ROLE OF URBAN STORMWATER BEST MANAGEMENT PRACTICES IN TEMPERATURE TMDLS

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ABSTRACT

Temperature TMDLs are being developed to protect habitats in coldwater streams throughout the nation, particularly in the Pacific Northwest. Concurrently, urban stormwater Best Management Practices (BMPs) are increasingly adopted as a requirement in local land development ordinances and under Phase II Stormwater Regulations to target pollutant loading and flow moderation. Sporadic pieces of information in the literature, however, have suggested that thermal enrichment of coldwater streams by urban stormwater runoff can be exacerbated by traditionally designed BMPs. We report in this paper the results of a five-year thermal enrichment study in a recently constructed regional stormwater treatment system discharging to a designated trout stream in Portage, Michigan. The Consolidated Drain stormwater treatment system is a three-stage treatment design with a sediment forebay, a wet detention pond, and an enhanced existing wetland. Results showed that the design of the stormwater treatment facility was an effective means to reduce stormwater thermal loading (45.2% during August-September of 2002). Mitigation of higher stormwater temperatures, however, was not accomplished in the more traditional two-stage treatment process (i.e., forebay and wet detention). The enhanced natural wetland accounted for most of the thermal load and temperature reductions with its dense canopy coverage and higher infiltration rate. The outflow temperature of the wetland was always near ambient air. Event-based thermal loading analysis indicated that flow reduction via infiltration was the primary mechanism for thermal load reduction by the wetland, while temperature mitigation was achieved mainly through vegetative shading and the utilization of natural groundwater input to the Consolidated Drain channel. Using the concept of temperature equivalent (TE), the flow-weighted average temperature of a flow component, we established the locations and polluting potency of thermal enrichment source areas as well as the mitigating sources in the study watershed. It was concluded that stormwater BMPs that promote infiltration and provide sufficient vegetative shading to detained runoff should be used in urban areas to protect the thermal integrity of coldwater streams.

KEYWORDS

Temperature TMDL, coldwater streams, detention ponds, stormwater BMPs, temperature, thermal enrichment, urban stormwater runoff.

INTRODUCTION

Temperature TMDLs and Urban Stormwater Runoff

Water temperature is the driving force of the distribution and physiology of aquatic biota. Acute thermal impacts include mortality as well as altered development, growth, and reproduction, while long-term thermal impacts associated with chronic conditions include evolutionary, physiological, and behavioral responses of fish (Matthews, 1987), invertebrates (Vannote and Sweeney, 1980), and periphyton (DeNicola, 1996).

In Maryland, most coldwater organisms are severely stressed at temperatures above 21 ^{o}C with a 2 to 3 ^{o}C change in temperature enough to eliminate sensitive insect species (Galli, 1990). Both of these temperature thresholds are commonly observed in urban watersheds (James and Xie, 1999). Hinz and Wiley (1997), for example, found simple linear relationships for growth rate and standing stock of juvenile brook and brown trout with mean daily temperature fluctuation in July in northern lower Michigan streams. Temperature was identified as a master variable with respect to growth and production of fish due to its influence on both rates of metabolism and foraging activities.

According to EPA data (http://oaspub.epa.gov/waters/national_rept.control), there are 298 approved temperature-related TMDLs in the nation, of which 273 specifically list temperature as the "pollutant." Most of these TMDLs were established in the states of the Pacific Northwest and Mountain regions to protect coldwater habitats, particularly for salmonids. Wisconsin, Louisiana, and Georgia also have temperature TMDLs established. Increased direct solar radiation to streams caused by loss of riparian shading has been identified in most of these TMDLs as the primary nonpoint heat source. Point sources include power plants, wastewater treatment plants, and other industrial sources. Although mentioned in some TMDLs (e.g., Upper Klamath Lake Drainage TMDL in Oregon), warm surface stormwater runoff is not considered a major heat source, likely due to the predominant non-urban land use types in these temperature TMDL watersheds.

However, as areas of the nation continue to undergo land development and urbanization, the protection of coldwater streams from thermal pollution in current and potential urban/suburban areas has become an increasingly important issue in our efforts to restore beneficial uses of these urban streams. This issue is particularly significant in the Midwest where in summer months, hot temperatures coincide with high precipitation characterized by frequent afternoon thunderstorms. Adding to the problem is that current TMDLs, for temperature or other pollutants, normally do not consider future growth when developing load/waste load allocations, which further increases the potential of failing to achieve the pollution reduction goals. Furthermore, because of the ubiquitous and ever presence of the largest thermal source—the sun, when individual pollutant TMDLs and their corresponding remediation practices are being developed and implemented for urban impaired waters, ignoring the thermal issue may lead to situations where these TMDLs have fully achieved their objectives of reducing the load of specific stressors but still not meeting the ultimate goal of pollution control, i.e., restoration of the ecological integrity and the beneficial uses of impaired waters.

For example, urban stormwater Best Management Practices (BMPs) are traditionally designed to reduce pollutant loading and moderate flow. Typically, stormwater pollutants of most concern have been total suspended solids, oil and grease, nutrients, pesticides, other organics, pathogens, biochemical oxygen demand, heavy metals and salts. With the Phase II Stormwater Regulations that took effect in March 2003, communities are expected to spend millions of dollars for urban stormwater BMPs. Correspondingly, the role of these BMPs in our efforts to achieve temperature TMDL goals is becoming more important than ever, particularly in urban areas with coldwater streams. Unfortunately, our knowledge on this subject is very limited. Sporadic pieces of information in the current literature, however, have suggested that thermal enrichment of coldwater streams by urban stormwater runoff can be exacerbated by traditionally designed BMPs (Schueler, 1987; Galli, 1990; James and Verspagen, 1997; Van Buren *et al*., 2000). Even so, there is generally a lack of information and data that quantify the thermal impact of stormwater BMPs in a typical urban setting. Moreover, design practices and new tools that can be used to mitigate these impacts have not been comprehensively researched and developed.

Coldwater streams are typically found in headwater areas and are hydrologically stable due to steady groundwater sources. In pre-development conditions, there are few heat storing areas in these areas. Surface runoff is substantially reduced through infiltration and vegetation canopy interception. Urbanization increases impervious ground cover (e.g., parking lots, roads, roofs), resulting in less infiltration and an acute flow response when stormwater rapidly runs off hard surfaces (Dunne and Leopold, 1978). Stormwater management has traditionally targeted this peak flow response and its associated pollutant load with BMPs that impound water temporarily before releasing it at a more natural rate in an attempt to mimic the natural flow regime. As a result, impervious surface cover and stormwater management practices change the flow source of coldwater streams from groundwater to a mix of ground and surface water (Booth and Jackson, 1997). This flow regime change may help explain the continued degradation of receiving waters despite BMP implementation.

Schueler (1987) explained that temperature increase of runoff could occur: 1) between runoff and impervious urban surfaces; 2) in unshaded conveyance channels; and 3) in impoundments such as stormwater detention ponds. Galli (1990), working in Maryland, demonstrated all three conditions in urbanized watersheds compared to an undeveloped reference watershed. He showed: 1) higher stream temperatures directly related to increasing levels of percent impervious surface across watersheds; 2) increased temperature of runoff as it passed through open channels; and 3) higher outflow temperatures (compared to inflow) in on-line stormwater management detention structures. In another study of the thermal balance of an on-line stormwater treatment pond in Ontario, Canada, Van Buren et al. (2000) also demonstrated net energy gain (thermal enrichment) in the pond during dry weather conditions. BMPs mitigate flow and treat for common pollutants but create a thermal loading condition (Galli, 1990).

Thermal impacts are not necessarily restricted to streams but can also be demonstrated in lakes. An in-line wetland constructed in 1985 to treat stormwater inflows to Lake McCarrons in Roseville, Minnesota was found to increase summer discharge temperatures by 5 ^{o}C (MCES, 1997). These heated inflows reduced the epilimnion of the 50-hectare lake, further exacerbating lake water quality conditions despite reduced chemical pollutant levels through the wetlands.

This Study

We investigated the processes that drive stormwater thermal enrichment to evaluate strategies that mitigate its impacts on the thermal regime of coldwater receiving streams. The hypothesis was that stormwater management plans and treatment designs could be developed to significantly reduce or eliminate thermal enrichment through enhancement or substitution of traditional design and BMPs. We directly tested this hypothesis by monitoring and evaluating the hydrologic and thermal regime of an existing urban drain and its receiving stream before and after the installation of an off-line regional stormwater treatment system. This effort included year-round field monitoring with a specific focus on the months of May-September as related to critical thermal tolerance limits of coldwater stream biota.

Fundamentally, there were three key objectives of this research that were necessary for addressing short-term and long-term design needs and habitat protection. These included:

1. Confirming the relationships between disrupted heat budgets found in urban areas and local hydrology;
2. Quantifying the impacts of thermally-enriched stormwater discharges on coldwater stream temperature regimes; and
3. Identifying effective management and design practices for stormwater BMPs and controls necessary to mitigate problems associated with urban stormwater thermal enrichment.

METHODOLOGY

Study Setting

The Consolidated Drain was an open channel waterway that drained approximately 187 hectares (ha) in the heart of the commercial center of City of Portage in southwest lower Michigan. Within this drainage, 33% of the land use is residential, 60% is commercial and 7% is wooded, wetland or open space. Stormwater loadings from this drain were identified as the largest single contributor of pollutants to Portage Creek, which was classified by the Michigan Department of Environmental Quality as a high-quality coldwater stream capable of sustaining trout and other higher-order vertebrates. Habitat restoration and protection of the coldwater receiving stream was the focus of the municipality's drain improvements. The City of Portage therefore embarked on a multi-million dollar effort in 1999 to develop a "Regional Stormwater & Trailways Facility" to address stormwater runoff discharging to Portage Creek via the Consolidated Drain. These goals were accomplished with the design and construction of the regional stormwater treatment system where stormwater was directed from the existing separate stormwater sewer system and open drain into a series of treatment cells (Figure 1).

In order to adequately achieve high levels of pollutant and sediment removal, stormwater passes through a sediment forebay (1.0 ha) for removal of floatable solids and coarse materials. Stormwater is then detained in a wet pond (4.6 ha) before discharging to an existing wetland (4.4 ha) for a treatment duration of 5 to 10 days before being discharged back to the drain channel. The forebay-wet pond system was designed for 2-year 24-hour storm events. Overflow from the wet pond in case of extreme storm events discharges into the drain channel directly over the berm separating the wet pond and the wetland (Figure 1). The drainage channel has been reconstructed into a more natural watercourse to provide natural habitat, erosion control and flood protection. The wetland areas not only provide enhanced water cleansing but also excellent natural habitat for a variety of native plants and wildlife. Selected features (e.g., strategic shading) that are often overlooked in conventional stormwater designs, were also incorporated into the facility to address thermal enrichment.

Instrumentation and Data Acquisition

Water temperature was monitored with Hobo Tidbit thermistors logging in ºC at 5-minute intervals. Thermistors were housed within or secured to permanent perforated standpipes or structures. Up to five RainWise tipping-bucket rain gauges with Hobo event loggers and two ISCO rain gauges recorded rainfall in 1/100ths inch per tip near the Consolidated Drain. Three meteorological instruments were located within the wetland treatment cell. A Hobo air unit was mounted 2 m above the ground surface and measured air temperature and humidity on 10-minute data intervals. A Campbell Scientific pyranometer was mounted 3 m above the ground surface and measured incoming total solar radiation (W/m^2) at 10-minute intervals. A Campbell Scientific logger with a Wind Sentry anemometer was mounted 4 m above the ground surface and measured wind speed and direction on a 10-minute interval. Global Water level loggers, ISCO level loggers, and an ISCO area velocity meter recorded water levels at 5- or 10-minute intervals at critical points in the treatment cells and channels during both pre- and post-construction time periods. An elevation/flow relationship was generated for each location by either: 1) development of a cross-sectional stage discharge curve; 2) fixed structure elevation calculation (e.g., a weir equation); or 3) area velocity calculation (e.g., submerged intermittent pipe flow).

Analysis Periods

There were four distinct monitoring periods for which detailed analyses were conducted to address study objectives. They included the following:

- ***Pre-construction period*** (1999 - 2000)
- ***Post-construction period*** (after July 21, 2001 when the stormwater treatment system came on-line)
- ***Post-construction modeling period*** (July 29, 2002 – September 8, 2002): Intensive monitoring of the treatment system during the summer of 2002 included this period of 42 days when the treatment system progressed from dry (having no inflow and outflow) to wet (continuously discharging treated stormwater from the outlet of the last treatment cell [the wetland]), and back to dry. Because of the storage capacity provided by the treatment system, there is a lag between the onset of a storm event and the exit of treated stormwater from the system. This time lag results in the overlapping and mixing of runoff produced by successive storms in the system, complicating analyses aimed at examining the system response to individual storm events or a group of storm events taking place in a predetermined time interval. This "dry-to-dry" period, however, presented an opportunity to study both the system's thermal treatment characteristics for this entire period and for individual storm events within the period. No outflow from the wetland

signifies the completion of the treatment of all runoff collected by the system from previous storms and where the remnant storage would infiltrate or evaporate unless a new storm brought more runoff.

- ***August – September comparative period*** (August 1 – September 30, 1999 through 2002): This window of 62 days, in each of the four monitoring years (1999-2002) was chosen to examine the total thermal loading from the pre-construction and post-construction Consolidated Drain watersheds to Portage Creek. The reason for choosing only the months of August and September for 2001 is that August 2001 was the first full month that the treatment system came on-line and September can still be considered a summer month of thermal loading concern (Galli, 1990). For 2002, detailed flow and temperature monitoring for various flow components in the post-construction Consolidated Drain watershed did not start until the beginning of August for logistic reasons. For 1999, August 2 was the start day for the monitoring work of this study. For 2000, the period of August 1 through October 1 was chosen to preserve consistency for the across multi-year comparison. Therefore, to compare the thermal impact of the treatment system on the creek during summer months for all the four monitoring years, August 1 through and October 1 was the only time period where meaningful comparisons of stormwater thermal impact on Portage Creek for pre- and post-construction periods could be made. An adjustment of one day was made (August 2 through October 2) for 1999 due to the absence of monitoring data for August 1.

Terms in bold-italic shown above will be used throughout this paper to refer to the specific time periods as defined by these terms.

RESULTS AND DISCUSSION

Treatment System Thermal Behavior

Because monitoring in 2002 recorded the first full vegetation growing season in the post-construction period, analyses on the treatment system's thermal behavior and its effects on stormwater thermal loading were conducted for the post-construction modeling period. Temperature and flow were recorded simultaneously at several locations in the system in this period, including:

- middle of the sediment forebay at a mid water column depth (termed "forebay"),
- outflow point of the wet detention pond ("wet pond out"),
- outflow point of the wetland ("wetland out"), and
- air temperature ("air").

For the entire post-construction modeling period, temperature changes of the three treatment cells can best be illustrated by comparing the average daily temperature records of each cell with the ambient air temperature (Figure 2). Subtracting the daily average air temperature from the average cell temperature, clearly shows that stormwater detained in the sediment forebay and the wet pond was always warmer than ambient air (ΔT average: 3.6, 2.9 ^{o}C; range: 1.0 to 6.8 and 0.5 to 6.4 ^{o}C, for the forebay and the wet pond, respectively). This confirms the heating effect or additional thermal loading to the collected stormwater runoff in the two ponds during the detention period due to solar inputs. In contrast, the wetland mitigated this thermal load and maintained wetland outflow temperatures near ambient air on a average daily basis (ΔT average: 0.1 ^{o}C, range: –2.8 to 4.1 ^{o}C).

The most obvious and significant differences among the three cells that can be used to explain this temperature regime difference demonstrated by Figure 2 are the vegetative cover and water depth. A well-shaded surface prevents direct solar radiation from reaching the standing water and enables it to equilibrate with the ambient air temperature in the wetland. Deeper ponds have smaller surface area to volume ratios, rendering these ponds less efficient in heat dissipation. The sediment forebay is essentially an open pond without any meaningful vegetative cover. The wet pond has a few tall cottonwood trees providing some limited shading and a variety of wetland scrub/shrub vegetation. Ponded areas in the wet pond, intentionally designed to provide habitat diversity, are basically devoid of any significant vegetative cover. In contrast, a layer of densely populated grasses and patches of trees cover the wetland cell. These provide substantial shading in the wetland, allowing average daily water temperatures to approach those of ambient air. In addition, the two ponds maintain a water depth 3 to 4 times greater than that of the wetland and the latter also has a smaller overall surface area. In essence, the system configuration is such that the two open ponds absorb heat more efficiently than the wetland during the day and release heat more slowly during the night, resulting in higher water temperatures. The close reverse correlation between the air temperature and the temperature differences between the treatment cells and the air (Figure 2) is another indication of the heat absorbing behavior of the stormwater detained by the treatment cells.

Figure 2 also illustrates the temperature difference between the air and thermistor 6 (“T6 – Air”), which is located in Portage Creek about 1,000 m upstream of the confluence with the Consolidated Drain channel. Clearly, Portage Creek almost always has a lower daily temperature than ambient air (ΔT average: -3.2 ^{o}C, range: –6.0 to 0.4 ^{o}C), signifying a coldwater aquatic habitat that has a lower temperature than the air during summer months. To maintain such a lower-than-air temperature regime in the creek, any sizable inflow to the creek should also have a temperature below the air. The implication is that despite the fact that the treatment system was able to bring the outflow daily average temperature near that of ambient air (with the help of the wetland), the outflow would still have had a warming effect on the receiving stream had it drained into the creek directly. Instead, wetland outflow drains first to the reconstructed Consolidated Drain channel where there is groundwater baseflow mitigating this warming effect.

Treatment System Stormwater Thermal Loading

The mass balance equation was used to reach a balanced flow budget for the forebay-wet pond combination, the wetland, and the entire treatment system as a whole, for the post-construction modeling period (July 29, 2002 – September 8, 2002).

$$Inflow + Rain\ Deposit + Outflow + Evaporation + Infiltration = 0 \qquad (1)$$

Table 1 shows the calculated flow components for each of the three systems. Negative numbers indicate water losses. In Equation (1), inflow, rain deposit (direct rainfall on the system), and outflow were calculated based on measured parameters only. Evaporation, including evapotranspiration, was calculated using monitored meteorological data from the system (solar radiation, wind velocity, air temperature, and humidity) and the Penman equation coupled with a Meyer estimate of lake evaporation (Penman, 1948; Meyer, 1944; Bedient and Huber, 1992). Various studies (Kadlec and Knight, 1995) have suggested that with vegetative cover, wetlands evaporate less due to reduced solar radiation from vegetative shading while transpiring more through the vegetation. In general, these two effects offset each other and the total evapotranspiration of wetlands is similar to that of lakes. There is no readily available, widely-accepted estimation method for calculating wetland evapotranspiration based on meteorological data. Therefore, the evaporation rate calculated based on lake evaporation is used for all three treatment cells. Infiltration was calculated to account for the residual flow to balance Eq. (1).

Uncertainty in the flow calculations rose mostly from the estimation of evaporation with Penman-Meyer approach. Different estimation methods can give somewhat different results for evaporation and hence, infiltration. For example, using equations recommended by the American Society of Civil Engineers (Jensen et al., 1990) would result in evaporation estimates about 20% higher than the Penman-Meyer approach for the post-construction modeling period. Consequently, the infiltration volume calculated with Equation (1) for the entire treatment system would decrease by 11% and the total water volume reduction accounted for by infiltration would then decrease from 82% to 73%. Therefore, uncertainty in evaporation estimation does not substantially change the flow budgeting. The Penman-Meyer approach was chosen for this study because it yielded a negative infiltration value (loss of water into the ground; Table 1) for the forebay-wet pond combination, consistent with the fact that the water level in the forebay-wet pond is always higher than the areal groundwater table.

Infiltration rates were derived from the residual flow reduction to further verify the calculations for infiltration. Infiltration rates were compared to hydraulic conductivity test results for soil samples taken from the system prior to construction. The forebay-wet pond combination had an infiltration rate of 7.44×10^{-7} cm/s while the value for the wetland was 2.24×10^{-5} cm/s. Overall, the system had an area-weighted average infiltration rate of 1.05×10^{-5} cm/s. Soil samples from the system had hydraulic conductivities ranging from 1.9×10^{-7} to 2.8×10^{-4} cm/s. Derived infiltration rates were well within this range. Furthermore, lithology investigations showed a confining layer of marl underneath most of the topsoil of the treatment system. This marl layer is most prominent in the western portion of the system (coinciding with the sediment forebay and the wet pond) and becomes thinner as it approaches the eastern side of the system (where the wetland is located). Directly below the marl layer is a sand unit. Consequently, the derived infiltration rates are reasonable estimates for the ponds and the system as a whole.

Thermal load was calculated here for the post-construction modeling period using the following equation widely applied in surface water quality modeling and heat budget calculations (e.g., Thomann and Mueller, 1987; Bedient and Huber, 1992; Van Buren et al., 2000):

$$W = Q \cdot \rho \cdot T \cdot C \cdot t \tag{2}$$

where W: thermal load (cal); Q: flow rate (m^3/s); ρ: water density (assumed to be constant at 1×10^3 kg/m^3); T: water temperature (°C); C: water heat capacity (assumed to be constant at 1 cal/g/°C); and t: time (s).

Equation (2) demonstrates that there are two ways for any stormwater treatment system to reduce the thermal load of runoff it receives—lowering the water temperature (T) or reducing the water volume (Q). Equation (2) further indicates that these two approaches are equally effective as flow has the same weight as temperature on the result of thermal load calculations. Consequently, it is possible for a treatment system to have a net thermal load reduction but not achieve temperature mitigation (a higher outflow temperature than inflow), when water volume reduction is the primary mechanism of the thermal load reduction. This is an important point because it means that to achieve complete thermal mitigation, it may well be necessary to deal with both thermal loading, of which temperature is a factor, and temperature itself. This issue is further explored in later sections of this paper.

Based on monitoring data and using Equation (2), it was determined that during the post-construction modeling period, there was a total thermal load of 2.585×10^9 kcal to the treatment system (the sediment forebay) through the stormwater pipe collecting runoff from the Consolidated Drain subwatershed (Table 2). This load was delivered by a total flow of more than 1.3×10^5 m^3 of stormwater to the sediment forebay. Within the system, the conventional stormwater treatment cell (i.e., the sediment forebay and the wet detention pond) combined resulted in a minimal heat load reduction of 1.3%. This load reduction was reflected by the small temperature decrease from the forebay to the wet pond outlet (Figure 2). The wetland, on the other hand, provided a 43.9% reduction of heat over the output it received from the wet pond. This resulted in a wetland outlet temperature much lower than the forebay and the wet pond.

The two mechanisms of heat and water volume reduction can be called upon to explain the higher thermal treatment efficiency of the wetland. The first is a higher infiltration rate for the wetland and the second is the shading provided by the dense vegetation growing in the wetland. Table 2 shows that the wetland accounted for most of the 42.2% total flow reduction by the system during the post-construction modeling period. A high infiltration rate enhances flow reduction and hence, heat load reduction. Shading directly reduces solar (short wave) radiation received by the system, leading to lower temperature extremes of water leaving the wetland compared to the air temperature (Figure 2).

A closer examination of the effects of the treatment system on stormwater runoff involves the evaluation of individual storm events taking place in the post-construction modeling period. Since we were most concerned with thermal enrichment on a treatment cell scale, a plug-flow approach was used here. To achieve a flow balance for each storm, the following steps and assumptions were made:

- As before, it was assumed that inflows and outflows of the system were storm runoff from the pipe feeding the sediment forebay, direct rain deposits on the treatment cells, evaporation, and infiltration.
- At 7.44×10^{-7} cm/s for the sediment forebay and the wet pond, and 2.24×10^{-5} cm/s for the wetland, these infiltration rates were assumed to be constant throughout the post-

construction modeling period. This is a reasonable approximation considering the constant presence of water over the sediment and underlying soils in the system during the period.

- Calculated daily evaporation rates were disaggregated into hourly values using the WDMUtil program from USEPA's BASINS model (version 3.0. U.S. EPA, 2001). Hourly values were then evenly divided into minutes.
- A storm runoff event was defined for the wet pond and the wetland with the beginning of the event marked at the time there was an abrupt increase of the flow on the corresponding hydrograph or immediately after the ending of the previous event. The end point of an event was identified at the point of time that all the inflow volume to the cell had exited the outlet of the cell, minus the evaporation and infiltration plus the direct rain deposit from the storm.

These assumptions resulted in a discrepancy, between the sums of the eleven individual events and the overall values for this period (Tables 1 and 3), of only 8.0% and 8.6% in stormwater heat and flow inputs to the system, respectively, and 1.5% and 1.7% in heat and flow output from the system.

Loss of flow by evaporation, including evapotranspiration, on average accounted for 19.9% of the total outflow while infiltration represented 40.8% (Table 3). Clearly, both flow loss mechanisms were important factors in the water balance of the system. Infiltration, however, was more dominant. While evaporation rates were similar across all the three treatment cells, the wetland had a much higher infiltration rate than that of the forebay-wet pond combination. Consequently, most of the infiltration took place in the wetland. Table 3 shows that the forebay-wet pond combination had a mere 3.23% flow reduction efficiency, compared to the wetland's 44.0%. Due to the exposure of detained water in the forebay and wet pond to summer solar radiation, these two cells combined had small or even negative heat reduction (i.e., heat gain) rates for the 11 events, with an average value of –0.9%, despite a positive average flow rate reduction. In contrast, the wetland had a higher average heat load reduction rate (49.8%) than the average flow reduction rate (44.0%), indicating that flow reduction was not the only mechanism that reduced heat load in the wetland. A likely explanation is that the shading provided by the dense vegetation during the study period (late July to early September) in the wetland prevented detained stormwater from adsorbing heat via solar radiation. This allowed the evapotranspiration in the wetland to have a net heat reduction effect.

For the entire treatment system, there is a close relationship between flow reduction and heat reduction. Figure 3 shows that for the Consolidated Drain stormwater treatment system, heat reduction outpaced flow reduction during the post-construction modeling period, likely due to the shading and evapotranspiration in the wetland. A net heat reduction can be achieved by the system as long as the flow increase (due to direct rain deposit onto the treatment cells) did not exceed 11.6% of the inflow volume to the sediment forebay.

Flow-weighted Thermal Loads to Portage Creek

Using Equation (2) to calculate thermal loads results in a heat content parameter expressed in an energy unit, i.e., calories. The value of this parameter is an extensive property influenced strongly by the flow rate (Q). Temperature, on the other hand, is an intensive property directly connoting the degree of thermal pollution. As shown earlier, the stormwater treatment system, with the addition of a wetland to the traditional detention ponds, is capable of substantially reducing stormwater thermal load (over 40%) during the "dry-to-dry" post-construction modeling period in 2002. This occurred primarily through a flow reduction mechanism—infiltration, and to a lesser degree shading and evapotranspiration. However, average daily temperature analysis showed that despite the significant thermal load reduction, the treatment system could only bring down the wetland outflow temperature to near ambient air temperatures. Because Portage Creek, as a coldwater stream, had a lower-than-air temperature (Figure 2) in terms of thermal loading to the creek, the treatment system outflow was still a thermal pollution source.

In evaluating the thermal loading contributions of various flow components in the post-construction Consolidated Drain watershed, the load approach, while yielding important information on the relative distribution of thermal loads, cannot pinpoint the sources and sinks of thermal pollution. Except for the flow within the treatment system, there are large fluctuations in the flow rate for other flow components in the watershed (e.g., runoff from the Crossroads Mall noted in Figure 1 is zero during dry weather conditions). As a result, average temperature comparison is not suitable in identifying thermal sources or sinks particularly over an extended period such as the two-month comparative period of August-September. To accurately reflect the effectiveness of the treatment system in mitigating thermal loading and to evaluate the thermal pollution contributions in the drainage area of the system, it was necessary to find a parameter that reflected the polluting potency of every thermal source over an extended period while taking into account the flow factor.

For this study, the following equation is used to define the parameter of *Temperature Equivalent* to address this issue:

$$Temperature\ Equivalent = \frac{\left(\dfrac{\sum Q_i \cdot \rho \cdot T_i \cdot C \cdot t_i}{\sum Q_i \cdot t_i}\right)}{\rho \cdot C} = \frac{\sum Q_i \cdot T_i \cdot t_i}{\sum Q_i \cdot t_i} \qquad (3)$$

where Q: flow rate (m^3/s); ρ: water density (assumed to be constant at 1×10^3 kg/m^3); T: water temperature (^oC); and C: water heat capacity (assumed to be constant at 1 $cal/g/^oC$); and t: time (s). The subscript i denotes the segment in the time series used in recording the values of the corresponding parameters.

The result of Equation (3) is termed *Temperature Equivalent* as it has units of degrees Celsius. It in essence is the flow-weighted average temperature of the flow component calculated in a pre-defined period of time (here, August 1 through October 1, 2002), a "first moment" approach to weighted averaging. In common pollutant terms, temperature equivalent (TE) is analogous to event mean concentrations (EMCs). In fact, as pointed out by Strecker et al. (2001), for evaluating stormwater treatment system's effectiveness in reducing pollutants, comparing the statistics of the long-term EMCs of the inflow and outflow is a technique far more scientifically sound than the conventional approach of averaging the load reduction efficiency of all the storm events monitored. The latter approach essentially treats all storms as "equal" while in fact storms vary widely in runoff volumes produced and associated pollutant concentrations. By using the TE, each increment of temperature change of a flow component in the watershed is weighted against the total volume of this component over the two-month comparison period. The resulting TE value is an indicator of the thermal polluting potency of each flow component, which takes into account flow volume. TE is a function of the physical characteristics of the flow source area.

Figure 4 shows the TE value for each of the flow components in the 2002 post-construction Consolidated Drain watershed during the August-September comparative time period. TE was also calculated for Portage Creek upstream of its confluence with the Consolidated Drain channel using USGS gage station data and temperature readings from a nearby thermistor installed in the creek. The average air temperature for the period was 20.0 ^{o}C. Figure 4 is a simple but very illustrative schematic of the thermal pollution contribution of each flow component in the watershed.

Stormwater runoff from the 32-ha regional shopping center at the heart of the urban corridor (i.e., the Crossroads Mall in Figure 1) had a TE value of 23.3 ^{o}C, 3.3 ^{o}C higher than the average air temperature and 5.8 ^{o}C above Portage Creek TE. The combined mall and upstream urban watershed runoff had a TE of 22.6 ^{o}C. This TE pattern indicates that impervious surfaces in the mall and its upstream areas were both absorbing heat and subsequently releasing the stored heat to storm water runoff. With regard to potential receiving stream impacts without a treatment system, runoff from these two areas was evidently a substantial source of thermal pollution.

With a prolonged detention period in the sediment forebay and wet detention pond, the TE value of the stormwater rose to 24.1 ^{o}C, a clear indication of the warming effect of these open ponds. The wet pond volume was designed for a minimum 24-hour detention time for the runoff produced by a two-year, 24-hour storm event. The detention time was effectively much longer as its outflow feeding the wetland was restricted to obtain a 5-10 day retention time in the wetland, which maintained standing water at depths below 0.31 m. The wetland, in contrast, was able to cool the outflow from the wet pond by 2.5 ^{o}C, to a TE of 21.6 ^{o}C. Overall, the treatment system lowered the temperature of collected stormwater by 1 ^{o}C TE, with the wetland cell accounting for all the cooling. However, with regard to the receiving stream, the treatment system is still be considered as a source of thermal pollution as its outflow TE was 4.1 ^{o}C higher than that of Portage Creek. This in-system TE pattern confirms the observation made earlier regarding the effectiveness of each treatment cell in mitigating thermal pollution of urban stormwater runoff. This also substantiates that the wetland's maximum cooling capabilities are tied to ambient air.

The other two flow components in the post-construction Consolidated Drain watershed are from the Schuring Drain and the Consolidated Drain channel starting from its confluence with Schuring and ending at its discharge to Portage Creek (see Figure 4). The location and channel bed elevation are such that both of these two drains are fed by a steady groundwater input that has a lower-than-air temperature during dry weather conditions. Although both drain channels receive pulses of stormwater due to the undetained stormwater runoff in the Schuring Drain subwatershed, most flow in the Schuring Drain was groundwater-fed baseflow. As a result, the TE value of the Schuring Drain flow was the lowest among all the flow components during the two-month period in 2002, including that of Portage Creek. This means that the Schuring Drain (i.e., its baseflow) generally constituted a thermal pollution sink to the wetland outflow. This was particularly significant during dry weather conditions when the wetland continued to discharge to the Consolidated Drain.

Groundwater baseflow of the lower portions of the Consolidated Drain channel also served to offset the warmer wetland outflow. Immediately above its confluence with Portage Creek, the Consolidated Drain TE value was 17.4 ^{o}C, slightly lower than that of the creek. This suggests the post-construction Consolidated Drain watershed over the two-month period in 2002 did not add thermal pollution to Portage Creek on a flow-weighted thermal load basis. This combination of features therefore illustrates the successful mitigation of thermal loading to Portage Creek.

When calculating and interpreting TE values in a watershed, one should take caution in choosing the time span on which the TE values are based. If a long time span is used, such as the TE values calculated here, TE represents the long-term thermal polluting potency of each flow component in a watershed. As a result, flows mostly composed of steady low-temperature baseflow show less or no chronic thermal impact on the receiving stream. On the other hand, if a short time period is chosen, such as the duration of a rain event, TE reflects the acute thermal impact of flow components from a watershed during that event. The advantage of using a long time span, however, is that it can capture the effect of thermal enrichment/mitigation processes that are of continuous and long-term nature, such as those taking place in stormwater treatment structures.

Diel temperature fluctuations

To illustrate diel temperature fluctuations in the system, Figures 5, and 6 show the difference between the daily temperature maximum and minimum for thermistors T3 (at Consolidated Drain channel ~15 m upstream of its confluence with Portage Creek), T4 (at Portage Creek ~5 m upstream of its confluence with the Consolidated Drain) and T5 (at Portage Creek ~50 m downstream of the confluence) for the two month comparative period in 2000 and 2001, respectively. Diel air temperature fluctuations are also plotted for 2001 (data not available for 2000 due to instrument malfunction). T3 records the water temperature of the Consolidated Drain channel just upstream of the confluence with the Creek. T4 gives the water temperature of the Creek just before it receives water from the Consolidated Drain channel. Readings from T5 directly reflect the temperature change in the Creek resulting from the mixing of water from the Consolidated Drain channel and the Creek.

Figure 6 indicates that diel temperature fluctuations in flow of the Consolidated Drain channel and Portage Creek closely followed those of the air, with exceptions occurring mostly during rain days. This suggests that despite substantial groundwater input in both the Creek and the Consolidated Drain channel below the Schuring Drain, heat transferring between flow and the environment by long-wave radiation and conduction (from the air) and direct short-wave solar radiation still causes substantial diel temperature fluctuations. Comparing Figure 5 with Figure 6, however, it is clear that the construction of the treatment system increased diel temperature fluctuations in the Consolidated Drain channel (T3) relative to that in the Creek, both upstream (T4) and downstream (T5) of the Consolidated Drain channel. Varying degrees of channel shading were the key to this change.

Before the construction of the treatment system, the Consolidated Drain channel was covered by a dense layer of vegetation growing in and around the channel. The Shuring Drain was not connected to the Consolidated Drain. Therefore, the Consolidated Drain channel carried a small base flow, shaded almost completely by vegetation, during dry weather. This condition resulted in low diel temperature fluctuations in the Consolidated Drain channel during dry weather (Figure 5). After the construction, due to the channel reshaping and the connection of the Shuring Drain, vegetation was lost and more flow area was exposed to direct solar radiation. Consequently, flow in the Consolidated Drain channel experienced higher diel temperature fluctuations than that in the Creek (T4 and T5). Nevertheless, with the treatment cells mitigating stormwater runoff, we see fewer peaks of high diel temperature fluctuation in 2001 than 2000 (Figures 6 and 5) during wet weather, although there were more rain days and total rainfall in 2001 than in 2000 during the comparative period (23 vs.19 and 10.92 inches vs. 6.28 inches, respectively).

Overall, Figures 5 and 6 indicate that diel fluctuations in stream temperature are primarily a result of ambient air temperature change but can be exacerbated by storm events. The highest single day temperature fluctuations (daily maximum minus daily minimum) for the Consolidated Drain (T3: 9.6 ^{o}C) and Portage Creek (T5: 7.2 ^{o}C) during the two month comparative period in 2000 and 2001 were both recorded on September 8, 2001, when a one-hour 0.7-inch mid-afternoon rain event occurred. During dry weather, however, vegetative cover plays a significant role in regulating diel stream temperature variations. Figures 5 and 6 also show that the Consolidated Drain can increase the diel fluctuations in Portage Creek up to 2.4 ^{o}C (September 8, 2001) during wet weather. On the other hand, due to its relative small flow rate, the Consolidated Drain did not have much effect on the diel fluctuations of the Creek during dry weather, even when the wetland treatment cell discharged nearly continuously throughout the two month comparative period in 2001.

CONCLUSIONS

Findings from this study suggest that shading and infiltration are the two keys to effectively protect coldwater streams from stormwater thermal pollution. It is also clear that open water detention ponds are not a suitable stormwater BMP option for stormwater treatment to protect coldwater habitats. Well-vegetated wetlands and infiltration basins are better alternatives. Urban stormwater treatment efforts have traditionally focused on mimicking the pre-construction flow regime and removing pollutants from the runoff. Open water ponds are effective devices to reach these goals. However, without infiltration and adequate shading, thermal pollution cannot be addressed, and thermal variation is a continuing process that does not stop with the cessation of rainstorms and runoff. Thus, these fundamental differences between thermal pollution and other common constituent pollutants may render the sole use of detention ponds as inappropriate for terminal treatment of urban stormwater that is returned to coldwater receiving streams.

Analysis of diel temperature fluctuations in the Consolidated Drain channel and Portage Creek both upstream and downstream of its confluence with the Consolidated Drain channel demonstrates the importance of shading in maintaining thermal regime in coldwater streams.

Similar analyses during the first summer of post-construction monitoring (2001) showed abatement of the acute thermal shock but pointed to a higher diel fluctuations due to a functioning treatment system and the loss of channel vegetative cover, respectively.

A temperature equivalent (TE) concept was examined which combines the temperature and flow volume in defining a parameter to describe the thermal pollution potential of various drainage areas in a watershed. We applied TE to not only stormwater runoff but also stream flows. Results showed that TE values agreed well with what was suggested by both temperature data and thermal load calculations. In addition, with units of degrees Celsius, TE is an illustrative indicator of the polluting potency of thermal pollution sources.

ACKNOWLEDGMENTS

This study was generously supported by the Water Environment Research Foundation (Project number 00-WSM-7-UR) and the Kalamazoo Foundation. The project team would like to thank Mr. W. Christopher Barnes, P.E., City of Portage for his support and cooperation throughout the project. Special thanks go to Ms. Nicole Ott, Mr. Brian Boyer, and Ms. Patty Hoch-Melluish of Kieser & Associates for their assistance in various aspects of this research.

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Table 1: Flow components of the treatment system during the post-construction modeling period.

(ft^3)	**Forebay-Wet Pond**	**Wetland**	**System Total**
Inflow	3,951,530	3,731,755	3,951,530
Outflow	-3,731,755	-2,283,163	-2,283,163
Total Loss	-219,775	-1,448,592	-1,668,367
Rain Deposit	243,119	200,013	443,132
Evaporation [1]	-409,976	-337,285	-747,261
Infiltration [2]	-52,919	-1,311,320	-1,364,239

[1] Including transpiration by vegetation, based on Penman (1948) and Meyer (1944).

[2] Residual of "Inflow ", "Outflow", "Rain Deposit", and "Evaporation" (see Equation [1]).

Table 2: Heat and water volume change through the treatment system during the post-construction modeling period.

	Heat (× 10^9 kcal)	**Flow Volume (ft^3)**
Forebay In	2.585	3,951,530
Wet Pond Out	2.551 [1]	3,731,755
First Reduction [2] (%)	0.034 [3] (1.3)	219,775 (5.6)
Wetland Out	1.431	2,283,163
Second Reduction [2] (%)	1.120 (43.9)	1,448,592 (38.8)
Total Reduction [2] **(%)**	**1.154** **(44.6)**	**1,668,367** **(42.2)**

[1] Temperature data not available from 15:10, September 6 through 10:20, September 8.

[2] First reduction: from Forebay In to Wet Pond Out; second reduction: from Wet Pond Out to Wetland Out; total reduction: from Forebay In to Wetland Out (the entire treatment system).

3 Actual value will be lower due to temperature data gap.

Table 3: Heat and flow reduction by the ConDrain stormwater treatment system for the 11 individual rain events during the post-construction modeling period.

Event No.	Heat-in ($\times10^8$) (kcal)	Heat-out ($\times10^8$) (kcal)	Heat red. (%)	Inflow (ft^3)	Outflow (ft^3)	Flow red.[1] (%)	Evap. [2] (%)	Infil. [3] (%)	Forebay-wet pond heat red. (%)	Wetland heat red. (%)	Forebay-wet pond flow red. (%)	Wetland flow red. (%)
1	2.20	0.89	59.3	309,249	131,401	57.5	24.6	41.9	3.7	57.7	-8.61	53.5
2	3.70	3.31	10.4	578,598	482,817	16.6	12.5	20.1	-17.2	23.6	0.88	17.3
3	0.67	0.58	13.6	83,673	91,324	-9.1	4.7	17.4	-3.7	16.7	13.62	3.9
4	5.69	2.76	51.6	849,523	458,528	46.0	19.7	34.6	5.1	49.0	-7.82	41.4
5	0.25	0.09	62.7	37,618	14,823	60.6	43.7	41.7	6.3	60.2	-16.08	53.1
6	0.90	0.39	56.7	136,763	60,032	56.1	20.7	52.5	-2.1	57.5	-3.63	54.5
7	0.44	0.15	65.3	69,232	23,927	65.4	24.0	54.9	4.1	63.8	-3.67	64.1
8	0.64	0.22	65.4	104,905	40,038	61.8	24.9	57.4	-1.6	66.0	-3.51	60.4
9	3.65	3.06	16.2	562,460	503,619	10.5	4.7	19.1	-6.9	21.6	5.56	15.2
10	5.09	2.53	50.3	790,318	419,344	46.9	16.7	38.2	-1.3	50.9	-3.89	44.8
11	0.58	0.11	81.3	88,879	19,565	78.0	22.9	70.9	3.4	80.7	-8.36	76.0
Sum	*23.8*	*14.1*	--	*3,611,219*	*2,245,417*	--	--	--	--	--	--	--
Ave.	*2.16*	*1.28*	*48.4*	*328,293*	*204,129*	*44.6*	*19.9*	*40.8*	*-0.9*	*49.8*	*3.23*	*44.0*

[1] red. = reduction

[2] Evaporation as a percentage of the total inflow.

[3] Infiltration as a percentage of the total inflow.

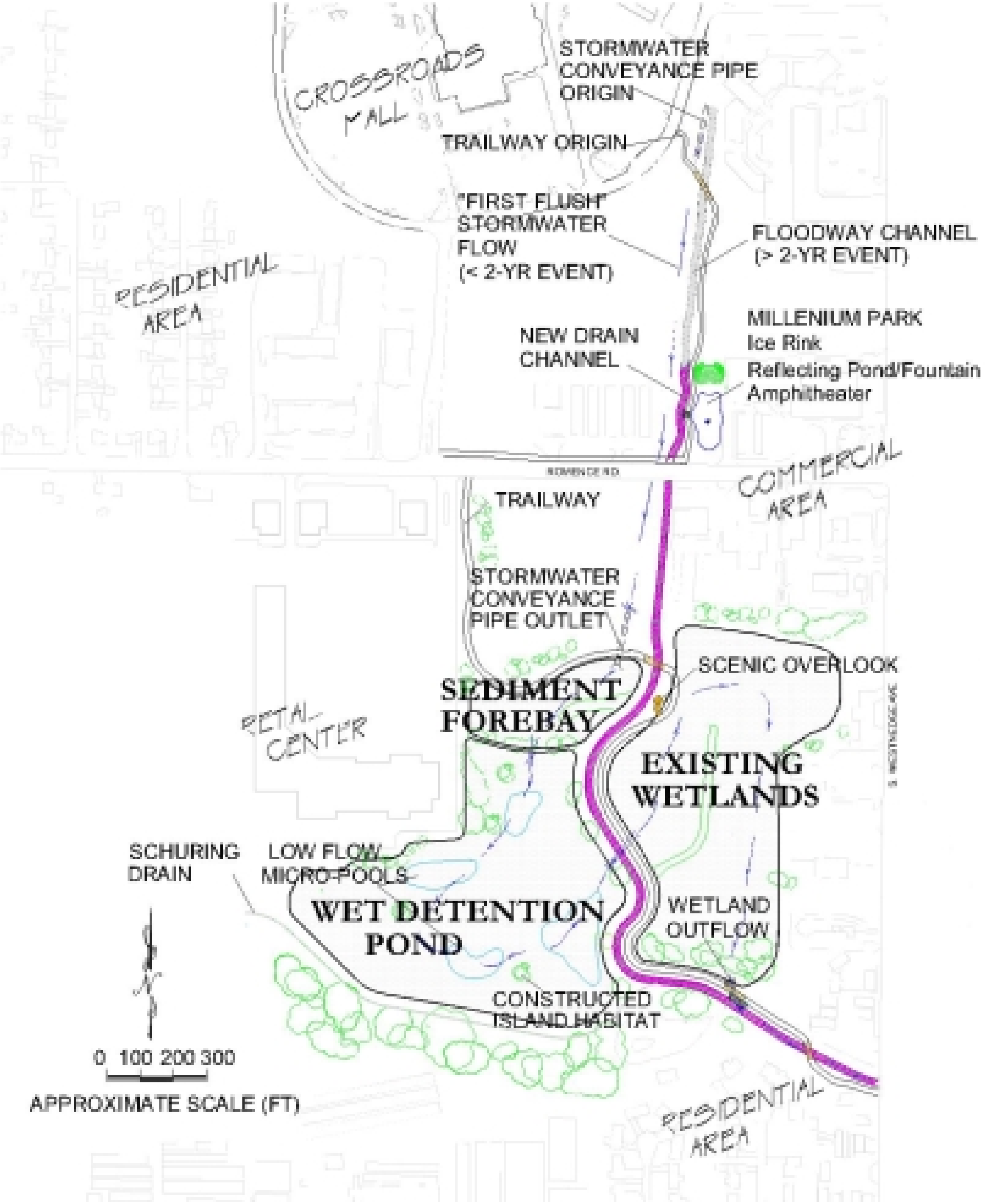

Figure 1. Diagram of the Consolidated Drain Stormwater Treatment System

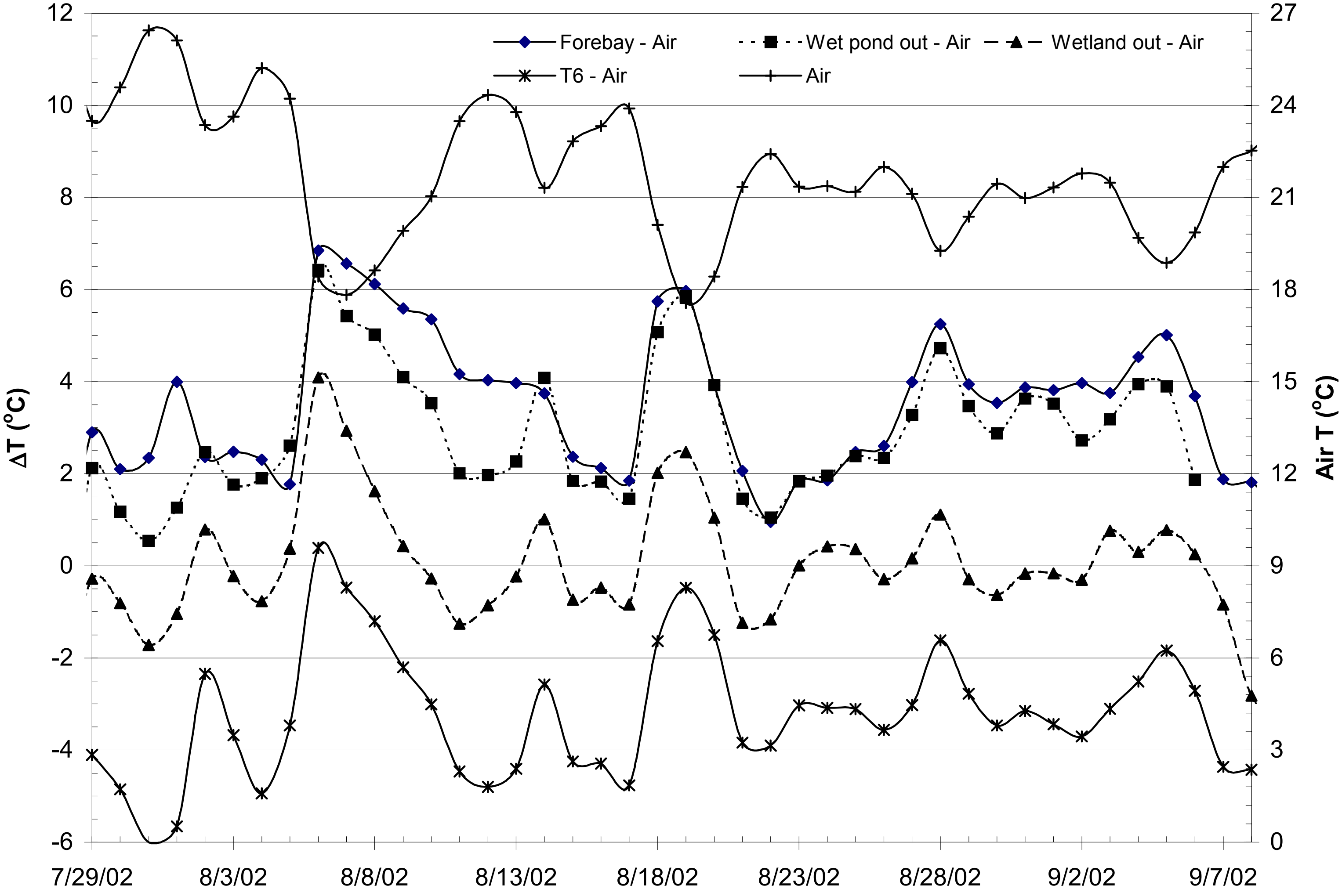

Figure 2: Average daily temperature difference between the air and the treatment system cells (and thermistor T6 in Portage Creek upstream of its confluence with the Consolidated Drain) during the post-construction modeling period.

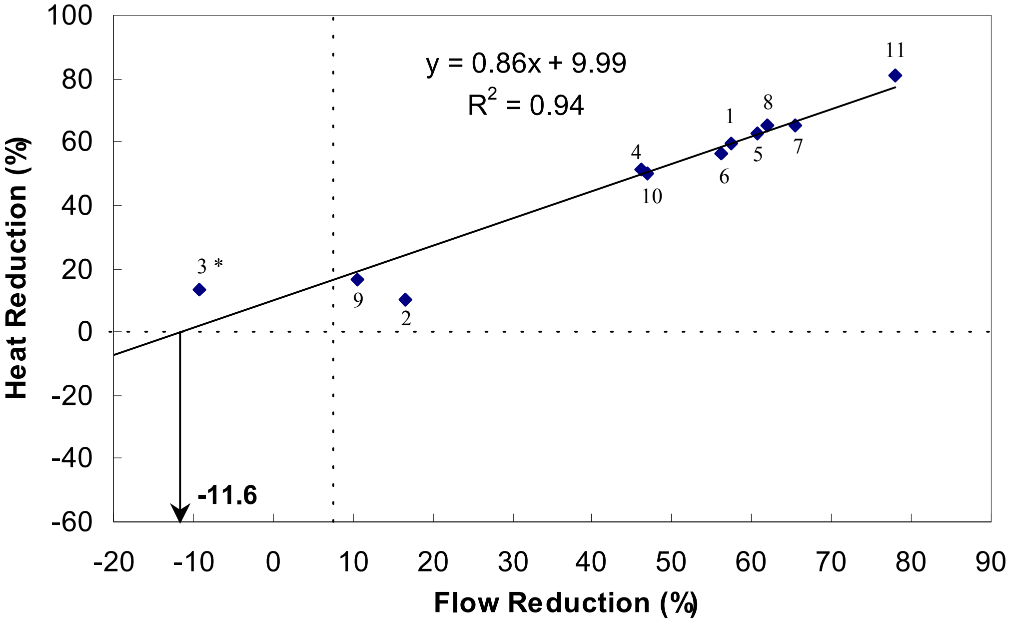

Figure 3: Relationship between system flow and heat reduction for the 11 individual events during the post-construction modeling period.
* Numbers near the data points are event numbers as shown in Table 3.

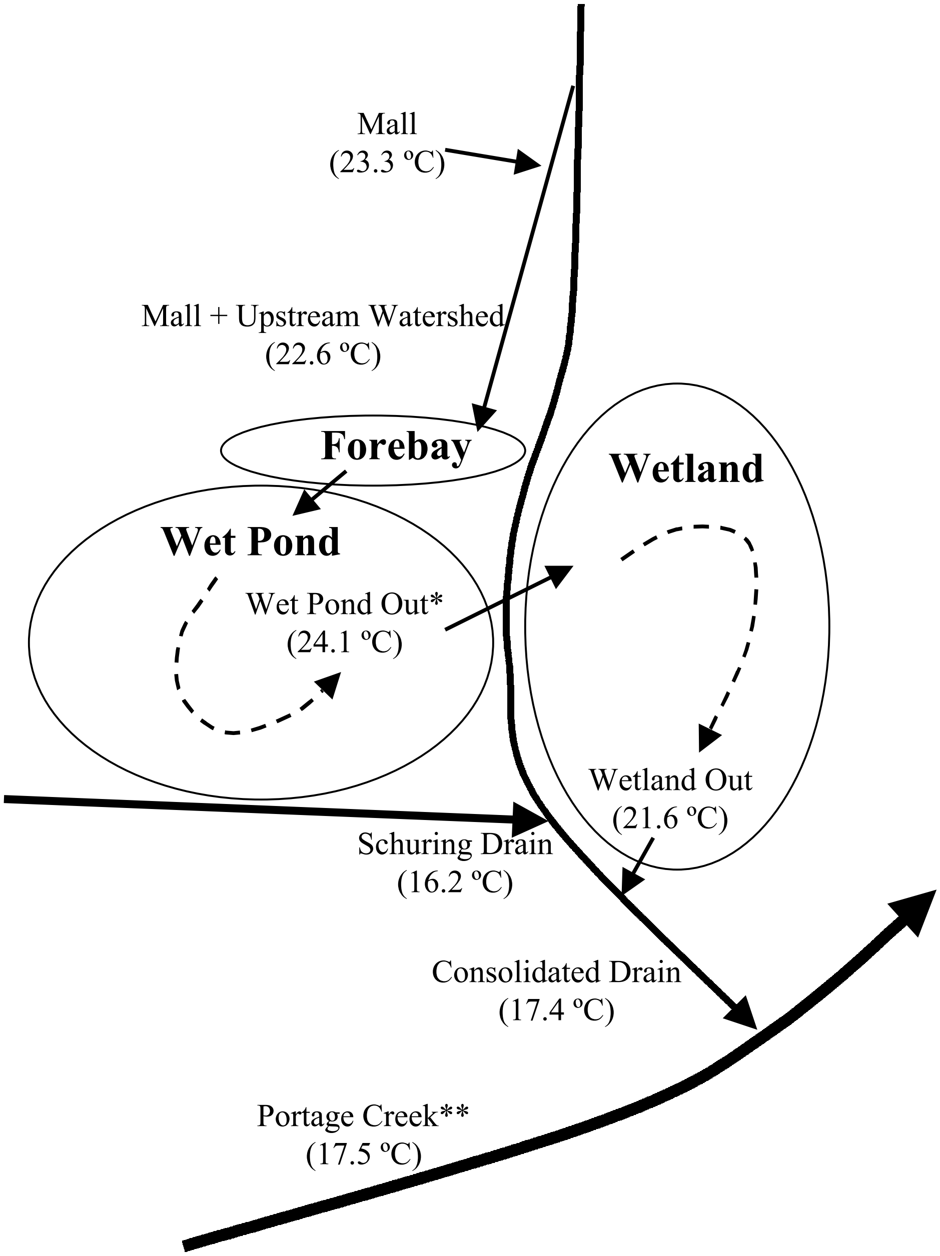

Figure 4. Temperature Equivalent (TE) of flow components in the post-construction Consolidated Drain Watershed during the two-month period of 8/1/02-10/1/02. Average air temperature during the same time period was 20.0ºC.
* [N=40 days monitored].
** [N=57 days monitored].

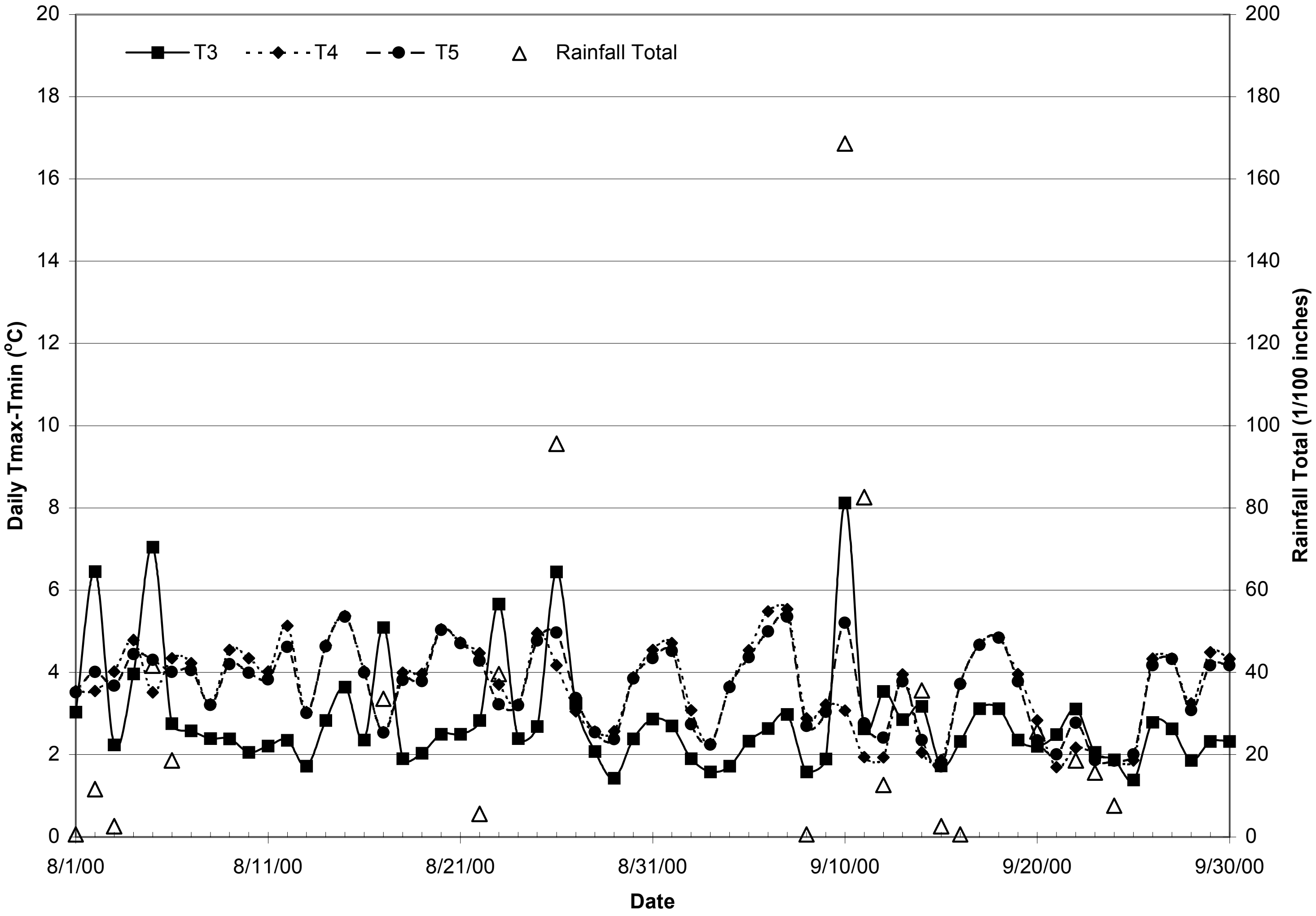

Figure 5: Diel temperature fluctuations of the Consolidated Drain channel and Portage Creek in the months of August and September in 2000 (before the stormwater treatment system came on-line), illustrated by the difference between the daily temperature maximum and minimum.

* Thermistor T3 located at Consolidated Drain ~15 m upstream of the confluence; T4 at Portage Creek ~5 m upstream of the confluence with the Consolidated Drain; and T5 at Portage Creek ~50 m downstream of the confluence with the Consolidated Drain.

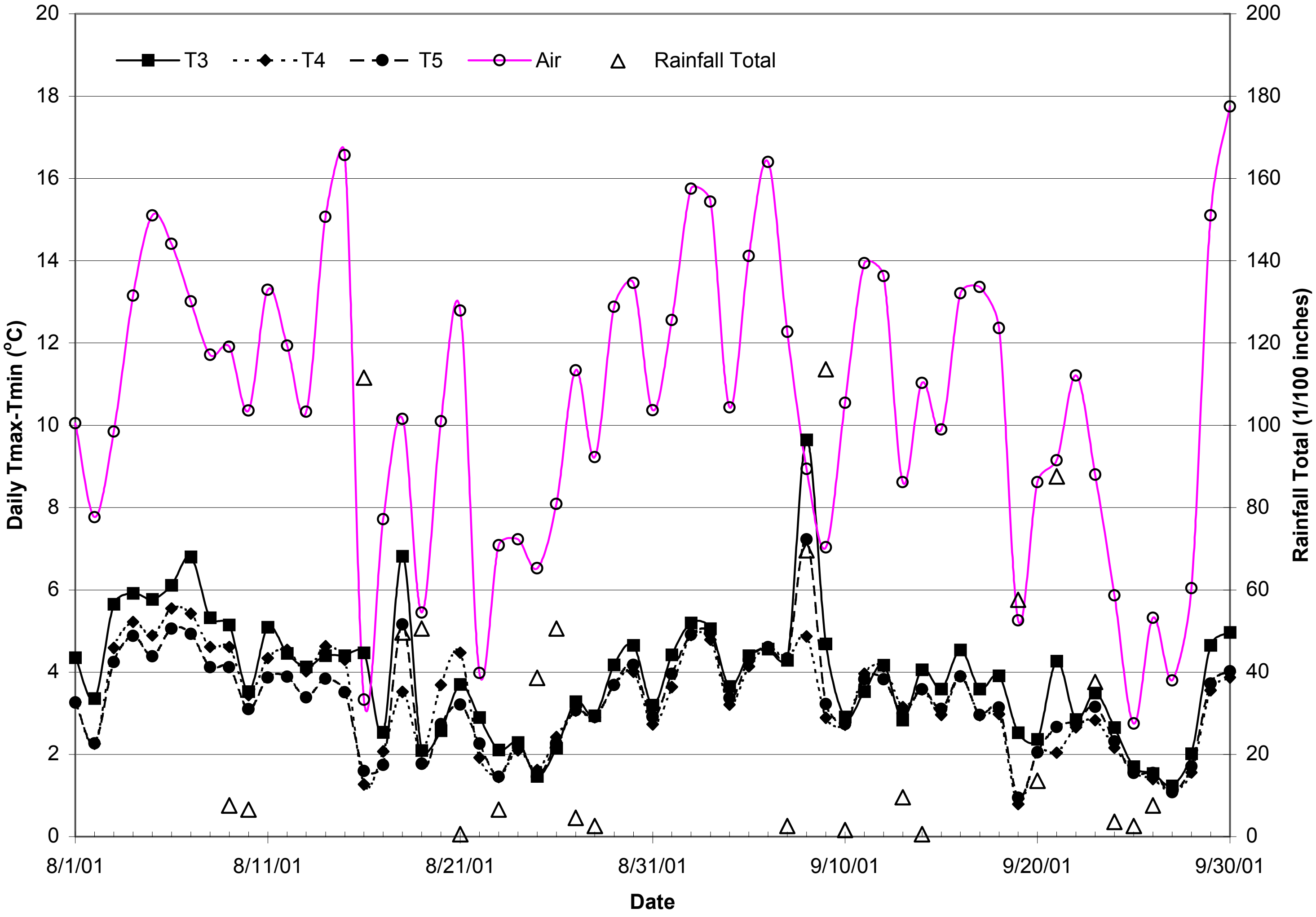

Figure 6: Diel temperature fluctuations of the Consolidated Drain channel and Portage Creek in the months of August and September in 2001 (after the stormwater treatment system came on-line), illustrated by the difference between the daily temperature maximum and minimum.
* Thermistor T3 located at Consolidated Drain ~15 m upstream of the confluence; T4 at Portage Creek ~5 m upstream of the confluence with the Consolidated Drain; and T5 at Portage Creek ~50 m downstream of the confluence with the Consolidated Drain.