Sustainable Technologies
EVALUATION PROGRAM

Data Synthesis and Design Considerations for Stormwater Thermal Mitigation Measures

Prepared by:

Toronto and Region Conservation Authority
Credit Valley Conservation

Prepared for:

City of Brampton

January 2019

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THE SUSTAINABLE TECHNOLOGIES EVALUATION PROGRAM

The water component of the Sustainable Technologies Evaluation Program (STEP) is a partnership between Toronto and Region Conservation Authority, Credit Valley Conservation and Lake Simcoe Region Conservation Authority. STEP supports broader implementation of sustainable technologies and practices within a Canadian context by:

- Carrying out research, monitoring and evaluation of clean water and low carbon technologies;
- Assessing technology implementation barriers and opportunities;
- Developing supporting tools, guidelines and policies;
- Delivering education and training programs;
- Advocating for effective sustainable technologies; and
- Collaborating with academic and industry partners through our Living Labs and other initiatives.

Technologies evaluated under STEP are not limited to physical devices or products; they may also include preventative measures, implementation protocols, alternative urban site designs, and other innovative practices that help create more sustainable and livable communities.

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Background

Urbanized landscapes provide less shade for watercourses than natural areas and supplies thermally enriched storm water runoff from heated paved surfaces and roofs. When runoff is drained through storm water ponds, solar radiation heats the open pond water, causing further thermal enrichment before it is released into the receiving stream. In some contexts, the thermal pollution from storm water ponds can offset the cool water temperatures of streams beyond the tolerance threshold of the inhabiting species.

Several practices have been developed to help reduce warming of stormwater by urban infrastructure and stormwater ponds. Regional data on the operation and effectiveness of many of these practices have been collected as part of monitoring programs mandated by the Ministry of Natural Resources and Forestry for the protection of endangered Redside Dace and other species of concern. Other Low Impact Development practices implemented upstream of ponds have been monitored extensively by the Toronto and Region and Credit Valley Conservation Authorities. However, the available data have not been rigorously analyzed and synthesized to determine the relative effectiveness and limitations of the different practices in achieving thermal objectives.

This project helps to address this knowledge gap by synthesizing existing performance data on thermal mitigation measures installed in southern Ontario, and offers insights on the design and application of the measures for future stormwater infrastructure projects. The focus of the synthesis is on measures that can be implemented within the stormwater pond block, and in areas upstream of the stormwater pond. Measures suitable for areas draining to existing or recovering habitat for red-side dace and other cool water species are prioritized.

Project Scope

This report focuses on the analysis of thermal mitigation measures that have been monitored for performance in a southern Ontario climate. Data on thermal and chloride stratification in ponds and the timing of warm water release are reviewed as context for understanding the performance and optimal design of some measures. Monitoring procedures for thermal mitigation projects are also presented to help improve consistency and identify key parameters for future monitoring programs.

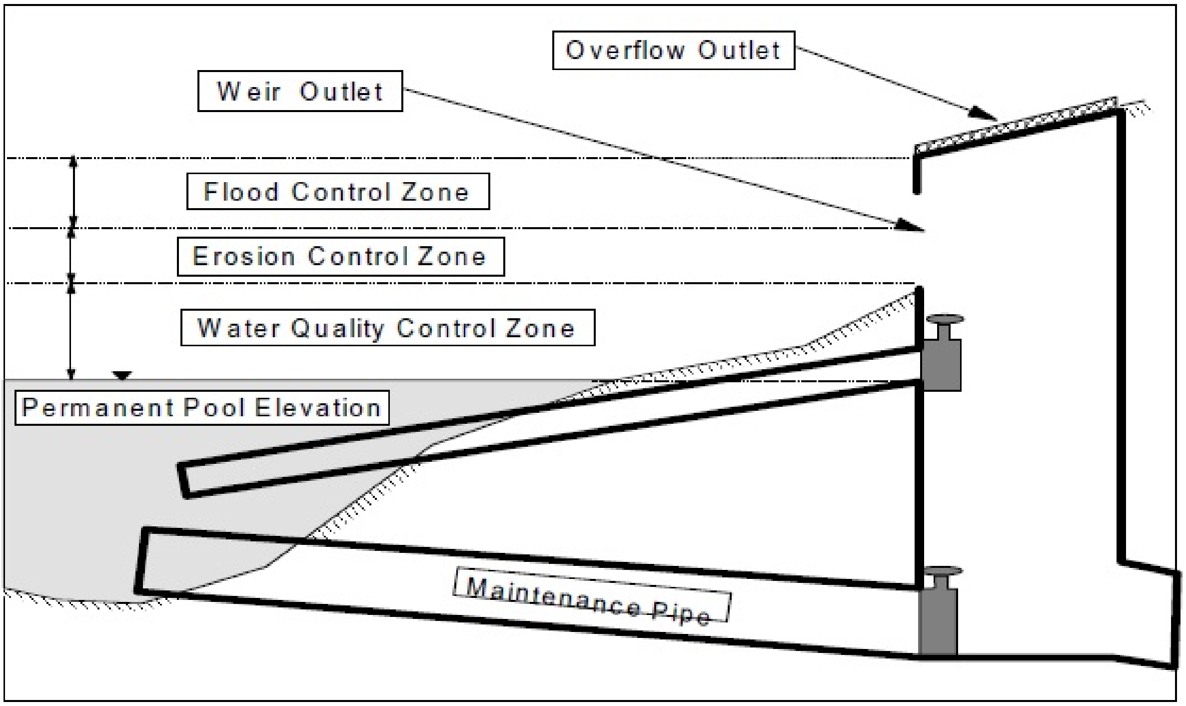
The monitoring data set of practices reviewed and analyzed in this project included 18 subsurface draw outlets, 18 cooling trenches, 14 Low Impact Development practices (bioretention/soil cells, infiltration trench, green roof, permeable pavement), one night time release outlet, one subsurface pond, one vegetated channel and one floating island.

Findings

Subsurface Draw Outlets

How do they work?

A reverse sloped outlet pipe drains cooler water from below the pond permanent pool water level to a control manhole that is accessible from the bank for ease of maintenance. Deeper outlets result in cooler outflows than shallow outlets because pond water temperatures decrease with depth.



Expected performance

- Although outflow temperature will decrease at outlet invert elevations starting at 0.5 m below the permanent pool water level, more significant cooling requires subsurface draw outlets to be located at least 1.2 m below the permanent pool water level, as this is the level at which significant reductions in the amplitude of diurnal fluctuations in water temperature are observed in most ponds.
- Meeting the 24ºC target for the protection of Redside Dace at least 95% of the time during an average year requires that outlets draw water from at least 2.0 m below the permanent pool water level.
- Relative to a surface draw outlet, the expected 95th percentile temperature reduction provided by a 2 m deep draw outlet for years with similar air temperatures is between 3 and 5ºC.
- Year to year average shallow subsurface draw outlet temperature differences of between 2 and 4ºC can be expected due to variations in weather, with dry, hot weather years generating the warmest outflow temperatures.
- Anoxic conditions of bottom waters are common in shallow and deep ponds, particularly older ones. Anoxic conditions can result in redox reactions that enhance the release of phosphorus and heavy metals from deposited sediments. However, there is insufficient evidence to suggest that anoxic bottom waters and redox reactions in deeper ponds would necessarily result in poorer effluent water quality than that of shallower ponds, or that subsurface draw outlets with sufficient separation (minimum 0.5 m) from the pond bottom would discharge poorer quality water than surface draw outlets.

Design and maintenance considerations

- Deep draw outlets require deep ponds to be effective from both a cooling and maintenance standpoint. Based on MECP guidelines on sediment maintenance frequency and accumulation volumes, it is estimated that a pond with an outlet 2.0 m below the permanent pool elevation should be at least 3.0 to 3.5 m deep at the outlet for drainage area impervious covers between 35 and 85%, respectively. These depths would allow some clearance between the outlet and pond bottom at the time of maintenance and avoid the requirement for pond cleaning prior to the normal sediment maintenance life cycle.
- Deep draw outlets should not be combined with scour pools in the immediate vicinity of the outlet, as these can reduce thermal performance by creating turbulence that enhances vertical mixing of thermally stratified water at the location of the outlet. Larger, gently sloping depth increases to the outlet will provide more consistent and dependable cooling benefits because of the larger volume of cool water below the outlet invert and the lower propensity for vertical mixing.
- Deeper ponds may require larger footprints to meet the MECP side slope requirements of 5:1 above the permanent pool and 3:1 elsewhere.
- Subsurface draw outlets require occasional inspection and flushing to prevent blockage. Perforated reverse slope pipes are not recommended as these can reduce thermal benefits by drawing warmer water from higher elevations in the pond.

Night time Release Outlets

How do they work?

Real time controls are installed on pond outlets to automatically close outlets during the day when surface outflows from ponds are warmer, and release it during the night when outflow temperatures are cooler. The outlets are configured and programmed to maintain release rates below threshold values for stream erosion and match pre-development peak flow rates.

Expected performance

- Based on modelling of four ponds, the 95th percentile temperature reduction for ponds with night time release outlets was calculated to be approximately 1.6ºC for surface draw outlets, and 0.6ºC for an outlet 1.4 m below the permanent pool level. For deeper outlets (i.e. below 1.2 m), including the one for which we had monitoring data, the benefits of night time release are very small as temperatures from these outlets do not exhibit strong diurnal variations.
- With optimized night time release outlets drawing from the surface, the 24ºC temperature target was calculated to be exceeded between 20 to 30% of the time over the period between June 15 and September 15.

Design and maintenance considerations

- Optimal 8 hour duration for night time release outlets was found to be between 3 AM and 10 AM inclusive based on data from 4 ponds.
- Optimal 4 hour duration release times were found to be between 6 and 9 AM inclusive.
- Robust automation technology is critical to avoid excessive repairs and down time.
- Electrical supply and back-up power are typically needed at the outlet to reduce operation and maintenance requirements

Cooling Trenches

How do they work?

Cooling trenches typically consist of one or more geotextile wrapped perforated pipes embedded in a clear stone filled trench that is buried underground. Contact of warm pond outflows with cooler stone media and side walls promotes transfer of heat from the water to the stone and surrounding soils, thereby reducing the temperature of outflows discharged to the stream. Built-in overflows bypass high flows to help enhance thermal function and prevent excessive sediment build-up in the trench. Cooling trenches may be installed downstream of the primary pond outlet or draw from a secondary orifice controlled outlet draining water from the pond at or below the permanent pool water level.

Expected performance

- Performance of primary outlet cooling trenches is highly variable, primarily due to differences in cooling trench sizing, trench design specifications, initial temperature of pond outflows, and degree of groundwater interaction, the latter of which has not been adequately quantified in monitoring programs.
- Nine of the 16 primary outlet cooling trenches reviewed had limited to no outflow cooling benefits, while others showed average summer outflow temperature up to 9ºC below the pond outlet temperature.
- Monitoring from two secondary outlet cooling trenches showed 95th percentile temperature reductions in the 4 to 5ºC range over the course of the summer. However, these were designed to cool only a small portion of total pond outflows.
- Cooling trenches have been combined with deep subsurface draw outlets, and found to provide additional cooling, despite the cooler starting temperatures.

Design and maintenance considerations

- Thermal sizing calculations indicate that trenches almost as large as the pond permanent pool volume are required to effectively cool all of the flows exiting the pond
- The empirical data did not provide definitive evidence on the required size of trenches for successful cooling. However, as a rule of thumb, and loosely based on the case studies reviewed, primary outlet trenches without groundwater interaction will likely provide summer temperature cooling of the warmest flows by roughly 1 to 3ºC if the trench storage volume is equal to or greater than 5% of the runoff volume discharged from the pond during the 25 mm event. Trenches with smaller storage volumes cannot be relied on to provide any cooling benefits, although the case studies suggest that under favourable conditions, these may still provide some cooling.
- Flush-out pipes, high flow bypasses and sediment pre-treatment mechanisms should be provided to reduce maintenance. Pre-treatment filters, energy dissipaters or isolator rows will require regular inspection and maintenance to ensure they are fulfilling their intended function.
- Secondary pond outlets that drain water from 0.5 m below the permanent pool elevation to cooling trenches can help to reduce or eliminate the long duration and very warm inter-event flows that often exceed pond design drawdown time targets.

Low Impact Development Practices

How do they work?

Low Impact Development Practices can be implemented within the upstream drainage area or pond block to provide cooling. They increase the capacity of streams to assimilate thermal impacts primarily by reducing stormwater volumes through infiltration, evapotranspiration and/or reuse, although several practices also reduce temperatures.

Expected performance

- Of the 12 LID practices monitored for thermal mitigation potential, only bioretention and infiltration trenches generated effluent summer temperatures consistently below the 24ºC target. Several of these had 95th percentile temperatures below 22ºC.
- All LID practices monitored showed median thermal load reductions of greater than 65% during the June to September period, and most had reductions above 80%.
- Practices with outlets located at least 0.7 m below the surface tended to have the highest thermal load reductions.

- Most LID practices produced outflows with constant temperatures that were not influenced by diurnal fluctuations in air temperature.

Design and maintenance considerations

- Calculations for three ponds with flow and temperature data showed that infiltration systems drawing flows from the pond surface would provide seasonal thermal load reductions equivalent to those of a deep subsurface draw outlet at bottom area sizes of up to 6.6% of the pond surface area in areas with tight native soils (3 mm/hour infiltration) and up to 1.6% of the pond area in areas with loamy and sandy native soils (>12 mm/hour infiltration). In the examples reviewed, achieving this condition required diversion of flows from the pond to the infiltration system at maximum flow rates of between 0.22 and 1.01 L/s.
- Systems may need to be located under raised areas such as access roads to provide separation distance between the bottom of the facility and the seasonally high groundwater table. This also helps reduce space used by the systems.
- When implemented for thermal mitigation in combination with stormwater ponds, LID practices are best located within the pond block where systems can draw water continuously from pond outflows that often discharge warm water for several days after rain events.
- Enhanced thermal load reduction benefits may be achieved if the primary pond outlet from which flow is being diverted is drawing cooler water from below the pond normal water level.
- Diverting sufficient flows to maintain a constant hydraulic head in the infiltration system will increase infiltration rates and enhance overall system cooling effectiveness.
- As with cooling trenches, infiltration systems require flush outs, bypasses and sediment pre-treatment mechanisms to enhance system function and maintenance.

Other practices

- Monitoring of a vegetated channel installed downstream of a pond with a 1.4 m subsurface draw outlet showed average temperature reduction benefits in the 1 to 2ºC range, which at that site was sufficient to limit impacts to the cooler receiving watercourse. Maximum and 95^{th} percentile outflow temperatures were not reduced by the channel.
- Underground detention chambers, such as the StormTrap system monitored under STEP, have the potential to cool inflowing runoff and maintain temperatures suitable for discharge to cool water fisheries (below 22ºC). Concrete detention chambers also have the added benefit of being easier to maintain than ponds, although eventually they will need to be replaced.
- A floating island was also investigated, but shown to have limited thermal reduction benefits, likely due to the limited areal extent of cover, which in this case was 10% of the pond area. Maintenance requirements can be higher for vegetated systems than for underground infrastructure.

Further Research Needs

A monitoring protocol for future thermal mitigation projects is provided to assist with practice assessment and further knowledge development aimed at improving the design and predictability of the practices being implemented.

This review has shown that practices that reduce both temperatures and thermal loads can be effective either as an alternative or in combination with more common subsurface draw systems. Further monitoring of temperature and flow from ponds and receiving waters is needed to determine appropriate sizing guidelines for these systems in different contexts. Research on installed systems is needed to optimize system designs from a performance and maintenance perspective, and to better understand long term operational requirements and constraints.

The performance of cooling trenches is influenced by a large range of factors that make outcomes difficult to predict. Improved monitoring programs that better document the initial temperatures, flow volumes and rates, groundwater temperature and interaction, surrounding native soil temperatures and other factors will help to provide a better basis for sizing and performance prediction.

Other less conventional practices, such as those that provide surface cover or active geothermal cooling using boreholes need further investigation as thermal mitigation options that may be feasible within a municipal context.

1.0 INTRODUCTION

1.1 Background

Stream health is dependent on a variety of factors including hydrology, temperature, geomorphology, habitat structure and water quality (Karr 1991). Among these, water temperature is a critical parameter as it regulates both biotic and abiotic processes in streams (Nelson and Palmer 2007). Therefore, it can be both the driving and constraining factor for the survival of aquatic organisms. The water temperature regime in streams is influenced by the source of discharge (*e.g.* groundwater, surface runoff), shading, solar radiation, and anthropogenic stresses. During the summer months, a longitudinal gradient of cooler upstream and warmer downstream waters can be observed. Near the headwaters, the streams are well shaded from solar radiation and primarily fed by cool groundwater, which averages approximately 8°C in southern Ontario (Chu et al. 2009). Cool water streams in southwestern Ontario undergo natural diurnal temperature fluctuations of 3 to 5ºC due to solar radiation and air temperature effects alone without input from surface runoff (Wren 2008). Urbanized landscapes provide less shade for the watercourse and supplies thermally enriched storm water runoff from heated paved surfaces.

When runoff is drained through storm water wet ponds, solar radiation heats the open pond water, resulting in thermally enriched discharges to the receiving watercourse. Section 4.4 of the MECP Stormwater Management Planning and Design Manual (MOE 2003) acknowledges that the use of stormwater ponds for water quantity and quality control can impair receiving stream habitat through heating of the discharge water. Maximum temperatures of pond effluents in Greater Toronto Area ponds typically range between 26 and 31ºC, with observed inlet to outlet temperature increases of between 4 and 11ºC during the summer months (TRCA, 2005; TRCA, 2013; CVC, 2011). Variations in discharge temperatures among ponds can be explained by several factors, especially detention time and the elevation of the outlet below the permanent pool. In some contexts, the thermal pollution from storm water ponds can offset the cool water temperatures of streams beyond the threshold of the inhabiting species.

Stoneman and Jones (1996) introduced three thermal classifications for streams: warm water, cool water, and cold water. Their characteristic maximum threshold temperatures are 38°C, 26°C, and 20°C respectively (Chu et al. 2009). However, organisms that survive within a certain stream thermal classification may actually prefer cooler temperatures than the stream classification's maximum. For example, rainbow trout is a cold water species that prefers a temperature of 11.3°C, while Redside Dace is a cool water species that prefers a temperature of 18.5°C (Chu et al. 2009). Redside Dace was designated as a special concern in Canada in 1987 and listed as endangered in 2007 mainly due to its sensitivity to habitat alterations that increase siltation and water temperatures (COSEWIC 2007). At the time of writing, the Ministry of Natural Resources and Forestry requires that temperatures from stormwater management facilities not exceed 24ºC for the protection of Redside Dace and other cool water species.

1.2 Project Objectives

This project synthesizes existing data on thermal mitigation measures installed in the City of Brampton and other GTA municipalities, and offer insights into the design and application of the measures for future stormwater infrastructure projects within the City.

The focus of the synthesis is on measures that can be implemented within the stormwater pond block, and in areas upstream of the stormwater pond. Measures suitable for areas draining to existing or recovering habitat for red-side dace are prioritized. Temperature and thermal loads are considered with the aim of providing a range of options that can be tailored to site conditions and cost effectively replicated in new and existing developments across the City of Brampton and in other urban or urbanizing areas across Ontario.

2.0 THERMAL MITIGATION MEASURES

2.1 Thermal mitigation options

Various options for thermal mitigation of stormwater runoff have been identified in the literature. These measures can be implemented at different locations within the catchment drainage network from the source of runoff generation to the receiving water with varying impacts on thermal loads to receiving waters. Table 1 presents options that have been employed by agencies. Comments on the applicability of measures within municipalities and anticipated operation and maintenance requirements are provided.

The level of operation and maintenance effort was assessed based in part on inspection and maintenance guides for storm ponds and Low Impact Development (LID) practices prepared by TRCA through the Sustainable Technologies Evaluation Program. Both of these documents were developed based on extensive literature reviews (TRCA 2016a; TRCA and CH2M Hill 2016). Other measures such as night time release outlets and floating islands were assessed based on surveys of municipal and CA staff with implementation experience. The addition of trees and vegetation within the pond block can impose additional maintenance burdens on municipalities, but unlike other measures, these contribute to municipal urban canopy and carbon sequestration targets, and provide community amenities that may justify implementation of the measure regardless of their thermal benefits.

2.1.1 Upstream Catchment

Within the upstream catchment, thermal mitigation measures that reduce the areal extent of impervious cover and promote natural processes of infiltration and evapotranspiration can result in substantial thermal load reductions. Runoff volume reductions consistent with the 90^{th} percentile target currently stipulated in the MOECC draft LID guidance manual would reduce thermal loading by at least 90% relative to a conventional pond design, particularly if this level of control allowed a dry pond to be used for flood control instead of a wet pond. Use of natural swales or ditches for drainage conveyance, enhanced canopy cover or using pipe materials that accelerate heat transfer to the surrounding ground can also help moderate temperatures.

2.1.2 Pond Block

A number of measures may be implemented within the pond block with limited impact on municipal operation and maintenance costs. The most common are physical structures such as subsurface draw outlets, cooling trenches and night time release outlets (although the latter may require more effort if robust automation measures are not employed). Unlike vegetative measures that require time to provide significant shading, these structural measures offer immediate cooling benefits.

Infiltration systems within the pond block are not often implemented despite having the potential to provide significant thermal load reduction benefits through flow volume and water temperature reductions. These can be inspected at the same time as the pond, and are easier to maintain than similar measures implemented within the upstream developed area. They can also help meet site water balance targets. Drainage to infiltration systems in the pond block may involve directing a portion of the treated pond water through a separate outlet, or installing a split flow device that diverts low flows to the infiltration feature. Systems can be elevated beneath access roads to create separation distance from the groundwater table while limiting space requirements. To reduce maintenance, flows to the infiltration system should have low sediment concentrations, and receive additional pre-treatment through measures implemented at or upstream of the inlet to the systems (e.g. isolator rows, gravel diaphragms, coarse filters for debris).

Table 1: Thermal mitigation options for urban drainage systems

Location	Thermal Mitigation Measure	Applicability	O&M Level of Effort
Upstream Catchment	Reduce Impervious Cover	Applicable at early planning stages	May reduce O&M relative to conventional development
	Enhance tree canopy	Long time periods required to establish significant canopy cover; Helps meet urban canopy targets	O&M covered under municipal urban forestry program
	LID Practices	Reduces thermal load through runoff volume retention and/or temperature reductions	Moderate; may reduce pond O&M if allows conversion to dry pond
	Drainage pipe materials	Municipal pipe material standards may limit the range of available options	Low
Pond Block	Infiltration practices	Reduces thermal load through runoff volume retention and/or temperature reductions; Groundwater table elevation may limit infiltration opportunities; requires additional space; can help meet water balance targets.	Low, assuming that flows draining to system have been pre-treated through the pond and additional pre-treatment is provided through the system (e.g. isolator row for chambers)
	Perimeter shading	Long time periods required to establish significant canopy cover; Helps meet urban canopy targets	Low
	Pond orientation and L:W ratio	Long ponds oriented in an east-west orientation enhance bank shading effects; not always feasible; Effective only once vegetation is mature	Low
	Direct pond shading	Floating vegetation attracts birds, prone to ice damage but provides other benefits; Coverage with inert materials also an option; Underground tanks costly but can increase area for park land	Moderate for floating islands; low for non-vegetative cover types
	Subsurface draw outlet	Requires sediment storage below pipe	Low
	Night time release	Daytime release may be required under some circumstances	Moderate, depending on level of automation
	Cooling trench	Requires significant land area to provide the necessary storage	Low for the same reasons as infiltration systems above
	Spreader swales or pocket wetlands	Generally applicable in most areas but effectiveness may be limited by available land area	Low
Receiving Watercourse	Enhanced riparian shading	Requires public ownership of riparian buffer	Low
	Use of natural woody materials	May not be suitable for all stream flow regimes	Low

Floating islands that provide at least 1/3 surface coverage may provide cooling benefits by reducing direct solar heating and removing heat through latent heat of vaporization. However, maintaining the floating mats may be cost prohibitive. Inert materials such as shade balls likely offer similar benefits with fewer maintenance concerns, although further monitoring is required to quantify benefits. Underground concrete chambers have been used in lieu of ponds in some areas of the GTA. These are often constructed beneath parks to avoid utilizing developable lands and offset installation costs. Sediment maintenance of these practices is more routine, using conventional vacuum truck equipment, and may be less costly than surface pond cleaning in the long run.

2.1.3 Receiving watercourse

Modifications to the receiving channel and riparian areas are generally not accepted as a standalone stormwater pond mitigation measure for the protection of sensitive aquatic species. It is mentioned here, however, as a measure that has been used to limit the extent of impacts within the stream, and provide cooling benefits to downstream areas. The primary measures of interest relate to the use or replacement of hard materials (e.g. concrete, rock) with softer, more natural materials, and riparian shading, the latter of which is comparably more effective than pond shading because of the long linear form of creeks and rivers. These measures may be implemented upstream or downstream of the point of pond discharge to the creek. Upstream enhancements would more directly mitigate thermal impacts from a pond outfall and could be more beneficial than an equal distance of treatment within the outlet channel draining the pond.

2.2 Selection of appropriate measures based on site conditions

The physical characteristics of a site will influence the effectiveness of measures selected to mitigate temperatures and thermal loads. In retrofit contexts, there may be limited opportunities to implement mitigation measures within the catchment, leaving the pond block and channel as the most suitable areas for intervention. On new development sites, the options are more variable, and can be combined with meeting other water quantity, water quality or water balance requirements. Some of the variables of interest and mechanisms through which they can influence the selection and/or design of thermal mitigation measures are presented in Table 2.

Table 2: Variables of interest and mechanisms through which they can influence selection and/or design

Variable	Influence on application of thermal mitigation measures
Fine textured native soils	Fine textured soils limits runoff and thermal load reduction potential
Groundwater table elevation	High g/w table in catchment may limit use of LID thermal load reduction measures
Groundwater interaction at outlet	High g/w at pond may provide opportunities for g/w interaction that enhances cooling trench performance; may reduce potential for deeper pond and reverse slope outlet
Good canopy cover	Good cover reduces summer heating of impervious surfaces
Pond block size	More space provides options for infiltration systems and other cooling features; Pond may be deeper while meeting maximum side slope requirements; may reduce available area for building lots
Available space at outlet	More space provides options for longer cooling trench or swale; May reduce available area for building lots depending on land ownership
Long drawdown time	Provides some protection from solar radiation to deeper waters by increasing the average annual pond water depth since slow release requires longer water detention
Deep pond	Provides option for enhanced cooling with deeper subsurface draw outlet
Outlet close to or within floodplain	Infrequent flood flows may damage thermal mitigation measures installed near outlet
Frequent overbank flows	Limits available options for riparian enhancements and use of natural materials in stream restoration; can adversely influence pond outlet thermal mitigation measures
U/S and D/S riparian area privately owned	Limits interventions that improve riparian cover

2.3 Temperature vs thermal load

Criteria for the protection of aquatic life are often expressed as temperature thresholds for species of varying tolerances. This is an appropriate metric for riverine and lacustrine habitats. However, when applied to point or non-point source discharge of runoff, the metric loses much of its meaning because both the discharge volume and temperature of runoff will influence the temperature regime of receiving waters. For this reason, the thermal load is the more relevant metric as it takes into consideration both the temperature and volume of runoff discharged to the stream. The thermal load (TL) is calculated as:

Equation 1: $TL = Q * \rho * T * C$

Where:

Q = flow rate (m^3/s)
ρ = water density (1000kg/m^3)
T = water temperature
C = heat capacity (4187J/kg/C)

Thermal mitigation techniques should consider both temperature and volume impacts to optimize in-stream benefits to aquatic organisms. Since current criteria are denominated as a set temperature threshold, it may be necessary for approvals purposes to show how projects that target volume reductions can produce equivalent thermal load reductions to projects targeting temperature alone. For instance, a project that reduces thermal loads via a shallow pond outlet and infiltration chamber system can be sized to achieve the same seasonal and/or event based thermal load reduction as a pond with a deep subsurface draw structure that meets the 24ºC target most of the summer.

Unfortunately, determining the size of infiltration chamber system prior to development requires generating an outflow thermal load, which may be difficult to accomplish using existing modelling tools. In this report we estimate the required infiltration volume and size of facility based on empirical data from subsurface draw ponds that have been monitored both for flow and temperature, not only at the outlet of the pond but also at different depths within the pond. From these data sets, thermal loads discharged from ponds can be calculated under different scenarios and used to assess the quantity of flow volume reduction (i.e. infiltration volume) required to achieve equivalent seasonal or event based thermal loads generated by a subsurface draw pond outlet with outflows meeting the temperature target. Oversizing the chamber or other infiltration system to account for potential errors would provide a buffer of safety to help address concerns about whether sufficient infiltration volume has been provided for the site in question. An example of such a calculation is provided in section 3.6.5 using continuous summer flow and temperature data from three ponds.

2.4 Shortlist of options to be addressed in this report

The focus of this data synthesis is on monitored measures listed in Table 1 above that can be implemented within the stormwater pond block, and in areas upstream of the stormwater pond. Low maintenance measures suitable for areas draining to existing or potential habitat for red-side dace are prioritized. Since thermal mitigation benefits need to be immediately available during and after construction of the pond, vegetative practices that require time to provide cooling benefits through shading will not be discussed. Thermal mitigation measures for which there are limited data will also not be discussed in detail, although some with potential applicability to stormwater ponds will be identified and described.

3.0 DATA SYNTHESIS AND ANALYSIS

The following sections present data from past projects that show (i) pertinent information on the function and characteristics of ponds as it pertains to thermal mitigation, and (ii) the effectiveness of different thermal mitigation measures that have been monitored. Based on these data and other relevant information, recommendations on practice design and application are provided for each measure.

3.1 Stratification in stormwater ponds

Stormwater ponds have been shown to stratify both thermally and chemically. Understanding the extent and causes of stratification is important to the design and configuration of thermal mitigation measures that take advantage of these characteristics of ponds, particularly outlets that discharge water from below the permanent pool surface.

3.1.1 Chloride stratification

Perhaps the most common measure for mitigating thermal impacts from stormwater ponds involves subsurface draw outlets that drain cooler water from below the surface of the pond. These subsurface draw outlets rely on strong vertical temperature and density gradients that resist breakup from mixing. While these gradients are largely brought about by air temperature and incident solar radiation, the accumulation of chloride from winter road salting is also an important contributing factor. Road salt (NaCl) is denser than water because its ions have greater mass and bind well with water creating a volume that is less than that of the water and salt combined. As salt water accumulates in ponds, it generates density gradients that inhibit mixing and promotes higher flow velocities at the surface.

Continuous summer chloride concentration measurements at the top and bottom of a pond in Newmarket show the degree of salt stratification and the gradual flushing process over the spring to fall period (Figure 1). While chloride was mostly flushed out of the top waters by June, a full year was required before the salt was fully removed from the pond bottom by flow from successive rain events. Temperatures of bottom waters were considerably less variable than surface waters during the warm summer months. Clearly the pond does not function as a plug flow reactor, with new water pushing out old water; nor are they fully mixed systems. Density and thermal gradients persist despite large volume flows, creating complex hydrodynamic patterns that can have an important influence on thermal performance.

Similar results were reported for a subsurface draw pond in Toronto (outlet at approx. 2.0 – 2.5 m below the normal water level), which included detailed depth profiles of chloride across the pond during the winter, spring, summer and fall (see Appendix A), as well as continuous chloride loads into and out of the pond. The pond was drained and cleaned in the fall of 1997 and continuous conductivity measurements were undertaken the following year. Figure 2 shows the gradual accumulation of chloride during the winter and early spring (load in > load out), and gradual release over the remainder of the year (load out > load in).

Some accumulation of chloride would have occurred prior to the beginning of sampling on February 24 and since a mass balance of chloride was achieved between February 24th and August 5th, it can only be assumed that the chloride accumulated prior to the initiation of monitoring in late February would have remained in the pond and been subject to further release during the late summer and fall of 1998. Detailed survey of the pond depths after 3 years of chloride in accumulation in 1997 and after only one year of accumulation in 1998 clearly show that chloride does accumulate over time (see profiles in Appendix A).

Sampling during the late winter period showed a distinct colour difference at the opening of the reverse flow pipe (2.5 m) and in the briny layer below (3.0m) (see Figure 3). While this colour difference became less pronounced during the summer, the presence of turbid water with fine textured sediments and high dissolved solids content suggest that drawing water from too close to the bottom may result in the resuspension of these loose sediments, reducing accumulation and generating poorer effluent water quality. Since the Rouge pond was 4 m deep at the outlet location, adverse effects were not expected, and good water quality in outlet samples supports this suggestion (SWAMP, 2004).

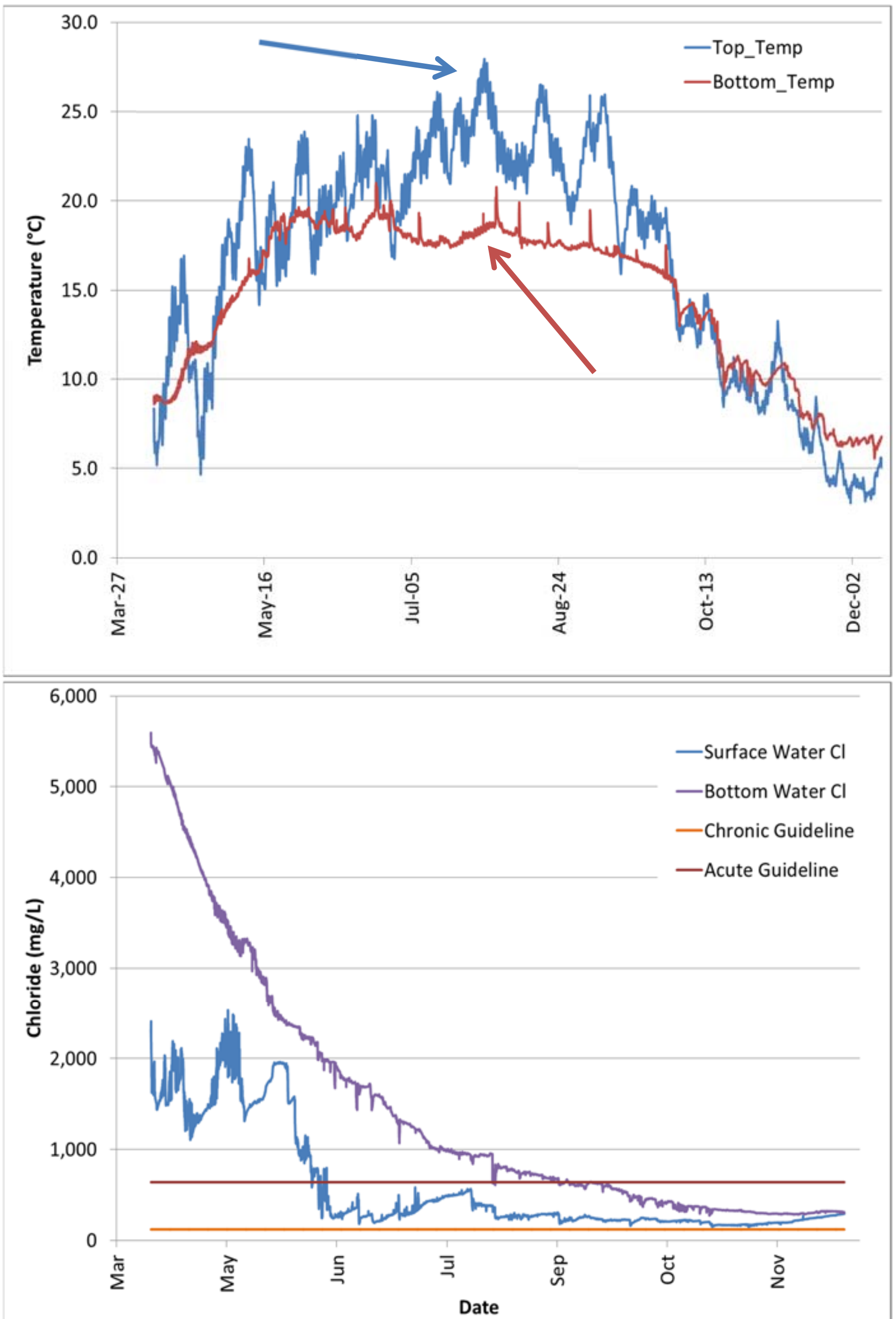


Figure 1: Thermal stratification (top) and chloride concentrations (bottom) in a Newmarket stormwater pond with top draw outlet (LSRCA, 2017). The chronic and acute lines refer to the respective chloride toxicity thresholds set by Environment Canada for sensitive aquatic species**.**

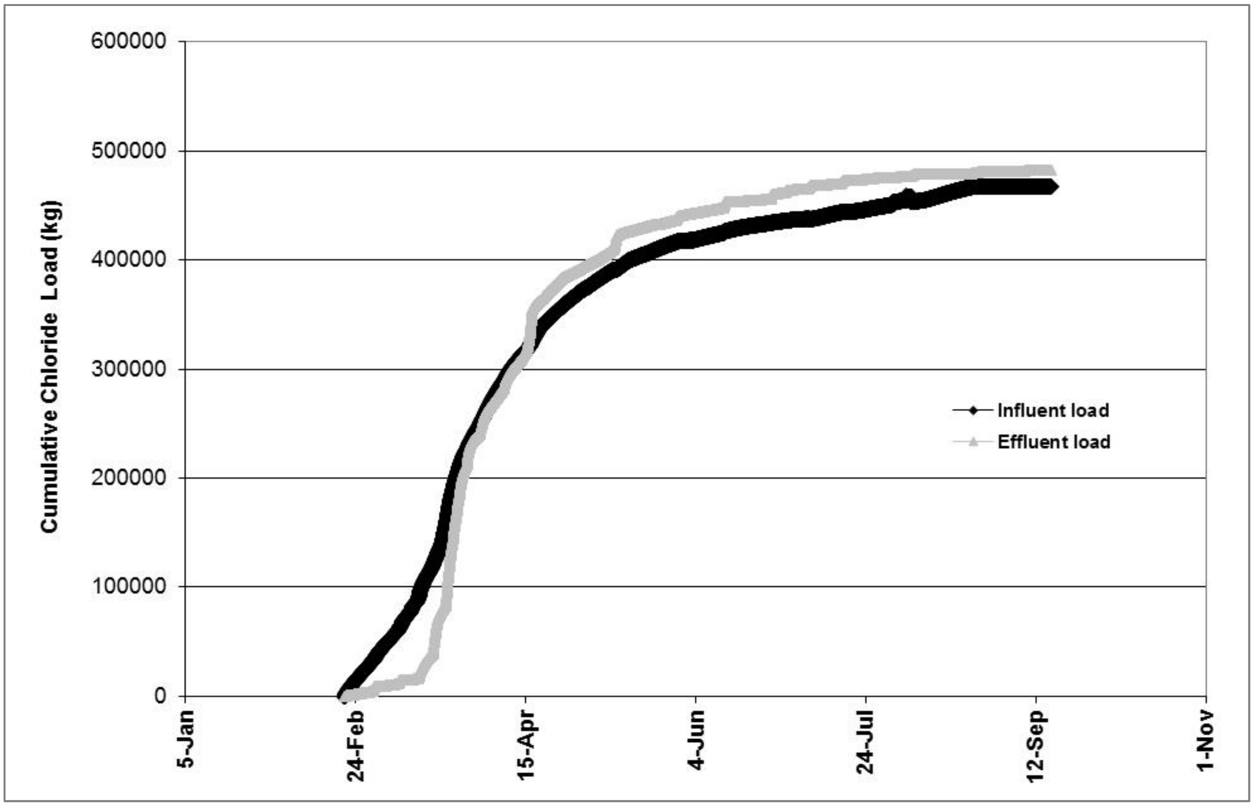


Figure 2: Chloride load into and out of a subsurface draw stormwater pond in Toronto from mid-February to mid-September 1998

Figure 3: Colour difference between samples collected from the Rouge pond in Toronto on April 1998 at 2.5 m (just below the outlet invert) and 3.0 m. See Appendix A for location of transects.

3.1.2 Thermal stratification

There is a wealth of data demonstrating that ponds stratify thermally. These data are derived from continuous temperature monitoring at various depths within ponds over the summer period. Figure 4 shows air and temperature frequency curves for six ponds where depth profiles were monitored. The 24ºC target for Redside Dace protection is shown to indicate the depth where the target is met.

All but one of the ponds (Pond 10) had data from June 15th to September 15th, which is the primary period of warming. Pond 10 was monitored late in the year in August and September, and was included because the air temperature S curve generally matches that of the other ponds, and stratification generally tends to weaken as the summer progresses. Hence, the profile is not likely to be an exaggeration of stratified conditions.

All of the profiles and associated time series graphs show that ponds are thermally stratified and remain stratified even after large rain events induce mixing and flush stored water out of the pond. This is true both for ponds with subsurface and surface draw outlets.

On average, the frequency curves show that temperatures at 1.5 to 2.0 m depth do not exceed the 24ºC target more than 5% of the time. During cooler summers the depth below the permanent pool water level at which the 24ºC target is met is greater than that shown during average or warmer summers. This is shown for the S7 pond in Brampton where air temperatures during the monitoring period did not exceed 29ºC, resulting in a shift of the curves to the left. Even temperatures at the 1.0 m depth below the permanent pool rarely exceeded 24ºC during this relatively cool monitoring period.

The Rumble pond in Richmond Hill and the HE5 pond in Brampton had subsurface draw outlets similar to that of the S7 pond (i.e. 1.5 - 2.5 m below the permanent pool elevation), but the warmer air temperatures meant that the 24ºC was met at a depth of 2.0 m, rather than the 1.0 m shown for the S7 pond. Other ponds with higher outlet elevations that were monitored during even warmer summers indicated that the temperature target is met at a 1.5 m depth (Majorwood, K74, Pond 10). This observation would suggest that lower outlet elevations may promote more vertical mixing relative to ponds with higher outlet elevations, and that depth profiles in shallow outlet ponds may not provide a reliable indicator of optimal outlet elevations for meeting temperature thresholds.

It should be noted that there were also a number of ponds where temperature depth profiles did not show stratification, or where stratification was not as pronounced. The Dunkers facility, for instance, included a pump back mechanism that moved significant volumes of water continuously from the cell where temperatures were being monitored to another isolated cell. This resulted in 24ºC temperature exceedance of roughly 15% above that of other surface draw ponds with similar air temperatures and no pump back mechanism. Even the 2.5 m depth showed some minor exceedances.

Other ponds that showed less stratification than expected appear to have been influenced by the outlet structure. Two of these are shown in Figures 5 and 6. In the Pickering example, the scour pool around the outlet appears to have enhanced mixing by creating a more variegated surface around the outlet pipe. Although some stratification is shown, the 1.8 depth below the scour pool within the sump was only marginally cooler than the 1.3 m depth just above it. In the case of Pond L-2, the perforated pipe is likely drawing water through the perforated pipe from multiple depths causing enhanced mixing. Although a depth profile was not available for this pond, the outlet temperatures are clearly not representative of the outlet pipe invert elevation.

In some cases, the pond was monitored shortly after cleaning. Thermal and chemical density gradients take some time to develop and may not become evident until the first or second winter after cleaning. The outlet flow rate can also influence stratification by creating higher velocity flows through the pond. The high outflow rates (as evidenced by low amplitude water level fluctuations during events) and pond cleanout less than a year before monitoring may explain the lack of a distinct profile in the Monarch pond in Markham (Figure 7).

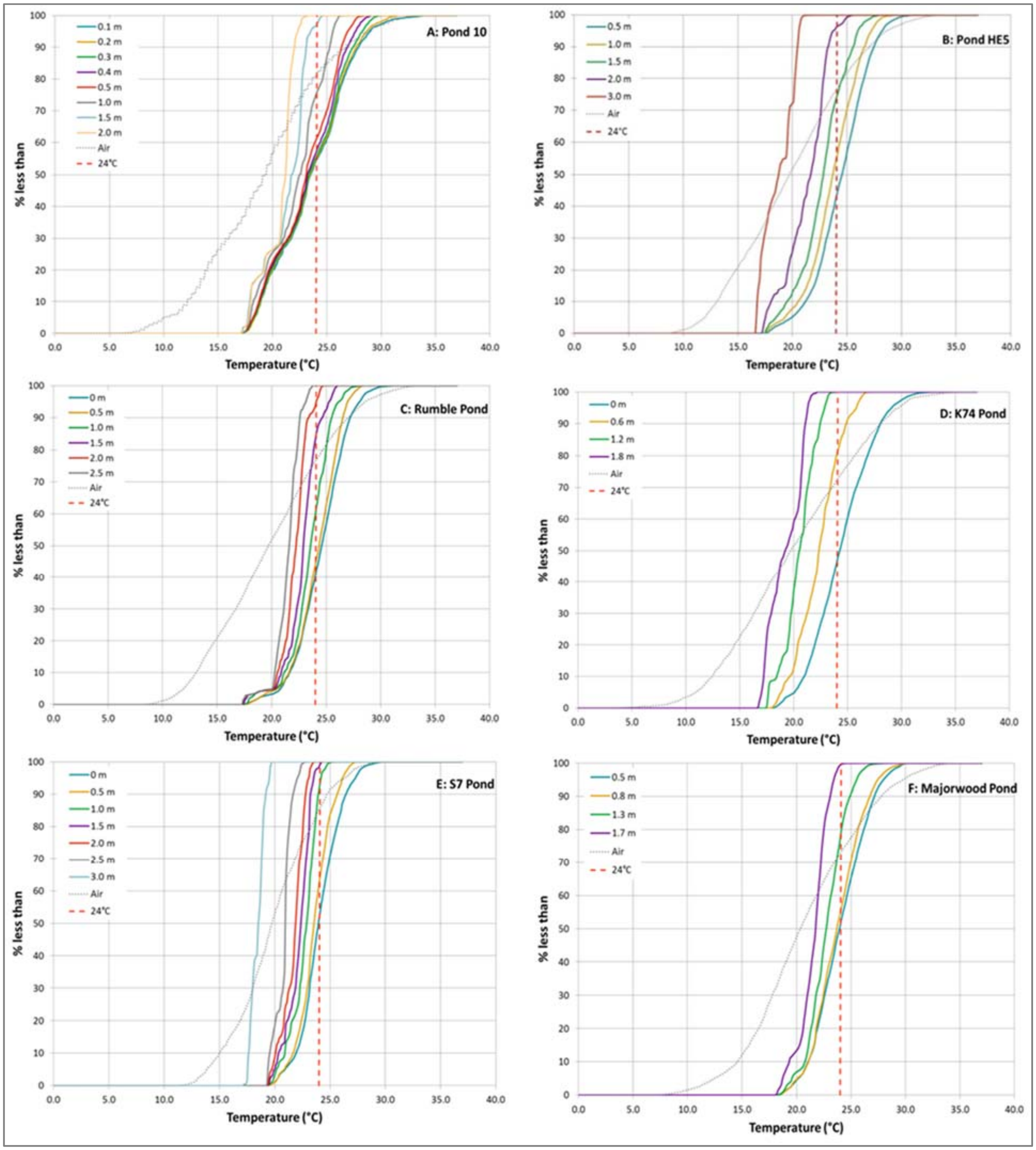


Figure 4: Temperature frequency curves for ponds. Depths are in meters below the permanent pool elevation.

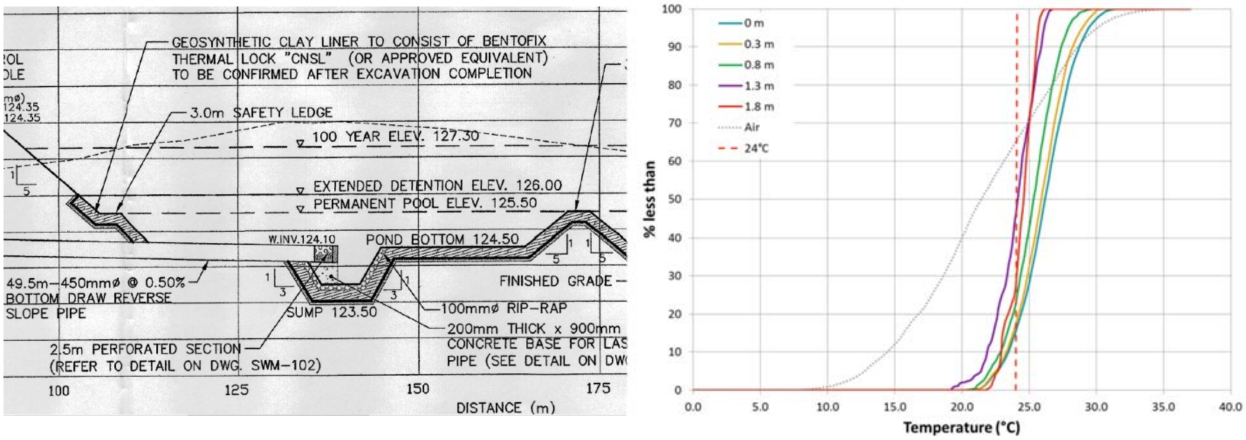


Figure 5: Pond with sump around the outlet, showing lack of vertical mixing below 1.3 m depth

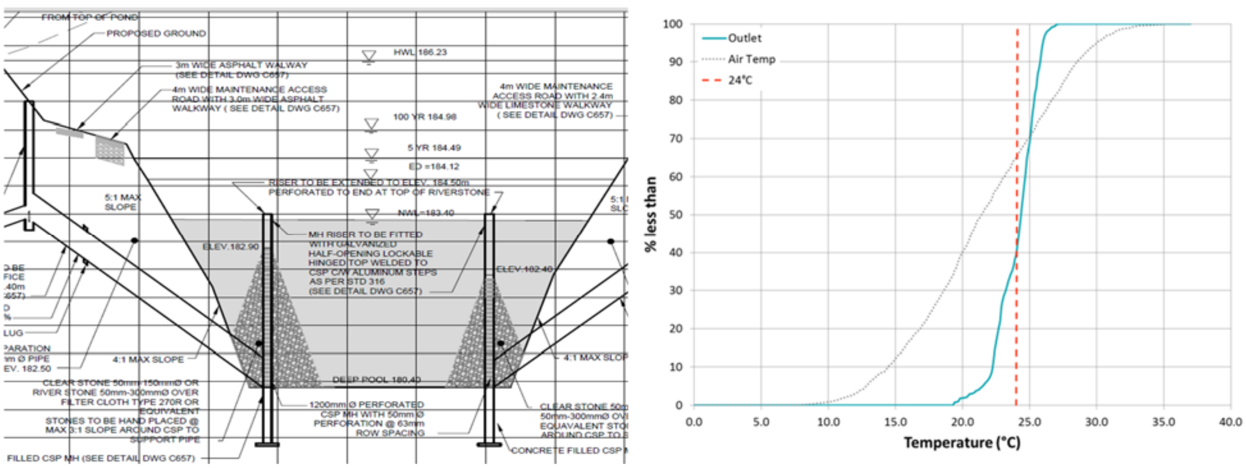


Figure 6: Deep draw outlet at 3 m connected to perforated hickenbottom riser. Outlet temperature is more representative of an outlet at 1.0 to 1.5 m below the NWL. (L2 pond in Brampton)

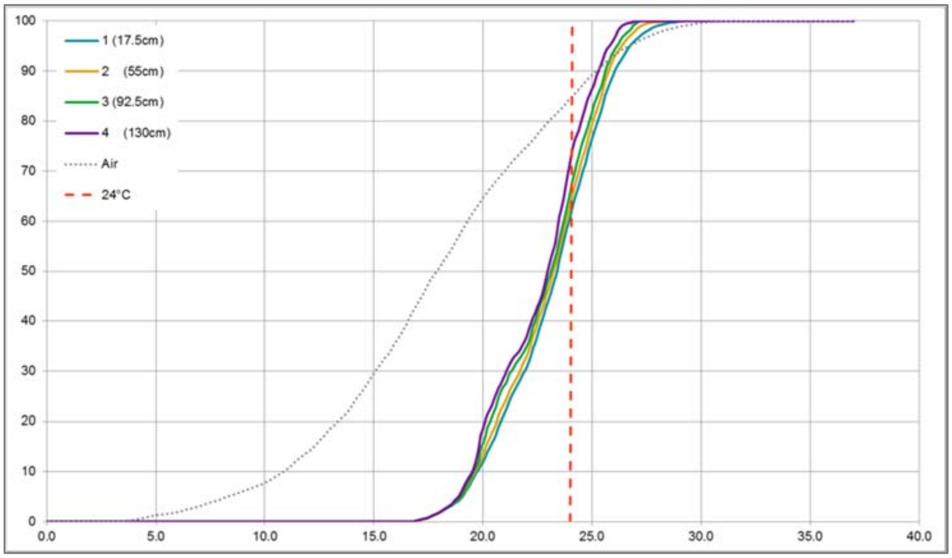


Figure 7: Temperature frequency curves for Monarch Pond

3.2 Subsurface draw outlets

As mentioned previously, outlets that draw water from below the surface of the permanent pool is one of the methods recommended by the Ministry of the Environment and Climate Change to reduce the thermal impacts of stormwater ponds (MOE, 2003). The outlet typically consists of a non-perforated reverse sloped pipe draining to an outlet chamber that is accessible from the bank for ease of maintenance. Orifice controls and weirs are installed within the structure to provide temporary storage and slow release of water to the receiving watercourse. The MOECC (MOE, 2003) recommends a minimum reverse slope pipe diameter of 150 mm, and a minimum orifice size of 75 mm (100 mm preferred to prevent clogging). Reverse slope pipes also help control oil spills because oil or other light liquids washed into ponds will be trapped at the surface rather than being discharged to receiving watercourses.

Both the invert of the outlet and air temperature influence outflow temperatures. The effect of air temperature is shown in Figure 8. The left graph shows year to year pond effluent temperatures from the Majorwood pond during years with similar air temperatures. Only small differences were observed, despite differences in rainfall patterns. The right graph shows the HE 5 pond outlet temperatures for years with different air temperatures. Median air and water temperatures both varied by 2.3ºC. However, in the neighbouring HE3 pond in Brampton, the variation in median outlet temperatures between the two years was 4.7ºC, highlighting the additional influence that pond design factors may have on outlet temperatures.

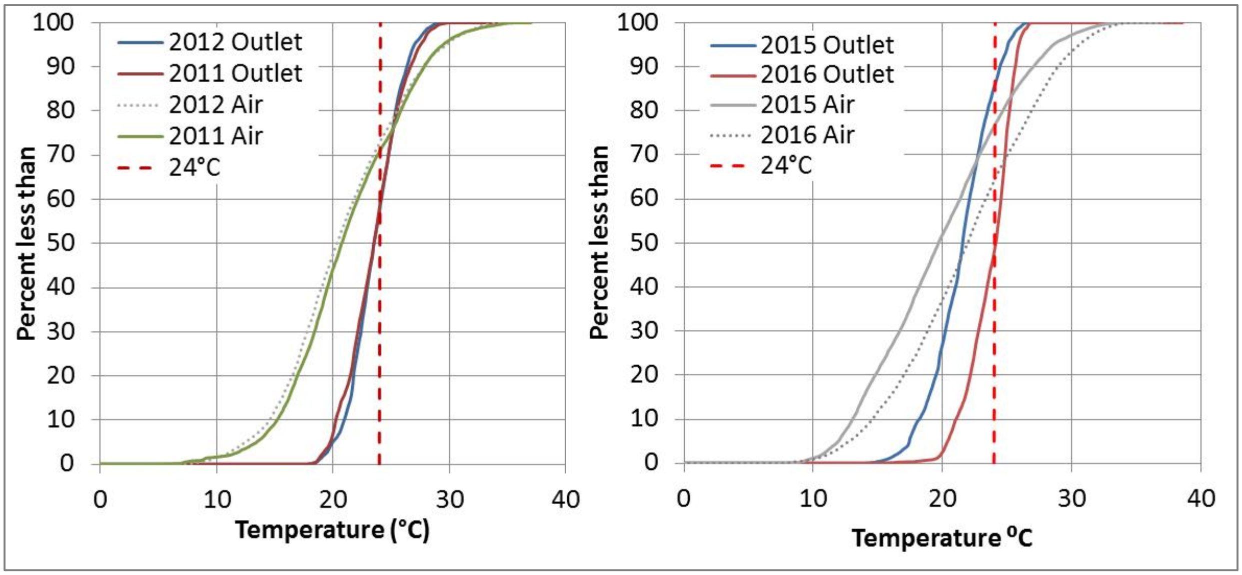


Figure 8: Pond outlet and air temperatures for two years at the Majorwood (left) and HE5 (right) ponds in Markham and Brampton, respectively.

Temperature frequency graphs for outlets at different elevations from different ponds are presented in Figure 9. The data show a distinct difference between surface and near surface draw outlets, and outlets greater than 2.0 m below the normal water level. Results between these two extremes are mixed due to differences in year to year air temperatures and other pond design factors. These data suggest that a subsurface draw outlet of roughly 2.0 m or greater would be needed to meet the 24^{o}C more than 95% of the time even during relatively warm summers. Even at 2.5 m, however, some exceedances could occur during warm years.

Relative to a surface draw outlet, an outlet drawing at greater than 2.0 m below the permanent pool elevation can normally be expected to discharge water at 90th percentile temperatures that are at least 3^{o}C lower and at maximum temperatures that are at least 5^{o}C lower. The thermal benefits are best achieved with deep ponds of 3.0 m or greater with non-perforated reverse slope outlets and even bottoms (no scour pools) that limit vertical mixing.

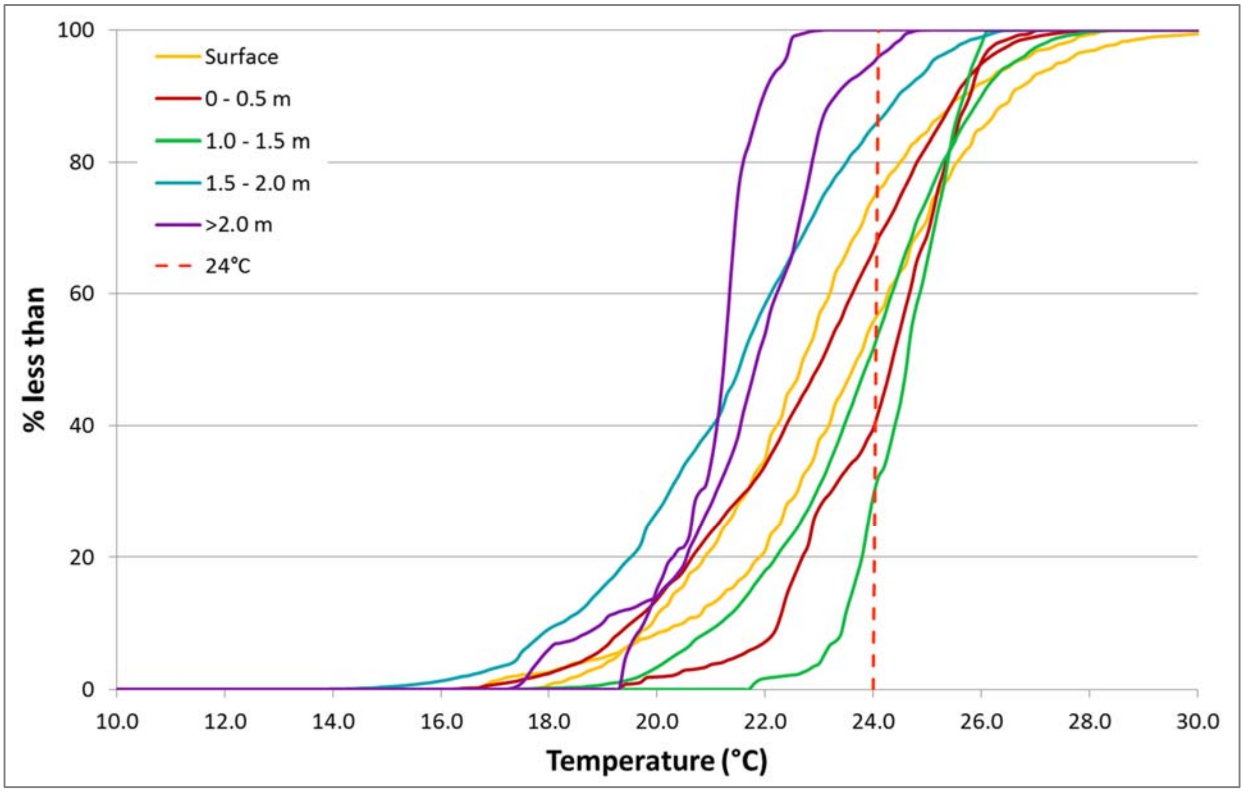


Figure 9: Temperature frequency plots for stormwater ponds with different outlet elevations (June 15 to Sept 15, different years). The coolest outlet temperature profile was from a 2.5 m draw pond in Brampton that was monitored from Jul. 8 to Aug. 28 during a year when air temperatures were cooler than normal.

3.2.1 Dissolved oxygen and pond performance

Subsurface draws often require very deep ponds in order to provide sufficient cooling while ensuring that adequate space is available for accumulation of deposited sediment below the outlet invert. Concerns have been raised that ponds greater than the maximum recommended depth of 2.0 m (MOE, 2003) may create anoxic zones that will result in the release of sediment bound phosphorus and heavy metals into the water column through redox reactions, leading to lower retention of these contaminants than would have been the case had the pond been shallower.

While there is ample evidence for the effects of low oxygen on pollutant adsorption/desorption, it is not clear that this process of enhanced release would necessarily be more problematic in deep ponds than in shallow ones. Monitoring has shown that all ponds have anoxic zones at depth, and that these anoxic conditions tend to worsen over time as sediment, particularly organic sediments, accumulate. This is shown with dissolved oxygen profiles in Figure 10 for a pond with a maximum depth of 3.5 m and a 2.0 – 2.5 m deep outlet (the Rouge River Pond in Toronto) and a shallower surface draw pond with a maximum depth of under 2.0 m (Harding Park Pond in Richmond Hill).

While the deeper pond shows anoxic conditions in the summer over a larger depth range, both ponds exhibit very lower oxygen in the bottom of the pond where sediments accumulate. The point at which oxygen conditions start improving in the deep pond is roughly equivalent to the location of the outlet invert, suggesting that deeper outlets may help oxygenate deeper waters above the invert of the pipe. By October 23rd, the second Rouge pond profile showed that conditions had improved as temperatures dropped and more chloride was flushed from the pond. Further evidence of low dissolved oxygen is provided in a comprehensive survey of 98 ponds in the Lake Simcoe Region, 42 of which were shown to exhibit daytime anoxic conditions in bottom waters (LSRCA, 2011).

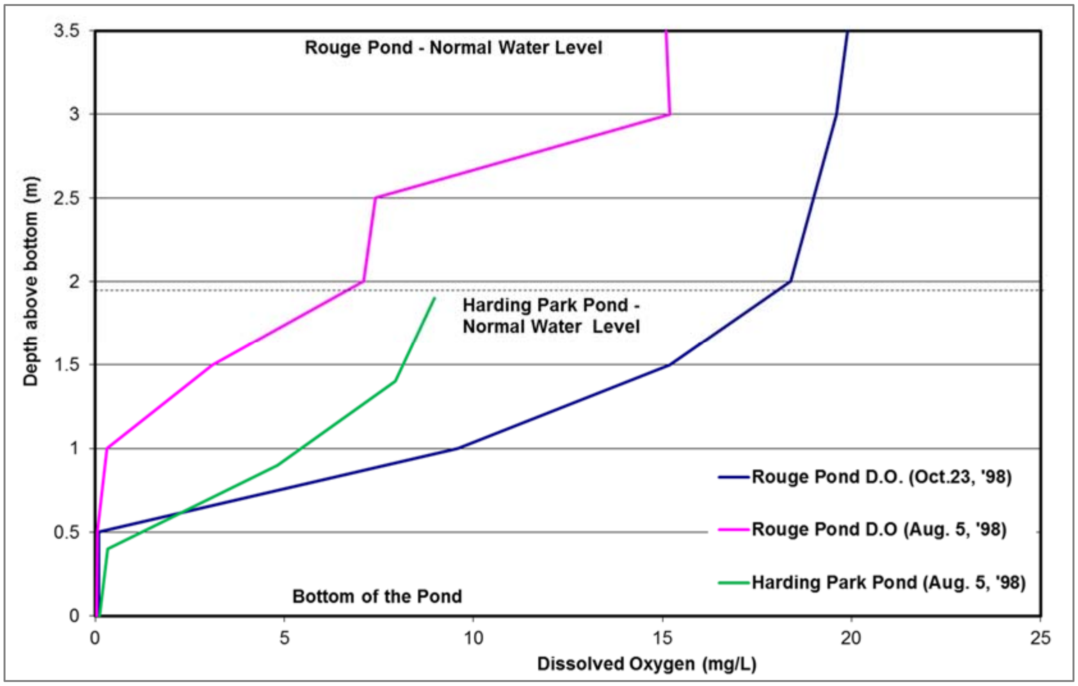


Figure 10: Dissolved oxygen levels in the Rouge and Harding Park stormwater ponds

To determine whether deeper ponds with subsurface outlets may be less effective at retaining phosphorus and heavy metals, the water quality performance of five ponds were compared, two of which had deep outlets 1.5 m or greater below the normal water level, and the remaining three with surface draw outlets. Results are presented in Table 3.

Many factors affect the water quality performance of ponds. Therefore, it is not possible through a simple comparison of outlet concentrations and removal efficiencies to determine whether subsurface draw outlets are impacting water quality. Nevertheless, the data presented in Table 3 do not suggest that subsurface draw outlets would have inferior water quality. Effluent concentrations and removal efficiencies are comparable across the various ponds. Harding Park is a smaller pond and would therefore be expected to exhibit lower water quality performance. The Rouge Highway pond had higher influent concentrations of metals, which is the likely cause for elevated metal concentrations. Outlet concentrations of total and dissolved phosphorus were generally in the same range. The influence of subsurface draw outlets on density gradients caused by salt accumulation may actually produce a performance benefit by allowing new inflows to mix more efficiently.

Table 3: Average Event Mean Concentrations and removal efficiencies for selected nutrients and metals for ponds with surface and subsurface draw outlets (source, TRCA, 2005; SWAMP 2002b)

Pond/ Parameter	Subsurface Draw Outlets		Surface Draw Outlets		
	Rouge Pond	Markham Pond***	Heritage Estates	Harding Park	Dunkers FBS
TP Inlet (mg/L)	0.39	0.55	0.28	0.39	0.28
Outlet (mg/L)	0.06	0.08	0.07	0.11	0.06
R.E. (%)**	85	83	80	42	77
PO_4 Inlet (mg/L)	0.03	0.08	0.06	0.03	0.05
Outlet (mg/L)	0.01	0.02	0.03	0.01	0.01
R.E. (%)**	78	76	71	87	77
Cu Inlet (mg/L)	52.1	17.1	42.0	22.2	19.3
Outlet (µg/L)	10.2	4.1	8.0	4.5	4.1
R.E. (%)**	85	84	76	48	85
Zn Inlet (µg/L)	302.1	87.2	80.0	66.7	66.5
Outlet (µg/L)	67.2	14.3	10.0	16.4	6.7
R.E. (%)**	84	87	71	70	89
Fe Inlet (µg/L)	1467	951	3150	1069	747
Outlet (mg/L)	471	181	320	386	234
R.E. (%)**	72	86	74	66	75
Max outlet temperature*	24	24	31	31	29

*Data from July and August, except the Markham pond, which was from June to mid-July. Summer air temperatures during the Rouge and Markham monitoring periods were cooler than normal. **Removal efficiencies are load based for paired events. ***Markham pond outlets and removal efficiencies are for the wet pond, not including wetland.

3.2.2 Subsurface draw outlet design considerations

Reverse slope pipes have become standard measures in ponds. It is recommended that they be installed in the pond with headwalls and connected to a control manhole located within the embankment to facilitate maintenance. Control orifices and weirs for extended detention, erosion and flood control would also be located in the manhole. Periodic flushing may be required.

The reverse slope pipe should provide sufficient space for the build-up of sediment in the pond. The MOECC recommends that cleaning should occur when sediment accumulation has reduced the total suspended solids removal rates by 5% below their original levels (MOE, 2003). Estimates of sediment volumes corresponding to a 5% reduction in treatment performance are provided in the *Stormwater Pond and Constructed Wetland Inspection and Maintenance Guide* (TRCA and CH2M Hill, 2015). In 'enhanced level' ponds, the required sediment storage volumes translate to approximately 29 to 37% of the permanent pool volume, for drainage area impervious covers ranging from 35 to 85%. Most of the accumulation would occur in the forebay. Therefore, it is conservatively estimated that the invert of the reverse slope pipe should be elevated off of the pond bottom by no less than 33% to 43% of the permanent pool depth (depending on drainage area imperviousness). The estimated values of 33% and 43% represent a 15% increase above the sediment storage volumes (i.e. 29 and 37%) that would trigger a cleanout requirement for ponds based on the 5% loss in performance rule. These values incorporate the following considerations:

(i) available storage volume decreases with depth below the permanent pool (i.e. the bottom of the pond fills faster than the top);

(ii) sediment accumulates faster upstream of the outlet; and
(iii) a minimum 0.5 m clearance between the outlet and accumulated sediment at the time of cleaning is needed to ensure suspended sediment and associated pollutants near the bottom are not easily re-entrained and discharged to streams during storm events.

To meet the 24ºC target for the protection of Redside Dace, the reverse slope pipe invert should be located no less than 2.0 m below the permanent pool water level (see rationale above). Therefore, the depth of the pond near the outlet would need to be at least 3.0 to 3.5 m (depending on drainage area imperviousness) in order to provide a sediment storage depth equivalent to 33 to 43% of the permanent pool depth. An outlet 2.5 m deep would require the pond to be between 3.7 and 4.3 m deep at the outlet. Extending the deep pool across the entire main pond area would improve cooling performance of the outlet by creating a larger reservoir of cool water.

If there are constraints to excavation of a deep pond, the reverse slope outlet may be placed at a higher elevation, but preferably below 1.2 m to avoid the pronounced diurnal fluctuations generated by solar heating that typically occur above this elevation. These mid draw outlets can be combined with other cooling or stormwater volume reduction measures to help maintain thermal conditions within the tolerance limits of aquatic organisms.

Base flow augmentation

Outlets can also be designed with base flow augmentation functions to help mitigate the effect of increased impervious cover on groundwater discharge to streams. This would entail providing an additional orifice control pipe within the outlet control chamber to permit slow release of stormwater during the inter-event period, thereby augmenting stream base flows. An example of such a measure in the outlet control manhole is shown in Figure 11. The hickenbottom structure shields the orifice from debris while providing continuous cool discharge from the reverse slope pipe to the downstream area.

Figure 11: Orifice control pipe within the outlet control chamber for baseflow augmentation (Markham, ON)

Another means of augmenting baseflows would be to install a separate inlet pipe with orifice control that draws water at a pre-defined flow rate from the surface of the pond through a cooling trench that discharges directly to the stream. The flow rate would be selected such that the total volume of flow passing through the cooling trench would be equivalent to the total volume of infiltration and evapotranspiration lost due to increased impervious cover within the catchment. Performance analysis of one such trench (see discussion in section 3.4.3 below) showed that the temperature of water discharged from the cooling system fluctuated between 20 and 25ºC during the warmest summer months, and was up to 5ºC cooler than the pond water entering the trench (Van Seters and Graham, 2013).

3.3 Night time release outlets

Another best practice recommended by the MOECC (2003) is to use real time controls to release water from the pond during the night when outflow temperatures are cooler. This technique can be promising where there is a surface draw outlet because ponds exhibit strong diurnal fluctuations in temperature that result in significantly higher daytime temperatures. Since deep subsurface draw outlets do not exhibit substantial diurnal temperature fluctuations, releasing water during the night time would have only minor temperature mitigation benefits with this type of outlet structure.

3.3.1 Optimal discharge times

Hourly temperature data were analyzed during the warmest period of the summer (July and August) to assess optimal timing for night time release. Results are presented in Table 4 for release durations of between 4 and 8 hours. For an 8 hour duration release time, the analysis showed that the outlet temperatures were coolest between 3 AM and 10 AM (including hour 10) most of the time. The 75th percentile ranges were between 23.1 and 26.0ºC over this time period. Release times may be shorter than 8 hours if the outlet could be programmed to release water over variable time periods based on pond water levels prior to discharge. The optimal hours for a 4 hour release time were 6 AM and 9 AM. However, the 75th percentile temperatures over this shorter time period were only slightly cooler, ranging from 23.1 and 25.4ºC.

3.3.2 Night time release performance

Pond outlet data was used to simulate the potential benefit of night time release for outlets of different elevations. The analysis was based on the optimal 8 hour period of release from 3 AM to 10 AM inclusive. Only outlets from 0 to 1.5 m below the normal water level were analyzed because, as mentioned previously, outlets below 1.5 m are not affected by diurnal temperature cycling, and therefore show little benefit from night time release. Note that these analyses assume that releasing greater volumes of water at night and storing it during the day will not significantly alter the outlet temperatures compared to a normally functioning outlet. This may not be the case, but it is a reasonable assumption as the effects are probably quite small.

Figures 12 and 13 show the results of the analysis of four ponds. Temperature changes range from 0.6ºC for the subsurface draw outlet at 1.4 m below the normal water level to 1.6ºC for the Heritage Estates pond surface draw outlet. None of the simulated results reduced temperatures enough to meet the 24ºC target 100% of the time.

3.3.3 Night time release outlet design considerations

Night time release outlets can reduce the temperature of pond outflows where outlets are above 1.5 m. The programmed hardware for these outlets should be in an accessible location and resistant to rust or damage from humidity. The availability of electrical supply to the control manhole is helpful for telemetered systems as this reduces the frequency of maintenance visits and helps prevent failures. Back-up supply should be provided in case of power outages.

Table 4: Optimal hours for surface draw outlets for each pond based on the 75th percentile of the hourly range. Data are based on continuous surface water temperature measurements for each pond.

Pond	Month	Number of Hours	Duration (Hour of Day)	75^{th} Percentile Temperature Range
Majorwood, Markham	July	8	3-10	25.1-25.9
		7	4-10	25.1-25.7
		6	5-10	25.1-25.6
		5	5-9	25.1-25.4
		4	6-9	25.1-25.4
	August	8	4-11	23.1-23.5
		7	4-10	23.1-23.5
		6	5-10	23.1-23.3
		5	6-10	23.1-23.3
		4	6-9	23.1-23.2
Dunkers, Toronto	July	8	3-10	25.1-26.1
		7	4-10	25.1-25.8
		6	4-9	25.1-25.8
		5	5-9	25.1-25.5
		4	6-9	25.1-25.3
	August	8	3-10	25.4-26.1
		7	4-10	25.4-26.0
		6	5-10	25.4-26
		5	5-9	25.4-25.8
		4	6-9	25.4-25.6
K-47, Kitchener	July	8	3-10	25.1-26.0
		7	4-10	25.1-25.8
		6	5-10	25.1-25.8
		5	5-9	25.1-25.6
		4	6-9	25.1-25.3
	August	8	3-10	23.4-24.4
		7	4-10	23.4-24.2
		6	4-9	23.4-24.1
		5	5-9	23.4-23.8
		4	6-9	23.4-23.7
Pond S7, Brampton	July	8	3-10	23.6-24.2
		7	4-10	23.6-24.1
		6	4-9	23.6-23.9
		5	5-9	23.6-23.7
		4	5-8	23.6-23.7
	August	8	3-10	23.3-24.0
		7	3-9	23.3-23.9
		6	4-9	23.3-23.8
		5	5-9	23.3-23.7
		4	5-8	23.3-23.6

An 8 hour release program from 3 to 10 AM inclusive was found to provide optimal cooling. The coolest temperatures were found between 6 and 9 AM. It is not feasible to meet the 24ºC target over 95% of the time with this technique alone. In constructed wetlands, where outlet temperatures may be lower due to plant shading during the summer, the added benefit of night time release may provide a lower 95^{th} percentile temperature than was the case for ponds. Similarly, combination systems with cooling trenches or volume control upstream or within the pond block can also help meet temperature and/or thermal load reduction requirements.

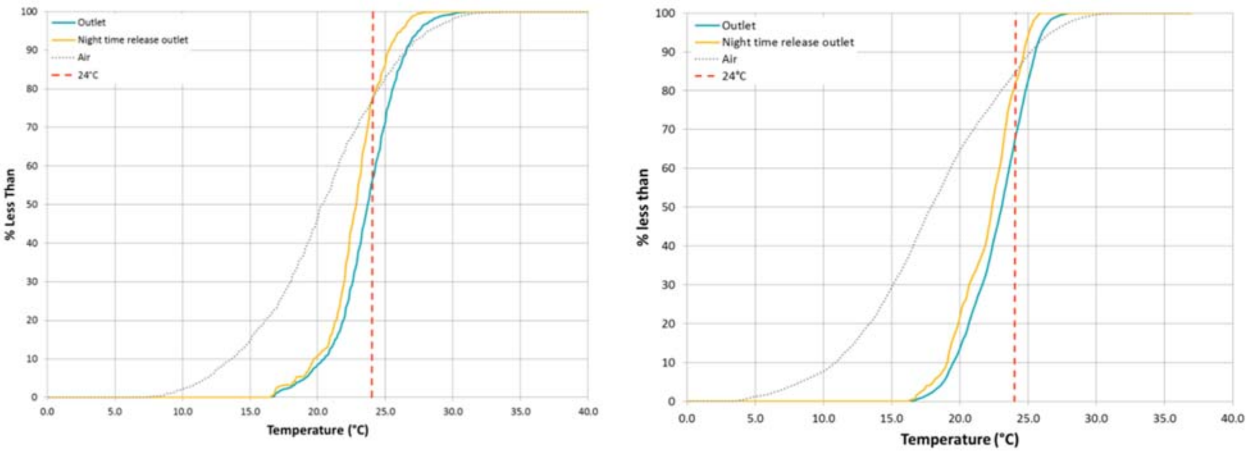


Figure 12: Temperature frequency graphs of pond outlets and simulated night time release outlets for: LEFT - Heritage Estates pond in Richmond Hill (surface weir). 95h percentile temperatures are 28.4 and 26.8ºC, respectively; RIGHT - Monarch pond in Markham (0.5 m below NWL). 95th percentile temperatures are 26.1 and 25.1ºC, respectively.

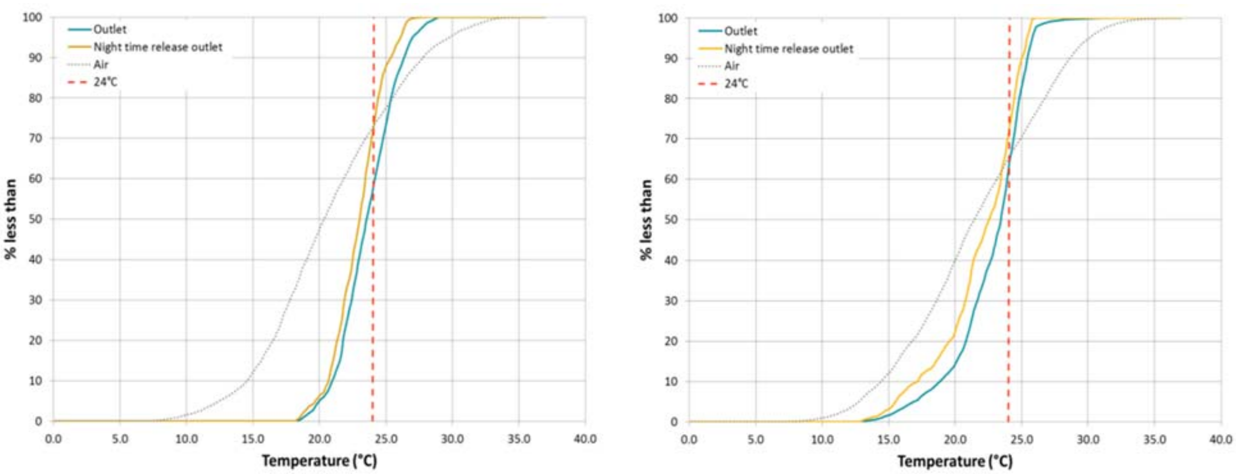


Figure 13: Temperature frequency graphs of the pond outlets and simulated night time release outlets for: LEFT - Majorwood pond in Markham (0.5 m below the NWL). 95th percentile temperatures are 27.0 and 26.1ºC, respectively; RIGHT – SWM 101 pond in Pickering (1.4 m below the NWL). 95th percentile temperatures are 25.8 and 25.4ºC, respectively

3.4 Cooling trenches

Cooling trenches are typically located downstream of the pond or constructed wetland between the outlet and the receiving water system. However, they can also be installed to receive water from a secondary outlet that draws water continuously from just below the permanent pool water level. The trenches usually consist of one or more perforated pipes embedded in a clear stone filled trench that is buried underground. Contact of outflows with the stone media and side walls allows transfer of heat from the water to the stone and surrounding soils, thereby reducing the temperature of outflows discharged to the stream. Sizing of the trench will depend on a number of factors, including the temperature of water discharged from the facility, duration and rate of flow release, and the available space between the outlet and receiving water course.

When designed for cooling, vegetated swales or channels are typically long, broad meandering swales that maximize contact with surface soils and vegetation and travel through heavily shaded areas wherever possible. Without shading or sufficient area for flow spreading, these swales may not be effective measures. By spreading the flows across a large area, volumes are reduced through infiltration and evapotranspiration, which in turn promotes increased vegetative growth that, enhances shading and further volume loss through evapotranspiration over time. The objective is to create self-sustaining ecosystems that naturally evolve into more densely vegetated and even forested areas that integrates effectively with the receiving water buffer and/or flood plain.

3.4.1 Timing of warm water discharges

While it is well understood that water is warmer when outdoor temperatures rise, and water heats up over the course of the summer, the relationship between warm water outflows from ponds and the rate/volume of flow is less well appreciated. This relationship has important implications on how trenches are sized and designed. If water is warm mainly during low flows, then trenches may be sized only to receive these flows. If the reverse is true or there is no correlation, much larger trenches may be needed.

To answer this question, average water temperatures at different pond water level elevations have been analyzed. The general correlation between flow and pond water levels allows continuous pond water levels to be used as a surrogate for flows. The results in Figure 14 for the Majorwood pond in Markham (0.5 m subsurface draw outlet) clearly show that average temperatures are negatively correlated with water levels, indicating that the warmest water occurs during low flows. This is particularly true during warm interevent periods when open water in ponds is heated by the sun. The data also show that flows are in the low and mid flow ranges 88 to 89% of the time. Therefore, designing systems to receive only the lowest and long duration flows, while bypassing higher ones, should optimize the available cooling potential of trenches. This would also help to reduce maintenance requirements because higher flows typically carry more sediment, which clogs pores and may reduce cooling efficiency over time.

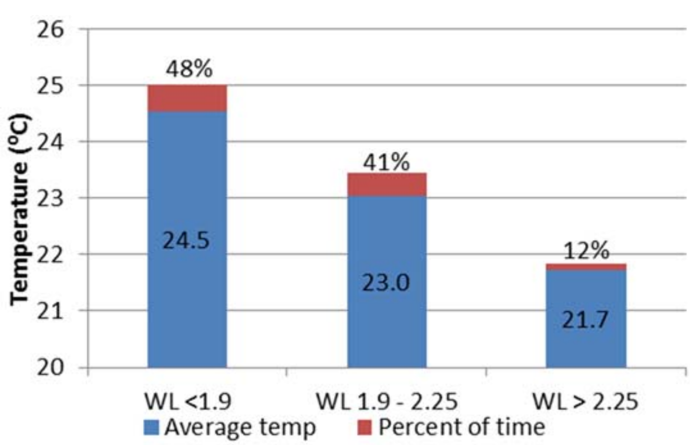


Figure 14: Relationship between water level (WL in metres) and average outlet temperature for the Majorwood pond in Markham. Percentages represent the percent of time between June 15 and September 15 that water levels fell within the indicated water level ranges. Pond water levels are directly correlated with pond outflow rates.

Another analysis of a stream (Morningside Creek) receiving outflows from ponds was conducted to determine whether stream temperatures are similarly correlated with flows. The analysis at several locations along the Creek is provided in Appendix C. Findings showed that creeks also exhibit higher temperatures during low flows, although in rare cases, rain can be warm, creating short term warming at higher flows as well. The observation that both the outflow temperature from ponds and the creek itself are warmest during dry weather (i.e. low flows) provides further support to the earlier suggestion that designing thermal mitigation measures to provide cooling primarily during the low flow period would produce the greatest benefit to the receiving water system.

3.4.2 Pond primary outlet cooling trenches

The performance of cooling trenches is controlled by the capacity of the trench to remove heat from the incoming water. This capacity is in turn influenced by the size of the trench relative to the flow volume and rate of flow through the trench, both of which affect the contact time and capacity to dump heat to the surrounding soils. Since soil absorbs heat very slowly, either very long contact times or very large trench surface areas are required to move substantial quantities of heat through the soil.

The difference between the temperature of the incoming water and that of the surrounding soil also influences the capacity of the trench to remove heat by altering the rate of thermal transfer. In general, it can be expected that, for a given ground temperature and trench design, cooler influent temperatures will result in less cooling than if the reverse were true.

In some cases, groundwater interaction can help remove heat, but only by transferring heat to the groundwater, which may result in groundwater discharge temperatures to streams that are lower than if such interaction had not occurred. If the effects of the cooling trench on groundwater discharge temperature are not considered, monitoring programs may exaggerate the cooling performance of the trench. In cases where travel time of groundwater to the stream is sufficiently long, or there is significant mixing with deeper groundwater, this potential negative effect on groundwater discharge temperatures to streams may be negligible.

Table 5 shows results from various cooling trenches that have been monitored in Ontario. Since flow volumes and flow rates were not monitored, the size of the trench is assessed based on the ratio of the permanent pool volume to that of the trench. Since most ponds are sized with permanent pool volumes equivalent to runoff from the 25 mm storm (MOE, 2003), this method of assessing size was judged to be a reasonable indicator of whether the trench was undersized or oversized relative to drainage volumes. Flow rates will increase with drainage area size, and are influenced by drawdown times, which can vary depending on erosion protection criteria. The design drawdown time of the pond is included to provide context for interpretation of data. In most cases, bypasses would have been installed for very high flows.

The data show a wide range of trench sizing and performance results. Some trenches, like those on L2 and S4 ponds in Brampton, pond 53 in Guelph, and the Baden and Richmond Hill ponds provided very limited cooling benefits. Others, such as the Kitchener Church, Kitchener 1, Elmira 1 and Guelph pond 33 trenches were much more effective. Sizing ranged from pond permanent pool volume only 2.4 times that of the trench volume, to one that was 383 times larger. The larger trenches generally performed better, and vice versa, but the correlation was weak. Another study of a cooling trench (14 m x 2 m x 1 m) in the Grand River watershed with a pond permanent pool volume to trench volume ratio of over 100 also showed very limited cooling benefits, except during low flows (CVC, 2011). Clearly, other factors like groundwater interaction, as in the pond 33 and Waterloo 1 cases, and overall trench design and inlet

Table 5: Cooling trench performance

Project	Ratio of pond perm. pool vm to trench vm	Pond drawdown time (hrs)	Avg/max influent temp (°C)	Avg/max effluent temp (°C)	Avg/max temp decline (°C)	Frequency outflows > 24 °C (%)	Comments
Brampton, pond L2	20:1	125	24.1/27.2	23.3/25.4	0.7/3.1	47	
Brampton, pond S4	n/a	n/a	23.2/28.9	23.1/29.2	Approx. 0	frequent	Appeared to be very shallow; report indicated no change in temperature
Richmond Hill, pond 417	n/a	n/a	21.1/24.2	20.8/23.1	0.3/1.5	0.0	Lined trench. Trench depth was 0.9 m. Pond outlet was 1.17 m below NWL
Richmond Hill pond 410	n/a	n/a	21.9/26.4	21.7/25.2	0.2/6.2	8.2	Lined trench. Trench depth was 0.9 m. Pond outlet was 0.95 m below NWL
Guelph pond 33	159:1	n/a	21.0/27.1	17.5/19.5	3.6/8.5	0.0	Only monitored from August 20 - Sept 15; likely g/w interaction. Trench only 0.4m deep
Guelph pond 53	383:1	n/a	22.5/29.2	22.6/28.9	-0.2/0.8	29.9	Only monitored from July 25 to Sept 15. Depth of trench only 0.6 m
Kitchener pond 74	158:1	n/a	20.3/26.4	17.7/20.7	2.5/8.9	0.0	Pond subsurface draw at 1.34 m below NWL. Possible g/w interaction. Only monitored during rain events which may exaggerate performance
Kitchener pond church	7:1	n/a	23.5/25.8	15.4/16.8	9.0/8.1	0.0	Small parking lot catchment – 5.1 ha. Trench was 2 m deep, 2 m wide and 95 m long
Kitchener, Stauffer Woods SWM1	200:1	103	21/24.6	12.9/15.1	8.1/9.5	n/a	Combined pond – infiltration chamber – cooling trench
Kitchener 1*	27:1	n/a	16.8/28.3	12.4/15.9	4.4/14.6	0	g/w interaction likely; pond subsurface outlet at 0.55m
Kitchener 2*	40:1	n/a	18.5/26.3	18.3/25.9	0.2/8.4	2	g/w interaction not likely; pond subsurface outlet at 0.5m;
Vaughan, Block 40 – pond 3	41:1	46	20.0/24.7	18.3/24.5	1.4/5.3	2	>2ºC change 15% of the time; <1^{0}Cchange 77% of time. 2 m deep pond outlet
Waterloo 1*	2.4:1	n/a	18.5/30**	10.9/14.8	7.6/20**	0	Confirmed g/w interaction; surface draw pond outlet
Waterloo 2*	68:1	n/a	18.2/30.8	18.4/30.8	0.3/6.2	3	g/w interaction not likely; surface draw pond outlet; Trench only 0.9 m deep
Elmira 1*	99:1	n/a	19.5/28.0	15.0/23.5	4.6/17.9	0	Confirmed g/w interaction; pond subsurface outlet at 1.0 m
Baden 1*	94:1	n/a	21.2/31.8	20.5/30.2	0.7/6.7	21	g/w interaction not likely; surface draw outlet; trench only 1.0 m deep

*The actual names of these ponds were not provided. The monitoring period is longer than other trenches (April – November, 2016 and 2017), which reduces the percent frequency > 24ºC values. **the maximum measured inlet and change in temperatures were outliers that did not reflect flowing conditions. Values were adjusted to reflect a more typical maximum inlet temperature for surface draw outlets, and the maximum change in temperature was adjusted down by the same amount.

temperatures also play important roles in performance. Overall, the data suggest that pond outlet cooling trenches cannot be relied on to provide more than 1 to 2ºC of cooling on average over the summer period, although they may well be more effective, particularly if groundwater interaction is present, and the systems are oversized.

The Block 40 pond in Vaughan was a good example of a relatively large trench that was able to further cool outflows from a deep draw outlet (2 m below NWL). In this case, exceedances of the 24ºC target were limited to a 34 hour period in mid-August, 2016. Data from 2013 and 2014 show no exceedances. In examining the data for this cooling trench, the consultants for the project, Azimuth Environmental, showed that trench performance improved significantly during low flow events. They suggested that slower flows increase contact times with the surrounding ground, and possibly enhances groundwater mixing ratios. Higher influent temperatures during dry weather when flows are lower likely also played an important role.

The very small Stauffer Woods trench in Kitchener was somewhat unique in that pond outflows were first directed to an infiltration chamber, then to a cooling trench. Outflows were extremely cool in that case, possibly because the trench received very low flows from the infiltration system, but also likely due to groundwater interaction as the outflow temperatures (max 15ºC) are more representative of ground temperatures than surface flows.

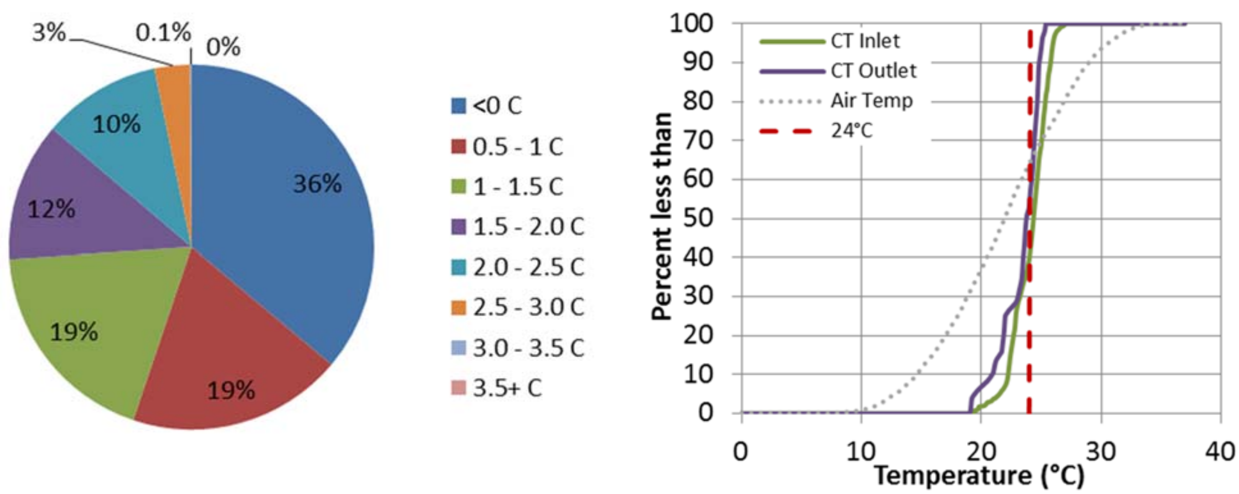


Figure 15: Pond L2, Brampton, cooling trench performance. Left graph shows temperature changes from the inlet to outlet. Right graph shows inlet and outlet temperature frequency.

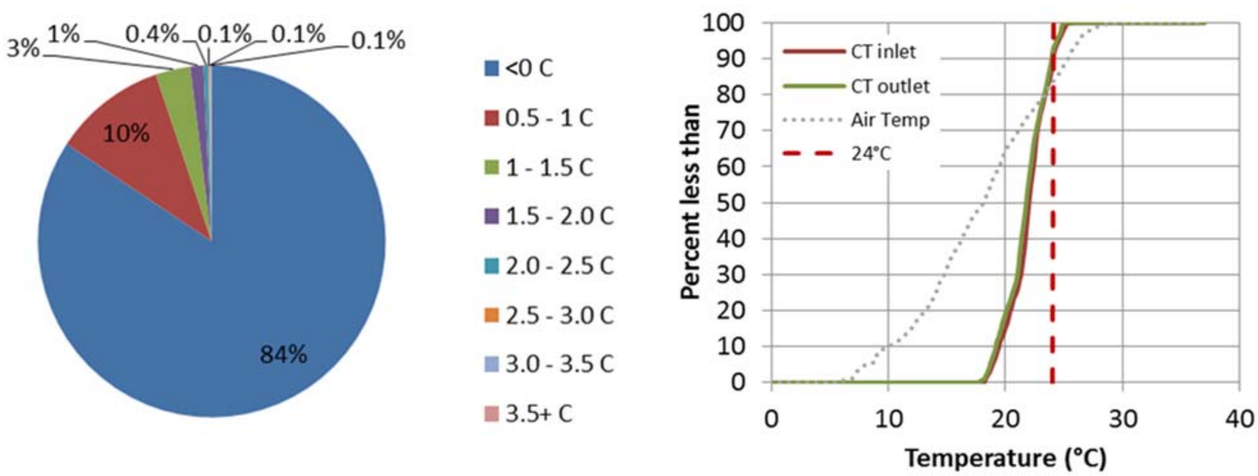


Figure 16: Pond 410, RH cooling trench performance. Left graph shows temperature changes from the inlet to outlet. Right graph shows inlet and outlet temperature frequency.

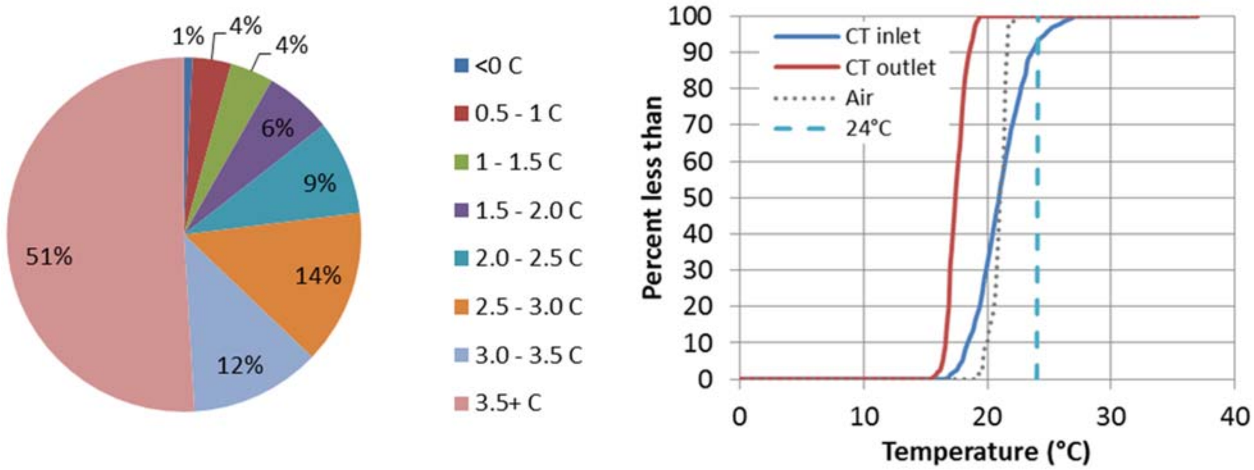


Figure 17: Pond G33, Guelph cooling trench performance. Left graph shows temperature changes from the inlet to outlet. Right graph shows inlet and outlet temperature frequency. Only monitored from August 20 to Sept 15.

3.4.3 Pond secondary outlet cooling trenches

Cooling trenches that draw water from a secondary pond outlet are relatively uncommon but are gaining wider acceptance. They were originally intended to replace groundwater discharge to streams lost as a result of reduced infiltration caused by increased impervious cover in the drainage area. The orifice on the secondary outlet is sized to replace the lost volume, and the trench helps to cool the water so that it is released at temperatures similar to that of groundwater. Although infiltration of water has not been a key objective of these systems, there is potential to reduce flow volumes through infiltration where the water table is not too near the surface, or the trench is constructed beneath elevated areas of the pond block.

The first detailed evaluation of this system was conducted by STEP in 2011 and 2012 on the Majorwood pond in Markham (Van Seters and Graham, 2013). The system design and pictures during construction are shown in Figure 18. The secondary inlet was located at 0.5 m below the pond permanent pool surface, allowing for a reduction in the permanent pool elevation to this level during the interevent period. In practice, however, the primary pond outlet never stopped flowing, in part because the inlet to the trench conveyed less than the design capacity. Results showed that the trench provided approximately 5ºC of cooling during the warmest periods, meeting the 24ºC target most of the time. Almost half of this cooling occurred in the conveyance of water from the pond to the control manhole prior to entering the trench.

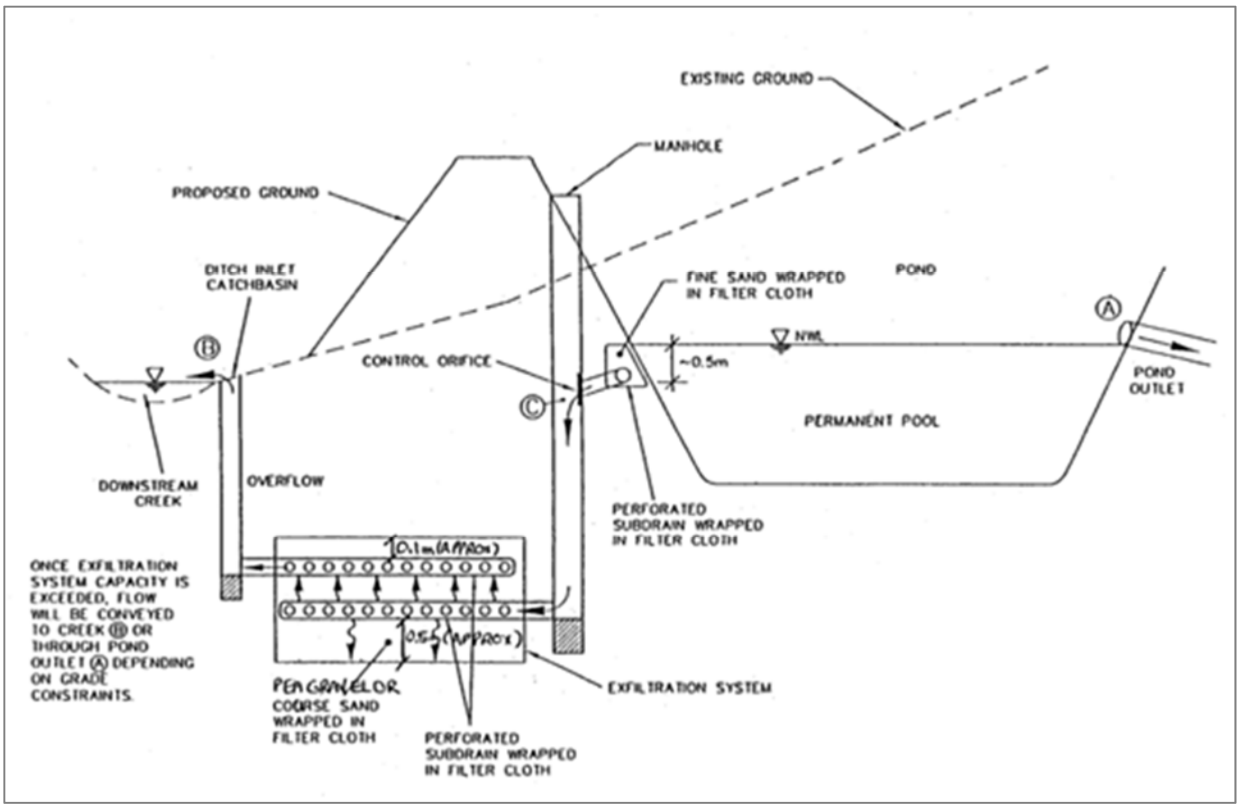


Figure 18: Schematic and pictures showing the design and construction of the secondary outlet cooling trenches in Markham. For more details see Van Seters and Graham, 2013.

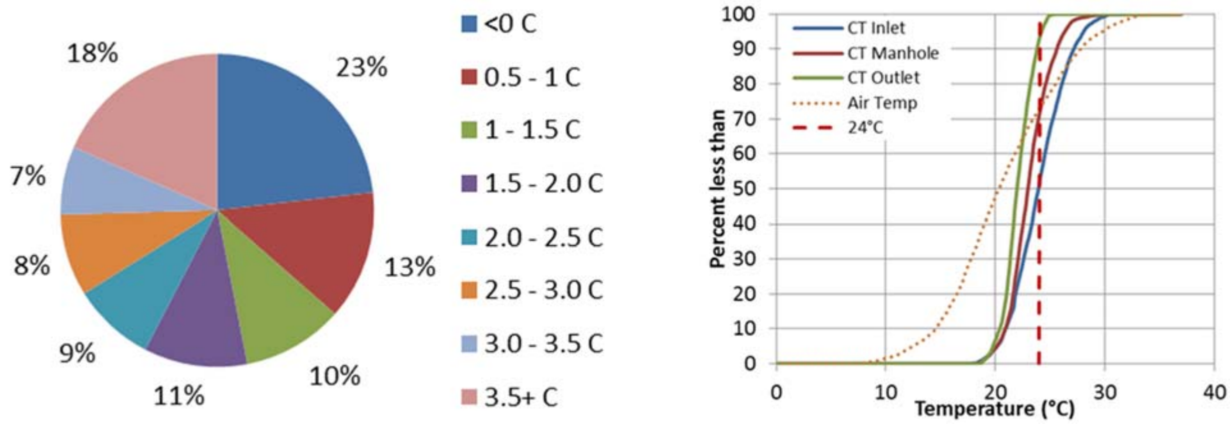


Figure 19: Secondary outlet cooling trench performance from June 15 to Sept 15, 2012, Majorwood Pond, Markham. Left graph shows temperature changes from the inlet to outlet. Right graph shows inlet and outlet temperature frequency.

Monitoring of a second, similarly designed cooling trench on the Monarch pond in Markham was initiated in 2017. In this case the inlet consisted of a perforated pipe embedded into a gravel/sand jacket within the pond bank 0.5 m below the permanent pool surface. Flows were conveyed to a control manhole and split to an east and west cooling trench before discharging through a catch basin. The results in Figure 20 show significant cooling, with 59 to 81% of the seasonal changes above 3.5ºC, and changes of between 6 and 8ºC during the warmest periods during the summer. The west catch basin was cooler than the east, likely due to enhanced groundwater interaction in this location. As with the Majorwood trench system, significant cooling occurred between the pond surface inlet and the manhole, and flows through the system were relatively slow, which may partly explain why the two systems worked as well as they did.

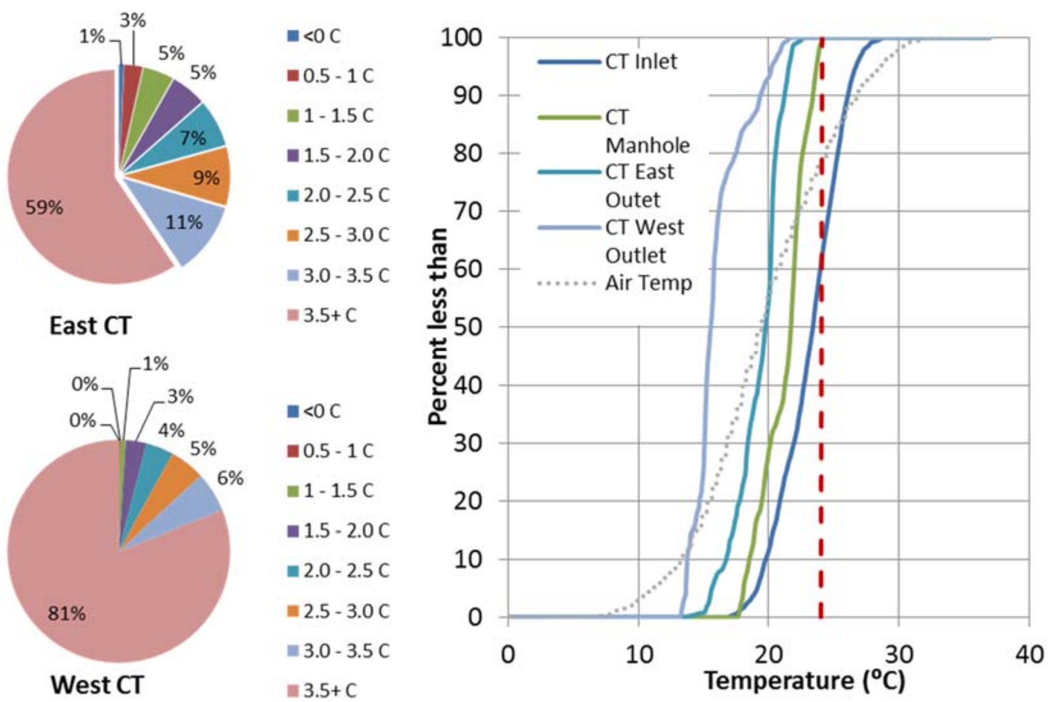


Figure 20: Secondary outlet cooling trench performance from June 15 to Sept 15, 2017, Monarch Pond, Markham. The pond discharges to a control manhole then to two cooling trenches. Left graph shows temperature changes from the inlet to outlet. Right graph shows inlet and outlet temperature frequency. Secondary outlet systems can be very effective, particularly for augmenting baseflows, but the low flows of the monitored systems were not sufficient to keep the primary outlet below the 24ºC target, even after mixing of the two flow streams. These systems should be tested at flow rates that are high enough to eliminate primary outlet flows during dry weather, as these dry weather flows tend to experience the highest outflow temperatures.

3.4.4 Cooling trench design considerations

The empirical data gathered over the course of this project was not sufficient to arrive at a recommended minimum size for cooling trenches in relation to stream thermal targets. Groundwater interaction is an important and cofounding variable that has not been adequately quantified. Without groundwater interaction, a large trench, with storage volume greater than 5% of the permanent pool volume may be required to provide at least 1 to 3ºC of cooling (based on findings presented here, and by others: *eg.* Roa-Espinosa, 2003). In many instances, the space for such a large trench is not available, and/or more substantial temperature reductions may be required. To overcome these constraints, a combination of thermal mitigation measures may need to be implemented.

Data showing the predominance of warm outflows occurring during lower pond water level elevations suggests that designing cooling trenches to receive only the lower flows would help optimize trench performance, while also saving on costs. This can be accomplished simply by installing a flow splitter at the outlet that bypasses larger, more turbid flows through a separate outlet. To meet the 24ºC threshold, a simple rule may be that flows with rates half that of the peak flow during a 25 mm 4 hour event could be diverted to the trench, as higher flow rates were more often found to meet or approach the 24ºC target.

An alternative viable option would be a secondary outlet that removes the warmest water from the surface of the pond, as discussed above. These have the potential to provide significant cooling that meets the 24ºC target with trench storage volumes of 50 m^3 or greater and discharge below 2 L/s. However, the primary outlet would need another thermal mitigation measure to provide the necessary cooling for larger flows.

The combination of cooling trenches with subsurface draw outlets can also be effective. This was shown in the Block 40, Pond 3 example, where a deep 2m draw outlet was combined with a 76 m long cooling trench. However, the benefit in this case was relatively small, and it is not clear that subsurface outlets at this depth (2.0 m) or lower always need the cooling trench to reduce 24ºC exceedances to 5% or lower, as was shown in the Rumble pond (Richmond Hill) and S7 pond (Brampton) examples. Since cooling trenches help reduce diurnal fluctuations, it stands to reason that they would work best on subsurface outlets that are 1.5 m or higher, as these outlets tend to experience higher amplitude diurnal temperature fluctuations.

Cooling trenches should be designed to include a flow bypass to facilitate maintenance and divert high flows directly to receiving watercourses. The bypass may also be used to divert flow away from the structures during cold months when they are not serving their primary cooling function. This will help to minimize sediment accumulation within the practices and lengthen their clean out interval. Clean out ports should be located at both ends of the facility to facilitate maintenance when it is required. If there are multiple outlet pipes, each should have its own clean out port. Perforated pipes should be 200 mm or larger to allow CTV inspection equipment access and incorporate filter fabric socks to reduce the accumulation of sediment in the surrounding stone.

3.5 Vegetated swales or channels

A potential alternative to trenches where there is significant separation distance between the stormwater pond and receiving watercourse is a vegetated swale, or spreader swale. The vegetated swale is constructed within the area downgrade of the pond as a shallow broad feature that attempts to use the existing and future planted vegetation for shading. The spreader swale is similar but is intentionally bifurcated into multiple channels or flat even areas to allow flows to spread across the surface, providing more opportunities for volume reduction through infiltration.

An example of a long vegetated swale in Pickering that was monitored by STEP in 2017 is shown in Figure 21. The pond outlet draws cooler water from 1.4 m below the surface of a relatively shallow pond with sump and drains to a vegetated swale. The swale travels through a forested area (temp sensors 1 - 3), then through an open field (temp sensors 4 - 7). Figure 22 shows the temperature frequency graphs for the forested area (‘average of temperatures in the ‘shaded area outlet’ locations) and open field (average of ‘open area outlet’ locations), as well as the temperatures in Ganatsekiagon creek upstream and downstream of the channel outlet.

Temperatures drop immediately as they pass through the forested area, and experience further cooling through the open field, which is somewhat shaded in the morning by the neighbouring forest. The overall benefits of the vegetated channel are small, particularly at the high end of the temperature spectrum, but still sufficient in this case to maintain cool conditions within the downstream receiving watercourse (Figure 22). The small creek (Ganatsekiagon) drains natural and agricultural areas prior to passing the outlet of the pond. Temperatures upstream of the outfall were less than a degree cooler than those downstream.

Figure 21: Location of the temperature sensors along the vegetated swale in Pickering

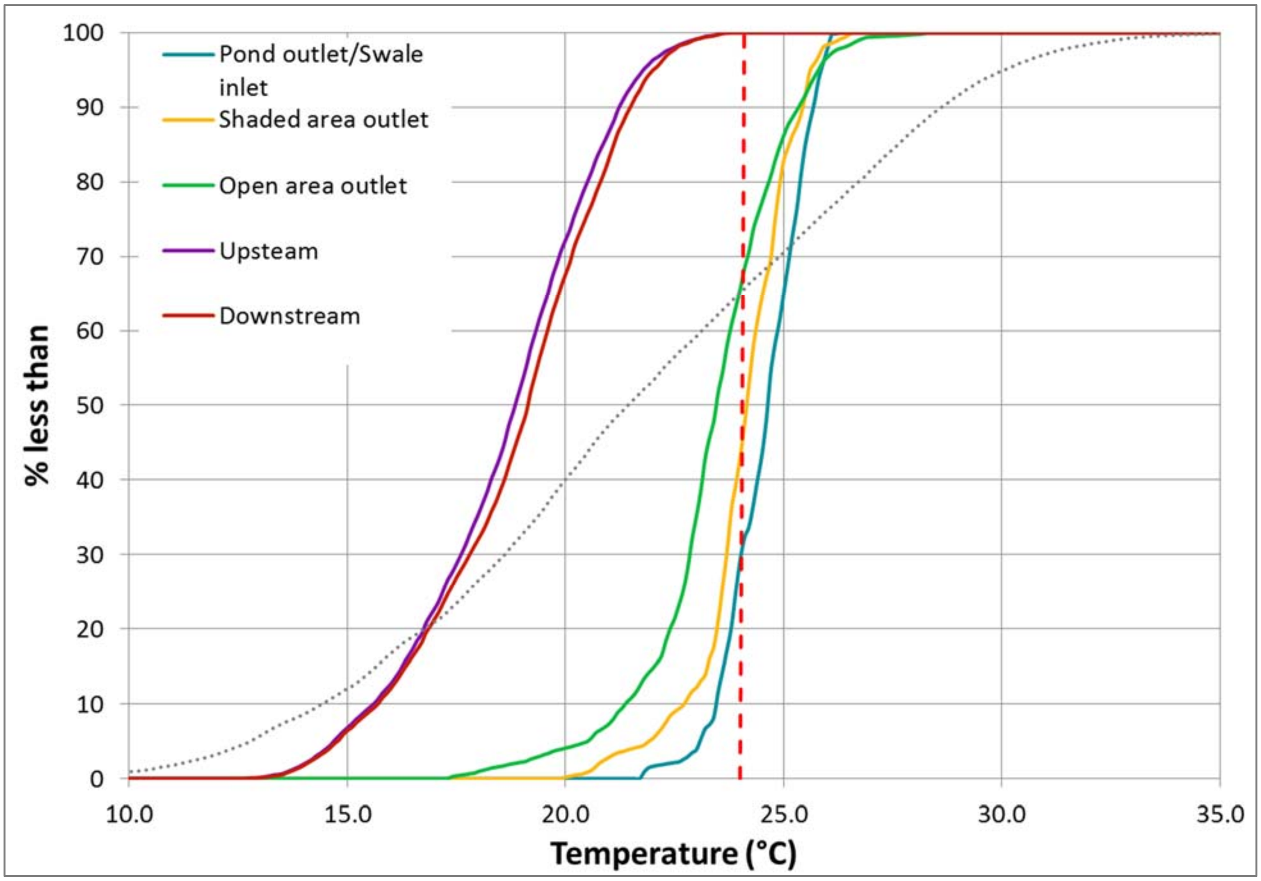


Figure 22: Temperature frequency graphs for the forested area ('shaded area outlet') and open field ('open area outlet'), as well as the temperatures in Ganatsekiagon creek upstream and downstream of the channel outlet.

3.5.1 Vegetated swale design considerations

This type of outlet is relatively simple to design. Shading should be maximized wherever possible by planting tall vegetation within or adjacent to the channel. A culvert should be installed where the channel passes across access roads or paths. Flow spreading should be practiced wherever possible to increase the surface contact area and promote infiltration. However, care should be taken in the development of these areas to avoid the potential for erosion, excessive ponding or flooding of natural features. Natural features can absorb additional water, but the health of these features will suffer if the capacity to assimilate the additional flows is exceeded. Maintaining a healthy cover of vegetation and ensuring all spreader areas and channels drain to the main watercourse are two simple rules of thumb that can help improve effectiveness.

3.6 Low impact development practices

In section 2.1, the importance of lowering stormflow volumes as a means of reducing thermal loads from urban areas was highlighted. Many low impact development (LID) practices are specifically designed to fulfill this role. They are also well suited to reducing runoff temperatures by storing and retaining water underground, in areas well sheltered from direct solar heating. Since the practices are required to meet water quality and quantity stormwater criteria on most sites, they should be carefully considered and designed as part of the overall site stormwater management and thermal mitigation strategy.

Structural LID practices may be implemented either within the upstream catchment or pond block. In some cases, where LID is utilized as a primary feature of the stormwater management strategy, dry ponds may substitute for wet ponds, the former of which have been shown to generate cooler flows than wet ponds (Galli, 1990).

In examining the benefits of LID, it is important to look at both their ability to reduce temperatures, as well as their ability to reduce thermal loads. Depending on the context, some LID may be designed with liners that prevent infiltration. In these instances, the thermal load reductions will largely reflect the capacity of the practice to reduce temperatures, although some load reductions may also occur from volume reduction through evapotranspiration. In other cases, on coarse textured soils for instance, significant volume reductions may be expected through a combination of evapotranspiration and native soil infiltration. In these contexts, the temperature reduction is much less important than the overall thermal load reduction, since very little of the runoff is actually released from the practice.

3.6.1 Temperature reductions through LID practices

Low impact development practices differ from ponds in that they typically only generate flow during rain events, and sometimes require rain events above 5 or 10 mm to generate flow. Drawdown times for these larger events are often controlled by the rate of filtration through the media, although sometimes orifices or elevated underdrains are incorporated to slow the rate of outflows and promote more infiltration. Since LID practices drain only during and after an event (not continuously like some ponds), the metric selected for the analysis of temperature changes is the Event Mean Temperature. As the term suggests, the event mean temperature (EMT) represents the flow weighted mean of temperature for the duration of the event, and is calculated as:

Where:

$$EMT_{in} = \frac{\sum T_{in} Q_{in} dt}{\sum Q_{in} dt} \qquad EMT_{out} = \frac{\sum T_{out} Q_{out} dt}{\sum Q_{out} dt}$$

T = temperature, Q = flow rate and t = time.

Event mean temperatures do not incorporate thermal reductions due to volume losses through LID practices, but the metric provides an understanding of thermal performance of the practices had they been designed with liners to prevent infiltration.

Figure 23 presents effluent EMTs for several LID projects that were monitored for at least one year. The data shown are for the summer period from June 15 to September 15 (in most cases) when streams are most vulnerable to thermal enrichment. The data show that bioretention typically generates very cool discharges. The IMAX parking lot bioretention cells are an exception in this regard, likely due to the shallow bedrock and full sun exposure at this site. The Central Parkway site is a soil cell in a boulevard median that also incorporates a different design than the typical bioretention facility. The infiltration trench effluent EMT median and range was similar to the Kortright bioretention which has exactly the same size and drainage area materials. Permeable pavements and green roofs can generally be expected to discharge warmer water than vegetated or underground LIDs as the stone base storage reservoir is relatively close to the surface (approx. 10 to 60 cm) where it is more exposed to solar radiation, and the pavement absorbs heat more readily than vegetated surfaces.

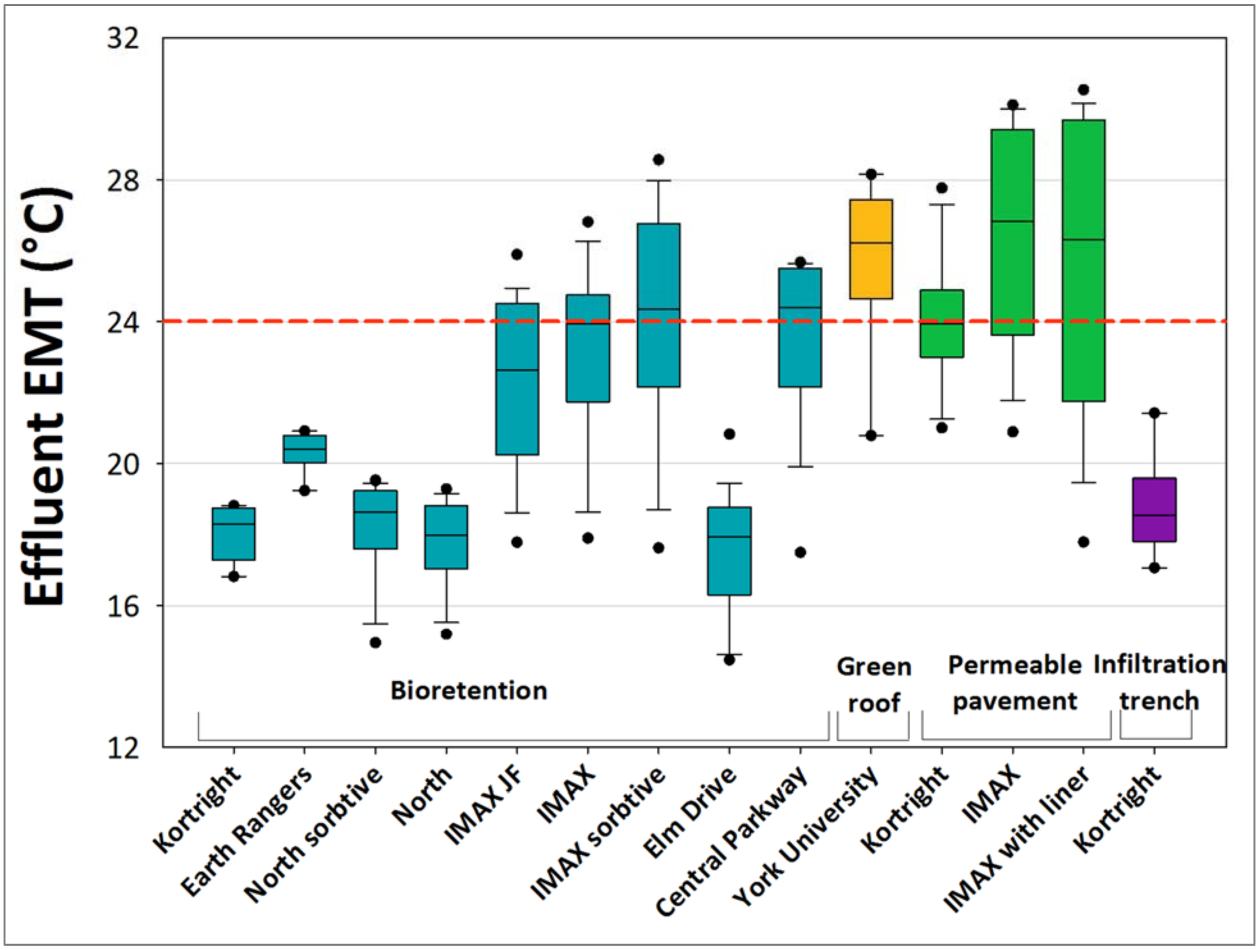


Figure 23: Effluent event mean temperature (EMT) for LID practices

The influent and effluent EMTs and EMT reduction values are shown in Figure 24 and 25. In many instances, the influent EMT is determined from monitoring of a nearby asphalt control pavement, since influent to bioretention or permeable pavements could not be practically measured. Negative median EMT reductions were found for only one of the bioretention cells, all of the permeable pavements, and the green roof. This suggests that these sites rely primarily on volume reduction through infiltration and/or evapotranspiration to provide thermal mitigation benefits.

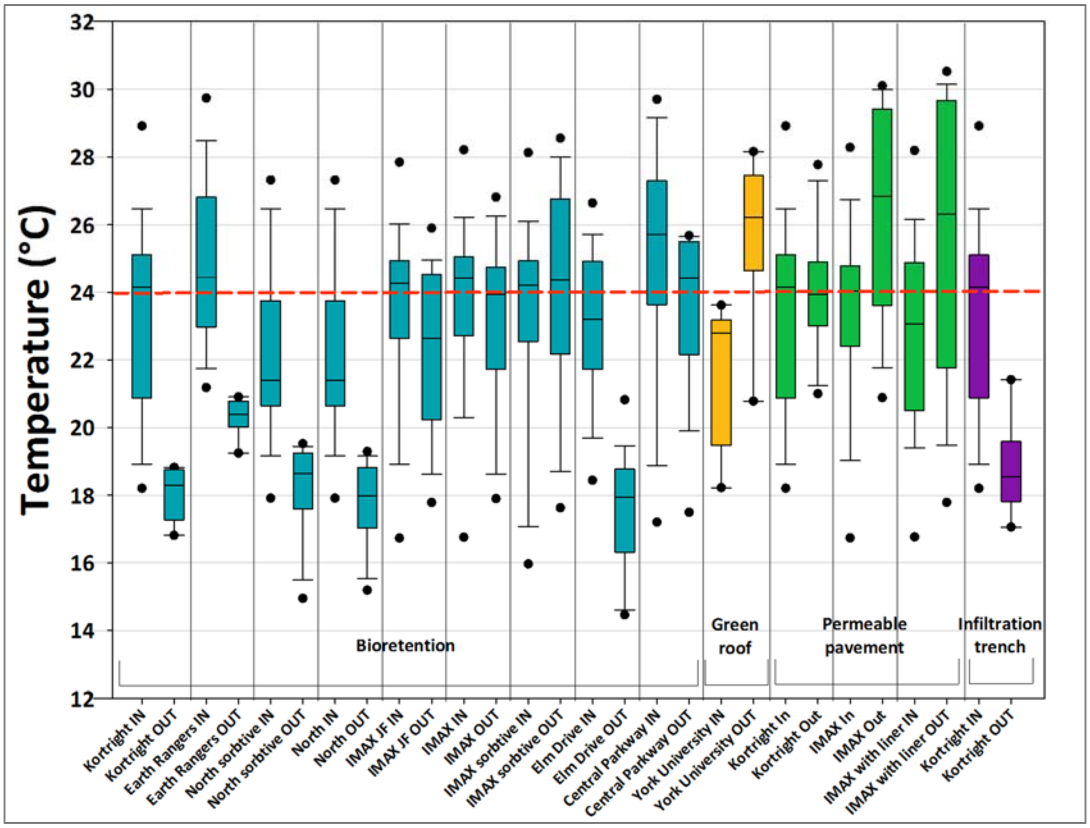


Figure 24: Influent and effluent event mean temperatures for LID practices

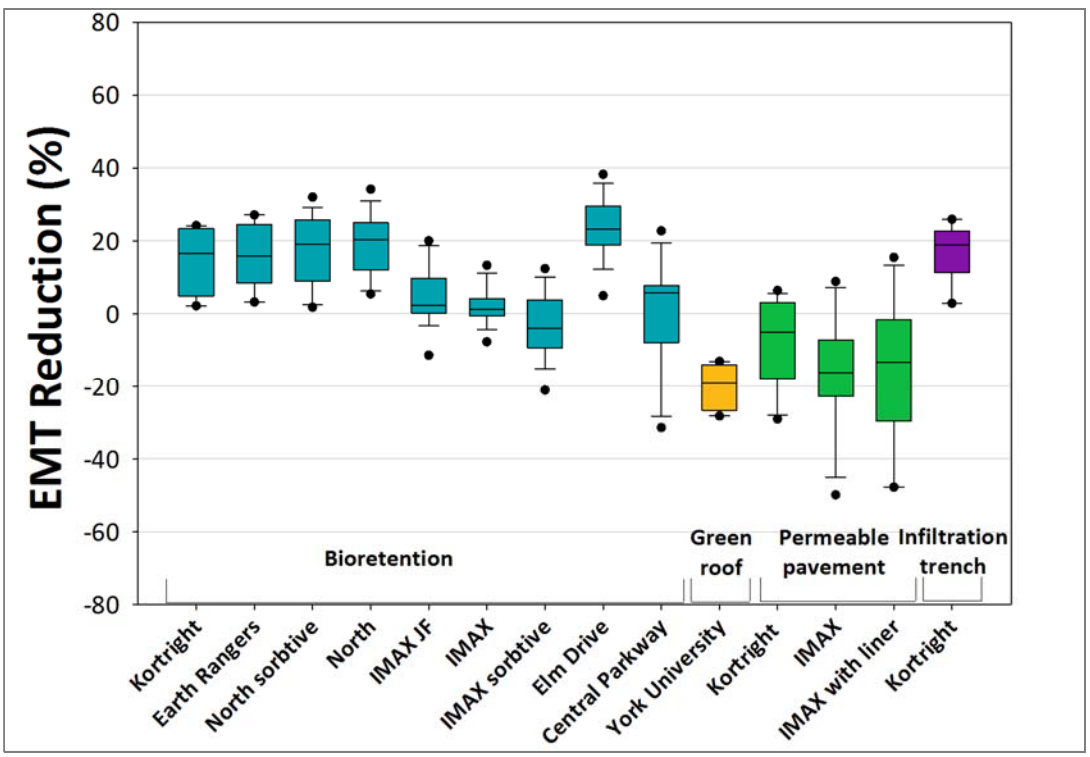


Figure 25: Event mean temperature reduction for LID practices

3.6.2 Thermal load reductions through LID practices

The relevant metric for evaluating thermal benefits of LID is based on thermal loads, since these practices have an influence on both the temperature and volume of runoff. Thermal loads are calculated using equation 1 provided earlier in section 3.6.1. The volume of runoff reduced by these practices will vary based on design, the size of the contributing drainage area and the native soil infiltration rates, among other factors.

Thermal load reductions for LID practices monitored are shown in Figure 26. All but one of the permeable pavements had median thermal load reductions above 65%. Even the green roof and permeable pavement practices that were found to have increased water temperatures showed impressive thermal load reductions. The Kortright permeable pavement was installed on fine textured soils that reduced runoff by only 45%, which explains why the median thermal load reduction in this case was lower.

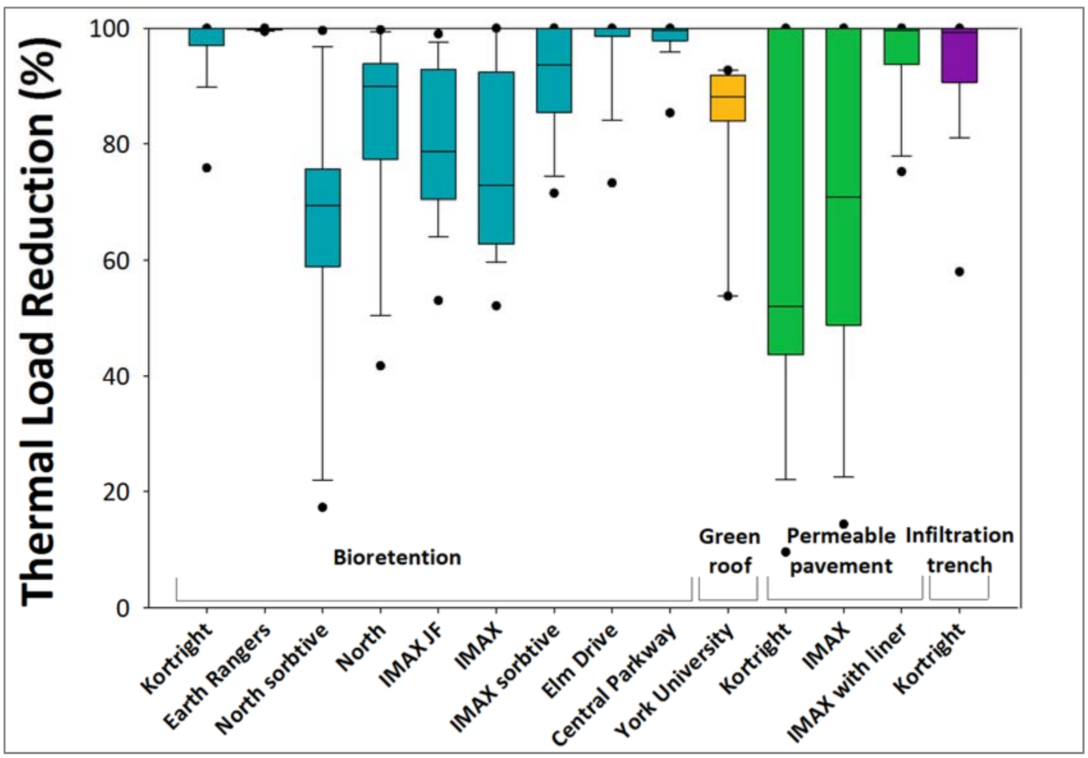


Figure 26: Thermal load reductions for LID practices

3.6.3 Time series analysis

A time series analysis of asphalt and LID practice performance was conducted during two rain events when day time temperatures were above 25ºC in July and August, 2013. This analysis provides insights into how temperatures during warm periods vary with flow on asphalt and at the outlet of three LID practices, all located at the same site. Some general observations were as follows:

- Asphalt surface temperatures peaked for brief periods at the onset of rainfall before being cooled by the rain. Peak temperatures were 28 and 30ºC.

- Permeable pavement flows were much lower and temperatures reflected the stored water inside the stone reservoir. Temperatures were relatively constant at 25ºC and did not show diurnal fluctuations. There was not much change in effluent temperatures between the early July and late August events.
- The bioretention and infiltration trench facilities showed very similar thermal responses to rainfall despite differences in media (one had soil, the other stone). Peak temperatures hovered around 20ºC during both events.
- Thermal load reductions relative to the asphalt pavement for the two events were above 48% for the permeable pavement, and above 88% for the bioretention and infiltration facilities.

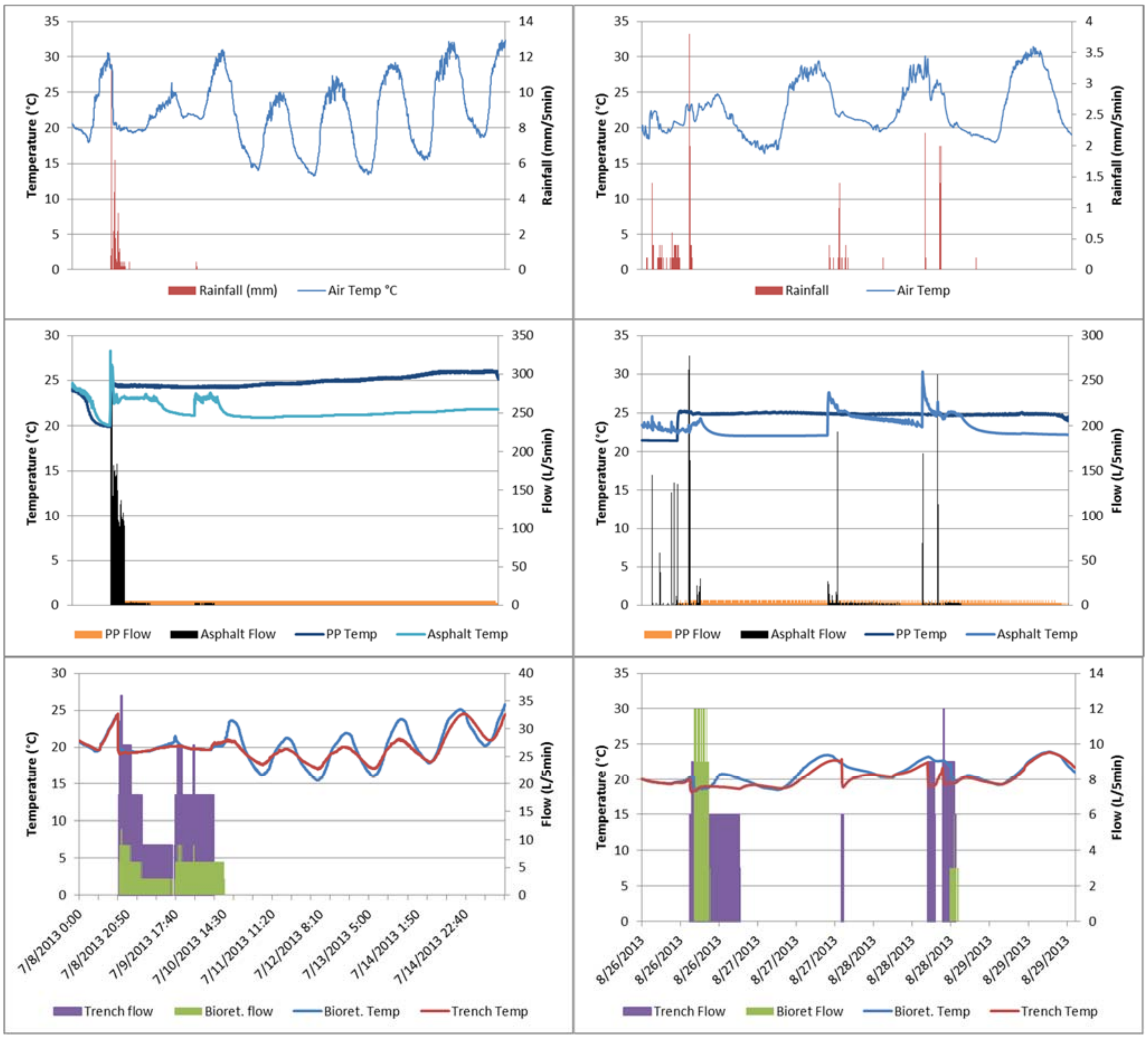


Figure 27: Time series plots for asphalt, permeable pavement, bioretention and an infiltration trench at Kortright on two warm flow events in July and August. Note that LID and asphalt temperatures outside of the period of flow represent the ambient temperature of the standing water where the sensor was located.

3.6.4 Thermal design and sizing considerations for LID

Most LIDs are not designed specifically for thermal mitigation, but rather for a range of stormwater control and treatment benefits. The key design components that would be important for thermal mitigation include but are not limited to the following:

- Deep media and underdrains in bioretention and infiltration trenches – 1.0 m or greater
- Good surface shade cover; trees are ideal
- Slow drawdown to encourage more infiltration
- Sizing that maximizes the volume of water infiltrated
- Location on coarse textured native soils to enhance infiltration
- On tight soils, maintain high hydraulic head in water storage reservoirs to enhance infiltration (Young et al, 2013)

Accurate sizing of infiltration practices for pond thermal mitigation using modelling techniques requires reliable data on pond water temperatures at the point of discharge to the infiltration system, rain temperatures and other parameters that are typically not available, and are difficult to predict. An alternative approach is to use empirical data from monitored ponds to calculate optimal sizing for defined thermal targets. This is the approach taken in this section for 3 monitored ponds. Confidence in sizing calculations based on empirical data will grow as more and more of these systems are built and monitored for thermal mitigation performance.

In order to determine the appropriate size of infiltration systems for thermal mitigation, it is necessary to show that thermal loads from ponds could be reduced through infiltration systems by an amount equivalent to the thermal load reduction achieved by practices that reduce summer temperatures alone (e.g. subsurface draw outlets). An example empirical data set is provided here for reference. It is assumed that the infiltration system is being implemented instead (rather than in addition to) a deep subsurface draw.

The data set used for this purpose is from a pond in Duffins Heights, Pickering that was monitored for water level and temperature. Flows into and out of the facility for a period between July 25th and August 24th, 2016 were determined by researchers at the University of Guelph using a hydrological model calibrated to water level data (Stajkowski and Gharabaghi, 2017). A continuous record of temperature at various depths within the pond (surface to 1.75 m) was also available for the same time period. The pond had a permanent pool of 5500 m^3, a residential drainage area of 127 hectares and a subsurface draw structure located at 1.4 m below the normal water level.

Table 6 shows the average, mean, median and maximum pond temperature at the surface, 0.25 m, 1.25 m, and 1.75 below the normal water level of the pond. The maximum and median difference between the surface and pond bottom was 5.1 and 1.5ºC, respectively. Under normal circumstances the infiltration system would be sized to provide thermal load reductions equivalent to an outlet that is below the water level surface (e.g. 0.25 to 1.5 m) as this would provide the most economical means of meeting the thermal mitigation requirement for the infiltration system. In this case, however, the sizing calculation is based on thermal mitigation of warmer surface temperatures as the subsurface draw outlet in the pond was not successful in meeting the 24ºC target for a portion of the summer. Basing the infiltration system sizing calculation on replication of the maximum temperature difference between the surface and 1.75 m depths, while implementing a system that combines shallow subsurface draw (between 0.75 and 1.0 m in this case) with infiltration would introduce a level of conservativism that better ensures thermal load reductions targets are met.

Thermal loads were calculated using equation 1 presented in section 2.3 based on data sets for surface and 1.75 m temperatures over the same period. Since the infiltration system would normally draw treated water from the existing outlet up to a certain maximum flow rate, a constant flow rate was subtracted from the outflow record to mimic the infiltration system operation. The quantity of flow deducted in this calculation was determined iteratively until the sum of thermal loads over the study period for the bottom and surface temperatures were equal (i.e. until the thermal load from a volume reduction facility paired with a surface draw outlet was the same as that achieved by a deep subsurface draw outlet). To achieve this objective, a constant flow of 0.22 L/s from the normal outlet needed to be redirected to the infiltration system. This flow rate will vary with pond size, but in this case the volume directed to the infiltration system represents 5% of the total pond outflow volume over the same period.

Assuming that the pond never stops flowing, the infiltration system would need to be sized to remove all of the water directed to it on a continuous basis over the summer. The infiltration size will, of course, vary based on the permeability of the underlying native soils. To help improve infiltration, the native soils may be scarified and a constant pool of water in the infiltration system can be maintained by increasing the flow rate slightly and allowing excess (cooled) water to overflow. Studies have shown that maintaining an elevated hydraulic head in underground infiltration systems throughout the summer can significantly increase the rate of infiltration through the bottom and sides of the system (Young et al, 2013). In Table 7, infiltration systems with bottom areas capable of fully infiltrating the required volume of pond outflow directed to them (i.e. flow rate multiplied by the time available to infiltrate) are provided for native soils with seasonal infiltration rates of 3, 12 and 25 mm/hour, representing soil textures for silty clay, clay/silt/sand loam, and sandy loam. It is conservatively assumed that all of the water infiltrates through the bottom (no side wall infiltration).

Table 6: Pickering pond temperature statistics (ºC) during two runoff events from July 25 to Aug. 24, 2016

	Outlet structure depth				Temp difference (surface to 0.75 m)	Temp difference (0.25 m to 1.75 m)	Temp difference (1.25 m to 1.75 m)
	Surface	0.25 m	1.25 m	1.75 m			
Average	26.4	26.0	24.9	24.9	1.5	1.1	0.0
Median	26.3	26.0	25.2	24.8	1.5	1.2	0.4
Maximum	30.8	29.4	26.5	25.7	5.1	3.6	0.7

Table 7: Infiltration area size required for thermal mitigation of pond outflows

	Infiltration System Bottom Area (m^2)/ Percent of pond area		
	Native soil IR = 3 mm/h	Native soil IR = 12 mm/h	Native soil IR = 25 mm/h
Surface draw outlet	269/4.0	67.2/1.0	32.3/0.5
Outlet 0.25 m below surface	168/2.5	42/0.6	20.2/0.3

As shown in Table 7, required infiltration system areas range from 0.3 to 4.0 percent of the pond area, depending on the native soil infiltration rate and outlet type. The data show that the system could be approximately 40% smaller if flows are drawn from a shallow subsurface outlet, rather than the surface. In this case, however, the shallow subsurface outlet would need to be combined with a larger facility to reduce temperatures shown in Table 5 to values below the 24ºC target.

While matching the seasonal thermal load may be a reasonable approach to protecting the long term health of aquatic life, short term spikes in temperature may not be fully mitigated using this approach. To address this potential concern, the analysis was repeated using two day dry and wet weather periods when pond temperatures were elevated (i.e. during the hottest times of the year). Table 8 shows the temperature differences between the pond surface and bottom for the short duration dry and wet periods. Temperatures at additional depths are shown to provide an understanding of how a system could work in combination with a shallow subsurface draw.

Table 8: Temperature statistics (ºC) during warm two day dry and wet weather periods

	Surface	0.25 m	1.25 m	1.75 m	Temp difference (surface to 1.75 m)	Temp difference (0.25 m to 1.75 m)	Temp difference (1.25 m to 1.75 m)
Dry weather							
Average	27.7	27.3	25.3	25.3	2.4	1.9	0.0
Median	27.5	27.1	25.3	25.3	2.2	1.8	0.0
Maximum	30.8	29.4	25.3	25.7	5.1	3.6	-0.4
Wet weather							
Average	27.1	26.4	25.1	24.7	2.4	1.7	0.4
Median	26.7	26.4	25.1	24.7	2.0	1.6	0.4
Maximum	29.8	27.9	25.1	24.8	4.9	3.1	0.3

Table 9 shows the infiltration system areas that would be required to provide thermal discharge loads that are equivalent to a subsurface draw outlet based on surface and shallow subsurface draw outlet locations. As before, the analysis was based on the warmest temperatures at the surface.

Table 9: Infiltration area size required for thermal mitigation of pond outflows during dry and wet weather

	Infiltration System Bottom Area (m^2) / Percent of pond area		
	Native soil IR = 3 mm/h	**Native soil IR = 12 mm/h**	**Native soil IR = 25 mm/h**
Dry Weather			
Surface draw outlet	72/1.1	18/0.3	9/0.1
Outlet 0.25 m below surface	60/0.9	15/0.2	7/0.1
Wet Weather			
Surface draw outlet	700/10.5	185/2.6	84/1.3
Outlet 0.25 m below surface	525/7.8	132/2.0	63/0.9

The flow rates to the infiltration system were calculated using the same method as previously. These were 0.06 L/s for the dry weather period and 0.59 L/s for the wet weather period. These flows accounted for 8 to 8.5% of total pond flows over the same period. As shown in Table 9, mitigating thermal impacts from the dry weather flows required a much smaller infiltration system than for wet weather flows because the thermal load to be mitigated was almost 10 times greater during wet weather. On tight soils, the infiltration system area would need to be approximately 1/10th the size of the pond area to provide adequate thermal mitigation during wet weather. A facility this size would exceed thermal load targets during dry weather, while just meeting them during wet weather. This is an important point because the warmest stream flows tend to occur during the inter-event period (see section 3.4.1 above); hence the much larger facility would provide seasonal thermal loads much lower than the deep subsurface draw outlet.

A similar analysis of seasonal thermal loads was conducted for two other ponds with continuous flow and temperature data in Newmarket (data courtesy of LSRCA). One of the ponds - the Oak Tree pond - was also monitored during 2016 but had very short event draw down times (approx. 12 hours) and no flow during dry weather. This meant that maximum (26.8ºC) and median (23.5ºC) surface temperatures were approximately 4 and 1.3ºC cooler than the Pickering pond, respectively (because wet weather typically has cooler flows). The difference in top to bottom median temperatures was also 2ºC greater, which would mean that greater thermal mitigation would be required to match bottom draw thermal loads.

Following the same procedure as described above, the infiltration area required to match bottom draw thermal load targets on a tight soil (IR = 3 mm/h) was approximately 4.7% of the pond area, which is about 18% greater than the 4.0% area calculated for the Pickering pond (Table 7). Flow needed to be diverted to the infiltration system from the primary outlet at a rate of 1.0 L/s to achieve the required infiltration.

In the case of the other pond – referred to as the Hillock pond – flows were more typical, with longer draw down times and outflows continuing throughout most of the early summer inter-event periods. To match seasonal thermal load of a bottom draw outlet in that instance required an infiltration system footprint for a tight soil condition that was approximately 6.6% of the pond area (Table 10). In this case, the diversion flow rate to achieve equivalency was only 0.27 L/s.

Table 10: Infiltration area size required for thermal mitigation of pond outflows from a surface draw outlet

Site	Infiltration System Bottom Area (m^2) / Percent of pond area		
	Native soil IR = 3 mm/hr	Native soil IR = 12 mm/hr	Native soil IR = 25 mm/hr
Oaktree Pond, Newmarket	54/4.7	13.5/1.2	6.5/0.6
Hillock Pond, Newmarket	323/6.6	81/1.6	39/0.8

Together these data suggest that some combination of cooler flows through a shallow subsurface draw (at 1.0 to 1.2 m) and volume reduction using infiltration systems that are sized to be up to 10% of the pond area would provide sufficient thermal mitigation to receiving waters both seasonally and on an event basis. These systems would alleviate concerns related to deep ponds and the clogging potential of outlet pipes close to the pond bottom, while also helping to satisfy volume reduction criteria for development sites. Designed carefully with appropriate pre-treatment, infiltration systems would be expected to require relatively minor additional maintenance over and above what is needed for the pond.

3.7 Underground tanks and chambers

In some urban areas, particularly where land is expensive, detention tanks and chambers are installed under public lands such as parks to save space. These systems are sized with permanent pool storage volumes similar to ponds, and as such can be regarded as an underground pond. Most of the systems installed in Ontario have closed bottoms, although infiltration functions can be built into these systems.

From a thermal mitigation perspective, these systems function much like an infiltration trench, but typically for much larger flows. In a study of an underground detention chamber in Markham conducted by STEP in collaboration with the University of Toronto, the temperature of outflows were found to be consistently below inflow temperatures throughout the warm season (Drake et al., 2016). Temperatures did not show diurnal fluctuations or significant changes in response to rainfall events. Outflow temperatures increased gradually from 8ºC in June to 13ºC in October. Strong thermal gradients were not present in the system.

The very cool temperatures are attributed to the absence of solar radiative heating, good insulation from the surrounding area (at 1.4 m below ground level) and the partially developed nature of the catchment (the system was sized for an area roughly 50% larger, but the catchment was not fully built out at the time of monitoring). Had the catchment been fully developed, the permanent pool would have been exchanged with new water more frequently, resulting in temperatures more similar to the inlet. Based on temperature data from other underground infiltration systems cited above, temperatures below 22ºC would be expected from underground detention basins under fully developed conditions.

3.8 Floating islands

Shading is often identified as a potential measure that can be used to mitigate the thermal impacts of ponds. As mentioned previously, however, trees and shrubs take time to grow, and do not provide the immediate thermal mitigation benefits typically required by approval agencies. An alternative that does not suffer from this drawback provides direct shading through floating materials that may be inert, such as shade balls, or living materials, such as vegetated rafts.

In 2011, floating islands were installed in a Brampton pond and monitored by Credit Valley Conservation staff to assess their thermal mitigation benefits. Floating islands are designed to mimic naturally occurring floating wetlands. They improve water quality, are aesthetically appealing and provide habitat for wildlife. The islands are typically constructed with a buoyant matrix (floating media) that houses the wetland vegetation (soil, plant species). The roots of the plants grow through the matrix, directly into the water. Floating islands are not significantly affected by water level fluctuations therefore have great potential for stormwater applications.

Designed more specifically for water quality control, vegetated islands may provide shading to the middle of a pond where few other techniques are effective due to the distance from shore. Previous studies have shown that floating islands can remove nitrate, phosphorus, ammonia, and are also effective at reducing total suspended solids and dissolved organic carbon (Masters, 2012). While the water quality benefits of floating islands have been well researched there were no studies of the thermal mitigation potential of the islands prior to monitoring conducted in Brampton.

Figure 28: Floating island in Brampton stormwater pond

3.8.1 Monitoring program

The Pond 10 floating islands in Brampton were monitored during 2011 and 2012 for their thermal mitigation potential. Details of the monitoring program and site are provided in a separate document (CVC, 2013). Air temperature, water temperature, and precipitation were monitored during select periods. The monitored data was compared for both the years, as well as analyzed for select hot and dry periods, warm and wet periods, and during rain events.

A total of 6 islands were installed (Figure 29), providing 740 square metres of shade and coverage for the stormwater pond. The islands cover approximately 10 percent of the surface area of the pond. Figure 29 shows the thermal monitoring locations at Pond 10. Three strings with temperature loggers at different depths were installed: String 1 installed before the floating islands, String 2 within the floating islands, and String 3 after the islands. Each string location had probes located at seven depths: 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 100 cm, and 150 cm. Additionally temperature loggers were installed at each of the two pond inlets and one near the outlet. Water Temperatures were measured continuously and logged at 30-minute intervals. Water levels were monitored at the outlet to provide an indication of the occurrence of outflow.

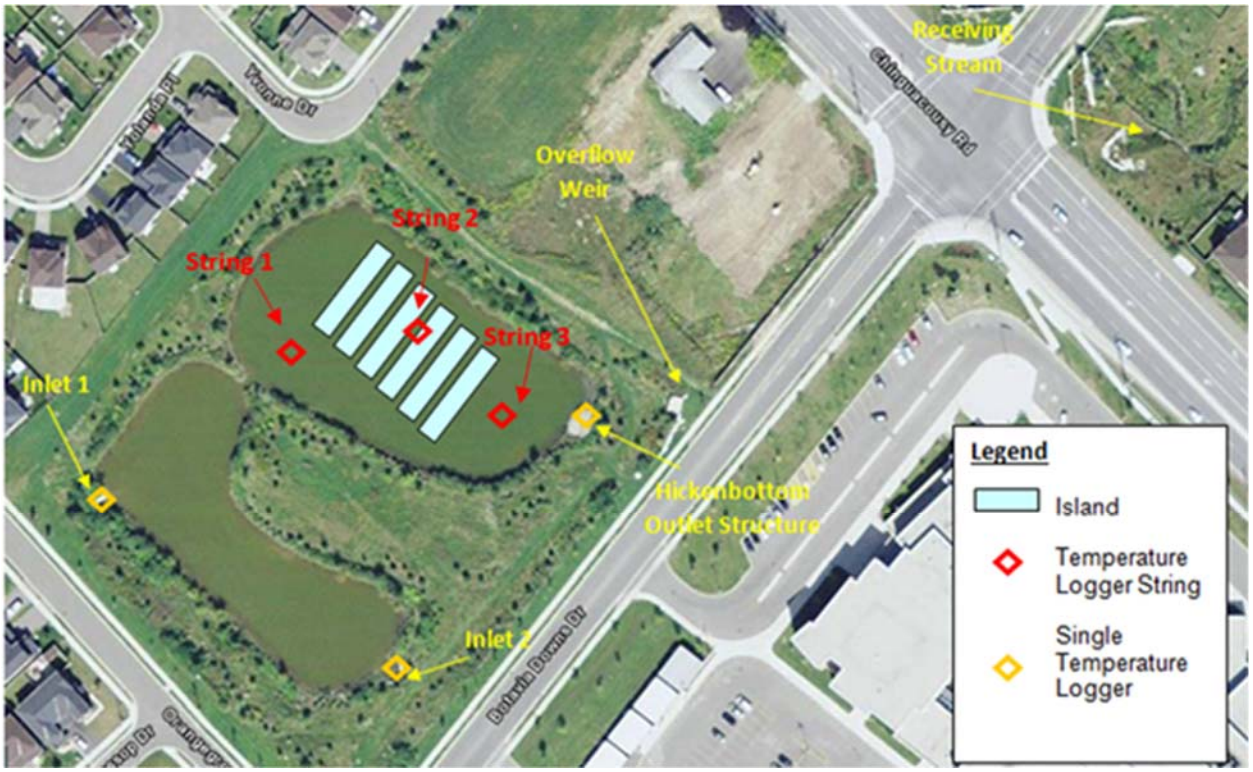


Figure 29: Deployment strategy for monitoring the thermal mitigation potential of a pond with vegetated floating islands

3.8.2 Summary and findings

Monitoring showed that, in general, the floating islands helped provide some cooling of the pond water by providing shading and reducing stratification, particularly in 2012 when the island vegetation was fully developed. Some of the specific conclusions drawn from the study are presented below:

- The mature island vegetation resulted in less stratification, thereby potentially reducing contaminant release caused by anoxic conditions at the pond bed. The vegetation also lowered the surface temperature; however, bottom temperatures were higher due to mixing, likely caused by the developed rooting system.
- During periods of outflow the observed maximum outlet temperatures were lower than the inlet temperatures for storms that occurred following a hot day. However, outflow temperatures were close to or a little higher for storm events following a cooler day. This suggests that the islands mitigated the thermal impacts by providing cooling and mixing during hot periods. However, outlet temperatures for storm events following a hot day still exceeded the 24^{0}C thermal targets indicating that further treatment may be required to lower the outlet temperature.
- As expected, pond surface temperatures fluctuated with air temperature. Hot dry days reflected higher pond temperature and greater stratification, especially when the floating vegetation was not fully developed. However, as with non-shaded ponds, the pond temperatures quickly dropped either before or during the storm event due to drop in air temperature, cooler rain temperature, and mixing.
- Lag time between inflow and outflow also plays an important role. Larger lag time promotes more mixing, therefore, better thermal mitigation for surface draw ponds. Therefore, regulating outflow could potentially help improve outflow temperatures.

Overall, vegetated floating islands may provide some thermal mitigation through shading, although coverage of at least 1/3 of the pond may be needed to provide tangible benefits. A treatment train option may be more promising means of achieving required temperature targets. The subsurface draw, night time release, and cooling trench techniques discussed previously could be used along with the floating islands to enhance benefits.

4.0 Monitoring Considerations for Thermal Mitigation Projects

4.1 Overview

Prior to designing and implementing a monitoring program, it is important to identify the overall program objectives and goals, and ensure that appropriate resources are allocated to ensure the questions of interest can be addressed in a robust and scientifically defensible manner. If it is expected that similar monitoring projects will be conducted in the future, monitoring design and data analysis methods that can be easily replicated should be selected to facilitate results comparisons among studies. Likewise, if other similar monitoring programs have been conducted by others in the past, it will be important to review results as part of the monitoring program design to gain an understanding of whether the selected methods adequately achieved the program objectives, and are worth replicating.

Each thermal mitigation measure requires a monitoring program specifically designed both for the measure and for the unique conditions present at the site. Detailed guidance on monitoring program design for all measures is beyond the scope of this chapter. Instead, a generalized protocol and set of recommendations is presented here, specifically as it relates to some of the more common thermal mitigation measures, such as ponds and cooling trenches. Additional monitoring equipment and analysis methodologies may need to be employed for LID practices and other non-traditional measures.

4.1.1 Define program goals and objectives

As mentioned previously, the data collected through a monitoring program should be tailored to the specific conditions present at the stormwater management facility under study. The conditions may dictate the technical and/or financial feasibility of achieving certain goals and objectives. For example, if the inlet of a facility is inaccessible, or is subject to backwater conditions, it may not be possible to gather the data needed to answer the questions of interest.

When monitoring thermal mitigation measures for stormwater management ponds, objectives that would be useful to consider upon designing the program could include:

- Understanding the thermal stratification occurring in the pond
- Pond outlet temperature compliance analysis for species at risk temperature targets
- Receiving stream sensitivity and other variables of interest to be monitored (i.e. conductivity, phosphorous, etc.)
- Cooling trench effectiveness assessment
- Thermal load balance

Table 11 provides details on the equipment required to address these objectives and outlines possible constraints. In most cases, temperature probes, level loggers and air temperature measurements are necessary. The level loggers provide an indication of flow conditions and allow determination of the conditions under which inlet/outlet temperatures may be elevated. The air temperature measurement indicates whether conditions were warmer or cooler than normal (when compared to historical norms), and is a critical piece of information when comparing water temperature results from different monitoring years and studies. It can also help in assessing whether the water temperatures are measuring water or air temperature in ponds that are not continuously flowing.

Table 11: Summary of potential objectives to address and the equipment required for each scenario.

Potential Objectives	Equipment Requirements	Constraints
Understanding the thermal stratification occurring in the pond	• Temperature loggers at the inlet and outlet of the pond as well as multiple loggers at different depths from the same point of origin. • Water level loggers near the depth profile. • Air temperature logger to characterize weather conditions and compare against water temperature data for QA/QC purposes.	Pond just constructed and has not been exposed to a winter season. Site accessibility—ensure both inlet and outlet are accessible.
Pond outlet temperature compliance analysis for species at risk temperature targets	• Temperature loggers at each of the inlets to the pond, one at the outlet structure to the receiving watercourse, and upstream and downstream of the pond outlet in the receiving watercourse. Outlet sensor should be downstream of mixing zone. • Pond water level logger. • Air temperature logger to characterize weather conditions and compare against water temperature data for QA/QC purposes.	Site accessibility—ensure both inlet and outlet are accessible. Watercourse needs to be accessible to install temperature sensors.
Receiving stream sensitivity and other variables of interest to be monitored (i.e. conductivity, etc.)	• Temperature probes at the inlet and outlet of the pond and conductivity probes submerged near the inlet and outlet inverts. • Pond water level logger. • Air temperature logger to characterize weather conditions and compare against water temperature data for QA/QC purposes. • Temperature probes in the receiving water upstream and downstream of the discharge point.	Pond just constructed and has not been exposed to a winter season. Development occurring upstream. Site accessibility—ensure both inlet and outlet are accessible.
Cooling trench effectiveness assessment	• Temperature probes at the inlet and outlet of the cooling trench, and in the bypass channel if present. • Level loggers within the cooling trench and pond. • Inlet and outlet flow measurements if there is a significant infiltration component. • Level loggers with temperature sensors in piezometers within and adjacent to cooling trench to determine potential groundwater interaction. • Air temperature logger to characterize weather conditions and compare against water temperature data for QA/QC purposes.	Inlet or outlet of cooling trench may not be suitable for flow measurement. Level logger installation within trench more costly and complicated if wells/piezometers are not installed during construction. Measurement of bypass flows requires infrastructure suited to this purpose.
Thermal load balance	• Temperature and flow loggers at each of the inlets to the pond and/or cooling trench, within the outlet pipe draining to the receiving watercourse. • Temperature measurements within the receiving watercourse upstream of the discharge location and downstream of the mixing zone. • Flow measurement upstream of the point of discharge can also be helpful. Level loggers in the pond and/or cooling trench. • Level loggers in piezometers within and adjacent to cooling trench (if present) to determine potential groundwater interaction. • Air temperature logger to characterize weather conditions and compare against water temperature data for QA/QC purposes.	Inlets and outlets of pond and/or cooling trenches may not be suitable for flow measurements. Level logger installation within trench more costly and complicated if wells/piezometers are not installed during construction. Measurement of bypass flows requires infrastructure suited to this purpose.

4.1.2 Thermal assessment

To understand the thermal impact of ponds and other thermal mitigation measures on receiving water courses, spot measurements are not sufficient. Continuous temperature and thermal load measurements of inflows and outflows should be assessed. Monitoring thermal loads is especially important if water is lost through the system via infiltration and evapotranspiration. Low impact development practices and infiltrating cooling trenches are examples of thermal mitigation measures with these characteristics. The thermal impacts of ponds and lined cooling trenches that do not lose significant volumes of water through evaporation and infiltration can be understood by measuring continuous temperatures and water levels without flow measurements.

As mentioned previously, event mean temperature (EMT) represents the flow weighted average temperature of water flowing in and out of the stormwater management pond facility during an event; whereas thermal load is the amount of energy introduced to the pond from heat transferred to stormwater from surface runoff and solar radiation inputs. Event mean temperatures can be a useful metric for thermal mitigation measures that only flow during rain events. For continuously flowing ponds or cooling trench systems, the EMT measure will underestimate impacts since the warmest flows often occur during dry weather. In these cases, frequency curves should be used instead to capture the broader range of flow and temperature conditions.

In order to assess thermal mitigation and calculate event mean temperatures and thermal loads, temperature and flow loggers need to be deployed at the inlet and at the outlet of the thermal mitigation measure. Depth profiles of pond temperatures are useful in this instance as it allows for calculation of approximate thermal loads from outlets deeper or shallower than the installed outlet, which can be an important comparative reference to installed measures. Refer to the Thermal Monitoring Equipment and Deployment Design section for further details on deployment strategies.

4.2 Monitoring protocol

The as-defined program goals and objectives will guide the monitoring program of the facility as they will help to determine the types of monitoring equipment needed, data collection intervals, sampling requirements, monitoring locations and how data will need to be later analyzed to satisfy the objectives.

4.2.1 Site assessment

Prior to implementing a monitoring plan to evaluate the efficacy of thermal mitigation measures, a detailed site assessment should be conducted. Typically this process would start with inspection of as-built design drawings, followed by a field assessment that confirms whether the drawings accurately depict conditions at the site. Differences between the drawing and actual conditions would then need to be noted to ensure that the design being monitored is accurately described in the final report.

In addition to confirming design details, the field assessment would identify where and how to monitor parameters of interest based on the layout of the site and potential constraints. Any safety measures that may need to be observed to prevent accidents during installation or regular equipment downloads would also be identified at this time. For ponds, this would involve determining the location of inlets and outlets, whether backflow conditions exist, how long the pond flows after rain events, the depth of the outlet invert and constraints that may prevent or complicate installation of monitoring equipment at desired locations.

For cooling trenches, key observations would include the configuration of inlets and outlets, presence or absence of wells, groundwater conditions in the area (if observable), the configuration of overflows or bypasses, and other relevant features.

LID and other practices that reduce thermal loads through volume loss to infiltration and/or evapotranspiration will involve similar inspections of inlets/outlets/overflows, and the configuration and function of infrastructure relative to as-built drawings. In addition, the filter media, plants (if present), underlying native soil properties and groundwater table elevation would also need to be assessed to determine the primary flow paths, pathways for thermal load reduction, and frequency of overflows. This assessment may simplify the monitoring program if certain conditions are not present. For instance, if overflows or surface ponding are not likely to occur for frequent storms based on the site assessment, sensors may not need to be installed to quantify these parameters.

The following sections provide further details on the specific tasks required before and during the monitoring period.

4.2.2 Considerations prior to initiating monitoring

- Test and calibrate all equipment prior to deploying the equipment in the field and at the end of the field season. It is especially important that temperature sensors be tested relative to one another to ensure the data are consistent, and any offsets are noted. This testing and calibration process should be conducted in reference to the equipment manufacturer's guidelines and protocols. Data collected should also be inspected shortly after collection to validate that the sensors are functioning as intended. The type of QA/QC procedure will vary by equipment type. For example, flow data should be validated by generating a stage-discharge curve at each download to ensure reference points are remaining stable, and the stage-discharge relationship remains robust over the monitoring period.
- Identify appropriate locations for the equipment to be deployed ahead of time so that damage caused by vandalism and extreme weather events can be mitigated. See Table 5 for guidance on equipment required for potential monitoring scenarios and objectives.
- Designate extra equipment as back-up equipment to ensure no data gets lost, in case the deployed equipment malfunctions during the monitoring period.

4.2.3 Considerations for monitoring

- Deploy equipment during warmest periods of the year, June 1 to September 30
- All equipment should be logging at the same time interval, where every 10 minutes is preferred.
- Equipment downloads should be conducted at intervals of no greater than once a month (every two weeks preferred) to ensure errors are detected in a timely manner and data are not lost.
- It is important to regularly check on the equipment and clean any build-up of dirt on the sensors as well as ensure the loggers are logging data continuously and the batteries are sufficient.
- Document all field visits by recording the date and time of visit, whether or not the equipment was removed for downloads (and the time at which this was completed), if the condition of the equipment is acceptable as well as the overall field conditions.
- Take detailed photos upstream of the inlet, at the inlet, at the pond, at the outlet, downstream of the outlet and within the receiving water body to validate the data collected. This documentation will help inform data analysis and interpretation.

4.2.4 Thermal monitoring equipment and deployment design

Depending on the goals and objectives of the program, specific equipment will be required for monitoring. Below are possible scenarios and the required monitoring equipment for each. For a brief summary, refer to Table 5 outlining the potential objectives a monitoring plan could address and the equipment required for each scenario.

Temperature loggers

In general, due to temporal fluctuations in temperature and the uncertain nature of storm events, temperature monitoring should be completed with automated temperature and level loggers. It is important that the same brand of equipment is used, and that the equipment be calibrated against a known reference point, and in relation to all other pieces of equipment to ensure consistent readings and results. As a general rule, flow measurements are needed for any measure that relies fully or in part on volume reductions to achieve thermal load reductions. Therefore, this section is directed primarily at non-infiltrating practices such as cooling trenches and ponds, where floggers may still be useful, but not essential in all cases.

Minimum deployment strategy

It is recommended that at a minimum, one temperature logger be installed at each of the facility inlets and outlet to the receiving watercourse (Figure 30 and 32 show examples for a pond). This will allow for an assessment of the impact the facility is having on the temperature of the stormwater during frequent events when bypass is not occurring. A level logger should also be deployed as an indication of when flow is occurring.

Additionally, it is important that an air temperature probe and rain gauge be installed within the vicinity of the pond to characterize weather conditions and assist with the QA/QC process during data analysis and interpretation. If not enough resources are available to monitor air temperature and rainfall probe, data from a nearby meteorological/rain gauge station can be used instead (ideally not more than 3 km away).

Sensitive system deployment strategy

Where the facility is discharging to sensitive streams, additional temperature loggers should be considered at bypass points, in the creek upstream of the pond outlet and in the creek downstream of the mixing zone. Additional temperature sensors may be needed for long outlet channels as these will help establish whether there is a warming or cooling trend as flows move from the facility outlet to the receiving watercourse. A level logger should be installed in the facility to indicate when flow is occurring. As mentioned above, and for the same reasons, air and rainfall measurements should also be measured on-site, or at a nearby meteorological station if resources are not available to install equipment onsite.

In ponds, it may also be useful to assess the degree of thermal stratification in the pond to provide the information needed to help optimize thermal mitigation practices in the future at the monitored site and/or at other sites. To successfully monitor thermal stratification, temperature loggers should be deployed at different depths from the same point of origin. The loggers deployed at different depths should be fixed via a stake or buoy to keep them anchored in place. The depth at which the temperature loggers should be deployed depends upon the total depth of the pond. To determine stratification across the entire pond, the depth profile of temperature loggers should be installed at the deepest point in the pond (see Figure 30). If instead the data are being used to assess whether deeper or shallower outlet structures in ponds would be preferred, the profile should be installed near the outlet, as it is the temperatures at this location that are of greatest relevant for outlet depth assessment.

The temperature loggers should be programmed to continuously log at the same interval so that data points can be matched up during analysis. A common problem cited by monitoring staff occurs where the profile is removed for downloading and replacement results in one or more of the sensors being snagged at a different elevation, resulting in a significant data gap. For this reason, measurements should be made to ensure that sensor locations have not changed after downloading.

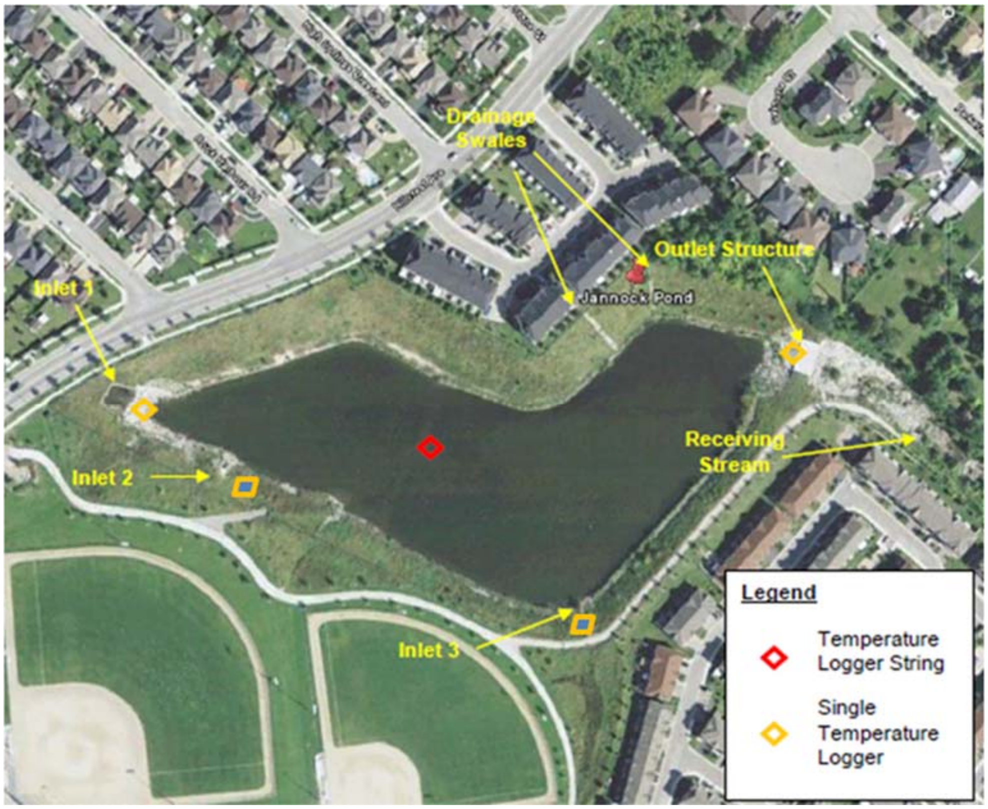


Figure 30: Example of a temperature logger deployment strategy for a pond.

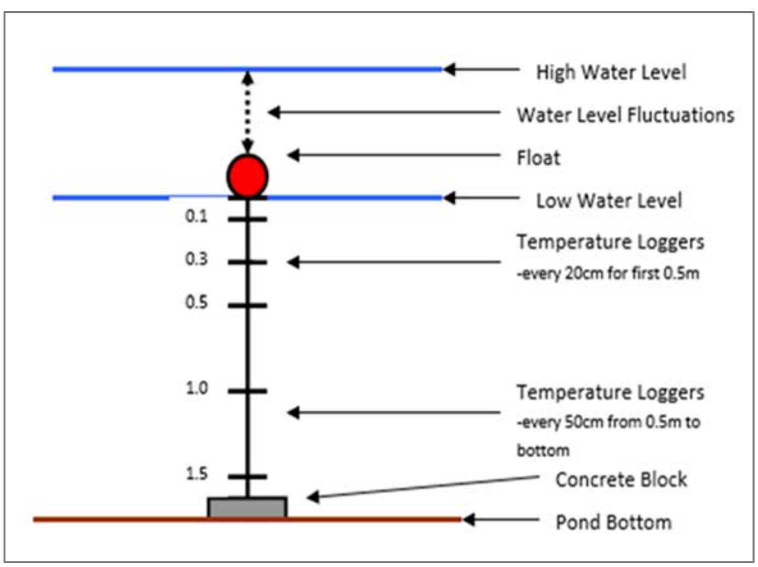


Figure 31: Temperature logger deployment strategy to capture thermal stratification in a pond. Note that the temperature sensors should not move with the float.

Depth/Flow loggers

Temperature loggers are typically used to assess thermal impacts on receiving waters because they are inexpensive to deploy and operate, data analysis is relatively simple, and targets are enumerated as temperature thresholds, making exceedances of thresholds simply to evaluate with temperature measurements. However, the true impact on receiving waters is not only a function of temperature, but also of flow volumes. The thermal load metric, expressed in energy units, captures this combined temperature and flow impact both for the facility and for the impact of the facility on receiving waters.

While it is generally true that thermal loads are essential for monitoring of thermal measures that reduce flow volumes, such as many types of LID practices, it can also be a useful metric for ponds and non-infiltrating cooling trenches because, compared to temperature measurements alone, this metric better captures the difference in thermal impact associated with a given temperature at low and high flows. An example of how flow, temperature and water level loggers would be set-up in a facility is shown in Figure 31.

Unfortunately, it is much more difficult and expensive to measure flows than temperatures, making it impractical to do for ponds and cooling trenches in most cases. For this reason, continuous hydrologic models are sometimes calibrated to pond water levels to estimate inflows and outflows and calculate thermal loads. The modelling method requires more analytical time, but only requires an inexpensive water level logger in the facility and temperature sensors at relevant points in the pond and receiving watercourse.

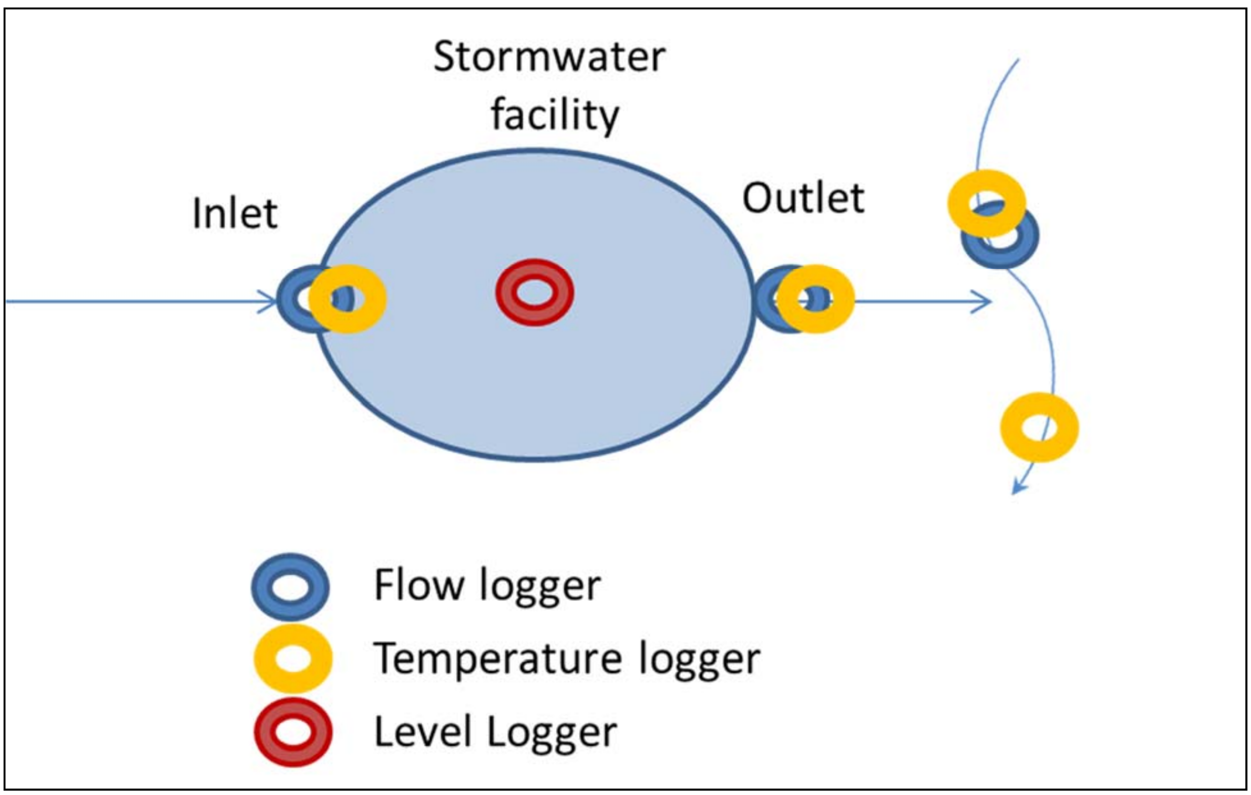


Figure 32: Suggested monitoring locations for temperature and depth/flow loggers in a stormwater facility.

Optional equipment depending upon program goals and objectives

Depending upon program goals and objectives, other sensors such as dissolved oxygen (DO) sensors and conductivity probes (for chloride) can be anchored and fully submerged approximately half a metre from the bottom of the pond and at varying depths to capture periods during which anoxia and/or high chloride levels may be present. Trends over the monitoring season can also be developed and compared with other ponds to better characterize conditions and facilitate analysis and interpretation of results.

4.3 Data QA/QC and analysis

Once the data has been collected, a thorough QA/QC process can be conducted followed by an analysis to determine the thermal impact of the stormwater pond on receiving watercourses.

4.3.1 Pre-Analysis

Prior to analyzing the data collected in the field, it is important to first organize and conduct a thorough QA/QC check of the data. An appropriate data organization layout can be seen in Table 12. This will be variable depending on the number of loggers deployed.

Table 12: Data organization example for temperature, water level and precipitation data

Day/Time	Site Name	Raw Level	Level adjusted	Raw Inlet Temp	Adjusted Inlet Temp	Raw Outlet Temp	Adjusted Outlet Temp	Air Temp	Precip
0:10:00		m	m	C	C	C	C	C	mm
2017-06-01 0:00	Pond1	0.063	0.063	24	24	23.5	23.5	26	0.02
2017-06-01 0:10	Pond1	0.063	0.063	24.6	24.6	23.5	23.5	26.2	0.02
2017-06-01 0:20	Pond1	0.06	0.06	24.82	24.82	23.5	23.5	26.2	0.02

The raw data files can be checked against air temperature to ensure no loggers were out of the water column and exposed to air temperature versus water temperature. Any data spikes, significantly high temperature maximums and erroneous data should be identified and removed. Blank or missing data points may also be identified and made note of through this process. It is further important to be aware of points in time during which data were downloaded from the equipment so that these data points can be removed from the dataset and not skew the results as it is typical for loggers to require some time to readjust to the system after being removed for downloads.

4.3.2 Data analysis

The data analysis methods will differ depending on whether the facility generates flows only during rain events, which is common for infiltration practices, or whether it also flows during dry periods, as is the case with many stormwater ponds.

If the facility flows only during rain events, the periods when flow is not occurring need to be removed, as sensors during these periods would be measuring ambient water or air temperatures. Water level sensor data and/or flow data can be used as indicator of when flow is occurring. If flow is available the thermal load and mean flow weighted temperature of water entering or leaving the facility can be calculated for each event. The latter measure is referred to as the Event Mean Temperature (EMT). The event based thermal loads and EMTs can then be analyzed to determine how temperature may vary based on rain event size and average air temperature over the same period. Changes in loads and EMTs from the inlet to outlet of the facility can also be determined and plotted.

If the facility flows continuously, time series plots and frequency curves can be developed to show diurnal fluctuations in temperature, trends related to air temperature and rainfall, and the frequency of occurrences greater or less than a given temperature. Where inlet/outlet flow data are available, time series graphs with secondary y axes can also show how temperatures relate to thermal loads over the monitoring period. If flow and temperature data are available in the stream as well, the effect of the facility on the stream thermal energy profile can be quantified.

4.4 Summary

Since field conditions often vary widely even for a similar thermal mitigation measure, monitoring strategies should be designed based on site specific details. A successful monitoring plan relies on understanding:

- overall program goals and objectives which will drive the monitoring design;
- available resources and resource constraints so that monitoring priorities can be established; and
- site conditions to determine if the monitoring plan will be functional and fully accessible.

5.0 SUMMARY AND CONCLUSIONS

This report summarizes and synthesizes data collected from over 50 projects that have been or may be used to mitigate the thermal impacts of stormwater ponds. The analysis has provided insights on the typical and expected performance of measures in different contexts, and helped to provide guidance on how practices can best be designed to optimize performance, while limiting maintenance requirements. Some of the key findings are as follows:

Thermal Stratification

- Ponds show distinct chloride and thermal stratification patterns that persist throughout the summer period.
- Chloride accumulation contributes to the formation of vertical density gradients that reduces mixing and helps maintain stratification during the spring and summer
- Maximum summer temperature differences between surface and bottom waters can be in excess of 9^0C.
- Diurnal fluctuations in temperature are often more pronounced in the upper 1.2 m of the pond than at lower depths.

Subsurface Draw Outlets

- The temperature of water discharged from pond outlets located below the permanent pool water level are invariably cooler than water discharged from surface draw outlets.
- Although some temperature improvements may be experienced at outlet elevations starting at 0.5 m below the permanent pool water level, more significant cooling requires subsurface draws to be located at least 1.2 m below the permanent pool water level.
- Meeting the 24^0C target for Redside Dace at least 95% of the time during an average year requires subsurface draws at least 2.0 m below the permanent pool water level.
- Year to year average shallow subsurface draw outlet temperature variations of between 2 and 4^0C can be expected due to weather, particularly air temperature, but also rainfall conditions, with drier, hotter years generating the warmest temperatures.
- Relative to a surface draw outlet, the expected 95th percentile temperature reduction provided by a 2 m deep draw outlet for years with similar air temperatures is between 3 and 5^0C.
- Deep draw outlets need to be combined with deep ponds to be effective from both a cooling and maintenance standpoint. It is estimated that a pond with an outlet 2.0 m below the permanent pool elevation should be at least 3.0 to 3.5 m deep at the outlet for drainage area impervious covers between 35 and 85%, respectively.
- Deep draw outlets should not be combined with scour pools in the immediate vicinity of the outlet, as these can reduce thermal performance by creating turbulence that enhances vertical mixing with warmer water above the outlet invert. Larger, gently sloping depth increases to the outlet will provide more consistent and dependable cooling benefits because of the larger volume of cool water below the outlet invert and the lower propensity for vertical mixing.
- Anoxic conditions of bottom waters are common to shallow and deep ponds. These conditions can result in changes in redox reactions that may enhance the release of phosphorus and heavy metals from deposited sediments. However, there is insufficient evidence to suggest that anoxic bottom

waters and redox reactions in deeper ponds would necessarily result in poorer effluent water quality than that of shallower ponds.

- Deeper ponds may require larger footprints to meet the MECP side slope requirements of 5:1 above the permanent pool and 3:1 elsewhere.

Night-time Release Outlets

- Optimal 8 hour duration for night time release outlets was found to be between 3 AM to 10 AM inclusive based on data from 4 ponds.
- The 95th percentile temperature declines for ponds with night time release outlets were calculated to be approximately 1.6^{0}C for surface draw outlets, and 0.6^{0}C for an outlet 1.4 m below the permanent pool level. For deeper outlets (i.e. below 1.5 m), the benefits of night time release are very small as temperatures from these outlets do not exhibit strong diurnal changes.
- With optimized night time release outlets drawing from the surface, the 24^{0}C temperature target was calculated to be exceeded between 20-30% of the time in the period between June 15 and September 15.

Primary Outlet Cooling Trenches

- The performance of primary outlet cooling trenches is highly variable due to differences in cooling trench sizing, inlet temperature, design, and degree of groundwater interaction, among other factors
- The empirical data did not provide definitive evidence on the required size of trenches for successful cooling. However, as a rule of thumb, and loosely based on the case studies reviewed, primary outlet trenches without groundwater interaction are not likely to provide summer temperature cooling of the warmest flows beyond roughly 1 to 3^{0}C for primary outlet trenches with storage volume equal to or greater than 5% of the runoff volume released from the pond during the 25 mm event.
- Several examples of trenches showing average summer cooling benefits greater than 2^{0}C are available, but this performance is reliant on site specific conditions, such as the presence of groundwater near the surface.
- Since these conditions cannot be relied on in every case, it is important for proponents to identify and prove in advance of construction that certain conditions are present, and that these will be sufficient to warrant the effective function of the facility, relative to the relevant targets.
- Cooling trenches have been combined with deep subsurface draw outlets, and found to provide additional cooling, despite the cooler starting temperatures.

Secondary or Split Flow Outlet Cooling Trenches

- Cooling trenches that receive only a portion of the total pond outflow can be more effective because (i) the warmest water is discharged during low flow, and (ii) cooling effectiveness is inversely correlated to flow volumes.
- Monitoring from two secondary outlet cooling trenches showed 95th percentile temperature reductions in the 4 to 5^{0}C range over the course of the summer. Half of this drop in temperature occurred in the transfer of water to the control manhole, prior to discharge to the cooling trench. However, flow rates through the trench were below 2 L/s.

- Primary outlet flows are not cooled by the secondary outlet trench and therefore require a different thermal mitigation measure to achieve overall pond cooling objectives.

Low Impact Development Practices

- Removing stormwater volumes from the system through enhanced infiltration, evapotranspiration and/or reuse can significantly improve the capacity of the stream to assimilate thermal impacts. This is particularly true if the low flow volumes are reduced as these typically exhibit elevated temperatures and are discharged during a period when the stream is also warmer than usual.
- Not all low impact development practices reduce temperatures, and some generate effluent concentrations above the 24^{o}C target. However, of the 12 LID practices monitored, all showed median thermal load reductions of greater than 65% during the June to September period, and most had reductions above 80%.
- Practices located well below grade and slowly filtered water tended to have the highest thermal load reductions.
- Monitoring of three different practices during the events preceded by air temperatures above 25ºC showed that asphalt has much higher peak water temperatures than LID. Most LID practices produce outflows with constant temperatures that are not influenced by diurnal fluctuations in air temperature.
- When implemented for thermal mitigation in combination with stormwater ponds, LID practices are best located within the pond block where systems can draw from treated primary pond outflows that often discharge warm water for several days after rain events.
- Infiltration systems drawing from the pond surface or surface draw outlet would provide thermal seasonal load reductions equivalent to those of a deep subsurface draw outlet at bottom area sizes of up to 6.6% of the pond surface area on tight native soils (3 mm/hour infiltration) and up to 1.6% of the pond area for loamy and sandy native soils (>12 mm/hour infiltration). In some areas, systems would need to be located under raised areas such as access roads to avoid intersection with the groundwater table.

Other practices

- Monitoring of a vegetated channel installed downstream of a pond with a 1.4 m subsurface draw outlet showed average thermal temperature reduction benefits in the 1 to 2^{o}C range, which at that site was sufficient to limit impacts to the cooler receiving watercourse. Maximum and 95th percentile outflow temperatures were not reduced by the channel.
- Underground detention chambers, such as the StormTrap system monitored by STEP, have the potential to cool inflowing runoff and maintain temperatures suitable for discharge to cool water fisheries (below 22ºC).
- Floating islands were also investigated, but shown to have limited thermal reduction benefits, primarily due to the areal extent of cover, which in this case was 10%.

Monitoring and Research Needs

A summary of the function, expected performance, performance variability, O&M level of effort and design considerations for each mitigation measured reviewed in this report are presented in Table 13. These results are based on the data and information synthesized in this report and should not be regarded as definitive. Values and general guidance will be continually refined as more data become available.

A monitoring protocol for future projects is provided for consideration to assist with practice assessment and further knowledge development aimed at improving the design and predictability of the practices being implemented.

This review has shown that practices that measures that reduce thermal loads to streams can be effective either as an alternative or in combination with more common subsurface draw systems. Monitoring of temperature and flow from ponds and receiving waters is needed to determine appropriate sizing guidelines for these systems in different contexts. Research on installed systems is needed to optimize system designs from a performance and maintenance perspective, and to better understand long term operational requirements and constraints.

The performance of cooling trenches is influenced by a large range of factors that make outcomes difficult to predict. Improved monitoring programs that better document the initial temperatures, flow volumes and rates, groundwater temperature and interaction, surrounding native soil temperatures and other factors will help to provide a better basis for sizing and performance prediction.

Other less conventional practices, such as those that provide surface cover or active geothermal cooling using boreholes need further investigation as a thermal mitigation option that may be feasible within a municipal context. Ongoing monitoring of pilot projects currently installed or planned in the City of Brampton is expected to provide the data needed to help fill this knowledge gap.

Table 13: Summary of expected performance and design considerations for mitigation measures reviewed in this report

Mitigation Measure	General Function	Expected Performance	Performance Variability	O&M effort level	Design Considerations
Subsurface Draw Outlet	Reverse sloped outlet pipe draws cooler water from below the Normal Water Level in the pond (NWL)	Relative to surface draw, 95th percentile temperature reduction of 3 to 5ºC for outlets 2.0 m or more below the NWL during years with similar air temperature. Outflows from a 2 m deep outlet meet 24ºC target most of the time during an average year.	Equivalent depth outlets may vary by ±1ºC depending on pond/outlet design. Higher outflow temperatures may be observed during warmer years and late summer heat waves.	Low. Periodic inspections and flush outs are necessary	• Pond must be ≥ 1.0 m deeper than the subsurface outlet invert elevation to provide sufficient sediment storage capacity and avoid sediment re-suspension. • Outlets accessible from the pond bank for maintenance via a control manhole. • Outlet inverts in the pond should be well supported with a headwall.
Nightime Release Outlet	Releases water only during the night and early morning period when pond discharge is cooler	95th percentile temperature reduction of up to 1.6ºC for surface draw outlets discharging during the coolest 8 hours of the day	May vary by ±0.5ºC depending on pond design. Temperature reductions decrease with outlet depth. Outlets 1.2 to 1.5 m below the NWL show negligible thermal benefits from night time release.	Low to set-up the system. Medium effort to operate and maintain with sufficient automation	• Coolest 8 hours typically between 3 AM and 10 AM inclusive. Rust-resistant hardware in easily accessible location. • Electrical supply and back-up power preferred. • Most effective on surface draw outlets, with diminishing returns as outlet depth increases.
Primary Outlet Cooling Trench	Removes heat through shading and thermal transfer to trench contents (air, water, stone) and surrounding soils	Dependable 95th percentile temperature reduction of 1 to 3ºC for well-designed system with a storage volume ≥ 5% of the runoff volume generated during a 25 mm storm	Cooling benefits vary widely with trench size, pond outlet temperature, trench design (e.g. shading, depth below surface, overflow trigger rate) and groundwater interaction.	Low. Periodic inspections and flush outs are necessary	• Trench storage volume designed as large as available space permits. • Can be combined with subsurface draw outlets to provide additional cooling. • Include high flow bypass and maintenance flush out ports. • Trench as deep as possible and shaded. • Including infiltration enhances thermal benefit.
Secondary Outlet Cooling Trench	Same as primary outlet cooling trench, but only for orifice controlled flows through a secondary outlet. System inlet may be located 0.5 m below permanent pool to reduce primary outlet dry weather flows and increase pond storage capacity prior to rain events.	Reductions of 95th percentile temperatures of 4 to 5ºC for continuous flows of 1 to 2 L/s through the system. Primary outlet flows require a different cooling measure.	Variability is expected based on the size of the trench and throughput flow rate. Infiltration can further enhance thermal load reductions.	Low. Periodic inspections and flush outs are necessary	• Well shaded trenches with maximized area of base and sides to enhance heat transfer with ground. • Outlet should be 0.5 m below permanent pool and drain to control manhole for pre-cooling. • Only low flows drain through the trench. • Install flush out ports for maintenance. • Subsurface draw on primary outlet to provide further cooling during high flows.
Outlet Channel or Swale	Provides vegetative shading of outflows and thermal heat transfer with underlying soils	Average temperature reduction of 1 to 2ºC in well shaded areas. Maximum and 95th percentile outlet temperatures may not change	Variability of ±1 - 2ºC is expected based on degree of shading and channel length	Low. Periodic inspections for erosion	• Maximize shading and spread flows as much as possible to enhance ground contact ratios and infiltration potential. • Avoid concentrated flows that cause erosion. • Large areas between the outlet and watercourse often needed for this practice to provide thermal benefits.

Table 14 cont'd: Summary of expected performance and design considerations for mitigation measures reviewed in this report

Mitigation Measure	General Function	Expected Performance	Performance Variability	O&M effort level	Design Considerations
Floating Islands	Floating mat of vegetation provides direct shading of a portion of the pond	Small islands have negligible effect on temperature. Thermal effects of larger island not well understood	Variability expected based on extent of pond coverage. May provide minimal benefits until vegetation is established.	Medium to high.	• Requires large pond surface cover areas. • May need to include additional materials to prevent inhabitation by birds. • Must be firmly anchored away from shore for safety
Underground detention chambers	Removes heat through direct shading and heat transfer with stored water and side walls of detention chamber	Relative to above ground surface draw ponds, 95th percentile temperature reduction of 8 - 10ºC.	Limited variability.	Easier to clean than normal ponds	• Sizing is similar to a normal pond. • Outlet elevation does not have a significant impact on outflow temperature.
Lined bioretention or infiltration trench	Removes heat through shading, evapotranspiration and heat transfer with filter media/gravel, surrounding soils and stored water	Effluent temperatures below 22ºC are common for systems greater than 1 m deep. Thermal load reductions of approx 40%	Temperatures may vary depending on shading in catchment. Thermal loads vary in proportion to the volume of water evapotranspired	Low for trenches, medium for bioretention due to plant maintenance.	• Good plant coverage and shading will enhance thermal performance. • Deeper trenches will likely outperform shallower ones.
Unlined bioretention or infiltration trench/chamber	Removes heat through volume reduction and shading/heat transfer with filter media/gravel and surrounding soils	Effluent temperatures below 22ºC are common. Thermal load reductions above 80% are common	Temperatures may vary depending on shading in catchment. Thermal loads vary in direct proportion to the volume of water infiltrated and evapotranspired	Low for trenches, medium for bioretention due to plant maintenance.	• Good plant coverage and underdrain configurations that maximize infiltration will enhance thermal load performance. • Deeper trenches will likely outperform shallower ones. • May be used to infiltrate a portion of storm pond outflows
Permeable Pavements	Removes heat through volume reduction (if unlined) and shading/heat transfer with pavement base materials and underlying soils	Typical 95th percentile temperatures range between 26 and 28ºC. Thermal load reductions above 50% are common	Temperatures may vary depending on shading of pavement and underdrain configuration. Longer drawdown can result in higher outflow temperatures but lower thermal loads	Medium	• Shade cover and underdrain configurations that maximize infiltration will enhance thermal load performance. • Deeper bases will have lower temperature outflows than shallow ones.

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Appendix A

Chloride Stratification in the Rouge Pond

The following graphics show the Rouge River pond, conductivity and temperature monitoring transects, and simplified schematics of chloride concentration ranges in the Rouge pond prior to and after sediment clean out for a period of one year. The chloride concentration ranges is based on interpolation of a series of detailed conductivity surveys horizontally, longitudinally and at 0.5 m depth intervals (Figure A.2). Conductivity measurements were converted to chloride using a rating curve derived from online measurements of chloride into and out of the pond (R^2 = 0.98).

The graphs show chloride accumulation in the winter followed by release in later months. Note that the chloride levels are higher in the summer/fall below the outlet elevation, suggesting that the subsurface draw may be releasing the chloride more quickly than may be the case with a surface draw outlet. Higher chloride levels in September 1997, prior to pond draining and sediment clean-out, than in August and October 1998, after one year of accumulation, suggests that chloride may accumulate for several years after clean out, potentially resulting in stronger density and thermal gradients over time.

Figure A 1: Rouge stormwater management pond

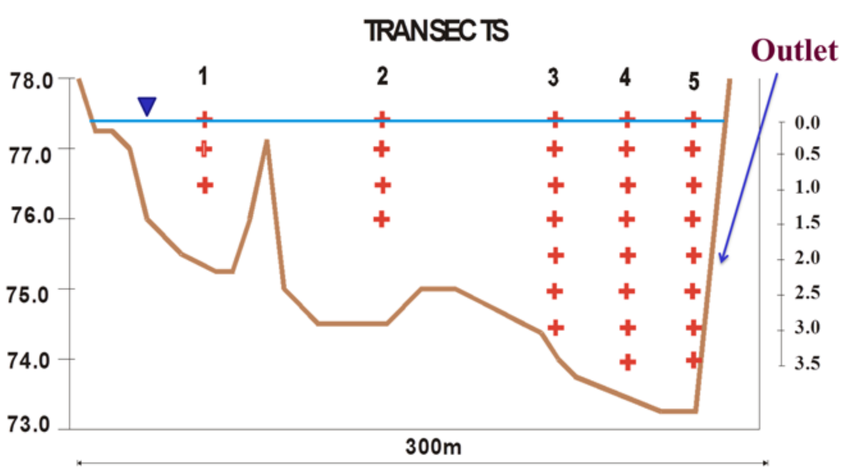


Figure A 2: Monitoring transects across the pond. Each point represents an average of three measurements taken perpendicular to the main flow path. The outlet invert was located at approximately 2.0 m below the normal water level (not to scale).

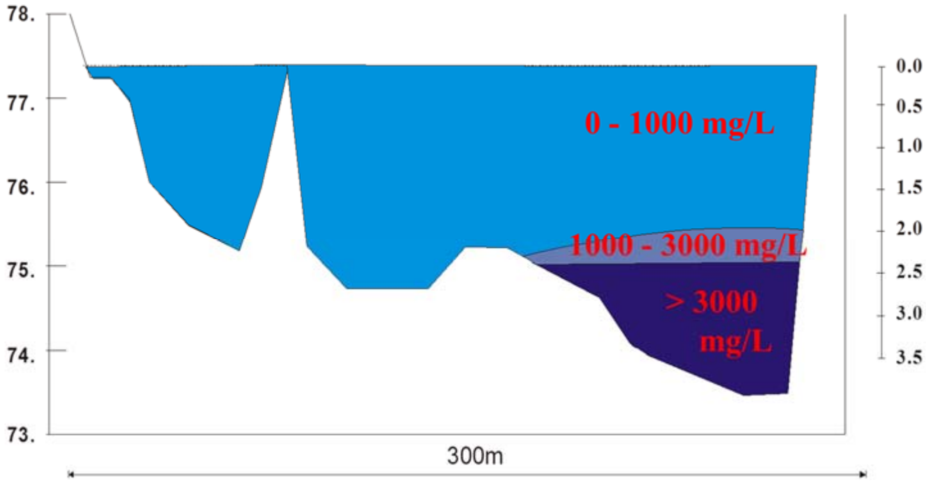


Figure A 3: Chloride concentration ranges on September 12th, 1997, prior to pond draining and sediment cleanout. The primary y axis shows elevation above sea level. The secondary y axis shows depth below normal water level.

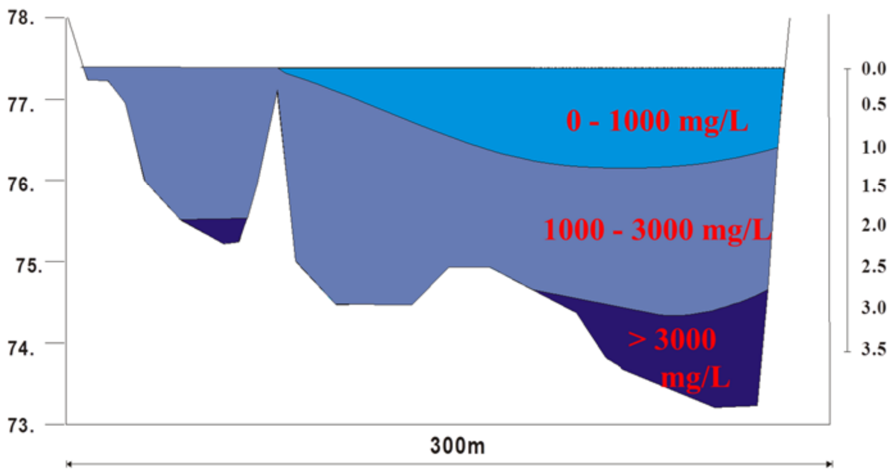


Figure A 4: Chloride concentration ranges on February 24th, 1998

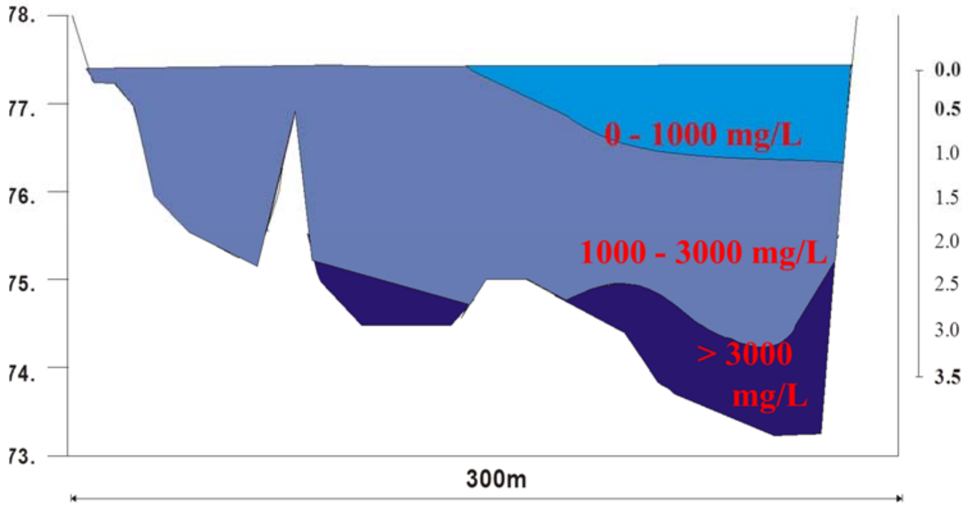


Figure A 5: Chloride concentration ranges on April 2nd , 1998

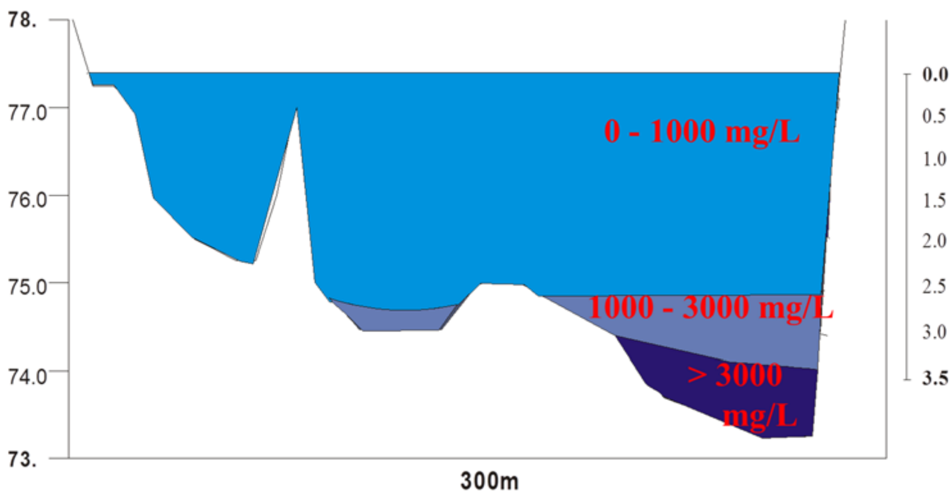


Figure A 6: Chloride concentration ranges on August 5th , 1998

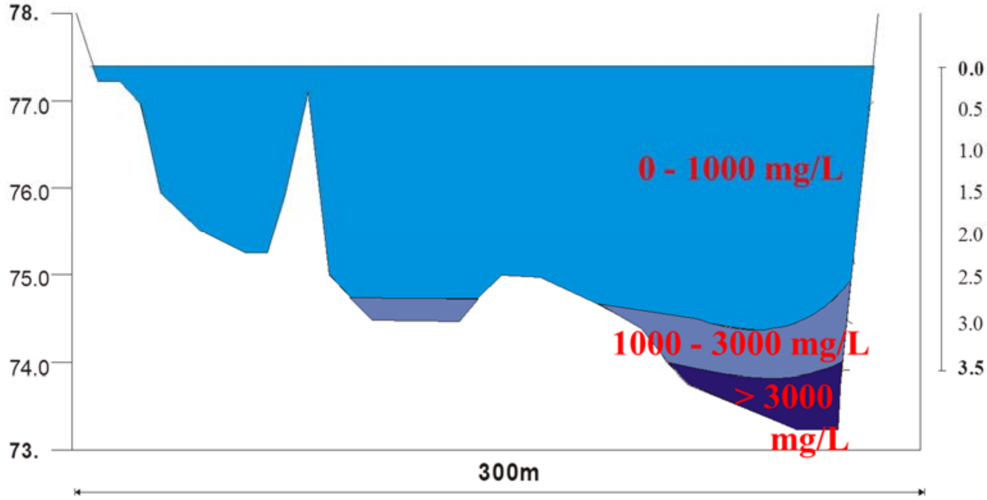


Figure A 7: Chloride concentration ranges on October 23rd , 1998

Appendix B

Pond Temperatures by Hour of Day

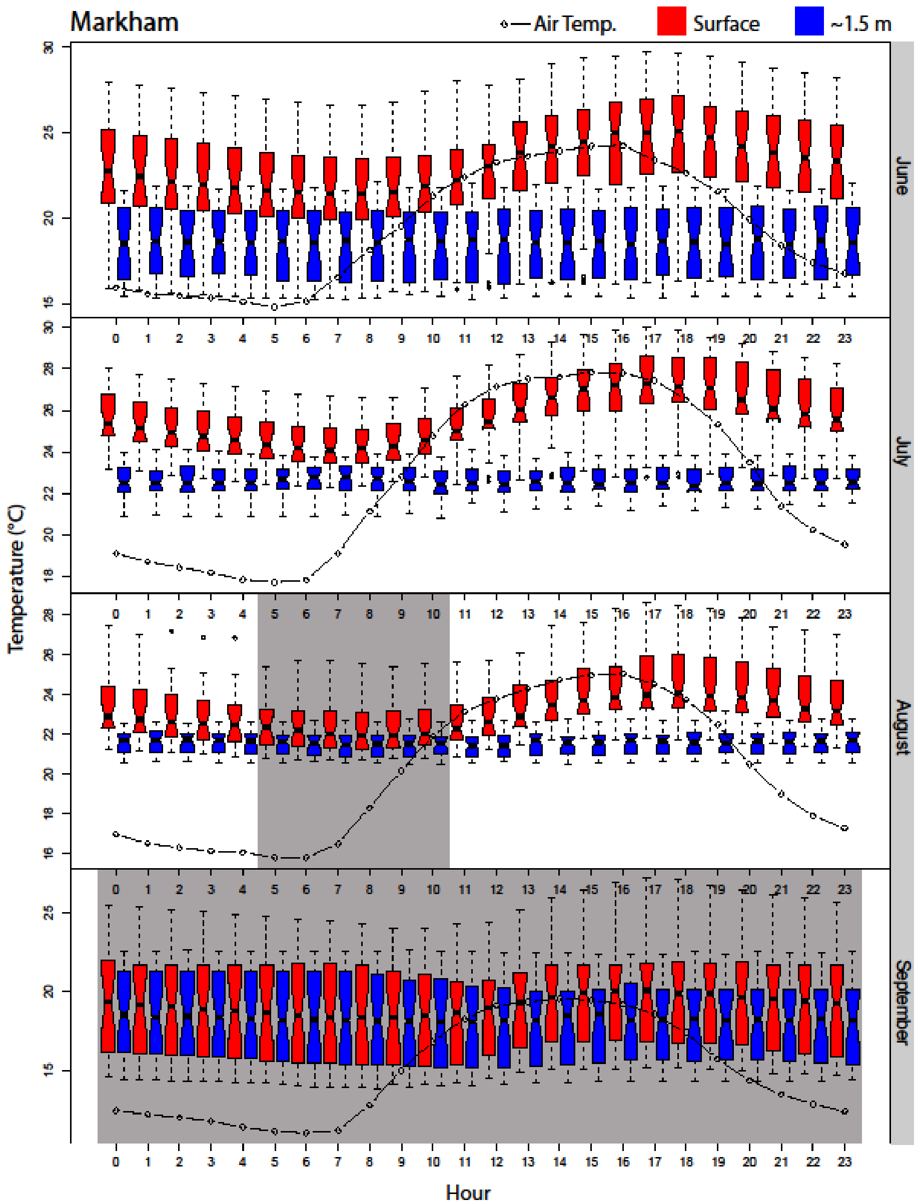


Figure B 1. The range of water temperatures at the surface and ~1.5 m below the surface of the Markham pond, plotted with the average air temperature for each hour from June to September. Hours during which surface temperatures do not significantly differ from bottom temperatures are shaded.

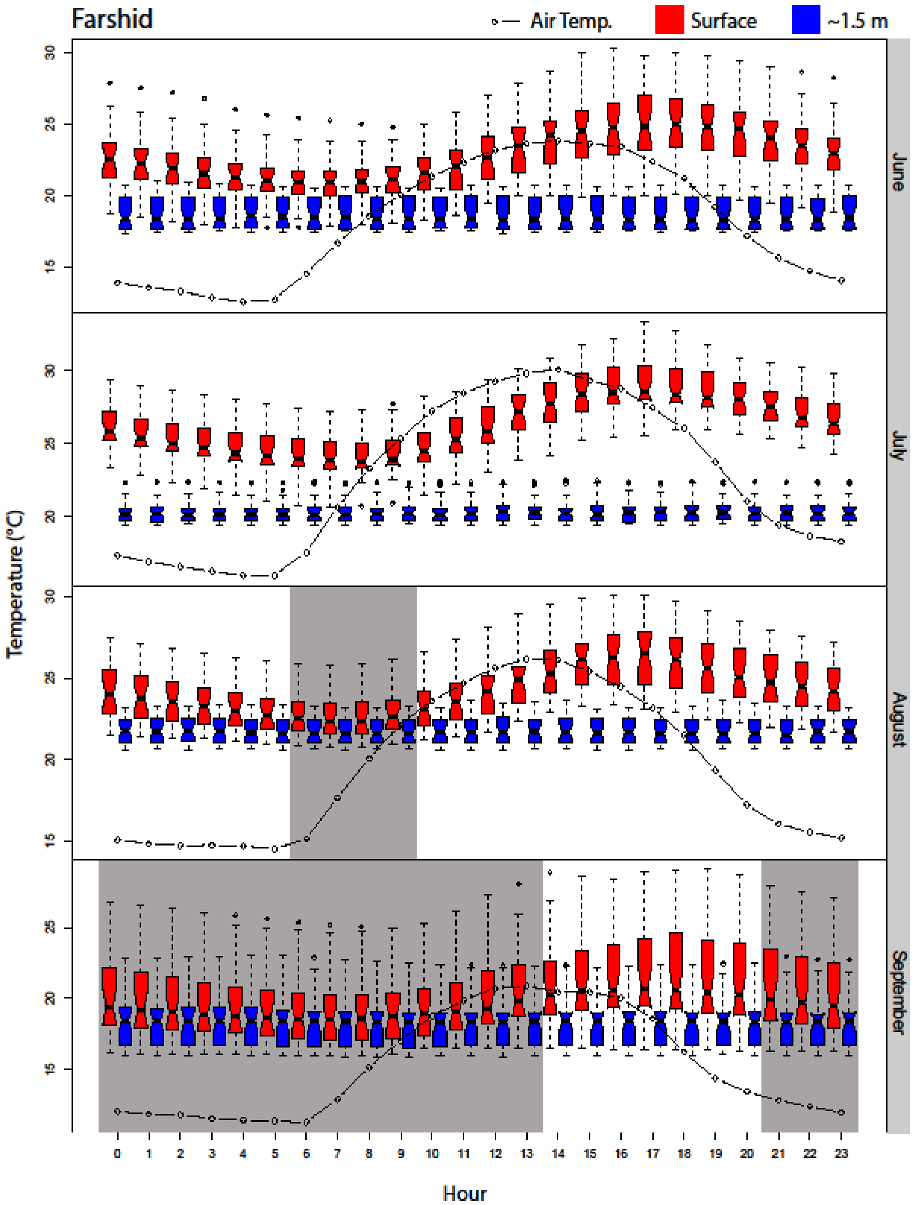


Figure B 2. The range of water temperatures at the surface and ~1.5 m below the surface of the Kitchener K-74 pond, plotted with the average air temperature for each hour from June to September. Hours during which surface temperatures do not significantly differ from bottom temperatures are shaded.

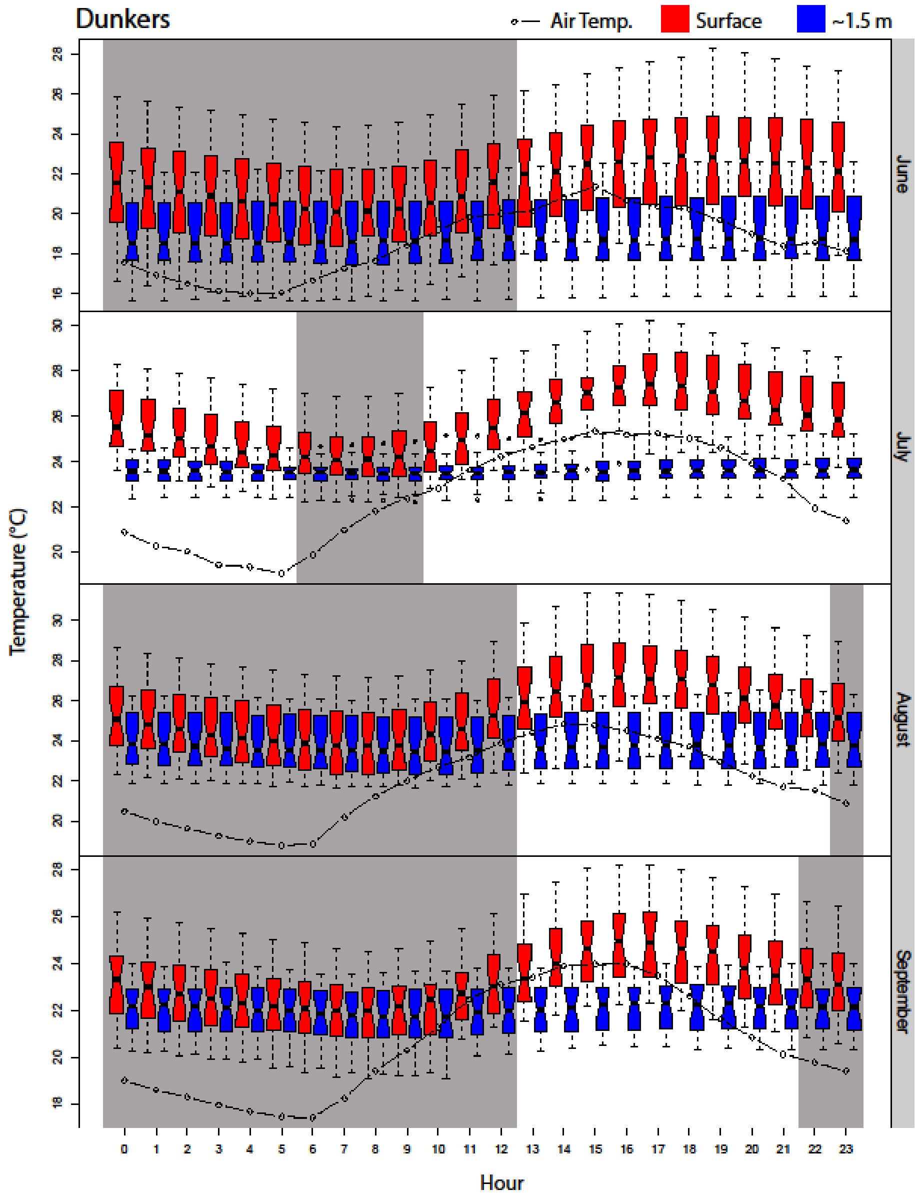


Figure B 3. The range of water temperatures at the surface and ~1.5 m below the surface of the Dunkers pond, plotted with the average air temperature for each hour from June to September. Hours during which surface temperatures do not significantly differ from bottom temperatures are shaded.

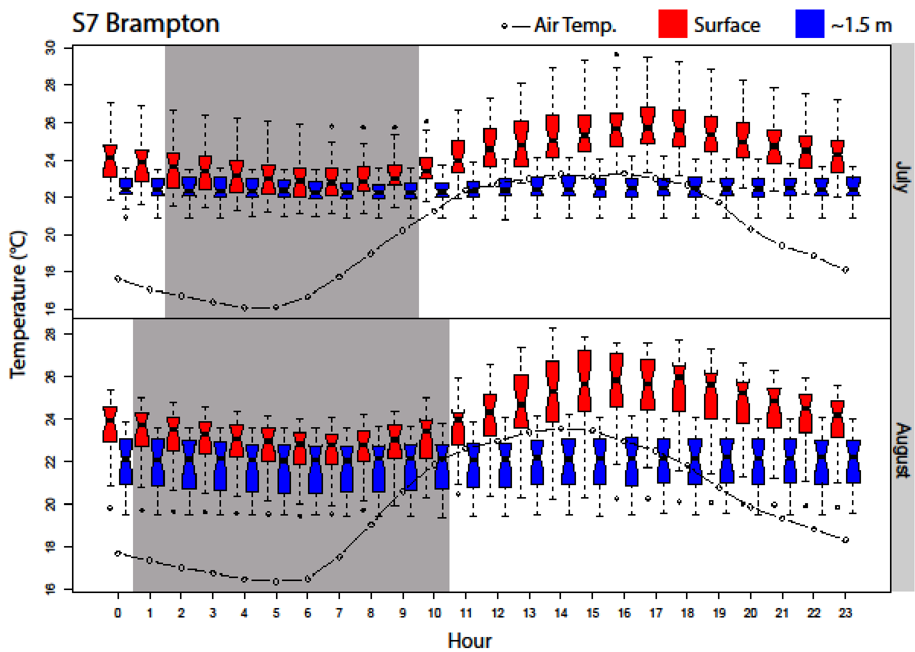
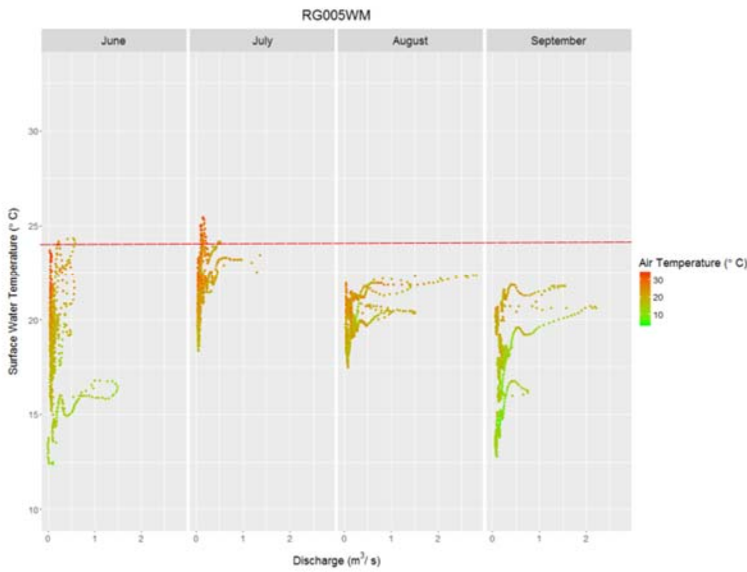


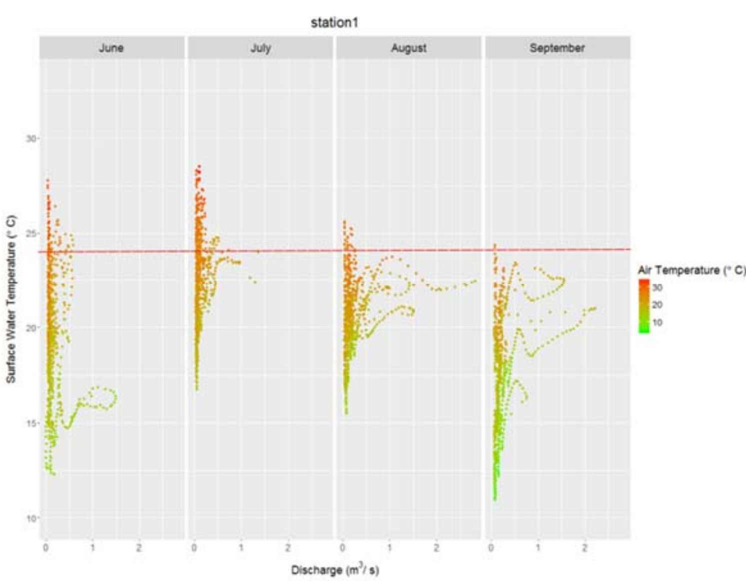
Figure B 4. The range of water temperatures at the surface and ~1.5 m below the surface of the S7 Brampton pond, plotted with the average air temperature for each hour from July to August. Hours during which surface temperatures do not significantly differ from bottom temperatures are shaded**.**

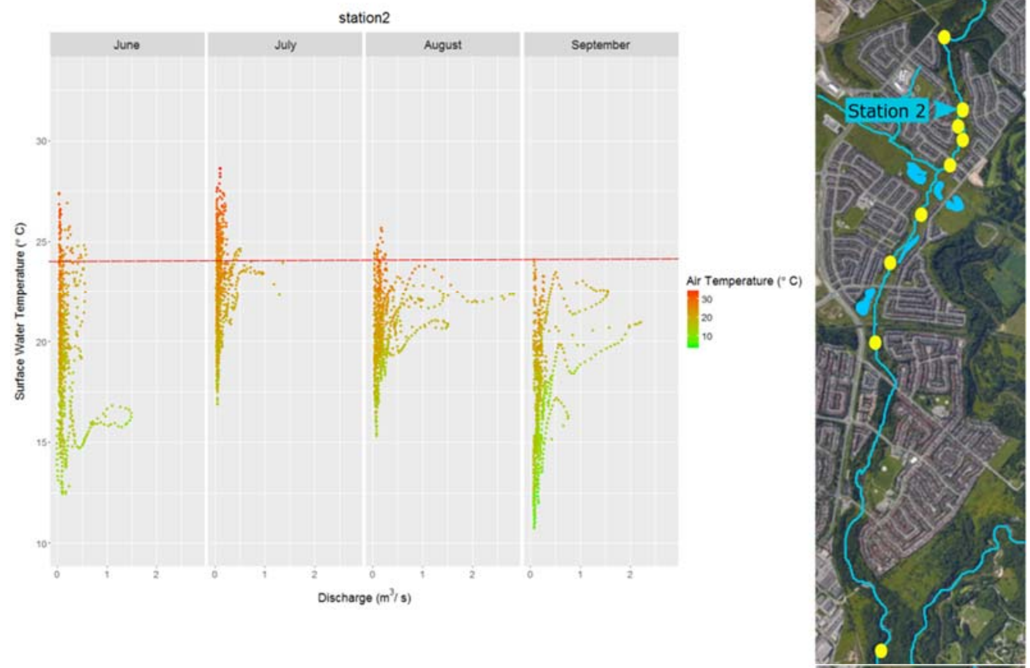
Appendix C

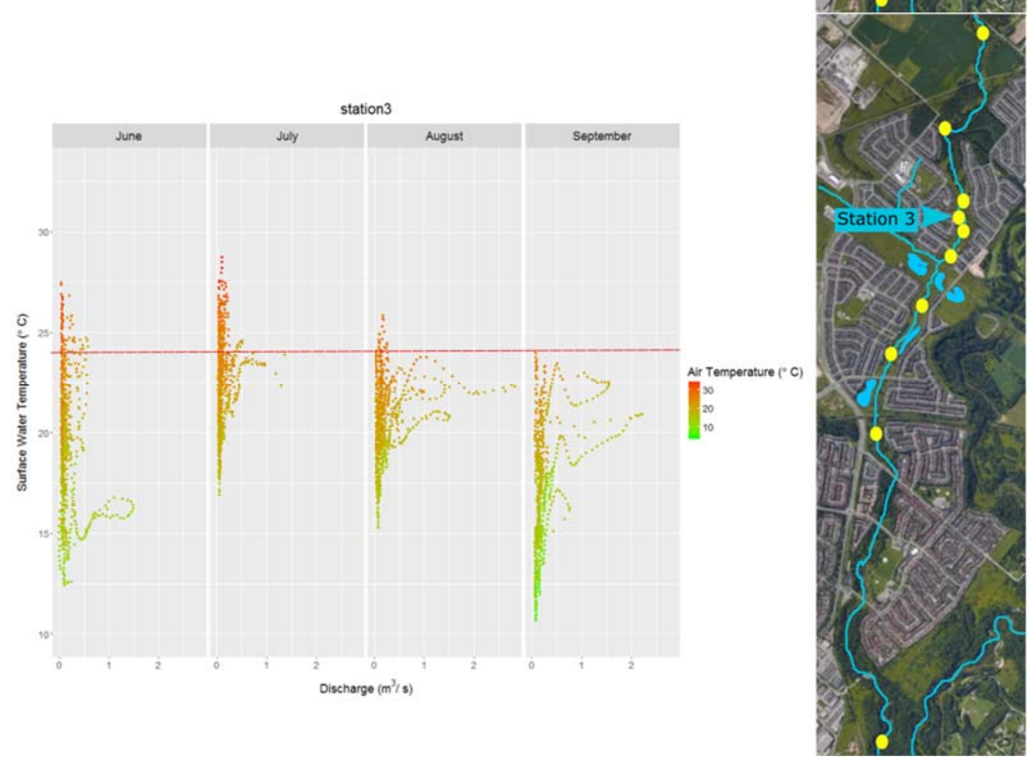
The Relationship between Stream Temperatures and Flow Rates

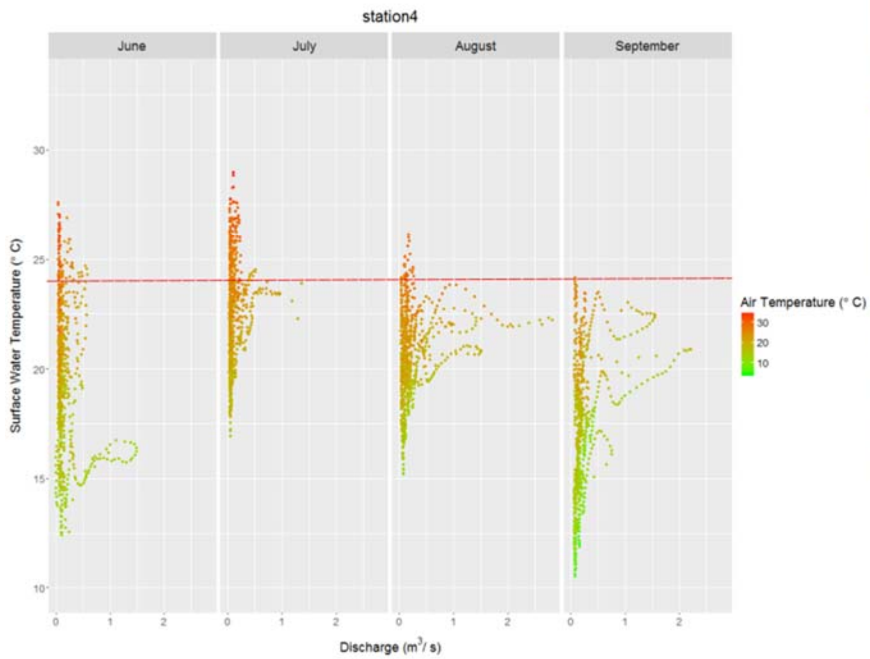
In this example, temperatures were monitored at various locations along Morningside Creek, both upstream and downstream of stormwater ponds. To determine, when temperatures were elevated, the continuous creek temperature data were plotted against flow rates (discharge) monitored downstream of the monitored reach. The data correspond to the station number on the right panel. Results show that temperatures tend to be higher at lower flow rates, as these occur during periods when the creek is exposed to sunlight, and at times when the creek receives warm water discharge from stormwater ponds. Temperatures tended to increase downstream of ponds, but not always.



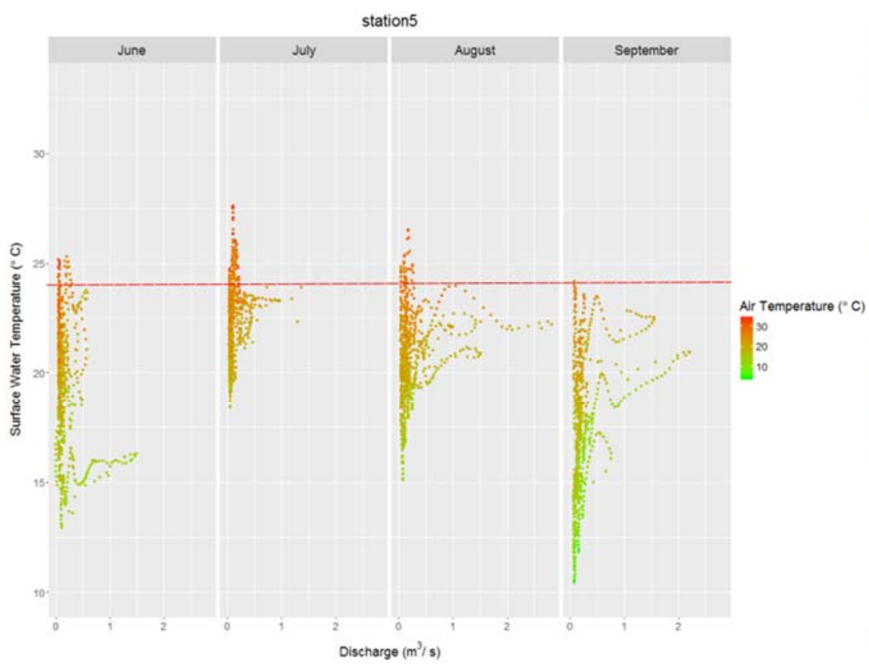



station2
June
July
August
September
Surface Water Temperature (° C)
Discharge (m3/ s)
Air Temperature (° C)
Station 2

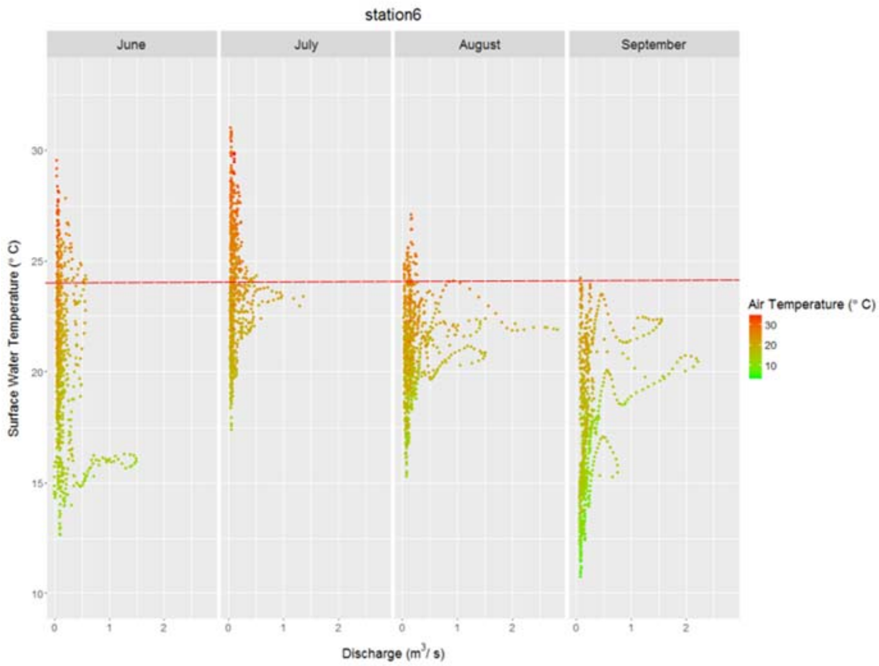

station3
June
July
August
September
Surface Water Temperature (° C)
Discharge (m3/ s)
Air Temperature (° C)
Station 3


station4
June
July
August
September
Surface Water Temperature (° C)
Discharge (m^3/ s)
Air Temperature (° C)
30
20
10

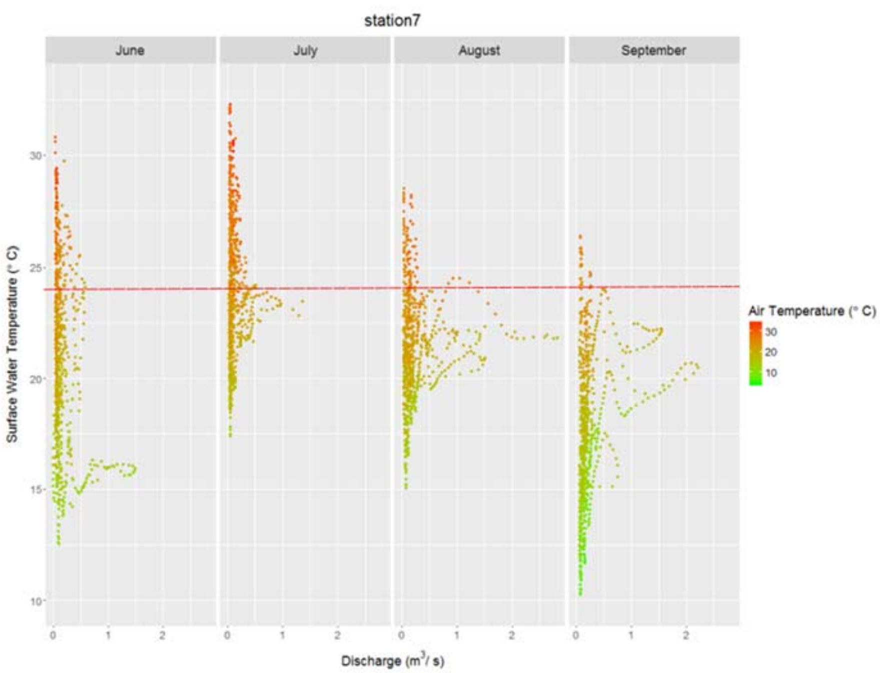

Station 4


station5
June
July
August
September
Surface Water Temperature (° C)
Discharge (m^3/ s)
Air Temperature (° C)
30
20
10

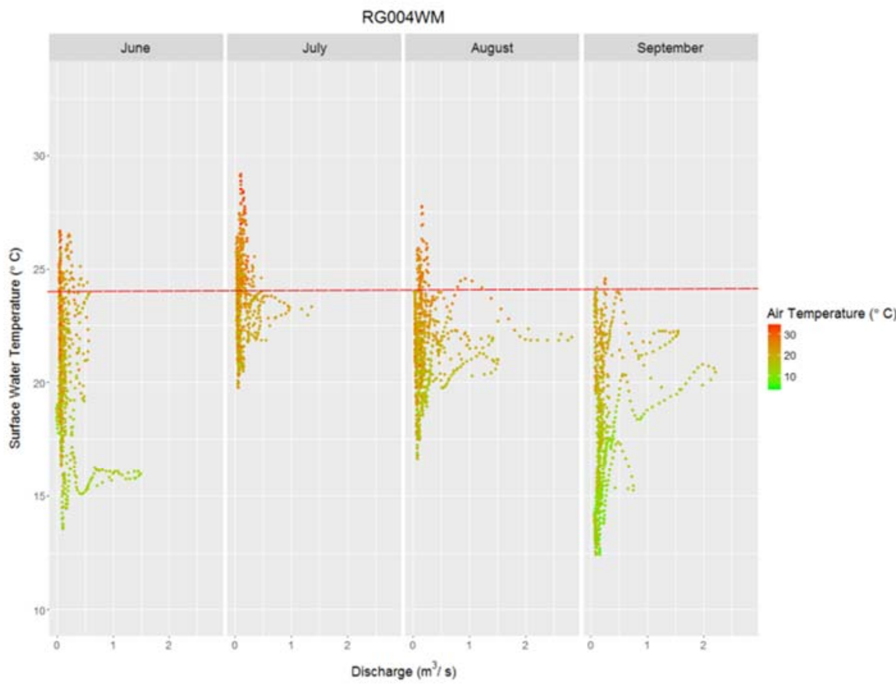

Station 5


station6
June
July
August
September
Surface Water Temperature (° C)
Discharge (m³/ s)
Air Temperature (° C)
30
20
10

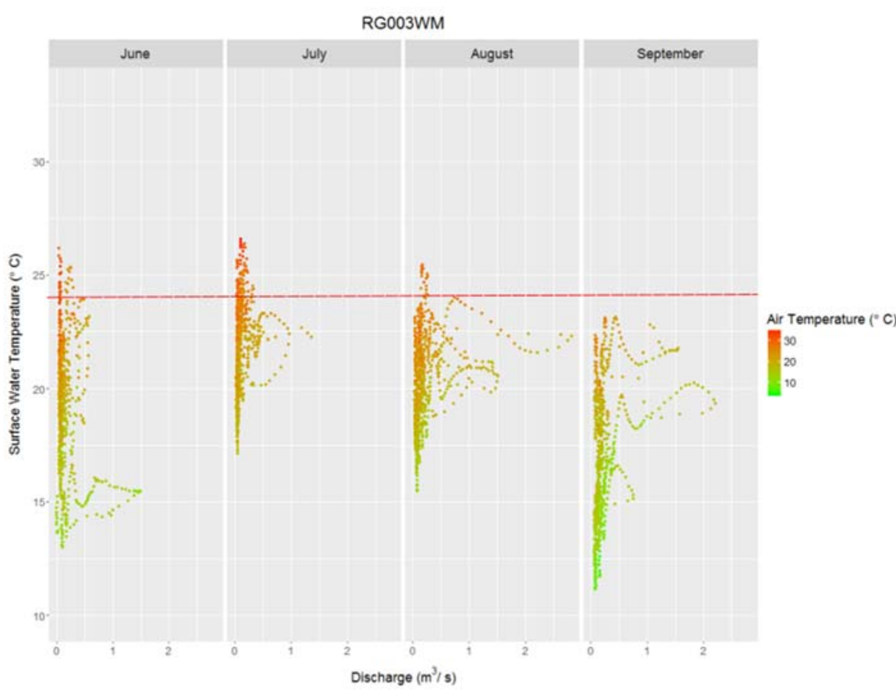

Station 6


station7
June
July
August
September
Surface Water Temperature (° C)
Discharge (m³/ s)
Air Temperature (° C)
30
20
10


Station 7


RG004WM
June
July
August
September
Surface Water Temperature (° C)
Discharge (m³/ s)
Air Temperature (° C)
30
20
10


RG004WM


RG003WM
June
July
August
September
Surface Water Temperature (° C)
Discharge (m³/ s)
Air Temperature (° C)
30
20
10


RG003WM