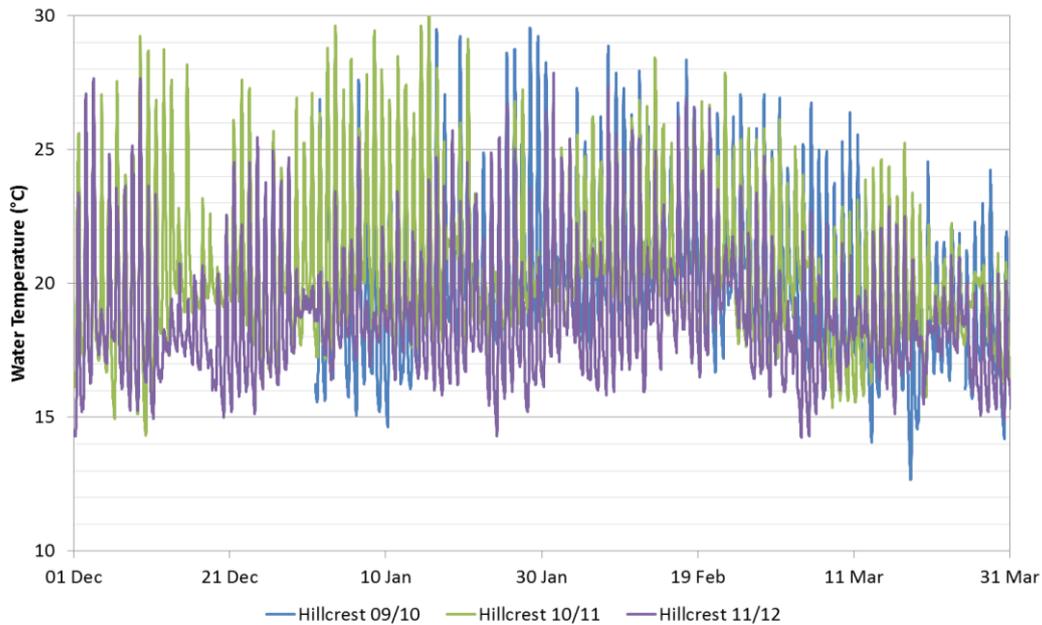


Figure 5: Representative Highly Impacted Urban Catchment (3 yrs. data)

4 MITIGATION OPTIONS

Analysis of Auckland stream temperature regimes (Section 3.1) indicates pastoral and urban catchments are negatively impacted by increased water temperatures—it is recommended that design of stormwater mitigation measures considers temperature effects. Guidance for protection of streams is currently being considered in Auckland with the Proposed Auckland Unitary Plan (Auckland Council, 2013) setting performance requirements based on land use activities, contaminants of concern (of which temperature is one), and receiving environments. Likewise, the Auckland Council draft guideline document “Water Sensitive Design for Stormwater” (GD04) promotes water sensitive design (see Section 4.1).

4.1 WATER SENSITIVE DESIGN AND BEST PRACTICE OPTIONS

Water sensitive design (WSD) is defined in the draft GD04 as an inter-disciplinary design approach to freshwater management for land use planning and land development. In its broadest sense WSD is about land and water management, however the specific context of the draft guideline has a stormwater management focus.

WSD seeks to protect and enhance natural systems, and mimic natural processes to achieve enhanced outcomes for ecosystem services and communities. WSD promotes land use planning practices that balance land development with the ecosystem services necessary to support it. This approach will ensure the resilience of Auckland’s environment, in particular the values and sensitivities of the harbours and watercourses.

Studies in Melbourne, Australia have identified that the primary factor in stream degradation in many urban areas, particularly as a determinant of taxa loss, is effective—rather than total—impervious area (Walsh, 2004; Walsh et al., 2005). Effective impervious area is the area of a catchment with a direct stormwater connection to stream channels. WSD approaches that reduce drainage connection are postulated as the most effective management solutions to protect stream biota in urban catchments; particularly measures that intercept rainfall from small events and then facilitate its infiltration, evaporation, transpiration, or storage for later re-use (Walsh, 2004; Walsh et al., 2005).

The water sensitive pathway to addressing temperature effects is to:

1. Reduce the area of contributing surfaces and thus avoid thermal enrichment,
2. Shade existing at risk areas to mitigate thermal effects, and
3. Integrate temperature moderating practices to treat stormwater runoff from at risk surfaces; thereby preventing, or mitigating the discharge of thermally enriched water directly into Auckland streams.

Table 3 provides a variety of stormwater management practices and how they perform with respect to thermal enrichment. While traditional pavement and wet ponds are the only systems identified in *Table 3* as producing thermally enriched runoff, that is effluent water temperature greater than influent water temperature, discharge temperatures from the other systems presented have still been shown to exceed 20°C at times.

In order to provide the most effective means of stormwater mitigation, particularly in the context of thermal mitigation, a treatment train approach may be used. A treatment train is based on a logical sequence of stormwater flowing through a catchment, beginning with stormwater runoff source controls, followed by capture and treatment of overland flows, and finally the enhancement of receiving environments. Designers should incorporate multiple concepts to optimise stormwater management and thermal mitigation. For example, within a single site a development may:

- Retain green space and allow for areas of landscape planting with appropriate species selection to provide shading
- Restrict impervious surface (roofs, pavement etc.) materials to lighter coloured and/or reflective "cool" materials
- Disconnect impervious surfaces to promote overland flow and infiltration rather than piped flow
- Incorporate features such as permeable paving parking areas and living roofs
- Include tree-pits/bioretenion within the edges of the road network or parking areas for infiltration and shading (avoid purely decorative traffic islands)
- Use underground detention tanks (with potential for re-use) as opposed to open systems such as ponds/wetlands
- Incorporate internal water storage into underground systems to provide a cool buffer for mixing with heated surface water
- Use level spreaders or dispersal bars to discharge water as sheet flow to riparian margins
- Utilise smart outlet design (setbacks and distributed discharge locations)
- Include regular catchpits to rapidly route stormwater flows into the underground piped network

These options intend to reduce the water entering stormwater reticulation, encourage infiltration, encourage thermal exchange and latent heat transfer via evapotranspiration, and incorporate shading. Where one system cannot achieve all the required objectives (i.e. water quality and quantity mitigation), multiple systems may be placed in series. For example, a wet pond may have been used to achieve water quality objectives, yet does not achieve water temperature objectives. Placing a rock crib in series will provide a cooling function while the wet pond meets quality objectives.

The WSD and treatment train approach discussed so far follows a whole of site method which can be broken down into three components, discussed in the following sections: source control, device selection for new build, and retrofit of existing devices.

Table 3: Summary of thermal enrichment characteristics of stormwater management practices

Device	Produces thermally enriched effluent ¹	Example peak runoff temperatures ²	Comments	Mitigation
Traditional Pavement	Yes	30-33°C	Impervious asphalt & concrete most common.	Reduce area of paving, use permeable paving or cool paving systems, shade paved surfaces.
Wet Pond	Yes	20-30°C, 2-10°C above influent temperatures.	Physical characteristics of ponds detrimental to stream temperature due to extended detention & surface heating.	Possible capacity of streams to buffer offline pond discharges, increase depth of water intake below surface due to thermal stratification, conveyance through underground concrete pipes to cool water.
Infiltration	No	Depends on sub-surface soil temperature, exceeded 20°C at times.	Bioretention, pervious paving, infiltration trench/basin, swale, soakhole etc.	Optimal method for mitigating thermal enrichment. Removes source of thermal enrichment, provides groundwater recharge.
Pervious Paving	No	2-4°C less than conventional paving.	A type of cool paving system. Provides volume reduction in addition to cooler discharge temperatures.	Thermal load reduction mainly driven by the reduction in runoff volume. Allowance for an internal water storage volume increases the ability to reduce outflow, thus reducing thermal load.
Wetland	No	19°C, 3-5°C below unshaded pond discharge.	Needs >80% vegetative cover for shading, or operates as a heat source	Has the ability to capture a number of rainfall events entirely, inherently mitigating thermal load.
Bioretention	No	Depends on sub-surface soil temperature, exceeded 21°C at times.	Soil temperatures may exceed discharge thresholds in summer.	Substrate depth >0.5 m to reach equilibrium with soil temperatures. Internal water storage volume increases retention, thus reducing thermal load. Impact of volume reduction greater than temperature reductions through contact.
Level Spreader	No	Exceeded 21°C at times.	Both grassed and wooded filter strips provide thermal mitigation.	Thermal mitigation attributed to both direct temperature reductions, and indirect reductions via runoff volume reductions
Thermal Exchange & Underground Systems	No	2-5°C less than influent, exceeded 20°C at times.	Rock cribs, pervious paving, infiltration trenches, buried tanks, etc. Underground systems will not necessarily impact on developable area as (incorporate into driveways).	May involve energy transfer by phase change (e.g. evapotranspiration), or via heat conduction and convection. Typically incorporates an internal water storage volume. Water re-use from tank systems removed heated water from the system.
Living Roofs & Roof Planters	No	Depends on substrate depth & water content.	A type of cool roof system.	Thermal mitigation due to volume reduction and cooling effect of evapotranspiration.

Notes:
 1. Indicating runoff or discharge is warmer than influent water temperature. 2. Examples from literature. See TR2013/044 (Young et al., 2013)

4.1.1 SOURCE CONTROL

In order to optimise mitigation of temperature, the first step is to implement source control to prevent thermal enrichment of stormwater. Methods include:

- Implementing land use control encouraging the retention of natural areas.
- Minimising compaction during development to retain soil infiltration capacity.
- Clustering development and reducing road widths
- Using materials of low thermal mass, i.e. materials that do not readily heat up.
- Shading surfaces that have the potential to become heated.
- Disconnect impervious surfaces from reticulation to minimise water contact with heated surfaces in order to prevent cumulative temperature increases, and reduce runoff volume by providing for infiltration and evapotranspiration.
- Retention or regeneration of riparian buffers.

Urban or agricultural activities in riparian areas can cause substantially more damage than the same activities away from stream channels (Wang & Kanehl, 2003). Although the riparian area is small in size relative to the total catchment area, protecting or restoring sufficient width of undisturbed buffer along riparian areas will offset some of the negative effects of development on stream ecosystems, and help maintain natural stream thermal regimes (Wang & Kanehl, 2003). Stream corridors with extensive plantings enhance evapotranspiration, and create overbank stream shading which lessens the influx of solar energy into the water. Likewise, vegetation minimises the absorption of radiative heat by both runoff and contributing impermeable surfaces. Shading may also provide the stream capacity to buffer thermally enriched stormwater runoff (Galli, 1990). Stream buffering capacity is influenced by the volume of water in the stream, and varies across the Auckland region. Many short and narrow low-volume streams have relatively low buffering capacities and are easily affected, while streams carrying large amounts of water resist heating and cooling (Poole et al., 2001).

However, restoration of streambank vegetation alone may be insufficient to meet stream temperature goals (Poole & Berman, 2001) as restoration approaches using riparian planting alone generally do not match the scale of the degrading process (Walsh et al., 2005). Protection and restoration of riparian margins will not mitigate thermal enrichment from point source outflows to streams, typically from impervious paved (roads, footpaths, etc.) or roof surfaces.

Disconnected impervious surfaces promote infiltration and evapotranspiration as runoff from surfaces such as roofs, driveways, and car parks, is directed to lawns, landscaping, or more formal infiltration systems such as bioretention, rather than connecting directly to stormwater reticulation. A simple example is to disconnect downspouts. Disconnecting impervious surfaces and utilising pervious surfaces such as permeable paving and other infiltration stormwater treatment devices prevents thermally enriched water entering the receiving stream, provides groundwater recharge, and cools any discharge that does occur (via underdrain) before it enters the natural receiving environment.

If a surface must be paved, and permeable paving is not an option, the surface type can be selected so as to minimise the transfer of heat to stormwater runoff, or to prevent the heated runoff from entering the receiving environment. A cool pavement (i.e. a surface with high albedo) lowers surface temperatures and reduces the amount of heat absorbed into the pavement. Although impervious cool pavements promote increased runoff volumes and flow rates compared with pervious ones, they have a reduced temperature effect when compared with traditional surfaces such as asphalt. Likewise, utilising living roofs or cool roofs with high reflectance and high emittance (similar to cool pavements) will minimise thermal effects from roof runoff.

Alternatively, providing shading of traditional paved surfaces, such as a tall canopy of trees over a car park, not only provides aesthetic benefit, but also reduces heating of the paved surface below.

4.1.2 DEVICE SELECTION FOR NEW BUILD

Stormwater management devices that convey stormwater through cooler underground structures or soil (bioretention, underground systems etc.) or reduce the overall volume of runoff (pervious paving, bioretention, infiltration facilities, vegetated filter strips etc.) have the highest capacity to decrease or buffer thermal load from urban catchments (Galli, 1990; Jones & Hunt, 2009; Kieser et al., 2003; Natarajan & Davis, 2010; Wardynski et al., 2013; Winston et al., 2011).

Infiltration capacity varies across Auckland, due to poor infiltration rates and/or contaminated soils. Although infiltration rates may vary, even clay soils permit a degree of infiltration (especially in summer, when temperatures are highest, soils are driest, and fissures may develop). Less permeable soils do not preclude the use of infiltration devices. Even if the device (for example a bioretention cell) is lined or exfiltration of water from the device to the subsoil below is limited, routing thermally enriched runoff from roads or pavements (which can reach 30°C during summer months, *Table 3*) through bioretention media, to a subsurface underdrain will allow volume loss via evapotranspiration and cooling via contact with the subsurface media. The first-flush runoff most affected by heating from impervious surfaces (Jones & Hunt, 2010; Pucci & Bowker, 2007; Winston et al., 2011) can comprise a relatively small volume compared to total runoff and may be mitigated by routing through an infiltration or sub-surface device, even if it ultimately discharges to reticulation via an underdrain.

Underground detention tanks with infiltration and/or rainwater tanks with re-use, as an alternative to infiltration methods, provide another means of mitigating the thermal effects of stormwater runoff by reducing the volume of runoff entering waterways. However, this should not be at the expense of stream recharge, which should be factored into any integrated design.

Devices that impound water, such as wet ponds and inadequately shaded stormwater wetlands, typically act as sources of thermal pollution; water temperature at the outlet is warmer than incoming runoff (Galli, 1990; Jones, 2008; Jones & Hunt, 2010; Kieser et al., 2004; Winston et al., 2011). When designing with temperature sensitive receiving waters in mind, devices that impound water should be avoided. Elevated stream temperatures can persist hundreds of metres downstream from ponds owing to the slow rate of cooling (c. 1°C/100 m) (Alexander, 1998; Lessard & Hayes, 2003; Maxted et al., 2005)—often with cumulative effects on aquatic biota. A moderate shift in fish community composition will occur in response to minor downstream warming, with increases in downstream water temperature by more than 2°C resulting in substantial shifts in species composition (Lessard & Hayes, 2003; Hayes et al., 2006). Without some cooling factor downstream, such as groundwater recharge or substantial shading, reaches with increased temperatures are not able to shed added heat, instead continuing to warm.

Wetlands designed with >80% vegetated cover were the only exception identified in the literature where water retained for extended periods was not thermally enriched. Kieser et al. (2004) and Chung (2007) noted that wetlands mitigated thermal loading with net heat reduction attributed to shading, evapotranspiration, and infiltration. However, cooling resulted only from heat exchange with ambient air (Kieser et al., 2004). Jones & Hunt (2010) found a wetland with 70% cover captured a number of rainfall events entirely, mitigating thermal load; however when outflow from the wetland did occur,

temperatures were higher than inflow temperatures, but significantly lower than wet pond discharges.

Vegetation cover, design depth, and surface area are key factors influencing water temperature in a pond or wetland. As wet ponds and wetlands do not normally decrease runoff volumes, substantial temperature reductions are required to mitigate the impact of thermal enrichment. Shading of open water surfaces is critical and can be achieved via:

- Mature trees over wetlands
- Mature trees as close to the water surface as pond stability constraints allow
- Planting tall emergent species adjacent to open water
- Central islands in water bodies to allow for planting of large trees to provide shade and “close the canopy” (these must be carefully designed to prevent short-circuiting)
- Floating wetlands / vegetated islands
- Pond orientation to maximise benefits of perimeter planting
- Where incorporating amenity features (e.g. walkways), route these over open water bodies

Careful design of the discharge outlet from an open water body is required. Thermal stratification is likely to occur within wet ponds and wetlands, with warmest temperatures at the surface (Jones, 2008; Jones & Hunt, 2010). Outlets should draw water from the cooler, deeper layers. One option may be a reverse sloping outlet, which provides additional benefit by preventing floatables clogging the outlet. An outlet drawing from the bottom strata may achieve effluent temperatures <21°C for wetlands, but likely not for wet ponds (Jones & Hunt, 2010). Maintenance of outlets at the base of ponds or wetlands must be done with caution. While the lower water column is cooler, if the outlet is too close to the base of the pond problems with respect to sedimentation, pollutant concentrations, and low dissolved oxygen may arise (Jones & Hunt, 2010).

Outlets discharging to a stream should be set back an appropriate distance from the natural channel, at an angle to the stream. A setback channel recovery reach (conveyance channel) will allow for energy dissipation while also providing opportunity for shading and thermal mitigation before flows enter the main channel. Energy dissipation in the form of riprap, baffles, or a bubble-up pit with scruffy dome promotes turbulence and provides aeration enabling contact between the cooler surrounding air and stormwater. However, these structures must be shaded or they may act as sources of thermal enrichment. Extended lengths of unshaded riprap lined channel heated water on average 1.1°C (Galli, 1990). Where possible, conveyance channels from outlet to stream should be heavily shaded and either promote contact with cooler surfaces (i.e. shaded riprap) or provide a deep, narrow channel. Where this is not feasible it may be appropriate to discharge water via a subsurface concrete pipe to provide cooling. Level spreaders and dispersal trenches or bars may be used for smaller discharges, with the added benefit of providing for some infiltration.

4.1.3 RETROFIT OF EXISTING DEVICES

A number of stormwater treatment devices are operational throughout the Auckland Region. Many of these devices, in particular over 350 wet ponds, have the potential to contribute to the thermal enrichment of Auckland’s streams. While it is impractical to consider completely mitigating the temperature effects from all ponds, there are a number of retrofit options including source control, enhanced buffering potential of receiving waterways, and reduced thermal enrichment in stormwater mitigation devices, that may be considered for these wet ponds, for example:

- Provide shading over existing paved areas to reduce thermal load.
- Restore riparian vegetation to provide shading of receiving waters.
- Provide intensive perimeter planting of existing wet ponds.
- Construct a planted central island to close the canopy over a wet pond—taking care to prevent short circuiting.
- Install a floating vegetated island to enhance shading (and provide additional water quality benefit).
- Convert wet ponds to wetlands and increase vegetative cover to >80%. A complete hydrologic assessment would have to be undertaken to ensure the resulting potential loss of storage volume will not cause problems downstream.
- Optimise outlet design to withdraw water from lower, cooler water layers.
- Shade outlet channels, particularly exposed rock lined channels that can act as a heat sink (if shaded) or source (if unshaded).
- Route discharges through rock cribs and other practices which reduce temperature through contact with cooler materials and cool air.

4.2 GUIDELINES AND REGULATIONS

Stormwater management strategies are typically governed by regulatory compliance and guidelines. In the context of water temperature, regulatory bodies can be driven through a variety of concerns, ranging from purely ecological considerations to financial drivers (i.e. the preservation of fisheries).

Temperature regulation in Auckland relates to ecological drivers only. 'Chapter 5: Discharges to Land and Water, and Land Management' of the Auckland Regional Plan: Air, Land and Water (ALWP; Auckland Council, 2012) states discharge of water is permitted on the condition that "the discharge does not change the natural temperature of the receiving water by more than 3°C after reasonable mixing". The Proposed Auckland Unitary Plan (Auckland Council 2013) presents an objective identifying temperature as a stormwater contaminant of concern when the land use activity is high use roads or car parks, or roofing metal. Effluent temperature must be below 25°C if the receiving environment is a river or stream (Auckland Council, 2013; Part 3, Chpt H, Sectn 4.14, proposed).

Comparable requirements are in place in North Carolina with a 21°C trout temperature threshold (Jones & Hunt, 2010; Wardynski et al., 2013), and Oregon with a 18°C temperature criteria to protect fish spawning, rearing, and migration (Jones, 2011). Pennsylvania (PADEP, 2007) defines maximum receiving water temperatures by calendar month, differentiating between Warm Water Fish (30.6°C Jul–Aug), Cold Water Fish (18.9°C Jul–Aug), and Trout Stocking (30.6°C Aug 16–30). PADEP (2007) also consider "first flush" runoff the most thermally loaded and require that thermal discharges do not result in a temperature change in the receiving water body by more than 2°F (1.1°C) during a 1-hour period.

To combat impacts of runoff temperature, the U.S. Congress included a provision in the Energy Independence and Security Act requiring all federally funded construction exceeding 464 m² to restore predevelopment hydrology with respect to "temperature, rate, volume, and duration of flow" (U.S. Congress, 2007). This is a particularly restrictive requirement, in that rather than simply setting a maximum temperature that must not be exceeded, the design is required to match predevelopment baseline temperatures, where predevelopment implies the land cover that typically existed on a site before human-induced land disturbance occurred (e.g. forest).

Heat is considered a pollutant under Section 502(6) General Definitions of the Clean Water Act (CWA) (Smith, 2006; USEPA, 1972). The CWA requires each State to identify

waters for which controls on thermal discharges under previous sections are not stringent enough to assure protection and propagation of a balanced indigenous population of shellfish, fish, and wildlife. Once identified, the State must estimate the total maximum daily thermal load required to assure protection and propagation of a balanced ecosystem taking into account the normal water temperatures, flow rates, seasonal variations, existing sources of heat input, and the dissipative capacity of the identified waters. Furthermore, estimates must calculate the maximum allowable heat input and include a margin of safety taking into account any lack of knowledge concerning the development of thermal water quality criteria for habitat protection in the identified waters (USEPA, 1972).

According to EPA data there are 298 approved temperature-related total maximum daily loads (TMDLs) in the USA (Kieser et al., 2003). However, Jones and Hunt (2009; 2010) noted that wide diurnal variation, a variety of climate factors, and the high variability of natural water temperatures at the pond surface (where discharge is typically drawn from) has made implementation of total maximum daily load (TMDL) programs for temperature control difficult. Likewise, it is difficult to predict actual fish behaviour in response to elevated temperatures, evidenced by inconsistencies between laboratory and field research data (Hocutt et al., 1981).

The Colorado Department of Public Health and Environment have implemented a comprehensive Temperature Criteria Methodology (CDPHE, 2011), the central concept of which is to establish standards to protect against negative effects to aquatic life, ranging from lethality to decreased rates of growth and reproduction. This methodology identifies a combination of criteria that can protect from adverse effects of temperature including:

- an acute or maximum temperature criterion (lethality);
- a chronic criterion for a longer duration average (growth, etc.);
- a season/location/species specific spawning criteria (sensitive life stages);
- a criterion to maintain a normal temperature pattern (upstream/downstream, normal spatial variability);
- a criterion to avoid effects due to sudden temporary changes (thermal shock); and
- a criterion to maintain normal seasonal and diurnal temperature patterns.

Establishing limits on both maximum (acute) and average (chronic) temperatures was identified to offer the best opportunity to protect aquatic life, and to address the variety of temperature regimes found in Colorado (CDPHE, 2011). Temperature criteria prior to this consisted of two parts:

1. Maximum temperatures of 20°C and 30°C for cold and warm water biota, respectively; and
2. A narrative contained in a footnote, including to: "maintain a normal pattern of diurnal and seasonal fluctuations with no abrupt changes", and reference to a maximum 3°C increase in temperature over a minimum of 4 h.

Concerns with these pre-existing criteria were that, in practice, the 20°C and 30°C limits were applied as maximum "not-to-exceed" discharge limits, and thus it was questioned whether this interpretation would meet the 3°C increase portion of the temperature standard. Significant research would be required for New Zealand native fish species to implement the full suite of criteria recommended by CDPHE (2011).

It is also possible to consider alternate controls that, while not specifically temperature targeted, will act to mitigate temperature as a stormwater contaminant. Examples include albedo controls (pale vs. dark coloured concrete), repaving using permeable paving (Chicago's Green Alley program) (USEPA, 2008a), and ordinances that require a

certain percentage of tree shade in parking lots. For example, Davis, California, and Sacramento each require 50% of the parking area to be shaded within 15 years after the lot is constructed (USEPA, 2008b).

5 CONCLUSIONS

Ideally, the management of water temperatures in Auckland should aim to prevent additional thermal enrichment and reduce existing background thermal enrichment levels where possible. The reference sites in this study provide data on baseline temperature regimes representative of bush (pre-development state), pastoral, and urban Auckland catchments. According to the daily mean water temperature at each representative catchment (Section 3.1) and hence the temperature organisms are acclimated to, different acute temperature criteria could potentially be applied within Auckland:

- 20°C (acclimation temperature ~15°C) for bush, pastoral, and impacted urban streams (Days Bridge and Alexandra), and
- 25°C (acclimation temperature ~20°C) for highly impacted urban streams (Hillcrest and Taiāotea).

The 25°C criterion is solely based on experimentally-determined thermal tolerances of the common smelt, whereas the 20°C criterion is based on other fish and a range of invertebrate species. Moreover, if mitigation criteria were to only target existing stream health, then potential future restoration projects may be limited; while aesthetic, riparian cover, and contaminant issues may be improved, sensitive organisms may not recover due to ongoing thermal impacts of stormwater discharges. Taking this into account, the more conservative temperature criterion of 20°C is recommended for all streams where the protection of stream ecological value is a management concern.

In the Auckland Region, the draft GD04 recommends water sensitive design to mimic natural processes in order to achieve enhanced outcomes for ecosystem services. The water sensitive pathway to addressing temperature effects is to: firstly reduce effective impervious area to avoid thermal enrichment, secondly to shade existing at risk areas to mitigate thermal effects, and thirdly to integrate temperature moderating stormwater practices to prevent, or mitigate, discharge of thermally enriched water directly into Auckland freshwater streams. This method is appropriate to both retrofit and new or re-development scenarios.

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REFERENCES

- Alexander, M.D. (1998) *Effects of beaver (Castor canadensis) impoundments on stream temperature and fish community species composition and growth in selected tributaries of Miramichi River*. New Brunswick, Department of Fisheries and Oceans. Canadian Technical Report of Fisheries and Aquatic Sciences 2227.
- Arrington, K.E. (2003) *Tools to support the protection of cold water streams from the thermal impact of development in Dane County, Wisconsin*. M.S. Thesis. University of Wisconsin, Madison.

- Arseneau, D., Weber, S., Scheidel, A.E., Walker, R.R., Tufgar, R.H. and Cartwright, P.J. (2010) 'Evaluating Temperature Impacts of Stormwater Management Ponds: A Case Study of the Hanlon Creek Business Park'. *4th International Conference on Natural Channel Systems*.
- Auckland Council (2012) *Auckland Council Regional Plan: Air, Land and Water*.
- Auckland Council (2013) *The Proposed Auckland Unitary Plan* (Notified 30 Sept 2013).
- Auckland Regional Council (2003) *Stormwater Management Devices: Design Guidelines Manual, Second Edition*. Technical Publication 10. Auckland Regional Council.
- Auckland Regional Council (2010) *State of the Auckland region 2009*.
- Bevelhimer, M. and Bennett, W. (2000) 'Assessing cumulative thermal stress in fish during intermittent exposure to high temperatures'. *Environmental Science and Policy*, 3:S211-S216.
- CDPHE (2011) *Temperature Criteria Methodology, Policy Statement 06-1*. The Colorado Department of Public Health and Environment, Water Quality Control Commission.
- Chung, P.Y. (2007) *Thermal Impacts of Stormwater Retention Ponds and Constructed Wetlands*. M.S. Thesis, University of Auckland Faculty of Engineering. Funded by Auckland Regional Council.
- Galli, J. (1990) *Thermal Impacts Associated with Urbanization and Stormwater Management Best Management Practices*. Produced by the Metropolitan Washington Council of Governments for the Sediment and Stormwater Administration of the Maryland Department of the Environment
- Hayes, D.B., Dodd, H. and Lessard, J. (2006) 'Effects of Small Dams on Cold Water Stream Fish Communities'. *American Fisheries Society Symposium*.
- Herb, W.R., Janke, B., Mohensi, O. and Stefan, H.G. (2009) 'Runoff Temperature Model for Paved Surfaces'. *Journal of Hydrologic Engineering* 14(10): 1146-1155.
- Hocutt, C.H., Stauffer, J.R., Edinger, J.E., Hall, L.W. and Morgan, R.P. (1981) *Power Plants: Effects on Fish and Shellfish Behavior*. New York: Academic Press.
- Jones, L.M. (2011) *Evaluation of Instream Flow Restoration Targets and the Carrying Capacity of *Oncorhynchus mykiss* according to Temperature, Whychus Creek, Deschutes Basin, Oregon*. Master's Thesis, Master of Science in Water Resources Science, Oregon State University.
- Jones, M.P. (2008) *Effect of Urban Stormwater BMPs on Runoff Temperature in Trout Sensitive Regions*. PhD Thesis, Biological and Agricultural Engineering, North Carolina State University.
- Jones, M.P. and Hunt, W.F. (2009) 'Bioretention impact on runoff temperature in trout sensitive waters'. *Journal of Environmental Engineering* 135(8): 557-585.
- Jones, M.P. and Hunt, W.F. (2010) 'Effect of Storm-Water Wetlands and Wet Ponds on Runoff Temperature in Trout Sensitive Waters'. *Journal of Irrigation and Drainage Engineering*, 136(9): 656-661.

- Kieser, M.S., Fang, F. and Spoelstra, J.A. (2003) 'Role of Urban Stormwater Management Practices in Temperature TMDLS'. *Water Environment Federation, TMDL 2003: Connecting you to a Higher Level of Expertise*, November 16-19, Chicago, IL
- Kieser, M.S. (2004) *Stormwater Thermal Enrichment in Urban Watersheds* (WERF Report 00-WSM-7UR). London: IWA Publishing
- Lessard, J. and Hayes, D.B. (2003) 'Effects of elevated water temperature on fish and macroinvertebrate communities below small dams'. *River Research and Applications* 19: 721-732
- Maxted, J.R., McCready, C.H. and Scarsbrook, M.R. (2005) 'Effects of Small Ponds on Stream Water Quality and Macroinvertebrate Communities'. *New Zealand Journal of Marine and Freshwater Research* 39(5): 1069-1084.
- Mills, G.N. and Williamson, R.B. (2008) *The Impacts of Urban Stormwater in Auckland's Aquatic Receiving Environment: A Review of Information 1995 to 2005*. Prepared by Diffuse Sources Ltd and Geosyntec Consultants for Auckland Regional Council. Auckland Regional Council Technical Report 2008/029.
- Natarajan, P. and Davis, A.P. (2010) 'Thermal reduction by an underground storm-water detention system'. *Journal of Environmental Engineering* 136(5): 520-526.
- Olsen, D.A., Tremblay, L., Clapcott, J. and Holmes, R. (2011) *Water Temperature Criteria for Native Aquatic Biota*. Prepared for Auckland Council, Environment Waikato and Hawkes Bay Regional Council. Cawthron Report No. 2024.
- PADEP (2007) *Commonwealth of Pennsylvania - PA Code Title 25. Environmental Protection - Chapter 93: Water Quality Standards*. Pennsylvania Department of Environmental Protection.
- Piggott, J.J., Lange, K., Townsend, C.R. and Matthaei, C.D. (2012) 'Multiple stressors in agricultural streams: a mesocosm study of interactions among raised water temperature, sediment addition and nutrient enrichment'. *Plos One*, 7.
- Poole, G.C. and Berman, C.H. (2001) 'An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-Caused Thermal Degradation'. *Environmental Management* 27(6): 787-802.
- Poole, G., Risley, J. and Hicks, M. (2001) *Spatial and Temporal Patterns of Stream Temperature (Revised)*. EPA, Issue Paper 3. Prepared as Part of EPA Region 10 Temperature Water Quality Criteria Guidance Development Project
- Pucci, A.A. and Bowker, M. (2007) 'Thermal Impact Assessment for Discharging Stormwater Runoff: Case Study'. *Proceedings of the 2007 Pennsylvania Stormwater Management Symposium*, Villanova University, 16-18 October
- Roa-Espinosa, A., Wilson, T.B., Norman, J.M. and Johnson, K. (2003) 'Predicting the impact of urban development on stream temperature using a thermal urban runoff model (TURM)'. *Proceedings of the US EPA National Conference on Urban Stormwater: Enhancing Programs at the Local Level*, Chicago, IL, 369-389. National Risk Management Research Laboratory, Cincinnati, OH.
- Shanahan, P. (1984) 'Water temperature modelling: A practical guide'. *Proceedings of the EPA Stormwater and Water Quality Model Users Group Meeting*, April 12-13.

- Smith, D. (2006) 'Stormwater Temperature Monitoring in Federal Way', WA. *Stormwater: The Journal for Surface Water Quality Professionals*. Retrieved from http://www.erosioncontrol.biz/SW/Articles/Stormwater_Temperature_Monitoring_in_Federal_Way_W_133.aspx
- Storey, R. and Wadhwa, S. (2009) *An assessment of the lengths of permanent, intermittent and ephemeral streams in the Auckland region*. Auckland Regional Council Technical Report 2009/028.
- US Congress (2007) Stormwater runoff requirements for federal development projects. Public Law 110-140 Energy Independence and Security Act, Title IV, Subtitle C, Sec. 438.
- USEPA (1972) *Federal Water Pollution Control Act* (known as the Clean Water Act, CWA)
- USEPA (2008a) Chapter 5: Cool Pavements. *Reducing Urban Heat Islands: Compendium of Strategies*. Retrieved from <http://www.epa.gov/heatisland/resources/compendium.htm>
- USEPA (2008b) Chapter 2: Trees and Vegetation. *Reducing Urban Heat Islands: Compendium of Strategies*. Retrieved from <http://www.epa.gov/heatisland/resources/compendium.htm>
- Walsh, C.J. (2004) 'Protection of in-stream biota from urban impacts: minimise catchment imperviousness or improve drainage design?' *Marine and Freshwater Research* 55(3): 317-326.
- Walsh, C.J., Fletcher, T.D. and Ladson, A.R. (2005) 'Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream'. *Journal of the North American Benthological Society* 24(3): 690-705.
- Wang, L. and Kanehl, P. (2003) 'Influences of watershed urbanization and instream habitat on macroinvertebrates in cold water streams'. *Journal of American Water Resource Association* 39(5): 1181-1196.
- Wardynski, B.J., Winston, R.J. and Hunt, W.F. (2013) 'Internal Water Storage Enhances Exfiltration and Thermal Load Reduction from Permeable Pavement in the North Carolina Mountains'. *Journal of Environmental Engineering* 139(2): 187-195.
- Winston, R.J., Hunt, W.F. and Lord, W.G. (2011) 'Thermal mitigation of urban storm water by level spreader-vegetative filter strips'. *Journal of Environmental Engineering* 137(8): 707-716
- Young D, Afoa E, Meijer K, Wagenhoff A, Utech C (2013). *Temperature as a contaminant in streams in the Auckland region, stormwater issues and management options*. Prepared by Morphum Environmental Ltd for Auckland Council. Auckland Council technical report, TR2013/044