

Supported by Toronto and Region Conservation Authority



Geothermal-based Thermal Mitigation of Stormwater Retention Pond Outflows

April 2020



PUBLICATION INFORMATION

Citation: Erik Janssen and Tim Van Seters. 2020. *Geothermal-based Thermal Mitigation of Stormwater Retention Pond Outflows*. Sustainable Technologies Evaluation Program, Toronto and Region Conservation Authority, Vaughan, Ontario.

Documents prepared by the Sustainable Technologies Evaluation Program (STEP) are available at <u>www.sustainabletechnologies.ca</u>. For more information about this or other STEP publications, please contact:

Tim Van Seters

Erik Janssen

Manager, STEP Toronto and Region Conservation Authority 101 Exchange Avenue Vaughan, Ontario E-mail: tim.vanseters@trca.ca Analyst, STEP Toronto and Region Conservation Authority 101 Exchange Avenue Vaughan, Ontario E-mail: erik.janssen@trca.ca

THE SUSTAINABLE TECHNOLOGIES EVALUATION PROGRAM

The Sustainable Technologies Evaluation Program (STEP) is a multi-agency initiative developed to support broader implementation of sustainable technologies and practices within a Canadian context. STEP works to achieve this overarching objective 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.

ACKNOWLEDGEMENTS

Support for this project was provided by the City of Brampton. Additional funding support is provided to STEP by the City of Toronto, York Region and the Region of Peel.

PROJECT TEAM

The STEP team included:

- Erik Janssen, Analyst
- Tim Van Seters, Manager
- Ricardo Brown, Technician
- Leigh St. Hilaire, Project Manager
- David Nixon, Advisor
- Svend De Bruyn, Advisor
- Mark Hummel, Technician
- Dean Luciani, Technician
- Gil Amdurski, Technical Coordinator
- Christy Graham, Coordinator

NOTICE

The contents of this report do not necessarily represent the policies of the supporting agencies. Although every reasonable effort has been made to ensure the integrity of the report, the supporting agencies do not make any warranty or representation, expressed or implied, with respect to the accuracy or completeness of the information contained herein. Mention of trade names or commercial products does not constitute endorsement or recommendation of those products.

EXECUTIVE SUMMARY

During warm weather, urban surfaces like pavement and rooftops heat up in the sun. Stormwater shed from these surfaces during rain events is significantly warmed. The warming continues in stormwater management ponds, a common feature in many urban and suburban areas, as the stormwater sits and absorbs more solar heat before discharging to the watershed. Without intervention, pond outflows can surpass 30°C. Currently, the Ministry of Natural Resources and Forestry suggests a maximum temperature of 24°C for the protection of endangered redside dace, but even cooler temperatures are preferred for brook trout and other headwater species. Without intervention, pond outflows can surpass 30°C. Solutions have been proposed with varying levels success.

In May 2019, The Sustainable Technologies Evaluation Program (STEP) of the Toronto and Region Conservation Authority (TRCA) completed the installation and commissioning of a pilot geothermal-based stormwater retention pond thermal mitigation system. A simple model of the system is shown in Figure A. It is a hydronic circuit where piping connects a stormwater heat exchanger (SHX) to a ground heat exchanger (GHX). A pump circulates a heat transfer fluid through the circuit. The SHX absorbs heat from the stormwater outflows and, via the circulating heat transfer fluid, that heat is rejected to the deep ground using the GHX. This cycle can be used to continuously cool the warm stormwater outflows.



Water to Wetland



Pictures of the system are show in Figure B. It was installed at a stormwater pond in Brampton, ON, with a surface area of approximately 3,000 m² and a permanent pool depth of 2 m (Figure B (i)). The system was not intended to meet the full cooling load of the pond but rather, to build knowledge around design and performance.

The GHX was a single 600 ft (183 m) deep borehole. It was installed with a drilling rig (Figure B (ii)) and consisted of a U-bend of 1-1/4" high-density polyethylene (HDPE) pipe encased in thermally-conductive grout. A fluid enters one side of the U-bend and then travels to the bottom before coming back up, rejecting its heat to the ground in the process. The SHX was composed of 230 m of 3/4" HDPE pipe (Figure B (iii)). It was installed in an existing vault at the site (Figure B (iv)) that was in the path of the stormwater outflow. Note that, while the SHX was well-sized for the single-borehole pilot, the approach of using coiled 3/4" HDPE pipe in the vault would not have worked well in a system sized to meet the full load because it is too bulky. Other SHX options are discussed in this report.



Figure B. From top to bottom and left to right: (i) The pilot took place at a Brampton pond. (ii) The borehole was installed with a specialized drilling rig. (iii) The SHX consisted of coiled HDPE pipe. (iv) The SHX was installed in an existing vault on-site that was in the path of the stormwater outflow. (v) The system was powered by a 1 kW PV array. (vi) All mechanical components were placed in a metal job box.

Power was provided by an off-grid 1 kW photovoltaic (PV) system (Figure B (v)) with battery storage contained in 2' x 2' x 4' job box. The off-grid system was selected as the easiest and cheapest power option, and it was also very familiar to the research team. However, a full-scale system would need grid power from the nearby subdivision. The off-grid power source put constraints on the power available to the circulator pump. An energy efficient variable speed ECM circulator was selected and it was able to achieve a flow rate of 4.5 gpm while consuming less than 60 W. Calculations indicated that this flowrate was sufficient for good performance.

All mechanical components like valves, gauges, manifolds, etc. were housed in 2' x 2' x 5' job box (Figure B (vi)) that was constructed off-site and then transported to the site as a package. The job box also contained an instrumentation package that continuously monitored all relevant system parameters including the pond and hydronic system flow rates and temperatures, among other parameters.

The system was simply left to operate continuously throughout the summer and into the fall/winter, switching the system to a proposed wintertime mode of operation when the pond temperatures were sufficiently cold. Wintertime operation was explored as a way to pre-cool the ground and improve system performance but it was ultimately found to be unnecessary. The continuous operation was interrupted periodically to make ground temperature estimates.

Figure C shows the stormwater flowrate, temperature, and thermal load to cool the water to 24 °C, from June to September 2019. The thermal load is expressed in tons refrigeration, which is a convenient unit in geothermal system design. Note that 1 ton is equivalent to 3.5 kW. The load has several peaks that would be difficult for any thermal mitigation system to manage. Suggestions for the management of these peaks are provided in the report.

Figure D shows a snapshot of the system operating over several days, and also the results from a calibrated model of system performance which agrees well with the actual data. Tp1 and Tp2 are the upstream and downstream temperatures of the stormwater with respect to the SHX. Figure E shows the system cooling power as a function of the stormwater temperature. Up to 2.25 tons of cooling was achieved when the stormwater outflow reached 30 °C.

The calibrated system model was used to size a full-scale system for the pilot pond. Figure F shows results. A relatively small system, consisting of six deep geothermal boreholes, would be able to keep the stormwater outflows below 24 °C for 95% of the time from June 1st to September 15th, 2019. Other methods have been suggested to manage the remaining 5%. It's estimated that the full system would cost less than 200k\$ to implement for the geothermal component. Without geothermal, temperatures would exceed 24 °C 50% of the time. The model was used to generate a companion prefeasibility sizing tool for this report that is available online.

To the author's knowledge, this pilot represents the first implementation of geothermal-based thermal mitigation. The system worked well, with minimal operational issues. It's design and performance were easily described by relatively simple models, developed within this study, making it a highly engineerable solution for different ponds. It is also highly space- and cost-efficient, and it does not impact the appearance of the pond or surrounding greenspace since most of the system is underground. These attributes make it suitable for retrofits as well as new ponds.

A number of other important topics surrounding geothermal-based thermal mitigation were explored within this work and, given the newness of this approach, there are a number of future work items that have been suggested. Chiefly among those items is the design and implementation of a full-scale system. Overall, this pilot demonstrated that geothermal is a very effective and promising option for thermal mitigation.



Figure C. Thermal load of the pond stormwater outflows for Summer 2019.



Figure E. The system provided up to 2.25 tons of cooling. (Note that Section 7.0 provides a full explanation of the trends in this plot)



Figure D. The system cools the stormwater over several days and cooling is highly predictable using a calibrated model.



Figure F. A small system, consisting of six boreholes, would keep outflows below 24 °C for 95% of the time during summer.

CONTENTS

1.0	Introduction	1
2.0	Study Goals	3
3.0	Study Site	5
4.0	Geothermal System Components, Sizing and Design	8
5.0	Analysis: System Model	
6.0	Monitoring	
7.0	Results: Geothermal System Cooling Capacity	23
8.0	Results: Geothermal System Model Validation	25
9.0	Results: Additional Item 1 - Thermal Load Modelling and Optimization	
10.0	Results: Additional Item 2 - Ground Temperature Modelling	47
11.0	Results: Additional Item 3 - Ground Pre-cooling to Enhance Performance and Reduce Costs	58
12.0	Results: Additional Item 4 - Borehole Performance Enhancement Using Deep Pond Cooling	64
13.0	Results: Additional Item 5 - Prototype Sizing Tool for System Optimization	68
14.0	Results: Example Sizing for Pilot Pond	69
15.0	Discussion	71
16.0	Future Work	75
17.0	Conclusion	76
18.0	Appendix A: Initial System Sizing	77
19.0	Appendix B: Machine Learning Modelling Details	

1.0 INTRODUCTION

During warm weather, urban surfaces like pavement and rooftops heat up quickly as they absorb and store heat from the sun. The stormwater shed from these surfaces during rain events is significantly warmed. This effect is further increased by stormwater management ponds, a common feature in many urban and suburban areas, as the stormwater sits and absorbs even more solar heat before discharging to the watershed.

This is a problem because the elevated temperatures negatively impact aquatic ecosystems. Currently, the Ministry of Natural Resources and Forestry suggests a maximum temperature of 24°C for the protection of endangered redside dace, but even cooler temperatures are preferred for brook trout and other headwater species. Without intervention, pond outflows can surpass 30°C.

Efforts to mitigate stormwater retention pond outflow temperatures have given rise to several strategies and technologies. These include bottom draw outlets, cooling trenches, subsurface trench outlets, automated discharge controls, shading, improved pond design and the application of stormwater management facilities without a permanent pool. However, these strategies vary in their feasibility, effectiveness and maintenance costs, and there is currently no consensus on the best options for both new construction and existing stormwater ponds.¹

For this reason, The Sustainable Technologies Evaluation Program (STEP) has partnered with the City of Brampton to pilot and evaluate promising new thermal mitigation measures in the City's stormwater ponds. This report discusses research results from a geothermal-based storm water retention pond cooling system implemented in a Brampton pond. A simple schematic of the system is shown in Figure 1-1.



Figure 1-1. Schematic of geothermal-based stormwater cooling system.

¹ Van Seters, T., Graham, C., Dougherty, J., Jacob-Okor, C., David, Y. 2019. Data Synthesis and Design Considerations for Stormwater Thermal Mitigation Measures. Sustainable Technologies Evaluation Program. Ontario.

Geothermal-based Thermal Mitigation of Stormwater Retention Pond Outflows

It is a hydronic circuit where piping connects a stormwater heat exchanger (SHX) to a ground heat exchanger (GHX). The GHX consist of one or more vertical boreholes extending hundreds of feet into the bedrock. Within each borehole is a U-bend of high-density polyethylene (HDPE) pipe encased in thermally-conductive grout. A pump circulates a heat transfer fluid through the circuit.

At the SHX, the heat transfer fluid is cooler than the warm stormwater outflows. This temperature difference drives heat from the stormwater and into the heat transfer fluid, cooling the stormwater in the process. At the GHX, the heat transfer fluid is warmer than the deep ground. This temperature difference drives heat from the heat transfer fluid into the deep ground, cooling the fluid to its original temperature. This cycle can be used to continuously cool the warm stormwater.

The system was implemented at a small-scale to study the feasibility of this approach and develop useful insights for a full-scale system. It was commissioned in Spring 2019 and monitored into Winter 2020.

2.0 STUDY GOALS

The overarching goal of this pilot was to implement a geothermal-based thermal mitigation system at a small-scale to study the feasibility of this approach and develop useful insights for a full-scale system. Using monitoring data from a full season of operation, the study initially sought to:

- 1. evaluate overall system effectiveness as installed;
- 2. assess full scale system sizing to meet temperature and thermal load reduction requirements;
- 3. provide recommendations on system components and configurations for enhanced performance; and
- 4. assess space and maintenance requirements.

The pilot was extended in August 2019 to encompass a number of other items, listed below.²

- 1. Additional Item 1: Thermal load modelling and optimization. Use machine learning software to develop a predictive model of pond outflows and temperatures based on environmental data (solar irradiance, ambient temperature and rain fall). The model can be run using climate normals to assess the thermal load of the pond during an average year.³ Sizing recommendations to be developed, both to optimize cost and performance on a seasonal basis, and also during peak thermal load periods.
- 2. Additional Item 2: Ground temperature modelling. As heat is dumped into the ground via the GHX, the ground temperature increases along with its capacity to cool pond outflows. An empirical model⁴ to be developed based on collected data at the pilot site that predicts borehole temperature changes over time based on pond thermal loads, both with and without pre-cooling during the winter. Quantifying the degree of warming will provide critical information on long term cooling capacity of the system and the potential need for pre-cooling during the winter. The geothermal system model will also be enhanced to allow for multi-borehole systems, which would be required for large ponds. Simulations will also be developed using a metallic heat exchanger (as opposed to HDPE). Metallic heat exchangers provide more heat transfer per unit area, allowing for cooling of larger thermal loads and more compact form factors.
- 3. Additional Item 3: Ground pre-cooling to enhance performance and reduce costs. Explore opportunities to pre-cool the ground during the wintertime using a heat exchanger in the pond that is connected to the GHX. A heat exchanger will be placed in the pond and the pre-cooling of the ground during the winter period is to be monitored. The resulting increase in geothermal system capacity due to cooler ground temperatures it to be calculated using a calibrated geothermal system model. It is anticipated that pre-cooling could significantly *increase* the summertime cooling capacity and drive down the size of the GHX.

² Note that the wording of these additional items is taken directly (or adapted) from the project agreement – although the order has changed for better flow within the report.

³ In practice, the models were run on environmental data for the previous 6 years since, in the context of a warming climate, these are likely to give a better approximation of future performance than looking at normals established using more historical data.

⁴ A physics-based model was ultimately used instead of a purely empirical model because it was better and more straightforward to implement.

- 4. Additional Item 4: Borehole performance enhancement using deep pond cooling. Opportunities for decreasing the size or number of boreholes will be explored by using a heat exchanger in the deepest part of the pond to assist with cooling the warm pond outflows during the summer. This could be done without disturbing the sediment in the pond and with limited installation effort. This would be largely a desk top exercise using the data collected from the ongoing pilot monitoring projects (e.g. temperature depth profile data, flows).
- 5. Additional Item 5: Prototype sizing tool for system optimization. A prototype sizing tool to be developed to provide sizing guidance based on pond design and historical environmental data in Brampton. This tool would build on the previous work, including the calibrated analytical geothermal system heat transfer model generalized to multi-boreholes, the machine learning model for stormwater temp/flow, and empirical model of the borehole thermal capacity. It would also be based on data collected on other ponds.

There is overlap between both the initial goals and additional items, particularly as it pertains to final recommendations for a full-scale system. For the sake of organization within this report, the results pertaining specifically to the initial goals and additional items are presented in individual sections and then final recommendations, across all aspects of this research, are presented in their own section.

3.0 STUDY SITE

The pond used in this study is located at 60 Upperlinks Drive in Brampton, ON (Figure 3-1 and Figure 3-2). The pond has a surface area of roughly 3,000 m² and a permanent pool depth of 2 m. During a storm event the pond level will rise as runoff from the subdivision enters the pond. Once the water level exceeds the permanent pool depth, it will begin to drain through the Hickenbottom structure. It enters a vault through a pipe, and then via another pipe, it discharges to the wetland. The vault is shown in Figure 3-3 to Figure 3-5.



Figure 3-1. Bird's eye view of storm water retention pond for this project (from Google Earth).



Figure 3-2. Cross-section showing pond depth.



Figure 3-3. Cross-section of vault.



Figure 3-4. Top view of vault showing manhole access.



Figure 3-5. Rear view of vault showing overflow opening.

4.0 GEOTHERMAL SYSTEM COMPONENTS, SIZING AND DESIGN

4.1 Concept and Overview

The geothermal-based stormwater pond thermal mitigation system has two *potential* modes of operation, one for summer and one for winter. During a storm event in the summer, the pond raises above the permanent pool level and begins to drain to the stream through a pipe. On the way to the stream, the warm stormwater flows over the stormwater heat exchanger (SHX). There are different ways of implementing the SHX. Figure 4-1 depicts it as a coil of black piping in a chamber.

The SHX is connected in a hydronic circuit with a deep vertical borehole (or multiple boreholes) which is (are) referred to as the ground heat exchanger (GHX). A heat transfer fluid circulates around the hydronic circuit using a circulator pump. As the fluid travels around the circuit, it absorbs heat from the stormwater outflow at the SHX and then rejects it at the GHX to the deep ground (which is at a much lower temperature). The temperature of the stormwater outflow can be reduced by several degrees using this approach. Note that pond heat exchanger (PHX) is *not used* during the summer.



Figure 4-1. Summer operation of the geothermal-based thermal mitigation system.

It takes time for the heat energy rejected to the ground during the summer to dissipate, and cooler deep ground temperatures promote better system performance. For these reasons, the system performance may be enhanced if it is reconfigured for wintertime operation. This was evaluated in the study.

For wintertime, the GHX is connected directly to the PHX, and the SHX is *not used*. As winter progresses, the pond gets very cold and may freeze over. Operating the circulator pump in these conditions will cool the ground. There is even the potential to cool the ground beyond its normal level in advance of the next summer and this may increase the cooling power of the system.

The benefits of geothermal-based thermal mitigation are that it can be more space and cost-efficient than other approaches. The only mechanical component it requires is a circulator pump and these are typically robust, requiring minimal maintenance or intervention.



Figure 4-2. Winter operation of system.

4.2 GHX

The size of the geothermal cooling system was constrained by the project budget, which allowed for a maximum borehole length of 600 ft (183 m). Borehole length describes the cumulative depth of all boreholes in a geothermal installation (i.e. number of boreholes multiplied by the depth of the boreholes). All other system components were sized around this constraint. Note that this length was much less than was required to meet the full thermal load of the pond but it was sufficient for a pilot that would provide insights for full-scale systems.

The GHX consisted of a single 600 ft borehole. A single deep borehole was selected because it was expected to supply cooler temperatures than multiple shallow ones. Cooler heat transfer fluid temperatures from a deeper borehole would result in a greater temperature differential and drive a greater amount of cooling capacity. A 1-1/4" SDR11 high-density polyethylene (HDPE) prefabricated geothermal U-bend of pipe was installed in the borehole and grouted with thermally enhanced bentonite grout. This formed the ground heat exchanger (GHX). Drilling and GHX installation took place during Winter 2018/2019 (Figure 4-3).



Figure 4-3. This drilling rig was used to drill a 600 ft borehole which housed the GHX.

4.3 SHX Material

There are different ways to implement the SHX. In this pilot, it was placed in the existing vault and constructed using bundles of 3/4" SDR11 HDPE pipe. This is the conventional approach for surface water geothermal systems, which are more common in parts of the U.S. It was inexpensive, robust, and a familiar form factor.

A major drawback of using HDPE pipe for this particular application is that the overall heat exchanger will take up a significant amount of volume for the amount of heat transfer it can provide. However, as will be shown, the sizing calculations indicated that an SHX made of HDPE with heat transfer capabilities to match the GHX could fit in the vault. Full-scale systems would likely need to take a different approach.

4.4 SHX Length

The SHX length was sized such that its heat transfer capacity was a good match for that of the GHX. This geothermal system is much different than a conventional system used to heat and cool a building, and conventional sizing and design approaches were not applicable. A new design procedure was derived. It is based on a system model that is described in greater detail in Section 5.0. Other details are provided in Appendix A.

The output of the design procedure is shown in Figure 4-4. For the given borehole length, and other system parameters, it shows the hydronic system flow rate and SHX length required to meet the thermal load of different stormwater outflows – in this case, assuming that the storm water temperature is 31°C and must be cooled to 25°C. As mentioned previously, the other primary consideration was the physical constraint of putting the SHX inside the vault and this is discussed further below. Ultimately the SHX length was sized at 720 ft (230 m). This length was estimated to be able to cool 7 gpm of warm stormwater outflow.

Figure 4-4 illustrates important trends. Beyond a certain point there are diminishing returns for increasing the SHX length – this is because the fixed borehole length becomes the limiting factor for heat transfer. The figure also shows that very low flow rates affect system performance but beyond a certain point, increasing hydronic system flowrates do not provide a benefit to the system.

Very low flow rates are to be avoided because the heat transfer fluid would end up cooling down to the ground temperature before leaving the ground heat exchanger, and once this occurred there would be no further heat transfer – essentially, some part of the GHX would end up not being utilized. Conversely, very high flow rates are to be avoided because the hydronic fluid would not spend enough time in the GHX to cool down to a point where it could generate a large temperature differential with the pond outflow. Larger flow rates than required would also increase system energy consumption.



Figure 4-4. The SHX exchanger sizing procedure produced a family of curves that represent the SHX length and hydronic system flow rates required to meet the thermal load for different stormwater outflows given other fixed parameters.

4.5 SHX Layout

The most space efficient form factor of the HDPE pipe SHX was a cylindrical stack of concentric piping. The minimum diameter of the stack was constrained by the recommended minimum bend radius of SDR11 3/4" HDPE pipe, the maximum diameter was constrained by the vault width, and the useful height was constrained by the vertical positions of the inflow and outflow pipes to the vault. A schematic of the SHX and vault is shown in Figure 4-5, an actual image is shown in Figure 4-6.

The stack was realized using four separated bundles stacked vertically and connected in parallel using a manifold. A parallel layout was used to keep the pressure drop across the SHX at a reasonable level. This also made it possible to pass the bundles in, one at a time, through a long rectangular opening in the side of the vault. The total length of pipe composing the SHX (i.e. not including the supply and return whips) was 180 ft, yielding the total SHX length at 720 ft (230 m).

Two identical bundles, in addition to the four deployed in the vault, were submerged in the pond itself. These bundles would not be used during the summer months, only in the late fall, winter and early spring, when the pond is cold or frozen. During this time, some of the heat absorbed by the borehole in the summer was rejected back to the pond.



Figure 4-5. The SHX was composed of a cylindrical stack of concentric 3/4" SDR11 HDPE pipe. The stack is composed of four bundles connected in parallel. Units are in inches.



Figure 4-6. The SWHE was installed in the vault.

4.6 Hydronic Flow Rate and Pump Selection

Figure 4-4 shows the impact of the hydronic system flow rate on overall system sizing – suggesting that a flow rate greater than 4 GPM was sufficient for the SHX and GHX sizing. The hydronic system pressure drop curve, including borehole, SHX and ancillary components, was calculated and compared against pump curves from different manufacturers and models. This was straightforward, and the details of the calculation have been omitted from this report.

A Taco VT2218 pump was selected. It was estimated to produce flow rates in the desired range. It also had a low energy consumption at 58W (due to the ECM motor) when compared to other models, four different flow rates, and integrated temperature control – all of which were desirable for this application. The pump produced 4.5 GPM of flow at maximum speed when installed in the geothermal system - well within the desired range.

4.7 Heat Transfer Fluid

The system was designed to operate year-round because the heat rejected to the ground during the summer was intended to be rejected back to the pond during the winter to create a balanced system. If the system was not balanced, and instead had a net heat gain, there was concern that performance may degrade year over year as the ground warmed. Note that the converse is also true. Wintertime operation may be able provide a beneficial imbalance that results in net cooling of the ground year over year – which would enhance cooling capacity in the summer. Either way, year-round operation meant that the system needed to be freeze protected.⁵

Freeze protection needed to be beyond that of conventional systems because in this application hydronic components are fully exposed to ambient conditions. Ethanol and propylene glycol solutions were considered – both would need to be at a 50% concentration to provide freeze protection beyond -30°C. Ethanol is less expensive and less viscous (resulting in a greater flow rate) but at 50% concentration the flash point of ethanol would be below the

⁵ This topic was evaluated in the study and results are presented in a later section. Ultimately, this turned not to be a concern. Although local warming of the ground was pronounced during the summer, the ground was able to return to its normal temperature relatively quickly. This also created a challenge for efforts to "charge" the ground with cooling, as will be discussed later.

working temperature of the system for periods of time during the summer. To avoid any risks with flammability, propylene glycol was chosen instead. It's nonflammable and, like ethanol, it is non-toxic.

Note that water was used for Summer 2019 and propylene glycol was only added to the system in Fall 2019. This was due to the time constraints of the project (i.e. the team was not able to fill the system with glycol before the summer began).

4.8 Location of Hydronic Circuit Components

A full-scale system would likely use a small permanent (for example, a 3' x 5' precast concrete shed) structure to house hydronic system components. However, in this study, the hydronics were assembled offsite in a metal job box (Figure 4-7) and then transported to the site (Figure 4-8). This made assembly more straightforward and would simplify removal at the end of the pilot project.



Figure 4-7. Hydronics were installed offsite in metal job box and then transported to site as modular package.



Figure 4-8. The modular hydronics box was installed on top of the vault. On the left, the box connects to the pond coils (left), the vault SHX (middle) and the GHX (right). Electronic components like the batteries, breaker panel, inverter and charge controller are housed in the adjacent job box to the right. Note that the vault opening was later protected using a metal grate.

4.9 Off-grid Photovoltaic System

Since there was no power directly at the site it was most straightforward, for research purposes, for the geothermal system to be powered by a small off-grid photovoltaic system. An actual system would require a physical grid connection since more power would be needed and the batteries require unwanted preventative maintenance. The off-grid system used 1.16 kWp (DC) of PV modules (Figure 4-9) and had 12.6 kWh of energy storage. Batteries and other electronics components were stored in a metal job box similar to the hydronics box (Figure 4-8). The system received a special electrical inspection to ensure safety.



Figure 4-9. The off-grid power system utilized 8 PV modules with a total capacity of 1.16 kWp. This image shows the modular hydronics box and modular battery box in the background, as well as the trenching to the vault with the buried cable and borehole pipe. The borehole location itself is just adjacent to the PV pedestal (in the trench).

The system could be recharged to 50% storage capacity in a single bright sunny summer day and could power the circulator power for several days without requiring a recharge. Further details about the sizing and design of the offgrid system and electronic components have been omitted from this report because they are not important to the overall geothermal system design. Sizing and design of off-grid PV systems is discussed in detail elsewhere.

4.10 System Control

System control pertains to the logic used in turning the circulator pump on or off. There were two options. The first option was to simply let the pump run all the time. There was enough battery off-grid power to do this if desired. The benefit is that it is simple and would provide additional cooling performance data that could help characterize the system. The drawback is that, if the system was used to provide cooling even cooling wasn't required, it would cause the ground to warm to a greater degree and this would degrade performance whenever cooling was required (due to the warmer ground).

The second option was to use the integrated temperature control of the pump. The pump had its own control logic that could turn the pump on whenever a temperature sensor reading surpassed a set-point value. This option would use less battery power and collect less data, but it would warm the ground to a lesser degree. The research team ultimately choose just to let the pump run continuously because it was simpler and would generate more data that could be of use to the study. Impacts on ground-temperature were analyzed separately.

4.11 Other System Design Elements

Figure 4-10 shows two other important design elements in the system. The first element is a weir with a V-notch across the outlet pipe of the vault. The weir was used to measure the water flow. The weir isn't necessary for a full-scale system an it will be removed after the pilot. The second element is the baffle wall that occurs just after the SHX. The baffle wall prevents water from flowing across the of the SHX top and directly to the outflow pipe. An opening at the bottom of the baffle wall forces flow downwards and ensures that the stormwater interacts with SHX. A smaller opening can be used to force the water back-up and create a standing volume which would be beneficial for cooling.



Figure 4-10. The weir (the plate covering the outlet pipe) was used to measure flow of water. The baffle wall directly after the SHX ensured the stormwater interacted with SHX.

4.12 System Design Summary

A full system schematic is shown in Figure 4-11 and the overall system is summarized below.

- **Power.** The PV modules charge the batteries in the battery box. The box also contains other electronic components (i.e. charge controller, breaker box, inverter). Power from the battery box is supplied to the hydronics box. This is used to run the circulator pump.
- **Stormwater.** The stormwater enters the vault and flows over the SHX. Heat from the stormwater is rejected to the SHX and the stormwater is cooled. The stormwater then hits a baffle wall which forces water flow downwards beneath the baffle wall. The stormwater must then flow over a weir before continuing on through the outlet pipe.
- **Geothermal System.** The circulator pump supplies cool heat transfer fluid from the GHX to the hydronics box. The heat transfer fluid reaches the manifold in the hydronics box where there are six parallel circuits. Two circuits head to PHX bundles in the pond and four circuits head to the SHX in the vault. During the summer, valves are configured such that flow is *only directed to the SHX in the vault*. The heat transfer fluid absorbs heat from the warm stormwater at the SHX. After returning from the SHX, the heat transfer fluid then flows back to the vertical GHX where it rejects heat to the deep ground. During the winter, valves are configured such that flow is only directed to the PHX. The effectiveness of wintertime operation was evaluated in this study.



Figure 4-11. Geothermal cooling system for stormwater retention pond outflow.

5.0 ANALYSIS: SYSTEM MODEL

A simple model of the geothermal-based thermal mitigation system is shown in Figure 5-1. The system is a hydronic circuit where piping connects stormwater heat exchanger to a ground heat exchanger. A pump circulates a heat transfer fluid through the hydronic circuit. At the SHX, the heat transfer fluid is cooler than the warm stormwater outflows. This temperature difference drives heat from the stormwater and into the heat transfer fluid, cooling the stormwater in the process. At the GHX, the heat transfer fluid is warmer than the deep ground. This temperature difference drives heat from the deep ground, cooling the fluid to its original temperature. This cycle can be used to continuously cool the warm stormwater.



Water to Wetland



Figure 5-1 shows the temperatures for different parts of the system. They are described further below:

- T_{p1} is the stormwater outflow temperature upstream of the SHX;
- T_{p2} is the stormwater outflow temperature downstream of the SHX;
- T_g is the deep ground temperature in the vicinity of the borehole;
- T_{h1} is the heat transfer fluid temperature leaving the GHX and entering the SHX;
- T_{h2} is the heat transfer fluid temperature leaving the SHX and entering the GHX.

The heat transfer (q_r) required to cool a given stormwater flowrate is given in Equation 1, where ρ_p is the density of water, \dot{V}_p is the flowrate of the stormwater from the pond, and C_p is the specific heat capacity of water.

$$q_r = \rho_p \cdot \dot{V}_p \cdot C_p \cdot (T_{p1} - T_{p2})$$
 Equation 1

The heat transfer to the SHX (q_{SHX}) can be described by Equation 2.⁶ In this equation, the SHX is assumed to be composed of HDPE pipe because that was the form factor used in the STEP pilot. A stainless steel plate heat exchanger

⁶ Equation 5.6 in Kavanaugh, Steve and Rafferty, Kevin. "Geothermal Heating and Cooling: Design of Ground-source Heat Pump Systems." ASHRAE, 2014.

is an option as well and this would require a slight adjustment of the equation. Note that L_{SHX} is the length of the SHX, R_{SHX} is the thermal resistance, and LMTD_{SHX} is the log mean temperature difference driving the heat transfer.

$$q_{SHX} = \left(\frac{L_{SHX}}{R_{SHX}}\right) \cdot LMTD_{SHX}$$
Equation 2
$$LMTD_{SHX} = \frac{T_{p1} - T_{h2} - (T_{p2} - T_{h1})}{ln\left(\frac{T_{p2} - T_{h1}}{T_{p1} - T_{h2}}\right)}$$
Equation 3

The heat transfer to the ground (q_{GHX}) can be described by Equation 4,⁷ where L_{GHX} is the total borehole length (depth of boreholes multiplied number of boreholes) and R_{GHX} is the thermal resistance. Defining L_{GHX} as one long length might seem to ignore the fact that the GHX may be composed of many boreholes which could have both series and parallel connections. However, it's straightforward to show that multiple boreholes connected in parallel can be described as one long borehole length provided the boreholes are spaced far enough apart that interactions between adjacent boreholes can be neglected. Series connections are trickier mathematically, and are beyond of the scope of this model.

$$q_{SHX} = \left(\frac{L_{GHX}}{R_{GHX}}\right) \cdot \left(\frac{T_{h1} - T_{h2}}{2} - T_g\right)$$
 Equation 4

In a steady-state where the system is exactly meeting the load, Equation 5 holds true.

$$q_r = q_{SHX} = q_{GHX} = q$$
 Equation 5

The relationship between T_{h1} and T_{h2} is defined by the heat transfer and the hydronic flow rate of the system according to Equation 6. In this equation, ρ_h is the density of the hydronic fluid, \dot{V}_h is the hydronic fluid flow rate, and C_h is the hydronic fluid specific heat capacity. The hydronic fluid may be water, an ethanol solution, or a propylene glycol solution. These solutions are all non-toxic. Note that T_{h1} can't drop below T_g .

$$T_{h1} = T_{h2} - \frac{q}{\rho_h \cdot \dot{V}_h \cdot C_h}$$
 Equation 6

Substituting Equation 6 into Equation 4 yields Equation 7 which can used to solve for a value of T_{h2} provided all other parameters are defined. It is then possible to find the value of T_{h1} . Putting all these equations together yields Equation 8 which describes the system as a whole. This equation is used to size the GHX and SHX based on the inputs for the required parameters. Equation 8 is calibrated for the pilot pond in the Section 8.0.

$$T_{h2} = q \cdot \left(\frac{L_{GHX}}{R_{GHX}}\right) + \frac{q}{2 \cdot \rho_h \cdot \dot{V}_h \cdot C_h} + T_g$$
Equation 7
$$0 = \left(\frac{L_{SHX}}{R_{SHX}}\right) \cdot \frac{T_{p1} - T_{h2} - (T_{p2} - T_{h1})}{ln\left(\frac{T_{p2} - T_{h1}}{T_{p1} - T_{h2}}\right)} - \left(\frac{L_{GHX}}{R_{GHX}}\right) \cdot \left(\frac{T_{h1} - T_{h2}}{2} - T_g\right)$$
Equation 8

⁷ Equation 3.1 in Kavanaugh, Steve and Rafferty, Kevin. 2014.

6.0 MONITORING

Monitoring commenced with system commissioning in Spring 2019. Monitoring points and sensors are outlined in Table 6-1.

	#	Description	Symbol	Sensor
¥	1	Heat transfer fluid supply temperature (from GHX)	T _{h1}	HOBO S-TMB-M002 Temperature Smart Sensor connected to Hobo U30 Logger; Mounted in thermal well using thermal grease.
Heat to GI	2	Heat transfer fluid return temperature (to GHX)	T _{h2}	HOBO S-TMB-M002 Temperature Smart Sensor connected to Hobo U30 Logger; Mounted in thermal well using thermal grease.
	3	Heat transfer fluid volumetric flow rate	, V _h	Grunfoss Vortex Flowsensor Standard (VFS 5-100 l/min) connected to Hobo U30 Logger
e n	4	Stormwater temperature at vault inlet	<i>T</i> _{<i>p</i>1}	HOBO S-TMB-M002 Temperature Smart Sensor connected to Hobo U30 Logger
eat fron ormwat	5	Stormwater temperature at vault outlet	<i>T</i> _{<i>p</i>2}	HOBO S-TMB-M002 Temperature Smart Sensor connected to Hobo U30 Logger
Ϋ́, Τ	6	Stormwater volumetric flow rate through vault	, V _p	Levelogger® Edge Model 3001 in vault with 22.5° V-notch weir
itions	7	Solar irradiance	N/A	S-LIB-M003 from Onset measured by Hobo Microstation
intal Cond	8	Ambient air temperature	N/A	HOBO S-TMB-M002 Temperature Smart Sensor installed in Stevenson screen and connected to Hobo U30 Logger
vironme	9	Ambient air temperature in vault	N/A	HOBO S-TMB-M002 Temperature Smart Sensor connected to Hobo U30 Logger
En	10	Rainfall	N/A	Collected from a local TRCA weather station
Data	11	Stormwater temperature leaving culvert and entering wetland	N/A	HOBO Water Temperature Pro v2 Data Logger
l Pond	12	Pond water temperature entering Hickenbottom structure	N/A	HOBO Water Temperature Pro v2 Data Logger
lditiona	13	Thermal profile of pond	N/A	HOBO Water Temperature Pro v2 Data Logger
Ad	14	Pond Level	N/A	HOBO Water Level Data Logger

Table o-1. Sensor overview	Table	6-1.	Sensor	overview
----------------------------	-------	------	--------	----------

Verification of sensor readings were performed on some the key sensors - those used to measure the heat pump cooling capacity and pond outflow temperature. Prior to deployment in the field, readings from the hydronic system

flow sensor were verified at the Archetype House (ASH) Lab at the Kortright Centre for Conservation in Vaughan, ON. During the verification, the volume of water passing through the sensor was measured for a known period of time and this was compared against the readings from the flow sensor. The flow sensor was connected to the same data logger, and on the same channel, used for the monitoring period. Results are shown in Table 6-2 and Figure 6-1.

Pump Speed	Sensor Avg. Voltage [V]	Sensor Flow [gpm]	Fill Time [s]	Fill Volume [gal]	Actual Flow [gpm]	Difference [%]
4	1.29	8.1	29.1	3.83	7.9	-2.1
3	1.07	6.3	36.9	3.89	6.3	1.3
2	0.87	4.6	51.7	3.89	4.5	-1.5
1	0.79	3.9	62.5	3.96	3.8	-3.0

Table 6-2. Flow sensor verification data.



Figure 6-1. Flow sensor calibration curve.

Several of the temperature sensors were also verified prior to deployment. The verification proceeded by placing all sensors simultaneously in a wet well calibrator and then comparing the measurements for different temperature setpoints. For the verification, sensors were connected to the data logger, and same channels, used throughout the monitoring period in the field. Results are shown in Table 6-3.

Table 6-3.	Temperature	sensor verification	data.
------------	-------------	---------------------	-------

	Calibrator Set-point			
Sensor	10°C	20°C	30°C	
<i>Tp</i> 1	10.2	20.0	29.7	
T_{p2}	10.3	20.0	29.9	
T_{h1}	10.3	19.9	29.8	
T_{h2}	10.4	19.9	29.8	

The cooling capacity calculation relies on the hydronic flow rate measurement as well as T_{h1} and T_{h2} . The verification exercise showed that these temperature sensors show very close agreement when measuring the same temperature and the flowrate sensor reads as expected within its experimental error (which is 1.5% of full-scale).

The cooling capacity will also be calculated using the flow rate measurement of stormwater through the vault in conjunction with T_{p1} and T_{p2} (Equation 1). However, much smaller temperature differentials are anticipated given the much higher flow rates and the fluid may not as well-mixed (impacting the temperature measurements). It follows that the capacity calculation using those sensors would be subject to greater error and it was only used as a high-level check on the cooling capacity determined using the hydronic sensors.

7.0 RESULTS: GEOTHERMAL SYSTEM COOLING CAPACITY

The upstream (T_{p1}) and downstream (T_{p2}) stormwater temperatures in relation to the SHX are shown in Figure 7-1. The upstream temperature reaches 30 °C as a maximum. The action of the geothermal cooling system is clear when the outflow temperatures are warm and the flows are low – under these conditions a temperature drop >2 °C can be observed.



Figure 7-1. The ability of the system to cool the stormwater outflows is clear when the upstream and downstream temperatures diverge, which occurs when the flowrate is low and the temperature is high.

When the flows are high, the upstream and downstream temperatures converge because the thermal load is much greater than the system can manage. Recall that this is a small-scale pilot that was never designed to handle the full load. When the upstream temperature is low at the beginning and end of the season, the temperatures also converge because the temperature differential between the deep ground and the outflow is small. The cooling capacity of the system is directly proportional to this differential so not much cooling occurs. Also note, that diurnal temperature fluctuations are significant, on the scale of 2 °C. Some trends are clearer over a shorter timescale. Figure 7-2 plots results from two weeks in July. Cooling over 3 °C is seen when the flow rate is low.



Figure 7-2. The cooling action of the system is clearer on a shorter timescale.

Sustainable Technologies Evaluation Program

Figure 7-3 plots the cooling capacity (in units of tons refrigeration) of the system as a function of the stormwater temperature for the summer. The scatter of the point cloud is due to the fact that there are other factors impacting the cooling capacity aside from just the stormwater temperature, chiefly the ground temperature and the flowrate of the heat transfer fluid.



Figure 7-3. The system cooling capacity increases for warmer stormwater outflows.

The data is aggregated into different categories of hydronic flowrate and ground temperature in Figure 7-4. Ground temperature estimates are developed in Section 10.0. Note that the system was intentionally operated with a low flowrate (2.0 gpm instead of 4.5 gpm) for the month of August to gauge the impact on the system capacity. The plot shows that system's cooling capacity is greater for lower ground temperatures and higher hydronic flowrates. However, recall that Figure 4-4 shows that past a certain point, increases in hydronic flowrate do not enhance system capacity – further improvements beyond 4.5 gpm are not expected. The remaining scatter in the data points is in part due to the thermal resistance of the SHX, which varies with the stormwater flowrate (discussed in Section 8.0).



Figure 7-4. The system cooling capacity is greater when the hydronic flowrate is higher and the ground temperature is cooler.

8.0 RESULTS: GEOTHERMAL SYSTEM MODEL VALIDATION

It is useful to demonstrate that Equation 8 accurately models the heat transfer properties of the system. In the pilot, parameters were either known constants (p_p , p_h , C_p , C_h , L_{GHX} , and L_{SHX}), continuously monitored values (T_{p1} , T_{p2} , T_{h1} , T_{h2} , \dot{V}_p , and \dot{V}_h), periodically determined values (T_g), or values calibrated based on the other data (R_{GHX} and R_{SHX}). To demonstrate the model's accuracy, a subset of data from the pilot was selected and the model was used to predict the stormwater temperature downstream of the SHX (T_{p2}) using other parameters. This was then compared against the actual value of T_{p2} . Data from July 11th to July 16th, 2019, was selected because it occurred directly after a ground temperature measurement. However, before discussing the validation, it is necessary to first discuss how T_g , R_{GHX} , and R_{SHX} were determined.

8.1 Ground Temperature Measurement

The ground temperature directly prior to this period was determined by turning the system off and letting the heat transfer fluid (water, in this case) equilibrate with the ground over a period of 5 full days from July 5th to 10th, 2019. The system was then turned on and the average temperature of the heat transfer fluid in the borehole was determined using the data collected for \dot{V}_h and T_{h1} . The T_{h1} sensor provided the temperature data and the \dot{V}_h sensor was used to tell when the heat transfer fluid that had been sitting in the borehole had made a complete pass across the T_{h1} sensor. The average ground temperature was estimated at 13.6 °C based on the data.

Note different approaches were taken in the study to estimate the ground temperature, and also that the average deep ground temperature will change as heat is extracted or rejected from/to the ground. This is discussed in Section 10.0 In a conventional geothermal installation, the average deep ground temperature used in a final system design is determined from a thermal conductivity (TC) test using a test borehole that will eventually become part of the final system. It will vary with the depth of the GHX and location of the system. In the GTA, the data which STEP has access to has ranged from 9.3 to 11.1 °C.

This is notably lower than the 13.6 °C ground temperature measured for the STEP pilot because the system had already been operating since late May 2019. In May, the ground temperature had been measured at 12.1 °C - so, by July, it had already heated up from its initial level. This is an important point for system design. *The designer needs to consider ground temperatures that reflect actual operating conditions,* which includes the local warming impacts of heat energy that is rejected to the ground.

8.2 Calculating R_{GHX}

With ground temperature value in hand it was possible to then determine R_{SHX} and R_{GHX} by using the monitoring data fit to Equation 2 and Equation 4, respectively. Both are linear equation of the form y = mx, where m is the (L/R) term. By finding the slope of the fit line, taking the inverse, and multiplying by the heat exchanger length, it was possible to determine the thermal resistance. The fit for the GHX is shown in Figure 8-1. Data is shown for 8 hours of steady-state operation on July 11th. The slope of the line was 859 W/°C. Taking the inverse and multiplying by L_{GHX} (183 m) yielded a thermal resistance estimate of 0.21 m°C/W.


Figure 8-1. R_{GHX} was determined by fitting the monitoring data to Equation 4.

R_{GHX} can be modelled as series heat transfer circuit (Figure 8-2⁸). There are many thermal resistances to take into account: the surface thermal resistance between the hydronic fluid and interior of the pipe, the HDPE pipe material of the pipe, the grout, the ground, interactions with ground water and/or other boreholes, etc. Borehole depth is an important factor as well. The standard approach to determine thermal resistance is through a TC test. A TC test was performed for the TRCA at a site in Vaughan, ON, and the result was 0.19 m°C/W. TC tests from other GTA sites, to which STEP has access, have produced values from 0.10 to 0.22 m°C/W - so 0.21 m°C/W from Figure 8-1 is a reasonable result.



Figure 8-2. The thermal resistance of a borehole is the sum of component thermal resistances.

8.3 Calculating R_{SHX}

R_{SHX} was determined by plotting the data and fitting to Equation 2. This is shown in Figure 8-3. The result is less straightforward than for the GHX because the heat transfer from the SHX also depends on the flowrate of the stormwater. Convective heat transfer increases with greater flows. This is illustrated in the figure, which has performed

⁸ Figure 3.1 in Kavanaugh, Steve and Rafferty, Kevin. 2014.

the fit for different stormwater flowrates. R_{SHX} as a function of stormwater flowrate is shown in Figure 8-4. Just like the GHX, the slope of each line was inverted and multiplied by the heat exchanger length (230m) to calculate the thermal resistance. Note that the higher flows do not occur at a steady-state operating condition and the equation for "q" does not strictly apply – the thermal resistance at higher flow rates is therefore a best guess based on the available data.



Figure 8-3. The thermal resistance of the SHX was determined.



Figure 8-4. The thermal resistance of the SHX is a function of the stormwater flowrate.

The thermal resistance of HDPE pipe in water can be modelled as the sum of component thermal resistance in series (Figure 8-5⁹). There is the film resistance on the inside of the pipe, the thickness of the pipe itself, the film resistance from the outside of the pipe and another term to take into account fouling of the heat exchanger. As shown previously, these terms will also depend on the flowrate of the water.

⁹ Figure 5.12 in Kavanaugh, Steve and Rafferty, Kevin. 2014.



Figure 8-5. The thermal resistance of the SHX is the sum of component thermal resistances.

It's useful to check the result from the STEP pilot, but before expending the time to estimate appropriate values for each term, it's helpful to first evaluate their relative weighting to the overall thermal resistance of the SHX. In the condition of turbulent flow of the heat transfer fluid within the SHX, the thickness of the pipe is estimated to make up roughly half of the overall thermal resistance and it can be very easily calculated (Table 8-1¹⁰). As an estimate, R_{SHX} could be assumed to be twice that of the pipe wall resistance.

Table 8-1.	The major components of thermal resistance of HDPE pipe.	

SWHE Type	Inside Resistance (Turbulent Flow)	Tube or Plate Resistance	Outside Resistance
3/4 in. (19 mm) HDPE	4%	58%	38%
1 in. (25 mm) HDPE	3%	68%	29%
1 1/4 in. (32 mm) HDPE	3%	72%	25%
Stainless Steel Flat Plate	11%	1%	88%

Figure 8-5 shows the equation for the thermal resistance of the pipe wall and it is also given below in Equation 9.¹¹ Equation 10 calculates the thermal resistance of the SHX assuming that it is approximately twice that of the pipe wall. For $\frac{3}{4}$ " DR11 HDPE pipe d_i=0.849", d_o=1.039" and k_p=0.45 W/m°C, yielding an estimate of 0.14 m°C/W for R_{SHX}. This agrees well with the result from Figure 8-4 in the limit of low flow.

$$R_p = \frac{\ln\left(\frac{d_o}{d_i}\right)}{2\pi k_p}$$

Equation 9

$$R_{SHX} \approx 2R_p = 0.14 \ m^o C/W$$

Equation 10

¹⁰ Table 5.4 in Kavanaugh, Steve and Rafferty, Kevin. 2014.

¹¹ Equation 5.15 in Kavanaugh, Steve and Rafferty, Kevin. 2014.

8.4 Putting It All Together

Given that all parameters of the model are now defined, it's possible to do what this section initially sought out to do - validate the model. Again, the approach was to predict T_{p2} using the model and compare it to the actual measured values. This requires a numerical solution since Equation 8 is an implicit equation with respect to T_{p2} (i.e. one can't simply isolate T_{p2} to solve it).

Figure 8-6 shows the measured values for T_{p1} , T_{p2} , and \dot{V}_{p} , as well as the predicted value using the model, over the course of several days in July when the hydronic flow rate was 4.5 gpm. Figure 8-6 shows the results over two weeks in August when the hydronic flow rate was 2.0 gpm. The ground temperature for this period was estimated at 14.2 °C based on the continuous ground temperature measurement method outline in Section 10.0. These plots validate the model and demonstrate its accuracy across changes in the system parameters.



Figure 8-6. When the hydronic flowrate was 4.5 gpm, the model is a good predictor of T_{p2} and the heat transfer properties of the system.



Figure 8-7. When the hydronic flowrate was 2.0 gpm, the model is a good predictor of T_{p2} and the heat transfer properties of the system.

Sustainable Technologies Evaluation Program

Note that the measured values of T_{h1} and T_{h2} were not used. They were determined within the calculation. Equation 6 and Equation 7 show that they are both a function of q, and Equation 1 shows q is a function of T_{p2} . It follows that Equation 8 can be written such that T_{p2} is the only unknown provided T_{p1} , \dot{V}_h , \dot{V}_p , and the constant parameters (density, length, heat capacity, and thermal resistance) are known. These were the only variable inputs into the model.

Since the model has been validated it is possible to use it to estimate full-scale system sizing given different input parameters. This has been done in the companion sizing tool available with this final report and in the full-scale sizing presented in Section 14.0.

9.0 RESULTS: ADDITIONAL ITEM 1 - THERMAL LOAD MODELLING AND OPTIMIZATION

9.1 Tasks

Use machine learning software to develop a predictive model of pond outflows and temperatures based on environmental data (solar irradiance, ambient temperature and rain fall). The model can be run using climate normals to assess the thermal load of the pond during an average year. Sizing recommendations to be developed, both to optimize cost and performance on a seasonal basis, and also during peak thermal load periods.

9.2 Thermal load during monitoring period

Figure 9-1 plots the stormwater outflow flowrate and temperature from late-May to mid-September 2019, as well as the total thermal load assuming the outflow needs to be cooled to 24°C. Figure 9-2 plots a cumulative histogram of pond outflow temperatures. Temperatures are above 24 °C 50% of the time. Starting in late June there is typically a baseload that is less than 5 to 10 tons. Directly after a rain event there is a short duration peak in the thermal load. This is because the warm top layer of pond water from the inter-event period is rapidly discharged once the stormwater from the subdivision enters the pond. The peaks are several times greater than the base load. This can be problematic for the geothermal system design because a significant amount of extra system capacity would be needed to meet the relatively few peaks occurring over the summer. It's important to consider opportunities to mitigate the scale of the peaks and this is explored in greater detail in the remainder of this section.



Figure 9-1. Pond outflow temperatures approach 30°C. The total thermal load of the pond is greatest directly following the beginning of a rain event.



Figure 9-2. Cumulative frequency histogram of stormwater temperature from pond.

9.3 Machine Learning Model

9.3.1 Machine Learning Introduction

The thermal load of the pond will vary from year-to-year but the monitoring period only encompassed a single season. It's therefore worthwhile to estimate the thermal load of the pond from previous years based on the available historical environmental data. A model of pond is required. The model needs to accept as inputs environmental factors like outdoor ambient temperatures, solar irradiance and precipitation, and output the stormwater outflow temperature and flowrate. A regression-based machine learning model was developed in Python this purpose.

A machine learning model finds relationships between the input variables and the output target variable(s). It is **not** based in the physics governing the system. It follows that if something significant about the pond or subdivision were to change the model cannot be adjusted to account for that change, it would need to be retrained with new data. This is in contrast to the analytical (physics-based) geothermal system model which predicts target variables based on the physical system parameters. The benefit of machine learning for this application is that it was significantly more straightforward than other options.

Details of the machine learning are available in Appendix B. Machine learning models for outflow temperature and flowrate were created.

9.3.2 Estimated thermal load in previous years

These models were used to predict the pond thermal load from each of the previous 6 years.¹² The 5-min aggregated rainfall data for the outflow flowrate model was available from a nearby TRCA weather station. Ambient temperature data was collected from Environment Canada via weatherstats.ca. The predicted temperatures and thermal loads are

¹² Looking at each year over the previous several years was done instead of looking at climate normals because these are likely to give a better indication of the pond's behavior moving forward in the context of a warming climate.



shown in Figure 9-3 and Figure 9-4, respectively. The greatest thermal load, both peak and seasonal, occurs during 2016 and 2018. This is primarily caused by the higher ambient temperatures in these years.

Figure 9-3. The machine learning model was used to predict pond outflow temperatures for the previous 6 years.



Figure 9-4. The machine learning models for flow and temperatures were used to predict the total thermal load for the previous 6 years.

9.3.3 **Opportunities to reduce peak loads**

The thermal load of the pond is dominated by pronounced peaks that are on the scale of an order of magnitude greater than the baseload. The peaks are caused when the hot layer of water at the top of the pond drains over a short period of time as new storm water enters the pond during a rain event. If a geothermal system was sized to meet the peak loads, it will be significantly oversized for the remainder of the season – the highest peaks are cumulatively only hours in duration. A system designed for peak loads would cost much more and overall be less feasible. As is the case in buildings, a better approach would be to first take measures to reduce the scale of the peaks prior to geothermal system sizing. This study explored three options:

- flow restriction causing longer drawdown times ("smooths" the peaks but does not change cumulative flow volume);
- subsurface draw to reduce temperatures (this can be an easy retrofit that doesn't affect drawdown times, detention times and can significantly improve thermal performance); and
- 3. infiltration to reduce overall flow.

9.3.4 Flow restriction

Figure 9-5 shows the flow peak resulting from an 11.8 mm rain event on August 27th, 2019. It takes approximately 2 days to drain down. If the flow was restricted it would drain down over a longer period of time and the flow peak would be diminished in magnitude – as would the corresponding thermal load peak. To achieve this, the pond would need to be re-designed with more extended detention capacity (higher berms surrounding the pond). It is a retrofit option, but typically takes more space that may not be available because side slopes need to meet certain criteria (3:1). New ponds can be designed from the start with more detention, so the utility of this section is to indicate how much more effective the system would have been had the flows been more drawn out - even if this may not be feasible in the pilot pond.



Figure 9-5. An example flow peak resulting from a 11.8 mm rain event.

It's possible to apply transformations to the flow data to explore the impact of flow restriction on the overall thermal load. Ideally the transformation would preserve the logarithmic decay shape of the peaks (and therefore preserve the "physics" of the phenomena), but that would require additional modelling that would be onerous and ultimately beyond the scope of this work.¹³

A simpler, easy-to-apply transformation would be an averaging filter which smooths out the shape of the peaks. While not a perfect representation of restricted flow, it is sufficient to still provide useful insights. Different averaging filters were applied to the peak shown previously are illustrated in Figure 9-6. Each filter subsequently adds an additional day to the drawdown time (i.e. '1-day' adds approximately 1 day to the draw down time). The shape changes as well and this is where the approach introduces errors because it would underestimate the actual magnitude of the peak, but this is unavoidable.

¹³ One would likely need to develop an analytical physics-based model that related the shape of the flow peak to the magnitude and shape of the rain event, and then change the model parameters to represent a restricted flow state.



Figure 9-6. Example of different averaging filters transforming an actual flow peak.

A series of averaging filter was applied to the 2016 data (the year with the greatest peak and seasonal loads) to explore the impact on the flow, thermal load and water level of the pond. The additional undrained volume of water at any point in time ($V_{add}(t)$) of the transformed flow data ($\dot{V}_{trans}(t)$) over-and-above the actual case ($\dot{V}_{act}(t)$), was determined using Equation 11 This was translated into height using Equation 12, where A_{pond} is the area of the pond.

$$V_{add}(t) = \int_{0}^{t} \dot{V}_{trans}(t) dt - \int_{0}^{t} \dot{V}_{act}(t) dt$$
 Equation 11
$$H_{add}(t) = \frac{V_{add}(t)}{A_{pond}}$$
 Equation 12

Results considering elongation of the drawdown times by one and two days are shown in Figure 9-7 and Figure 9-8, respectively.



Figure 9-7. Modelling results when the 2-day drawdown period is elongated by an additional day.



Figure 9-8. Modelling results when the 2-day drawdown period is elongated by an 2 additional days.

Restricting the flow and forcing the pond to drain over a greater period of time can significantly impact the peak thermal load and make the pond more amenable to geothermal cooling. For example, by elongating the drawdown period from 2 days (currently) to 4 days total, the peak thermal load can be reduced from nearly 120 tons to below 50 tons. This would cause the pond level to raise by an estimated 14" over-and-above the current case with the 2-day draw down. Flow constriction would be an important consideration for new ponds especially. It is less applicable to retrofits of existing ponds due to the need for extra storage volume within the pond.

9.3.5 Subsurface Draw

The pond in this pilot used a surface draw, but temperatures at the surface of pond are the warmest and this increases the thermal load. A subsurface draw could drastically reduce both the peak and seasonal thermal loads. Data from sensors measuring the pond's temperature profile is shown in Figure 9-9. The sensors were connected to a chain at different length increments. The bottom of the chain was anchored to the bottom of the pond with a brick, while the top of the chain had a float to keep the chain taut. Data up until mid-July is erroneous and the reason is not known. In mid-July, technicians removed the set-up from the pond, gathered data and then redeployed it. This appears to have rectified the issue. The series' labels indicate the depth of the sensor from the bottom of the pond. Note that, depending on the pond level, the 240 cm sensor may be floating right at the pond surface.



Figure 9-9. The temperature profile of the pond for summer 2019 is shown. The sensor which is closest to the bottom (Sensor 1) is typically 2 to 3 °C cooler than the sensor closest to the surface. Note that the data prior to July 14th, is erroneous.

It's clear that at 60 cm from the bottom of the pond the temperature may be on the scale of 2 to 3°C cooler than the top of the pond, and also that the diurnal temperature variations are much less pronounced. Ponds vary in their stratification, but this pond actually has a much smaller amount of temperature stratification than has been observed in other ponds.

To gauge the impact of a subsurface draw on the thermal load, the machine learning model was retrained, this time using the subsurface temperature data 60 cm from the bottom of the pond (described in Appendix B). The rest of the analysis proceeded in a similar fashion to the other machine learning models.

The estimated subsurface temperature for the previous 6 years is shown in Figure 9-10, alongside the temperature data determined previously using the top draw temperatures. Figure 9-11 shows the resultant thermal load. These

plots demonstrates that a subsurface draw has the potential to significantly impact both the peak and annual thermal loads, and, in some years, eliminate the thermal load entirely. However, it's important to note that this is *only an approximation*. If the pond water was being removed from below the surface then it would impact the pond temperature profile and outflow temperatures would deviate from the estimated values presented here.



Figure 9-10. The machine learning models for top and subsurface temperatures applied to the previous 6 years show that the subsurface temperature may be significantly lower that top draw temperatures.



Figure 9-11. The lower temperature of a subsurface draw would create a much lower thermal load or nearly eliminate it entirely for some years.

9.3.6 Infiltration

The final option considered for reduction of the thermal load was an infiltration trench or infiltration chamber. These provide two benefits for thermal mitigation – both of which ultimately reduce the direct flow of warm stormwater to the watershed. The first benefit is that it can hold a volume of a water and the second is that the water being held can slowly infiltrate into the water table. The ability to hold water can reduce the flow peak and the amount of reduction depends on the storage volume of the trench or chamber. The ability to infiltrate water provides a small degree of instantaneous flow reduction and is necessary to empty the chamber. It is dependent on the area of the trench and infiltration rate of the soil.

An infiltration trench with an area equal up to 10% of the pond area was initially assumed as a potential upper limit (Figure 9-12). In this study, the percentage area of trench with respect to the pond is represented by β . Infiltration

Sustainable Technologies Evaluation Program

rates (α) of 0.5 mm/hr (clay), 2.3 mm/hr (clay loam), 4.3 mm/hr (sandy clay loam), 13.2 mm/hr (loam) and 25.9 mm/hr (sandy loam), were considered. The actual infiltration rate of the soil at the pilot pond was not measured. The pond area was estimated at approximately 3,100 m² using Google Earth. The calculation for the volumetric infiltration was straightforward (Equation 13).

$$\dot{V}_{in} = \beta \cdot A_{pond} \cdot \alpha$$
 Equation 13



A closer evaluation of the flow peaks is required to gauge the impact of the *trench's storage volume* on the flow peak. Figure 9-14 shows a flow peak from August 2019. The totalized flow volume is also shown. Even if the chamber started empty and was able to hold the first 300 m³ of stormwater volume, it would have an almost negligible impact on the flow peak since it would be full in the vicinity of the peak flow; i.e. the point on the stormwater flow curve which corresponds to 300 m³ total flow occurs just after the peak. At 600 m³ of storage volume, it would be able to reduce the flow peak from below 70 m³/hr to below 50 m³/hr, approximately 30%.



Figure 9-13. The volumetric infiltration rate depends on the mm/h infiltration rate and the area of the infiltration trench. Under the most optimistic scenario with the largest trench and highest rate, the volumetric infiltration rate is still only able to infiltrate approximately 10% of the volume from the greatest flow peaks. It is therefore not able to significantly mitigate the magnitude of the peaks.



Figure 9-14. The totalized storm water flow is very large and would cause a smaller infiltration chamber to fill entirely before notably impacting the peak flow.

Infiltration chambers provide more storage volume than trenches because they provide open space that is not filled with aggregate. The largest infiltration chamber section from Cultec is 1.2m tall, 1.3m long, and 2.0 m wide.¹⁴ An example is shown in Figure 9-15. It has a volume of 1.61 m³ per linear m of chamber. To a achieve a storage volume of 300 m³ it would require 186 linear m of chamber. This is 167 chamber sections and it would provide 434 m² of infiltration area.



Figure 9-15. Example of Cultec's stormwater chambers.

The perimeter of the pond at the distance of the service road is approximately 300m (Figure 9-16), and it might be possible to place 2 chambers side-by-side underneath the service road. It would therefore take between a third and two thirds of the pond's perimeter (i. e. the area underneath the service road) to achieve 300 m³ of storage. However, this is amount of storage is overall not that impactful at mitigating the flow peak. Doubling that value, at 600 m³, could reduce the peak by approximately 30% (greater once the infiltration rate is taken into account) but it would be a substantial infiltration chamber with 868 m² surface area (about 25% area of the pond itself, Figure 9-17). This would likely need to be implemented in the open area away from the pond and this much area is typically not available on other ponds so it would be a site-specific solution.

To make an impact on the flow peak using the infiltration chamber approach requires a substantial amount of area given the high peak flow rates. It is essentially like building a secondary pond about a quarter the area of the main pond, but instead implemented underground. While it is feasible to do this when the area is available, it would be much more cost-intensive than the other two options considered – subsurface draw and flow restriction.

¹⁴ <u>http://cultec.com/products/stormwater-chamber-recharger-902hd/</u>



Figure 9-16. The perimeter of the pond is approximately 300m.



Figure 9-17. An area of about 868m² would be required to generate 600 m³ of storage capacity. This would be capable of reducing peak flows by more than 30%.

9.3.7 Summary of Measures to Reduce Thermal Load

The greatest challenge for geothermal-based stormwater retention pond cooling is the pronounced peaks in the thermal load profile. Best practice in conventional geothermal system design includes consideration for opportunities to make the load more amenable to a geothermal system. In the context of this study, that means reducing the peaks.

Three opportunities to reduce the thermal load peaks were considered: flow restriction, subsurface draw and infiltration chambers. The most impactful and easiest to implement measure is subsurface draw. Flow restriction can also significantly mitigate the peaks but it is a solution more applicable to new ponds than existing ones.

Infiltration chambers could be designed sufficiently large to infiltrate and/or store a large portion of the peak flow but this would be very cost-intensive and require very large amounts of area – akin to the creation of a secondary, albeit smaller, pond. It is therefore likely a distance third in comparison to the overall feasibility of other two measures.

9.3.8 Multiple Measures to Reduce Thermal Load

It's worthwhile to consider combining different measures, particularly flow restriction and subsurface draw. To evaluate the impact of the combined measures, the subsurface temperature draw for 2016 (the worst-case year for thermal load) was combined with the corresponding *transformed* flow data. This is shown in Figure 9-18. It demonstrates that it is possible significantly decrease the scale of the thermal load peaks.

Combining the subsurface draw with an elongated draw down, from the current 2-days extended to 4-days, the peak thermal load can be reduced from approximately 120 tons to below 25 tons. This is a load that is much more reasonable to fully meet with a geothermal-based cooling solution consisting of several boreholes.



Figure 9-18. Combining flow restriction to elongate the drawdown time and subsurface draw to reduce the temperature makes a significant impact on the thermal load.

10.0 RESULTS: ADDITIONAL ITEM 2 - GROUND TEMPERATURE MODELLING

10.1 Tasks

As heat is dumped into the ground via the GHX, the ground temperature increases along with its capacity to cool pond outflows. An empirical model will be developed based on collected data at the pilot site that predicts borehole temperature changes over time based on pond thermal loads, both with and without pre-cooling during the winter. Quantifying the degree of warming will provide critical information on long term cooling capacity of the system and the potential need for pre-cooling during the winter. The geothermal system model will also be enhanced to allow for multiborehole systems, which would be required for large ponds. Simulations will also be developed using a metallic heat exchanger (as opposed to HDPE). Metallic heat exchangers provide more heat transfer per unit area, allowing for cooling of larger thermal loads and more compact form factors.

10.2 Overview

This item required data on the ground temperature as well as data on the heat energy rejected to the ground. It is not feasible to directly and continuously monitor the ground temperature. Recall, that the borehole is 600 ft deep and the "ground" in this context means the bedrock surrounding the deep borehole and this is not easily accessible with temperature sensors. There were three approaches to estimating ground temperatures considered in this study.

Option	Description	Considerations
1	Turn system off, leaving heat transfer fluid to sit in borehole for a period of 5 days allowing the fluid to equilibrate	Most accurate and simplest approach to take a ground temperature.
	with the ground. Turn system back on and monitor temperature and flow coming out of borehole. Using the flow and temperature data, determine the average temperature of the fluid that had previously been in the borehole.	Need to stop rejecting heat to the ground to take a ground temperature measurement, <i>but this allows the ground itself to cool</i> as it equilibrates with the far ground temperature. The process of measurement therefore interferes with the measured value.
		No continuous data monitoring. This means that are no indications in the data if the heat transfer fluid has, in fact, equilibrated with the deep ground temperature. Must therefore leave it for a long time (5 days) to be sure that it did.
		The temperature sensors installed in thermal wells (which provide the best measurement of instantaneous temperature) were installed far away from the borehole, in the hydronics box on top of the vault. The shallow ground temperature surrounding the trenched pipe, and also, the air temperature, could impact the measurement.
2	Bypass the SHX and PHX, leaving heat transfer fluid to continually circulate through the borehole. The supply and return of the borehole are directly	As in Option 1, this option requires that heat rejection to the ground be paused and this interferes with the value being measured.

Table 10-1. Different options for estimating the deep ground temperature.

	connected with no other loads. The heat transfer fluid will eventually equilibrate with the ground temperature.	However, since there is continuous data monitoring, it is possible to have a shorter downtime and use heat transfer physics to extrapolate the data to find the ground temperature. The temperature decay of the heat transfer fluid follows Newton's Law of Cooling. The data can be fit to this relationship and the deep ground temperature is a fit parameter that is determined. An issue is that the electrical load of the pump and the piping runs that are outside the borehole both introduce heat into the system. This creates a small amount of measurement uncertainty.
3	Given known values for q _{GHX} , R _{GHX} , L _{GHX} , T _{h1} and T _{h2} , it's possible to estimate T _g using Equation 4 (below). In other words, it's possible to estimate the ground temperature based on how much heat transfer is occurring given the other known system parameters. $T_g = \left(\frac{T_{h1} - T_{h2}}{2}\right) - q_{SHX} \cdot \left(\frac{R_{GHX}}{L_{GHX}}\right)$	This provides an estimate of the deep ground temperature using data that is already being collected and there is no requirement to turn off the system temporarily. It provides a truly continuous estimate of the deep ground temperature. However, Equation 4 is a steady-state equation. If there is a period where the heat transfer is quickly changing then the equation is not strictly true. Furthermore, R _{GHX} was determined at one point in time for a specific hydronic flow rate and given heat transfer fluid. It was observed to be different for different hydronic flow rates and it would be different for different heat transfer fluids. It is therefore important to be careful about estimating temperature using this method.

Option 2 was used at three points throughout the summer: May 27th/28th, August 3rd/4th, and Sept 24th to October 23rd. The system unintentionally went down from July 5th to 10th due to a minor issue with the off-grid power system, which provided the opportunity to use Option 1. The data was filtered to eliminate non-steady-state operating points as much as possible and Option 3 was used to the estimate the ground temperature on a continuous basis.

10.3 Using Option 1 to Estimate Deep Ground Temperature

The system unintentionally went down from July 5th to 10th, which provided the opportunity to use Option 1. Figure 10-1 shows the temperature and flow data from when the system was brought back online. The first data point is from when the fluid was sitting in the hydronics box with no flow. Inside the box, it reached 45 °C. The second data point has flow but the system had just turned on and the temperature is from fluid that had been sitting in piping that was exposed to the ambient air (i.e. not in the box) or from piping that was buried underground between the borehole and the hydronics box. By the third point the fluid that had been in the borehole had reached the temperature sensor. By the fifth point it is estimated, based on the flowrate, that half the volume of the borehole (~45 gal) had passed the temperature sensor. The average of the third to fifth points is 13.6 °C.





10.4 Using Option 2 to Estimate Deep Ground Temperature

Once the system was commissioned, the ground temperature was determined by bypassing the SHX entirely while leaving the pump to run and monitoring the supply temperature from the borehole. This allowed the hydronic working fluid to slowly release any heat to the ground and to approach thermal equilibrium with the ground temperature.

This was first done on May 27th/28th (Figure 10-2) after the system had been operating for approximately one week. The system was not left long enough for the hydronic fluid to sufficiently equilibrate with the ambient deep ground temperature but, given the known heat transfer physics of the system, it was possible to extrapolate the curve to determine the actual ambient deep ground temperature.

The measured temperature change in the supply temperature from the borehole is logarithmic and governed by Newton's Law of Cooling (Equation 14). It states that the rate of temperature change for the hydronic fluid at any given time (*t*) should be proportional to the temperature difference between the hydronic fluid (T(t)) and the ambient deep ground temperature (T_a). The parameter T_0 is the initial temperature and *k* is a constant dependent on the heat transfer dynamics of the system.

$$T(t) = T_a + (T_0 - T_a) \cdot e^{-kt}$$
 Equation 14



Figure 10-2. Deep ground temperature was determined by bypassing the vault SHX, while letting the pump run, such that heat transfer fluid approaches equilibrium with the ground temperature. The data shows that the heat transferfluid did not fully equilibrate.

The parameters T(t) and T_0 are plotted in Figure 10-2. It's possible to solve for T_a and k by rearranging Equation 14 into Equation 15. The best estimate for T_a is that which provides the best linear fit for kt. This is shown graphically in Figure 10-3, where the best fit was obtained with T_a at 12.1 °C. Note that the x-axis has been transformed such that T(0) is equivalent to T(10) in Figure 10-3. This was done because the first 10 hours of data was disregarded.¹⁵ The experimental data is plotted against Equation 15 in Figure 10-4.

$$y = \ln\left(\frac{T(t) - T_a}{T_0 - T_a}\right) = -kt$$
 Equation 15

¹⁵ This is standard practice during formal thermal conductivity testing, which also depends on the logarithmic relationship between the hydronic and ambient deep ground temperatures. It's done because there are transient effects at the beginning of the experiment that create errors.



Figure 10-3. The best linear fit to Equation 15 occurs when the ambient ground temperature is set at 12.1 °C. The fit is very good indicating that the temperature change is indeed logarithmic and sufficiently described by Newton's Law of Cooling.



Figure 10-4. The extrapolated curve suggests that the ambient deep ground temperature is 12.1 °C.

This exercise was repeated on August 1st but left approximately 3 days to allow a longer time to equilibrate. However, a new issue arose. There is a section of piping about 20 ft long, and running ~2 ft underground, that connects the top of the borehole to the hydronics box where the measurements are taken. There is also the piping contained in the box itself. During the first experiment, the perfect logarithmic fit indicates that these section of the pipe did not cause any diurnal variations– likely because the temperature of the ground directly below the surface was very near that of the deep ground. During the second experiment, in August, significant diurnal variation were observed (Figure 10-5).

To account for this, Equation 15 was applied only to the local minima of the data. The local minima would occur where the impacts are weakest. This is shown in Figure 10-6. The relationship is near-perfectly logarithmic indicating that the effects are minimal. The estimated ambient deep ground temperature was 13.6 °C, this is 0.3 °C lower than

the lowest temperature that was actually measured during the experiment. The actual and extrapolated data is shown in Figure 10-7.



Figure 10-5. Significant diurnal variations were seen in the heat transfer fluid temperature due to the changes in subsurface ground temperature and ambient temperature (recall that there is ~20' of piping buried ~2' underground which connects the borehole to the hydronics box).



Figure 10-6. Equation 15 was applied to the local minima from Figure 10-5 showing near-perfectly logarithmic behaviour, with the ambient deep earth temperature estimated at 13.6 °C. Again, the time axis in this plot is shifted from that above such that the intercept is zero.



Figure 10-7. The fit line attempts to extrapolate the equilibrium temperature from the actual while data while neglecting the diurnal variations. The ambient deep ground temperature was estimated at 13.6 °C.

This approach to ground temperature measurement was also used at the end of the season. The system was left to equilibrate with the ground from September 24th to October 23rd. This period of time was long and no extrapolation was needed to estimate the ground temperature when the test was completed on October 23rd. Note that the temperature does not decay to a steady value because, as the heat transfer fluid equilibrates with the deep ground in the vicinity of the borehole, the deep ground in the vicinity of the borehole equilibrates with the far ground. The latter just happens much slower so a gradual decrease is observed. Based on this testing, the temperature of the ground on October 24th was estimated at 12.4 °C.



Figure 10-8. Option 2 was used to estimate the deep ground temperature in Sept/Oct at 12.4 °C.

10.5 Using Option 3 to Estimate Ground Temperature

Option 1 and 2 provided a snapshot of ground temperatures at different points in time. It is useful to compare those snapshots to Option 3, which was the only method that offered continuous ground temperature estimates. The estimated ground temperatures from Option 3 are shown in Figure 10-9.

There is data missing from the plot when Option 1 and Option 2 were used to estimated ground temperature because the equation could not be applied. There is also data missing from August. During this time, the flow rate was reduced to look at the impact on system performance (which is why q is smaller). The reduced flowrate increased the ground temperature estimate, likely because it changed the thermal resistance (R_{GHX}) but a new value of R_{GHX} with the reduced flow was never determined so the data was just omitted from the plot.

Option 3 suggests ground temperatures higher than 16 °C occurred during July when the system was rejecting large amounts of heat to the ground, which the ground was not able to quickly dissipate.





This additional work item sought to develop a model of the ground temperature to help understand system performance. The simplest model that can describe the ground is shown in Equation 16, where T_i is the deep ground temperature for the ith time interval, T_{i-1} is the deep ground temperature from the previous interval, q_i is the heat rejected to the ground during the ith time interval, T_0 is the initial ground temperature (and also, the far ground temperature to which the deep ground in the vicinity of the borehole will eventually settle), and both α and β are constants. Equation 16 then shows the temperature after a given time period depends on the initial temperature, the energy gain from the geothermal system, and the energy lost to the far ground (which is proportional to the temperature difference).

$$T_i = T_{i-1} + \alpha \cdot q_i - \beta \cdot (T_i - T_0)$$
 Equation 16

This simple model was fit to the data with results shown in Figure 10-10. Also shown are the ground temperature measurements from Option 1 and 2. The model's agreement with the data is shown in Figure 10-11. The fit coefficients were $T_0 = 11.8$, $\alpha = 1.8$ e -7 and $\beta = 1.7$ e -4 (note that these coefficients apply to the data at 5-min intervals).



Figure 10-10. The ground temperature can be modelled with a simple equation.



Figure 10-11. The simple model shows good agreement with the experimental data.

It's clear that whenever the system is off (q = 0) the ground begins to decay back to its original temperature. Conversely, whenever heat is rejected to the ground it causes a local warming effect. The agreement across all measurements and the model is quite good except for the data from August $3^{rd}/4^{th}$. The ground temperature taken using Option 2 seems quite low given all other parameters. For example, it had been preceded by a period of time with a high level of heat rejection to the ground but measures the same value as before that heat rejection occurred (from the beginning of July). There is no explanation for this – but it is believed to be incorrect because it is not in keeping with everything else that is known about the system.

In conclusion, while the highest ground temperature actually measured was 13.6 °C, the system performance suggests that temperatures could have reached beyond 16 °C between measurements for short periods of time. Also of note is the rate at which the ground temperature returns to its original temperature. In roughly the span of a month the ground dropped an estimated 2 °C when no heat was rejected to it. It nearly returned to the original starting temperature. This shows that, given the next time the system will be needed for cooling is in June 2020, there is enough time for the system to dissipate all the heat it absorbed during the summer without having to actively cool the ground during the winter.

A last point to note is that the system would benefit from controls which limited operation only to those times when cooling was needed (this pilot simply ran the system at all times). This would give time for the heat rejected to the ground to dissipate and keep the deep ground temperature in the vicinity of the borehole cooler overall.

10.6 Multi-borehole Model

This additional work item included the development of a multi-borehole model of the geothermal system. While Equation 8 looks like it considers only a single borehole, it is actually is capable of modelling multiple boreholes in parallel in the limit of large borehole spacing (where interactions between boreholes can be neglected). This is shown below. Consider three boreholes. The total heat rejected from all boreholes to the ground is the sum of that from each borehole:

 $q_{GHX} = q_{Borehole1} + q_{Borehole2} + q_{Borehole3}$

The heat rejected to the ground from an individual borehole is below, note that all boreholes are connected in parallel so the heat transfer fluid temperatures to and from the borehole are equivalent (also assuming they are the same length and have the same thermal resistance):

$$q_{Borehole1} = \left(\frac{L_{Borehole1}}{R_{Borehole1}}\right) \cdot \left(\frac{T_{h1} + T_{h2}}{2} - T_g\right)$$

If the borehole lengths of all boreholes are equal, the borehole length of for an individual borehole can be rewritten:

$$\frac{L_{GHX}}{3} = L_{Borehole1} = L_{Borehole2} = L_{Borehole3}$$

The thermal resistance of all boreholes could be assumed as equivalent:

$$R_{GHX} = R_{Borehole1} + R_{Borehole2} + R_{Borehole3}$$

Rewriting the first equation yields:

Sustainable Technologies Evaluation Program

$$\begin{split} q_{GHX} &= \left(\frac{L_{GHX}}{3}\right) \cdot \left(\frac{1}{R_{GHX}}\right) \cdot \left(\frac{T_{h1} + T_{h2}}{2} - T_g\right) + \left(\frac{L_{GHX}}{3}\right) \cdot \left(\frac{1}{R_{GHX}}\right) \cdot \left(\frac{T_{h1} + T_{h2}}{2} - T_g\right) + \left(\frac{L_{GHX}}{3}\right) \\ & \cdot \left(\frac{1}{R_{GHX}}\right) \cdot \left(\frac{T_{h1} + T_{h2}}{2} - T_g\right) \end{split}$$

Which can be simplified to:

$$q_{GHX} = \left(\frac{L_{GHX}}{R_{GHX}}\right) \cdot \left(\frac{T_{h1} + T_{h2}}{2} - T_g\right)$$

Equation 8 is a therefore a multi-borehole model, it just neglects the heat transfer between adjacent boreholes. This is a reasonable approximation in the limit of large borehole spacings like would be possible for most geothermal-based thermal mitigation systems. Note that it may still be advisable that detailed system design be based on commerciallyavailable geothermal design packages like GLD which includes more advanced modelling capabilities.

10.7 Metallic Heat Exchanger

This additional work item involved the consideration of a metallic heat exchanger. It's first useful to look at the total heat transfer capacity of the plastic pipe used in this study. There was 230 m of pipe in the SHX and, in the limit of low flowrates, the thermal resistance was estimated at 0.16 (m °C)/W. This means it will transfer 1.4 kW of heat energy for every degree of temperature difference between the heat transfer fluid inside the pipe and the water temperature in which it is immersed.

In comparison, stainless steel plate heat exchangers can achieve 105 W per ft² of plate per °C of of temperature difference.¹⁶ It follows that the heat exchanger used in this project (a stack of concentric pipes 2' tall and 6' in diameter) could be replaced by 13 ft² (for example, a single 2' x 6.5' x $\frac{1}{2}$ ") plate heat exchanger, which is far more compact. This is a much better option for very large installations. Different ways of implementing this are possible.



Figure 10-12. Stainless steel plate heat exchangers provide a much more compact form factor for the SHX.

¹⁶ These heat exchangers are available under the brand name "Slim Jim" at <u>www.awebgeo.com</u>.

11.0 RESULTS: ADDITIONAL ITEM 3 - GROUND PRE-COOLING TO ENHANCE PERFORMANCE AND REDUCE COSTS

11.1 Tasks

Explore opportunities to pre-cool the ground during the wintertime using a heat exchanger in the pond that is connected to the GHX. A heat exchanger to be placed in the pond and the pre-cooling of the ground during the winter period is to be monitored. The resulting increase in geothermal system capacity due to cooler ground temperatures it to be calculated using a calibrated geothermal system model. It is anticipated that pre-cooling could significantly increase the summertime cooling capacity and drive down the size of the GHX.

11.2 Work

The system sizing calculator created for Additional Item 5 was used to estimate the impact of ground temperatures on system size and cost. All input parameters were held constant and then ground temperatures from 5 to 15 °C were used to look at the impact on system cost. The fixed parameters were:

- $\dot{V}_p = 5 \text{ L/s}$
- T_{p1} = 30 °C
- T_{p2} = 24 °C
- R_{GHX} = 0.21 (m°C)/W
- 50% propylene glycol heat transfer fluid
- R_{SHX} = 0.05 (m°C)/W
- GHX cost = 44 \$/m
- SHX cost = 5 \$/m
- GHX and SHX represent 50% of total system cost

Results are shown in Figure 11-1. As an example, a system with deep ground temperature of 15 °C is 75% more costly than one with a deep ground temperature of 5 °C. It may be possible to drive the deep ground to lower temperatures using wintertime pre-cooling.

In the Brampton pilot project, the system was configured for wintertime operation. The valves for the SHX in the vault were turned off and the GHX was connected directly to the PHX in the pond. The PHX was composed of 2 bundles of ³/₄" DR11 HDPE pipe connected in parallel with a combined length of 115 m.

This length was not based on detailed design calculations. It was ultimately constrained by the higher pressure drop of the system. The higher pressure drop was a result of fewer parallel circuits and the use of 50% propylene glycol as a more viscous heat transfer fluid (with freeze protection to below -30 °C). The higher pressure drop meant lower flow rates. In practice, approximately 1 gpm was achieved whenever there was sufficient power from the off-grid system (which was not able to provide enough power sporadically throughout the winter due to less sunlight).

Note that the pre-cooling was not optimized because it was an additional item that was included in August 2019 and not included in the original system design. However, while it was not optimized, the set-up was sufficient to demonstrate that the ground could be cooled over the course of the winter using this approach.



Figure 11-1. Deep ground temperature has a significant impact on system size and cost.

The sensors measuring the heat transfer fluid temperatures to and from the borehole that had been initially installed with the rest of the system were placed in the metal job box with the other of the hydronic components. This was approximately 20' away from the borehole. Buried piping connected the borehole to the hydronics box (Figure 11-2) but the piping was uninsulated. In the case of low flowrates during wintertime operation, this length of buried piping would impact the ground temperature measurement.

In September 2019, additional temperature sensors were added to the system to gain better ground temperature measurements. They were installed on the piping to/from the borehole directly at the top of the borehole (adjacent to the 90° elbows). The temperature sensors were strapped to the pipe, covered with thermal grease, sealed with electrical tape, and then insulated as best as was possible (Figure 11-3).

Ideally, the sensors would have been installed in a thermal well rather than strapped to the pipe wall but this would have been more costly and invasive. The drawback of installing the sensors on the pipe wall is that any instantaneous changes in temperatures will take longer to detect.

The temperatures measured by these sensors from mid-September to late February are shown in Figure 11-4. Whenever the temperatures diverge, the system is on and actively cooling the deep ground. After November, whenever the temperatures converge, there is no flow and the sensors are slowly equilibrating with the ground temperature. There was no flow either due to lack of power from the off-grid system or air in the system (introduced from the switchover of the heat transfer fluid from water to 50% glycol) that required purging. From November to March, the system is on greater than 50% of the time and operating to cool the deep ground.



Figure 11-2. Piping that connected the borehole with the hydronics box was placed in a trench (trench is shown but piping not shown).



Figure 11-3. Additional temperature sensors were placed closer to the borehole to improve the ground temperature measurement.

When the temperatures converge in September/October, there was flow but the system was short-circuited such that the borehole supply was directly connected to the borehole return and there was no SHX or PHX in the circuit to cause heat rejection from/to the deep ground (so there is no temperature change across the borehole). Recall, that this is Option 2 as discussed in the previous section.





Data from the shaded areas can be used to estimate deep ground temperatures before ground pre-cooling and also, after it occurred for part of the winter. The ground temperature measurement from October is discussed in Section 10.0 . It was 12.4 °C. Note that the starting temperature from the previous May was estimated at 11.8 °C. So by October the system was already not far away from its estimated starting temperature.

The temperature measurement in February used Option 1 instead of Option 2 because the run of piping trenched underground, and the piping in the hydronics box, would have introduced error if the system was allowed to continually circulate. The pump was off and the fluid sat in the ground for 5 days and then the pump was turned on, while the temperature and flowrate coming from the borehole was monitored.

In Figure 11-5, the pump turned on at the point the temperatures start to increase – this was at 9:10 am. By 10:00am, approximately 45 gallons (half the volume of the borehole) had passed by the temperature sensor, and the average temperature of the fluid during this time was 8.2 °C.

This value is actually not a correct estimate of the ground temperature. The temperature of the deep ground needs to be greater than the temperature of the heat transfer fluid that is coming from the borehole once the system achieves a steady-state (because it is the deep ground temperature that is warming the fluid up).

The issue is from the fact that temperature sensors provide a poor instantaneous temperature measurement because it strapped to the pipe wall rather than installed in a thermal well. As the temperature from the borehole rises, it's clear that it overshoots the steady-state value before coming back down. The overshoot indicates the warmer ground
temperature but the overshoot is dampened by the mounting-style of the sensors so a proper reading was never obtained.

However, based on Equation 4, and looking at where the temperatures arrive at a steady-state, a best guess of the ground temperature is that it is below 10 °C. It is very close to the temperatures coming from the borehole in a steady-state because the flow rates are slow, measured at 1.2 gpm, for 50% glycol at these temperatures.





This demonstrates that, just like the ground can be heated, it can also be cooled. A larger PHX and pump could push the ground to a colder temperature, but the bigger issue is the ability of the ground to store that temperature until it is needed in late June. Pre-cooling is no longer possible once the temperature of the pond exceeds the temperature of the ground. The colder the ground is pushed, the sooner this will happen, and the longer it will have to warm up before being needed during the summer. It is likely that pre-cooling is no longer possible at some point in March or April.

For example, assume that pre-cooling stops at the end of March and the system is left off for April, May, and June until it is needed for cooling. During this time, it will return to its starting point value. Figure 10-10 showed that the ground temperature is estimated to have dropped from 14.4 to 12.4 °C *in only a month* (with the far ground temperature estimated at 11.8 °C) when the system was left off. Given that the cooling will need to stay in the ground *for 3 months* it is likely that most of it will actually be lost before it could be used.

Based on the simple ground model from Figure 10-10, if the deep ground in the vicinity of the borehole was cooled to 5 °C by March 31st, and then left until June 15th, then, in that time, it would have warmed to 11.6 °C (with the far ground temperature being 11.8 °C). In other words, even if the ground could be cooled by very large amounts, the length of time it needs to sit means that much (or all) of that pre-cooling will dissipate before it is actually needed.

Greater experimental and simulation effort is required to fully confirm this finding and to explore impacts of different borehole arrangements, but overall it would seem that the length of time that the borehole needs to sit once it has been pre-cooled will significantly dampen or eliminate the benefits of the ability to store cooling. Furthermore, precooling is not actually needed to balance the ground temperature. If the system is left of from October to June then that is more than enough time for the ground to return to its initial temperature in advance of the next summer.

A final point is that a water-to-water heat pump could continue to cool the ground right up into the late spring, and this may make pre-cooling more viable. However, this increases the complexity of the system beyond what is warranted for the application.

12.0 RESULTS: ADDITIONAL ITEM 4 - BOREHOLE PERFORMANCE ENHANCEMENT USING DEEP POND COOLING

12.1 Task

Opportunities for decreasing the size or number of boreholes will be explored by using a heat exchanger in the deepest part of the pond to assist with cooling the warm pond outflows during the summer. This could be done without disturbing the sediment in the pond and with limited installation effort. This would be largely a desk top exercise using the data collected from the ongoing pilot monitoring projects (e.g. temperature depth profile data, flows).

12.2 Deep Pond Cooling System

It has been shown previously that subsurface draw could significantly reduce the thermal load because the temperatures at the bottom of the pond are cooler than those on the top, due to thermal stratification. However, in many cases, it may not be feasible or desirable to convert the outlet structure from top draw to subsurface draw. In these cases, it may still be possible to make use of the cooler temperatures at the bottom of the pond by using a similar technique to the geothermal system. A schematic of a system capable of doing this is shown in Figure 12-1.



Figure 12-1. Using a heat exchanger at the bottom of the pond, it's possible to reduce the stormwater outflow temperature before the geothermal system is used.

This system would place a heat exchanger (termed "SHX initial" or SHXi in the figure) in the stormwater outflow before the SHX used in the geothermal system. The SHXi would be connected to a heat exchanger in the bottom of the pond (a pond heat exchanger or PHX). A heat transfer fluid would flow around the circuit and the heat from the

Sustainable Technologies Evaluation Program

warmer stormwater would be rejected to the bottom of the pond. The heat exchangers could be HDPE pipe or stainless steel plates.

The key point to note is that, with either option, this approach to cooling could cost less than using the GHX. The primary limitation is that the stormwater outflow can't be cooled to a temperature below that at the bottom of the pond, which is often still warmer than is desirable. This system would therefore offset some of the required GHX but could not replace it entirely – at least not for the pilot pond.

To gauge the opportunity of this approach, it was examined mathematically. However, to simplify the analysis and avoid complicated implicit equations requiring numerical solutions, more approximate equations for heat transfer were used than with the geothermal system. Equation 17 describes the approximate heat transfer from the SHXi and Equation 18, from the PHX. The average temperature from the pond outflow and hydronic fluid were used as an approximation (Equation 19 and Equation 20), rather than the log mean temperature difference.

$$q_{SHXi} \approx \left(\frac{L_{SHXi}}{R_{SHXi}}\right) \cdot \left(T_{p,ave} - T_{h,ave}\right)$$
Equation 17
$$q_{PHX} \approx \left(\frac{L_{PHX}}{R_{PHX}}\right) \cdot \left(T_{h,ave} - T_{b}\right)$$
Equation 18
$$T_{p,ave} = \left(\frac{T_{pi} + T_{p1}}{2}\right)$$
Equation 19

$$T_{h,ave} = \left(\frac{T_{h1} + T_{h2}}{2}\right)$$
 Equation 20

If the length and thermal resistance of both heat equations can be assumed as equal (Equation 21), the analysis is simplified further. Again, this is only an approximation because the thermal resistance of the SHXi will be lower since it is in moving water. With that simplification, setting Equation 17 and Equation 18 equal to each other (Equation 22) then yields Equation 23. Solving it further yields Equation 24.

$$\frac{L_{SHXi}}{R_{SHXi}} \approx \frac{L_{PHX}}{R_{PHX}} = \frac{L}{R}$$
Equation 21
$$q_i = q_{SHXi} = q_{PHX}$$
Equation 22
$$(T_{p,ave} - T_{h,ave}) = (T_{h,ave} - T_b)$$
Equation 23

$$T_{h,ave} = \left(\frac{T_{p,ave} + T_b}{2}\right)$$
 Equation 24

Equation 24 can be substituted back into Equation 17 to yield Equation 25. If the system is sized to produce the maximum benefit, then $T_{p1} = T_b$ (i.e. the stormwater outflow is cooled the same temperature as the bottom of the pond), then Equation 25 simplifies further to Equation 26. The heat transfer is now defined in terms of known system parameters.

$$q_{i} = \left(\frac{L}{2R}\right) \cdot \left(T_{p,ave} - T_{b}\right)$$
 Equation 25
$$q_{i} = \left(\frac{L}{4R}\right) \cdot \left(T_{pi} - T_{b}\right)$$
 Equation 26

The main aim of this exercise was to estimate the length of heat exchanger needed to reduce the pond outflow temperature to the temperature at the bottom of the pond. Towards this end, the heat transfer is also described by Equation 27. Setting Equation 26 equal to Equation 27 and solving for length yields Equation 28. All parameters are constants except for the volumetric flow rate from the pond (\dot{V}_p) so it is possible to group all the constants together

to a single value (Equation 29). Interestingly the term describing the temperature difference cancelled out of the equation. This is because, while heat transfer is increased for greater temperature differences, so is the amount of cooling that is required, and these effects cancel out.

Equation 27	$q_i = \dot{V}_p \cdot \rho_p \cdot C_p \cdot \left(T_{pi} - T_b\right)$
Equation 28	$L = 4 \cdot R \cdot \dot{V}_h \cdot \rho_p \cdot C_p$
Equation 29	$L \approx \alpha \cdot \dot{V}_n$

Assuming the thermal resistance is 0.12 m°C/W (the midway point between high and low flow from Figure 8-4), α equals 127 m/gpm (i.e metres of HDPE pipe heat exchanger required per gpm of stormwater outflow). In 2019, flow peaks as high as 650 gpm were measured. To cool this peak such that the outflow temperatures was the same as the temperature at bottom of the pond it would require **83 km** of pipe for each heat exchanger. This is much larger than could be feasibly implemented, with HDPE pipe or with plate heat exchangers. It would be much more straightforward just to change the outflow structure to a subsurface draw to achieve the same effect. It follows that this approach **is not** a replacement for a subsurface draw outlet in terms of mitigating peak thermal loads.

Section 14.0 will show that, for the pilot pond in Brampton, a geothermal system consisting of 6 deep boreholes is sufficient to keep the pond outflow temperatures below 24 °C for 95% of the time during the summer. The remaining 5% of the time consists of thermal peaks that even a much larger geothermal system would not be able to manage – and other techniques would be required to reduce those peaks. Without geothermal, this temperature would be exceeded 50% of the time.

The important thing to note is that the geothermal system *is small* and would be relatively inexpensive. The system described in this section might be able to reduce (but not eliminate) the number of boreholes but it would be at the expense of additional mechanical components and additional complexity. This application requires a system to be as simple as possible. The trade-off of fewer boreholes with increased system complexity would not be worth it.

If there were other ponds with sufficient temperature stratification and no significant thermal peaks, then the system outlined in this section may be able to handle the thermal load entirely without the need for geothermal. However, it wouldn't necessarily be cheaper to implement. This is explored in the example below.

Example 1

Say the peak flow was much smaller, at 20 gpm, and the temperature at the bottom of the pond was always below the desired outflow temperature. To cool the outflows such that they were equal to the temperatures at the bottom of the pond, it would require 2.5 km of HDPE pipe.¹⁷

This length of pipe could be put in the pond, but on the stormwater outflow side of the system, stainless steel plates would be required to make it more compact – approximately 200 ft² of plate.¹⁸ This is approximately 17

 17 20 gpm \cdot 126 m/gpm = 2520 m

¹⁸ $(2520 m) \cdot \left(\frac{W}{0.12 m^{o}c}\right) \cdot \left(\frac{ft^{2 o}c}{105 W}\right) = 200 ft^{2}$ *Note heat transfer coefficient information for the plates is from www.awebgeo.com/sizing/

Sustainable Technologies Evaluation Program

plates measuring 2' x 6' each. These plates are going to be on the scale of 2k\$ each based on pricing from a supplier, totaling approximately \$34k.

Figure 4-4 showed a single borehole is capable of cooling a 7 gpm stormwater outflow by several degrees. To cool 20 gpm it would take three boreholes and they may cost around \$10k each, totaling approximately 30k\$.

The boreholes come out as cheaper using these assumptions, but it is also feasible that the flowing stormwater would result in a lower thermal resistance for the plates than was assumed, and this could make the plates a slightly cheaper option.

However, overall, the options are not likely to be that different in terms of cost and the boreholes provide a more reliable source of cooling since they exchange heat with the cool ground.

It follows that an approach which tried to use the cooler temperatures at the bottom of the pond as a source of cooling for warm stormwater outflows is likely not going to be a better solution than geothermal. It can avoid the use of geothermal boreholes but since the temperature differential between heat source and sink is lower, it requires more heat exchanger area, and this would end up significantly reducing or eliminating any potential cost savings.

There may be some benefit to using both in a combined system but then issues of system complexity arise, and it makes sense to just choose one option. Geothermal would be a much better option in the opinion of the authors.

13.0 RESULTS: ADDITIONAL ITEM 5 - PROTOTYPE SIZING TOOL FOR SYSTEM OPTIMIZATION

13.1 Task

A prototype sizing tool to be developed to provide sizing guidance based on pond design and historical environmental data in Brampton. This tool would build on the previous work, including the calibrated analytical geothermal system heat transfer model generalized to multi-boreholes, the machine learning model for stormwater temp/flow, and empirical model of the borehole thermal capacity. It would also be based on data collected on other ponds.

13.2 Tool

A prototype sizing tool is currently available online. Documentation is provided with the tool and has not been duplicated here. Please see <u>sustainabletechnologies.ca</u> to access the tool.

14.0 RESULTS: EXAMPLE SIZING FOR PILOT POND

As a final exercise, it was worthwhile to combine the calibrated geothermal system model and ground temperature model to generate an estimate for a full-size geothermal system at the pilot pond. The aim was to show how it can be done using the methods developed in this study – but note that that this was *not intended as a full detailed design* for this pond.

Previous sections have mentioned different points about geothermal system design – like the importance of considering all opportunities to reduce the thermal load, or for using machine learning pond model to estimate future thermal loads. These considerations have been considered separately in those sections. For this exercise, these considerations were ignored. The measured pond outflow temperature and flowrate for Summer 2019 were used and opportunities to reduce the thermal load were not considered. This is just for the sake of simplicity – again, the aim was just to show how a full system could be sized.

Stormwater temperature and flowrate data from June 1st to September 15th were considered. A number of modelling iterations were then performed on this data. Iterations considered different GHX sizings by incrementally increasing the number of deep (183 m) boreholes. The SHX was considered to be composed of HDPE pipe. The ratio of SHX to GHX was held constant (i.e. there was 230 m of SHX for every 183 m of GHX).

Other system parameters like the GHX and SHX thermal resistance were as calibrated elsewhere in this report. As an output, each modelling iteration considered the fraction of time (with respect to the duration of time from June 1st to September 15th) that the stormwater temperature downstream of the SHX was below a set-point value. In this case, 24 °C was selected. The modelling iterations also assumed that the system turned on only when the outflow temperature exceeded 24 °C since this is simple to implement and would help maintain cooler ground temperatures. Results are shown in Figure 14-1 and Figure 14-2.



Figure 14-1. The impact of geothermal system size on pond outflow temperatures for the summer.



Figure 14-2. An example of the modelling output for a geothermal system using 6 boreholes.

With no geothermal system, the pond outflows are below 24 °C for 50% of the time from June 1st to September 15th, A geothermal system with 6 boreholes is enough to maintain the outflow below 24 °C for 95% of the time. The installed cost of the boreholes would likely be greater than 60k\$ and certainly less than 100k\$. It is estimated that these would be on the scale of half of the total cost of the geothermal installation. The geothermal component of a full-scale system is therefore estimated to be less than 200k\$ to implement.

There are rapidly diminishing returns beyond 6 boreholes. This is because of the short duration thermal peaks that are much larger than the more constant background thermal load. For this system, it would make sense to manage those thermal peaks using a measure other than geothermal (different strategies have been mentioned in Section 9.0) and then size the geothermal system for the remainder of the load - as shown, the geothermal portion does not actually need to be very large.

15.0 DISCUSSION

The main findings of this study are summarized in Table 15-1.

	Торіс	Key Findings				
1	System operation	The system worked well. It cooled the stormwater and agreed well with a calibrated model. The only issues encountered during the summer had to do with the off-grid PV system (and issues were minor) which wouldn't be used in a larger-scale installation.				
2	Full-scale system sizing and cost	The calibrated geothermal system model was used alongside the ground temperature model to estimate the performance of different system sizings for a full-scale system at the Brampton pilot pond.				
		Using data spanning from June 1 st to September 15 th , 2019, the pond outflow temperatures were less than 24 °C only 55% of the time. A geothermal system consisting of 6 deep (183 m) boreholes could keep the temperatures below 24 °C for 95% of the time. The remaining 5% is from large-magnitude thermal peaks. Even 60 boreholes would not be able to satisfy these peak loads and they would need to be met with other measures discussed in this report.				
		The installed cost of the boreholes would likely be greater than 60k\$ and certainly less than 100k\$. It is estimated that these would be more than half of the total cost of the geothermal installation. The geothermal component of a full-scale system is therefore estimated to be less than 200k\$ to implement.				
3	Ground temperatures during summer	Heat is rejected to the deep ground in the vicinity of the borehole. This heat is dissipated to the surrounding bedrock, but the dissipation is slower than the heat rejection and localized warming occurs. Warmer deep ground temperatures are a problem because it <i>decreases</i> the cooling capacity of the geothermal system.				
		This study estimated that the deep ground in the vicinity of the borehole started at 11.8 °C but rose to above 16 °C during the summer for short periods of time. This significantly impacts system sizing. For example, a geothermal system operating with a deep ground temperature of 16 °C is >50% more costly than a system with a deep ground temperature of 10 °C because it must be larger to compensate for the poorer heat transfer.				
		In this study, the system was turned on starting mid-May and left to operate regardless of whether cooling was actually required. This warmed the ground more than was necessary. Ground temperature modelling indicated that if the system was not operated all the time, and instead operated only when the pond outflow temperature exceeded 24 °C, then the ground temperature would have reached 15 °C (instead of 16 °C) as a maximum. This is straightforward to implement and recommended in future installations.				
4	Pre-cooling of ground to enhance	Just like it is possible to locally <i>warm</i> the deep ground in the vicinity of the borehole, it is also possible to locally <i>cool</i> it. If the ground can be kept cooler, then significant savings in system cost are possible. This study explored the possibility of using wintertime operation				

	system performance	to "pre-cool" the deep ground in advance of the summer with an aim to increase the system capacity.			
		A heat exchanger was placed in the pond prior to winter and the cold pond temperatures were used to cool the deep ground. The system was not optimized but it was shown that, by the beginning of February, the ground had cooled by an estimated 2 °C from its normal value. This was a good result. However, the larger issue is not the ability to locally cool the ground, but rather, the fact that the cooling will be dissipated over time.			
		Since ground cooling is only effective when the pond temperature is below the deep ground temperature, it means that pre-cooling must stop sometime in March or April and the ground must sit until late-June or early-July until that cooling is actually needed. The ground temperature modelling showed that, in duration of time, all the cooling will have dissipated. Even if the ground was cooled to a much greater degree (say to 5 °C) – the cooling would still be nearly completely dissipated.			
		The research concluded that the only way pre-cooling would be somewhat effective is to use a water-to-water heat pump but this would increase the system complexity beyond what is warranted for this application.			
		Overall, the study concluded that the limited benefits of pre-cooling is not worth the increase is system cost and complexity. This result should be confirmed with modelling studies that also consider multiple boreholes in different arrangements.			
5	Modelling of pond thermal load	This study demonstrated that machine learning models can easily model pond stormwater temperatures and flowrates. Temperature and flowrate data from a single season can be used to train a model which can be applied to environmental data in other years. This is the best way to estimate the thermal load for system sizing in already-existing ponds. This approach can also take into account expected environmental changes due to climate change and "future proof" the system sizing. It can further be helpful when exploring other measures that help reduce the pond thermal load (as had been done in this study).			
6	Improvements in the SHX	In this study, the SHX was constructed using coiled $\frac{3}{4}$ " DR11 HDPE pipe because it was inexpensive, robust, and familiar from pond-based geothermal system. An alternative is stainless steel plate heat exchangers. It was shown that the HDPE pipe SHX, which measured 2' high by 6' in diameter, could be replaced by 13 ft ² of stainless steel plate (2' x 6.5' x $\frac{1}{2}$ ' for example). It is a <i>much</i> more compact form factor and would be a better solution in larger installations. That being said, there are different ways of implementing the SHX that have not been explored and HDPE pipe may prove a useful option in some cases.			
7	Opportunities to reduce the thermal load of the pond	To promote a cost-effective system overall, it makes sense to consider all opportunities to reduce the thermal load of the pond (by reducing the maximum flowrates and/or outflow temperatures). Three specific measures were considered: (1) utilizing subsurface draw (instead of top draw); (2) constricting flow to smooth flow peaks; and (3) utilizing an infiltration trench to shave the flow at all points in time.			
		Temperature stratification measurements in the pond indicated temperatures nearer the bottom are typically 2 to 3 °C cooler than those on the top. Drawing water from the bottom of the pond would significantly reduce the geothermal-system sizing. For example,			

		it would reduce thermal load peaks by on the scale of a half and, in some years, be sufficient to keep temperatures within recommended limits <i>without the need to even use</i> <i>the geothermal system</i> . If conversion to a subsurface draw is possible for a given pond, then it is highly recommended.				
		If the flow passing through the outlet structure is constricted, for example, by using an orifice plate, then the <i>peak</i> flows can be reduced (the total flow volume is the same, it is just spread out over a longer time). Currently, the pond takes about 2 days to draw down to normal levels after a storm event. If that period of time is elongated by a day it would reduce the flow peaks (and the thermal load) by on the scale a third while temporarily raising the pond level an additional 9" in the worst year considered (over the past several years). This would impact the ability of the pond to deal with more extreme events but it is feasible to design the structure such that the most extreme events are not constricted.				
		Lastly, a substantial amount of area is required for an infiltration chamber to make an impact on the peak flow rates. It would essentially be like building a secondary pond about a quarter the area of the main pond, but instead implemented underground. While it is feasible to do this when the area is available, it would be much more cost-intensive than the other two options considered. Infiltration is therefore a tool for reducing the more constant background thermal load than it is to reduce the peak flows.				
		If the both subsurface draw and flow constriction are used it's possible to reduce the thermal load peak in the worst year considered (over the past several years) from more than 120 tons down to less than 25. The complete thermal load (i.e. 100%) could be handled by a system on the scale of 10 deep boreholes.				
8	Deep pond cooling	This study explored the use of a heat exchanger placed in the bottom of the pond as part of an ancillary system to help cool the stormwater outflows. Ultimately, this approach would require a prohibitively large heat exchanger and the benefits of reducing the already small number of boreholes would not be worth the added mechanical complexity in the opinion of the authors. In some ponds, it is feasible that this approach could work without requiring any geothermal but this isn't expected to result in a lower cost system overall and geothermal would still be a better option.				
9	Sizing tool	A high-level sizing tool was created as part of this work and is available through a link provided on the project webpage at sustainabletechnologies.ca. It allows the user to find cost optimized solutions to the heat transfer equations governing the system given the input parameters provided by the user. It can also be used to evaluate the impact of each of those parameters on system size and cost, While it can be used to provide a first assessment of system cost in comparison to other options, it is important to note that the tool enhances, rather than replacing the knowledge of a qualified professional. More details are provided in the Documentation provided with the tool.				

15.1 Sizing Procedure

Based on the findings of this study, an outline of a recommended geothermal system sizing procedure for any stormwater pond is provided below. This represents the ideal scenario for sizing in the view of the authors but there may be other acceptable approaches.

- 1) **Collect data.** Data on the stormwater outflow temperature and flowrate is needed to size a cooling system for an existing pond. If that data is not already available, then it should be collected for a full season.
- 2) Normalize data. The collected temperature and flowrate data pertain to the environmental data (ambient temperature and rainfall) from the year in which it was collected. This data should be normalized to a design set of conditions. Design conditions may be a historical year or a projected year. Design conditions represent a scenario in which the geothermal cooling system ought to meet some predetermined fraction of the pond's thermal load. This study used a machine learning model of the pond to normalize data to other years.
- 3) Set a design goal. The design goal consists of a recommended limit and also, the fraction of time the system operates within that limit. A system that keeps pond outflow temperatures within some recommended limit 95% of the time will have a much different sizing than a system design for 100%. In the pilot pond, a system with 6 boreholes could keep the system within recommended limits 95% of the time while, because of the thermal peaks, a much bigger system keep the system within recommended limits only 97% of the time. Returns can be drastically diminishing.
- 4) Within a model, iterate through different geothermal system sizes. The model developed in this study can be used, or another model if available possibly using industry-standard design packages like GLD. Generate a curve as in Figure 14-1 that relates the fraction of load being met (in design conditions) to the size of the system. This curve provides information on the system sizing required to meet the design goal. If the thermal load has significant thermal peaks than alternative measures to reduce those peaks may need to be considered.
- 5) Consider alternative measures to reduce thermal load. If a reasonable geothermal system size is unable to meet the design goal, then other design measures must be considered. For each measure, a designer would need to estimate the impact on the data from Step (2) and then redo Step (4). Ideally, the designer also considers the cost of those measures in relation to the benefits they provide in terms of system size and cost.
- 6) Optimize sizing to reduce costs. Once a designer has a system capable of meeting the design goal it is worthwhile to rerun the modelling while varying the relative sizing of the SHX and GHX to identify the lowest system cost possible. Often the SHX is much cheaper than the GHX, it is possible to oversize the SHX to reduce the size of the GHX.
- 7) Final reporting. The final reporting should be clear about the data used to inform the design, design conditions and the process of normalizing the data to design conditions, the design goal, alternative measures considered, modelling results, and considerations around cost optimization.

16.0 FUTURE WORK

This is the first implementation of geothermal-based thermal mitigation and there are many remaining items that ought to be studied in future work, including:

- the implementation and evaluation of a full-scale system;
- the implementation of metallic heat exchangers and other SHX options;
- the implementation and optimization of other measures used in combination with geothermal;
- confirmation of findings about pre-cooling with expanded modelling study;
- continuation of monitoring at the pilot pond for a second season looking specifically at system
 performance with the 50% propylene glycol heat transfer fluid;
- further work evaluating ground temperatures under different environmental conditions specifically in the worst years historically speaking or moving forward in the context of climate change;
- incorporation of metallic heat exchangers into the sizing tool;
- further refinement of the sizing tool;
- as well as other topics.

17.0 CONCLUSION

To the author's knowledge this pilot project represents the first implementation of geothermal-based thermal mitigation of stormwater retention pond outflows. The system worked well with minimal operational issues. It's design and performance were easily described by relatively simple models, developed within this study, making it a highly engineerable solution. It is also highly space- and cost-efficient, and it does not impact the appearance of the pond or surrounding greenspace since the majority of the system is underground.

Based on the 2019 data, the calibrated system model showed that a relatively small system, consisting of six deep geothermal boreholes, would be able to keep the stormwater outflows below 24 °C for 95% of the time from June 1st to September 15th. Other methods have been suggested to manage the remaining 5%. It's estimated that the full system would cost less than 200k\$ to implement for the geothermal component. Without the geothermal system, temperatures would exceed 24 °C 45% of the time (again, based on the 2019 data).

A number of other important topics surrounding geothermal-based thermal mitigation were explored within this work and, given the newness of this approach, there are a number of future work items that have been suggested. Chiefly among those items is the design and implementation of a full-scale system.

Overall, this pilot demonstrated that geothermal is a very effective and promising option for thermal mitigation.

18.0 APPENDIX A: INITIAL SYSTEM SIZING

The maximum cooling potential, system hydronic flow rate and SHX length was determined using Equation 8 and solving for L_{SHX} while iterating through different values of \dot{V}_h and \dot{V}_p . Using the below conditions, results are shown in Figure 18-1. These were the estimated conditions for sizing before any individual parameter (specifically, R_{GHX} , R_{SHX} , and T_g) was investigated in more detail within the study. It follows that these parameters **should not** necessarily be used for subsequent sizing procedures.



Figure 18-1. The required minimum SHX is shown for different system hydronic flow rates and storm water outflows. The target design is highlighted in red – these are values achievable with the experimental set-up. Note that roughly twice the amount of SHX length would be required to cool a stormwater outflow of 8 gpm, versus one of 7 gpm.

19.0 APPENDIX B: MACHINE LEARNING MODELLING DETAILS

19.1 Feature Engineering

The machine learning (ML) model of the pond is a multi-variable linear regression model of the type shown in Equation 30, where the target variable(s) (pond outflow temperature or flow rate) is predicted based on features (x_i) and corresponding coefficients (C_i). The primary aim of the modelling is to identify the best values for the coefficients.

$$y = C_0 \cdot x_0 + C_1 \cdot x_1 + C_2 \cdot x_2 + \dots + C_n \cdot x_n$$
 Equation 30

The dataset collected during the monitoring period needed to be adjusted prior to modelling. This is because the data was time-series (example shown in Table 19-1). The model shown in Equation 30 could not be directly applied to time-series data because both current and historical parameter values impact the target variable. For example, the total quantity of rain over the previous several hours is a much more important parameter for flowrate than the instantaneous rain at any given point in time. It follows that the model could not take rain, ambient temperature and solar radiation as the input features, as is, to predict outflow flowrates and temperatures.

	Rain_mm	Amb_Temp_C	Sol_W/m2	Outflow_Temp_C	Outflow_gpm
6/6/19					
0:00	0.00	14.31	0.60	17.03	197.82
6/6/19					
0:05	0.00	14.34	0.60	17.01	198.16
6/6/19					
0:10	0.00	14.34	0.60	17.01	197.48
6/6/19					
0:15	0.00	14.36	0.60	16.99	197.14
6/6/19					
0:20	0.00	14.36	0.60	16.99	196.46
6/6/19					
0:25	0.00	14.31	0.60	16.99	195.61

Table 19-1. Example time-series data

The features need to be engineered such that each row of data contains all the relevant information necessary for predicting the target output variables. The time-series data for rainfall, solar radiation and ambient temperature each needed to be transformed into a new set of parameters, like:

- sum or average over the previous hour;
- sum or average over the previous 2hours;
- sum or average over the previous 4 hours;
- sum or average over the previous 6 hours
- sum or average over the previous 8 hours;
- sum or average over the previous 10 hours;
- sum or average over the previous 12 hours;
- sum or average over the previous 1 day;
- sum or average over the previous 2 days;
- sum or average over the previous 3 days;
- sum or average over the previous 4 days;
- sum or average over the previous 5 days;

Sustainable Technologies Evaluation Program

- sum or average over the previous 6 days; and
- sum or average over the previous 1 week.

These formed the features of the ML model. An example of feature engineering on time series data is shown in Table 19-2. Note that the feature engineering was slightly different when the ML model was applied to predict the pond outflow flowrate versus the temperature, and this is explained in greater detail in each subsection.

Features				Tarc	gets
Rain_mm_1hr	Rain_mm_2hr	Rain_mm_4hr		Outflow_Temp_C	Outflow_gpm
1.00	1.00	1.00		17.03	197.82
2.00	3.00	3.00		17.01	198.16
0.00	2.00	3.00		17.01	197.48
0.00	0.00	3.00		16.99	197.14
0.00	0.00	2.00		16.99	196.46
0.00	0.00	0.00		16.99	195.61

Table 19-2. Example of feature engineering on time-series data.

19.2 Machine learning model of pond temperature

The aim of developing the ML model for pond temperature was to be able to predict pond outflow temperature based on historical environmental data for rainfall, solar radiation and ambient temperature. Rainfall data at 5-minute resolution for at least the previous 6 years was available from a nearby TRCA weather station. However, solar irradiance data was only available for 1-hr resolution at best. All environmental data collected during the monitoring period was therefore aggregated in hourly totals for the ML model such that the model can then be used on historical data which is also typically hourly aggregated. Features were then engineered as in Section 19.1, starting with the hourly totals and including totals at different timestamps up to 1 week. This was done for the rainfall, ambient temperature and solar radiation, yielding 42 features in total.

The ML model was developed in Python using the Sci-kit Learn library. The dataset was randomly divided up into training (80% of the data) and testing portions (20% of the data). The model was developed using the training portion and then tested for accuracy using the testing portion. Note that the testing portion was **not** used to inform the model. The process described above therefore evaluated the model using data that the model had not yet 'seen.'

All features were normalized using the MinMaxScaler() function in Sci-kit Learn. This transformation first subtracts all data in a given feature by the minimum value and then divides by the range (i.e. the difference between the minimum and maximum) such that the new transformed features each have a value ranging from 0 to 1. This does not remove any information and it was done such that the resulting coefficients for each feature can be more directly compared so as to provide insights on which are more important. If features were not normalized, then the coefficient values would be impacted by the magnitude of the feature values themselves. For example, without normalization, the magnitude of the coefficient applicable to the 'solar radiation in the past week' feature would be much smaller than that for the 'solar radiation in the past hour' variable, even if both features were equally important, because the 'solar radiation in the past week' has a much larger magnitude than 'solar radiation in the past hour.'

The model had a variance score of 0.93 (1 is perfect prediction) when applied to the testing portion of the dataset (Figure 19-1), indicating that it is very good representation of the pond temperature. Figure 19-2 shows the model applied to the full dataset including both the training and testing portions.



Figure 19-1. The ML model is a good predictor of pond outflow temps.



Figure 19-2. ML model predicting pond temperature using full dataset

The coefficient values indicated that the features related to ambient temperature were suitable on their own (i.e. without the solar radiation or rainfall data) to make a predictive ML model. However, the variance score was slightly worse, at 0.89, compared to when the solar radiation and rainfall data was incorporated as well.

19.3 Machine learning model of pond flow rate

The ML model for pond flow rate had a much lower variance score than that for pond temperature when the hourly aggregated data was used. This is because flowrates can change much more dramatically over a short duration when compared to temperature. The modelling exercise was therefore repeated but instead using the 5-minute data. This is permissible because historical data is available at 5-min intervals for rainfall. Only features related to the rainfall were

considered in the pond outflow flowrate ML model. Feature engineering transformed the time series data into the following feature set:

- rain in last 5 min;
- rain in last 10 min;
- rain in last 30 min;
- rain in last 1 hr;
- rain in last 2 hr;
- rain in last 6 hr;
- rain in last 12 hr;
- rain in last 1 day;
- rain in last 2 day;
- rain in last 3 day;
- rain in last 4 day;
- rain in last 5 day;
- rain in last 6 day;
- rain in last 1 week;

The data was separated in training (80%) and testing (20%) sets, just as with the temperature model. All features were also normalized using the same procedure as the temperature model. The resulting model had a variance score of 0.79 indicating that it is a good predictor of pond outflows. Figure 19-3 shows the predictive capabilities of the model when applied to the testing set (again, note that the testing dataset did **not** inform the model). Figure 19-4 shows the model applied to the whole dataset including both the training and testing portions.

There are a few issues worth identifying. The first is that the model underpredicts the magnitude of some of the peaks, particularly the largest peak. This may be because the peak is an outlier and there was not sufficient data to train the model to capture all outliers. The second is that the model predicts a peak in the flow when there was no peak in the actual flow data. The reason for this is not known. The peak does correspond to an actual rain event, just one that did not cause significant outflow from the pond. Despite these factors, the model is sufficient for the requirements of this study since overall agreement is good and there are no better options for estimating the historical thermal load of the pond.



Figure 19-3. The ML model is a reasonably good predictor of pond outflows when applied to the testing data set.



Figure 19-4. When applied to the full dataset the ML model shows reasonably good representation of the actual flow, although it underpredicts some peaks and predicts 1 peak that did not show up in the actual data.

19.4 Subsurface Temperature Modelling

Using the lowest sensor (60 cm from the pond bottom) of the pond temperature profile measurement, features were engineered in the same way as before and the dataset was split into 80% training and 20% testing. The R² of the resulting model was 0.87. A plot of the predicted versus actual subsurface temperature for the testing set is shown in Figure 19-5.



Figure 19-5. This plot of predicted versus actual subsurface temperature (using the testing data) demonstrates that the machine learning model is reasonably good.

The model applied to the whole dataset, testing and training, is shown in Figure 19-6. Ideally, there would have been more data, covering the whole season, to train the model but the results are sufficient for the estimates in this study.



Figure 19-6. The machine learning model for subsurface temperature shows reasonably good agreement with the actual data.