Waste Management

vladimir Buelvas-Hernandez

Home | Main Menu | Submit a Manuscript | About | Help

Revisions Being Processed for Author

Page: 1 of 1 (1 total revisions being processed) | Results per page 10

Action	Manuscript Number	Title	Date Submission Began	Status Date	Current Status
View Submission View Reference Checking Results Send E-mail	WM-24-653R2	Evaluation of Thermal Parameters with Geothermal Energy Recovery from a Cold Climate Municipal Solid Waste Landfill⋆,⋆⋆	Sep 03, 2024	Sep 03, 2024	With Editor

Page: 1 of 1 (1 total revisions being processed) | Results per page 10

Gmail | Pesquisar e-mail | Ativo

Escrever

Caixa de entrada 2.259

Com estrela

Adiados

Autolabel | 1–50 de 4.241

Marcilia H.S. Masca.	Fwd: Informe sobre Concurso para Professor Hidráulica e ...	
Waste Management	Submission Confirmation for WM-24-653R2 - #AU_WM# To ensure t...	3 de set.
Waste Management	Your PDF has been built and requires approval - Waste Management ...	3 de set.

Gmail | Pesquisar e-mail | Ativo

Escrever

Caixa de entrada 2.259

Com estrela

Adiados

Enviados

Rascunhos 10

Mais

Marcadores

2 de 4.241

Submission Confirmation for WM-24-653R2

Externa | Caixa de entrada ×

Waste Management ter., 3 de set., 18:09 (há 17 horas)

para mim

#AU_WM#

To ensure this email reaches the intended recipient, please do not delete the above code

In compliance with data protection regulations, you may request that we remove your personal registration details at any time. (Remove my information/details). Please contact the publication office if you have any questions.

Caixa de entrada 2.254

Com estrela

Adiados

Enviados

Rascunhos 10

Mais

Marcadores

Correos Importantes 1

Eventos

Panamericano de Chile

Ms. Ref. No.: **WM-24-653R1**
Title: Evaluation of Thermal Parameters with Geothermal Energy Recovery from a Cold Climate Municipal Solid Waste Landfill⋆,⋆⋆
Waste Management

Dear Vlad,

The peer review process for your manuscript has been completed. Based on the referee comments, and upon my review of the manuscript, I feel that your paper presents information of interest to the readers of Waste Management but that minor revisions are needed prior to publication.

Please use the attached comments to produce a revised manuscript.

Please prepare a reply to each reviewer's comment and suggestion within the structure of a table with three columns, in which each reviewer's comment is reported in the left column and the author's response is clearly addressed in the center column. For significant revisions of multiple paragraphs/pages, the author(s) should indicate these changes in the revised text column with references to the track changes version of the manuscript [see below].

Example Table Format for Author's Response:

Example Table Format for Author's Response:

Reviewer Comment	Author' Response	Revised Text
Correct Spelling of "landfill"	Corrected	The landfill was.. (Page 4 Line 120)

In addition to the completed table form, we would like to receive the following by **Sep 21, 2024**:

-- a clean version of your revised manuscript in Microsoft Word (or compatible) format.

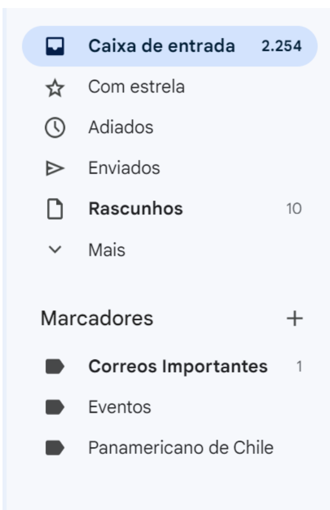
-- a MS Word version with all changes indicated with the "track changes" function. Please include page and line numbers in this version.

To submit your revision, please do the following:

1. Go to the EM site

2. Enter your login details

3. Click [Author Login]



Comments from the editors and reviewers:

Reviewer #1: Line 103: Capitalize "the" at start of the sentence.
Please check all in-text citations. Some appear to be missing periods, parentheses, and proper formatting in the introduction section.
Lines 187 and 234 (and other parts of the manuscript): "Northern Landfill" used here, I thought this was at the Loraas landfill? It appears the full name is "Loraas Northern Landfill" which I'd recommend using the first time to avoid confusion when using "Northern Landfill" later, or just use one name and do not interchange throughout the manuscript.
Page 9, Line 199: Please clarify the sentence "Yesiller et al (2016) identified radial zone of influence" - The sentence seems to be incomplete and should have additional information to frame this in the context of the paragraph.
Line 308: fix "ffor"
Line 312: Update (Equation 6) to "Equation 5"
Line 443: Figure 6 is referenced twice.
Section 4.2: The summer test was discussed before the winter test, I would suggest flipping Figure 5 and 6 (since the summer test is primarily discussed earlier).
Line 491: Figure 6 is referenced twice, which I believe is the summer test? Please check manuscript to be sure correct figures are being referenced in each discussion.

Evaluation of Thermal Parameters with Geothermal Energy Recovery from a Cold Climate Municipal Solid Waste Landfill★,★★

Vladimir Buelvas[a,*], Logan Morhart[a], Tyler Casavant[a], Ian Fleming[a] and Claudio Mahler[b]

[a]University of Saskatchewan, 57 Campus Drive, Saskatoon S7N5A9, Canada

[b]Universidade Federal do Rio de Janeiro, Coppe, Rio de Janeiro, Rio de Janeiro, CEP (Postal Code): 21941-598. Brazil

∗Corresponding author

vlb037@usask.ca (V. Buelvas); ian.fleming@usask.ca (I. Fleming); mahler@coc.ufrj.br (C. Mahler)

A b s t r a c t

This study presents finite element method (FEM) modeling with COMSOL Multiphysics to estimate the thermal properties of a waste landfill through back-analysis of temperature responses from buried thermistors during a full-scale multi-week active thermal response test. Field tests were conducted at the Loraas MSW landfill in Saskatoon, Canada, using instrumented equipment, including a vertical borehole heat exchanger and thermistor strings. The test consisted of two phases: a heat injection test during the summer and a heat extraction test in the winter. The study focused on a landfill 25 meters deep, observing temperature changes at various depths over time. The effect of heat generation rate (HGR) on landfill temperature was investigated. Thermal conductivity and volumetric heat capacity increase with depth, with close alignment between summer and winter results, validating the tests. This research enhances the understanding of thermal parameters in MSW landfills by combining field tests and numerical modeling, offering insights into landfill behavior in cold climates. These findings hold significance for optimizing geothermal energy recovery from such landfills, calibrating thermal parameters for coupled

models in landfills, and improving waste management practices.

Keywords:
Geothermal heat extraction. Coupled processes. Heat extraction. Landfill.

1. Introduction

The design, construction, and operation of municipal solid waste (MSW) landfills present challenges to both design engineers and landfill operators due to the relatively complex behavior of the heterogeneous materials buried within them. A landfill is a biologically active system where the primary constituent is actively decaying during and after the service life of the structure. During the anaerobic decay of MSW the solid degradable organic fraction is converted to gaseous CO_2 and CH_4 which reduces the solid volume (leading to settlement) and produces heat. The decay of MSW is not only a thermal and biochemical process but is additionally influenced by the hydraulic and mechanical conditions present on site. The combination of these processes results in a complex system that is difficult to simulate using analytical methods. Thus, study into the behavior of landfills through numerical modeling and simulation has been a priority of researchers.

Research into the thermal properties of landfills through the simulation of heat transfer models has increased in recent years resulting in an improved understanding of heat generation and settlement rates as well as the potential for faster waste stabilization (Hanson et al., 2006), (Yesiller et al., 2005), and (Lu et al., 2020). The two main thermal parameters required to simulate heat transfer are thermal conductivity (kt in W/m°C), and specific heat capacity, or heat capacity (either as specific, C_P in kJ/kg°C, or volumetric, HC in MJ/m^3°C).

These two main thermal properties are obtained for any particular site through active thermal response testing ATRT. ATRT involves pumping a fluid of known temperature through a borehole heat exchanger BHE. The induced ATRT response can then be solved, using either analytical models or numerical models, to better understand the thermal properties of the test media. It is important to note, however, that there is a coupled effect between the fluid flow in the ATRT system and the surrounding media. These coupled heat transfer effects in addition to the coupled nature of heat generation during MSW decay, i.e., that the rate of decay, thus the rate of heat generation, itself depends upon the temperature of the waste fill itself which is not captured by traditional models. In the last two decades, several studies have investigated the thermal properties of MSW landfills through either detailed field investigations or by conducting numerical simulations, but rarely are both methods of investigation used together. A summary of the relevant numerical models and previous field tests performed for MWS landfills are as follows.

An analysis of the numerical model was carried out by (Rowe et al., 2010) based on the conditions at the Tokyo Port Landfill and the proposed arrangement of cooling pipes which served to evaluate cooling the liner to prolong the service life of the liner. Even though (Rowe et al., 2010) was primarily a mathematical exercise involving a liner, field data was collected and calibration to the literature data was performed which is like the case study presented herein. In (Rowe et al., 2010) temperatures were measured along the depth of the landfill, and thermal properties such as thermal conductivity, heat capacity, and heat generation were calibrated based on estimation by Yoshida and Rowe (2003). The heat source was assumed based on the technical literature for both saturated and unsaturated materials and those exposed to air. In the case of this study, such materials exposed to air are not considered since they have already been deposited and have a cover to insulate them from the atmosphere. In addition, in that study, a 3D analysis was carried out to evaluate the impact of heat convection along the pipeline.

(Zanchini et al., 2010) developed a two-dimensional axisymmetric model using COMSOL Multiphysics software to evaluate methods of optimizing short and long coaxial heat exchangers. The development of a numerical model using COMSOL has the benefit of being able to simulate the coupled effect of fluid flow and heat transfer. The potential benefit of coupling these effects was not entirely known as there was no accompanying field data for this study.

Several studies have been carried out to determine the thermal conductivity and heat capacity of municipal solid waste (MSW) using various measurement methodologies. For instance, (Faitli et al., 2015) and (Yeşiller et al., 2016b) examined heat generation, gas and leachate production, which are the three primary by-products of MSW landfills. These authors designed and installed a prototype heat extraction system that is similar to the one used in this paper. Their system comprised a heat extraction unit with a closed-loop vertical piping network and a monitoring array spaced at one-meter radial intervals from the heat extraction well with fluid circulation pipes placed against the wall of a large borehole within the waste mass. However, it was not possible to evaluate the thermal properties of the waste from their results. (Yeşiller et al., 2016a) further expanded on their initial prototype by incorporating temperature sensors inside the waste at an MSW landfill in California. The piping was made of HDPE and pipe diameter of 25 mm was used. In parallel, (Faitli et al., 2015) developed a new measuring apparatus for gauging heat flow and conducted an evaluation method to determine both the thermal and physical properties of MSW landfills.

According to Megalla (2015) and (Megalla et al., 2016), the authors devised both theoretical and numerical heat transfer models using temperature data from the Ste. Sophie landfill to calibrate their models. The authors conducted temperature simulations for the Ste. Sophie landfill waste, using thermal conductivity values of 0.3 W/mK for the waste within the top meter of a waste lift and 0.67 W/mK for the rest of the waste, which is comparable to the approach employed by Rowe in (2010). The results indicated that the thermal conductivity increased with depth and time, which aligns with the assumptions made by (Megalla et al., 2016).

Berquist (2017) employed COMSOL Multiphysics to develop a numerical model that used the optimization module to determine the thermal conductivity and specific heat of waste as functions of time and depth. This model aimed to align well with temperature and settlement data sourced from the Ste. Sophie landfill site. The authors of the study did not present a graph showcasing the results from the software used. Additionally, the author provided a comprehensive summary of typical thermal conductivity and heat capacity values reported in various studies. It is worth noting that most of the thermal properties found in the literature are not directly measured; instead, estimated from back-analysis a system where some field measurements such as temperature have been taken. These approaches are used to capture the overall system behavior and characterize average material properties over large volumes of waste.

Additionally, (Shi et al., 2018) constructed a prototype heat exchanger system at a MSW landfill in Wuxi City, China, spanning 30 m of old MSW, and studied materials from a relatively young 8.4 m MSW landfill. The researchers circulated water through a piping system at different flow rates and contrasted the results with those from (Yeşiller et al., 2005). Heat exchange and monitoring tests were successfully conducted over a period of 14 months. In this study, the authors focused solely on field tests, specifically measuring the temperature response using sensors placed in the open pipes of the system. These tests did not involve any numerical modeling to determine parameters such as thermal conductivity and heat capacity.

(Nocko et al., 2020) used a full-scale instrumented geothermal heat extraction (GHT) system installed during the construction of the first cell at an MSW landfill in Santee, San Diego County, California. At three different elevations within the MSW cell, horizontal geothermal heat exchanger pipes were arranged in a serpentine configuration. As a result of this configuration, temperature readings (and therefore estimates of thermal conductivity) over time at different elevations were obtained. An analytical solution for a mathematical expression was obtained to calculate the heat transfer rate for the different heat exchangers; nonetheless, the model did not seek to fit the field data and the reported variation in thermal conductivity between the layers was minimal. Likewise, (Rowe et al., 2010) conducted a study to explore a method of temperature control in landfill liners in the Tokyo landfill, which involved the development of an alternative model incorporating serpentine configuration like (Nock et al., 2020). The research employed both two-dimensional and three-dimensional numerical models, utilizing finite volume methods. Owing to limitations in the flow rate imposed during the test, laminar flow was assumed for all scenarios. The thermal properties and heat generation rate for the waste were sourced from technical literature.

The study carried out by (Hanson and al., 2006) at the Anchorage Regional Landfill in Alaska collected temperature and gas data from multiple cells, using both horizontal and vertical arrays for an extended period. The purpose was to investigate the spatial and temporal variations in waste temperatures and gas compositions in the region characterized by cold climates with temperatures ranging from approximately -1°C to +35°C. The heat generation and thermal properties of the model were determined by calibrating it with the collected field data. The methodology employed in this study closely resembles the approach used by (Hanson et al., 2006), which will be further explained below.

Numerical modeling in 1-D and 2-D was conducted by (Hanson et al., 2022) to investigate the feasibility of a vertical heat extraction system and the effects of system configuration on the overall thermal behavior of a landfill over a 40-year period. This study focused on two variables: variations in pipe diameter and fluid velocity. The authors analyzed temperature profiles at different depths: cover line, shallow, mid-depth, deep, and bottom-liner with 30m of waste depth. The authors concluded that greater seasonal temperature fluctuations occur in both waste temperature and (heat extraction system) HES temperature near the ground surface. Additionally, the influence of the HES on landfill temperature is most significant at the central depths of the landfill, with less impact observed at the cover and liner locations.

2. Methodology

Despite significant focus by researchers, few studies have comprehensively addressed the calibration of thermal parameters that integrate both field data and model simulation with depth. The aim of this paper is to investigate the thermal properties of the Loraas MSW landfill, located in Saskatoon, Canada. This investigation is conducted initially through field tests and subsequently through finite element method (FEM) modeling. To facilitate this study, an instrumented vertical borehole heat exchanger (BHE) and surrounding thermistor strings were installed on-site. These instruments monitored two active thermal response tests (ATRTs) undertaken for this research. The finite element modeling software, COMSOL Multiphysics, was chosen to model the coupled effects of heat flow (thermal) and the inner BHE fluid flow (hydraulic conditions). The numerical model developed was then calibrated using data obtained from the field tests conducted at the landfill site.

The numerical model operates as a mechanistic tool to estimate the effects of heat generation rates within the waste and to predict thermal properties. Sensitivity analyses are expected in identifying variables that best replicate field behavior. However, achieving a perfect fit across multiple variables is challenging because changing one parameter can cause discrepancies in others, especially at different depths due to the multi-layered structure of the model.

To enhance the accuracy of the model, parametric sweeps were performed using the modeling software. This approach allows for finding precise solutions by varying parameters of interest systematically. In this study, combinations of thermal conductivity (kt) and specific heat capacity (C_P) were tested, particularly for the central layers where temperature influence is most pronounced. The modern capabilities of software provide a robust method for solving sequences of stationary or time-dependent problems, which is essential for fine-tuning the model to align with the observed field data

2.1 Experimental location

All the field tests conducted for this experiment were performed at the Loraas Ltd. landfill, located approximately 10 km north of Saskatoon, Saskatchewan, Canada. The site is located in a temperate, semi-arid climate which experiences a large variation in air temperature from summer to winter (40 °C to -30 °C). The Loraas landfill is a medium-sized landfill mainly composed of industrial commercial, and institutional (ICI) wastes and construction and demolition (C/D) waste. The field tests were conducted in wells spanning the entire depth of the landfill with depths ranging from 23.6 to 25.4 m below the surface. For a more detailed account of the age of the waste, a visual description of sampled MSW, and the dispositional history of the landfill please refer to Hucl (2021) and Morhart (2022).

2.2 Surface installation

2.2.1 Monitoring well

Between 2018 and 2020, a total of six thermistor strings, five gas wells, and one vertical coaxial BHE were installed across the Loraas Northern Landfill using sonic drilling methods as seen in Hucl (2021) and Morhart (2022). The BHE was denoted as GT20-02 and was surrounded at various distances by control boreholes with thermistor strings used to monitor the temperature variation during ATRT. The thermistors strings TH19-02A; TH19-02, BH19-02A were spaced at a radial distance of 1.8 m, 5.1 m, and 7.2 m respectively from GT20-02 and an additional gas well (BH18-

02) located 11.2 m away. All the installed thermistor strings had thermistors located at depths of 1 m, 3 m, 5 m, 10 m, 15 m, 20 m, and 24 m (± 15 cm) below the surface of the landfill.

The analysis focused solely on data from TH19-02A (1.8 m radial distance), as other control boreholes showed minimal temperature fluctuations throughout the test period, aligning with existing literature. (Shi et al., 2018) developed a prototype heat extraction system in Wuxi City, China, demonstrating that thermal response diminishes as radial distance from the heat exchanger increases. Their findings indicated negligible temperature variations beyond 4 m from the source. (Yeşiller et al., 2016a) observed temperature reductions of approximately 20 °C, 5 °C, 2 °C, and less than 1 °C at radial distances of 0 m, 1 m, 3 m, 5 m, and 7 m, respectively, from the heat extraction well, spanning its entire depth. These findings suggest that the influence of the heat extraction well extends to a maximum distance of 3 m.

2.2.2 BHE Design

The BHE used here had a coaxial design with the annular portion consisting of a A53 steel pipe with a 1/4 in (0.1143m) (SCH 40) diameter and 0.237 in. (0.0060 m) wall thickness. Following the installation of the annular pipe with a sonic drill rig, a 2 in. PVC pipe was installed in the center of the steel pipe, with the bottom 2.5 ft (76.2 cm) being slotted and having 16 additional holes drilled. To ensure the PVC pipe remained centered during and after installation, 10 stainless steel centralizers were attached to the PVC pipe.

A thermistor string with thermistors spacing at 0 m, 2 m, 9 m, 14 m, 21 m, and 23 m measured from the top of the landfill was attached to the outside of the PVC pipe to measure the temperature of the circulating return fluid inside the annular spacing of the BHE. Following installation, a well cap was designed for the top of the system, and a second thermistor string was installed inside the centered pipe with thermistors at 23 m in depth and immediately above the top of the exchanger.

The second thermistor installed inside the center pipe was used to measure the outlet temperature of the fluid. The final cross-section of the coaxial borehole heat exchanger can be seen in the as-built drawings in Appendix A.

2.3 Surface installation and active thermal response testing

Two ATRT were performed at the Loraas Northern Landfill for this study. The first ATRT was a 35-day heat injection test which took place from July 23 to August 28, 2020, followed by a 25-day recovery period. The average flowrate of the circulation fluid was recorded to be 4.1 USGPM (15.3 L/min), and the target inlet temperature was 37.0 °C for the first nine days of the test and 39.0 °C for the remaining 26 days.

The second ATRT was an 82-day heat extraction test, which took place from December 13, 2020, to March 5, 2021, followed by an 83-day recovery period. The average flow rate for the first 16 days was 4.2 USGPM (15.9 L/min) and 8.5 USGPM (32.2 L/min) for the remaining 66 days. The flowrate was increased during the test to promote greater heat transfer between the BHE and the surrounding MSW. The target inlet temperature for this trial was kept between 5.0 °C and 7.0 °C although there were periods where the inlet temperature exceeded this range. The cooling system for the second ATRT was designed to vent the excess heat extracted from the BHE using radiator and the cold winter (atmospheric temperatures of – 30 °C to – 10 °C). These periods of excessive inlet temperature were either due to unseasonably warm temperatures reducing the effectiveness of the cooling loop or a short period of time where the external cooling radiator broke as a result of unseasonably cold weather freezing the glycol cooling fluid. The circulation fluid was modeled as 70 % water by volume and 30 % propylene glycol (used to avoid freezing of the fluid at low landfill temperature). Additional details including illustrations (conceptual and onsite photos) of the surface apparatus constructed for the active thermal response tests at the Loraas Northern

Landfill are presented in Morhart (2022).

3. Numerical modeling

An axisymmetric (2D) model of an ATRT landfill was used to obtain thermal parameters based on a field model presented in this study. Two studies were conducted: Initially a stationary hydraulic study was performed for turbulent flow. Thereafter, a time-dependent heat transfer study was carried out, which considered the velocity measured as part of the first study through non-isothermal flow. The effect of fluid flow rate from the first study was then analyzed during the second study by employing heat transfer fluid for different MSW layers within the stratigraphic profile and an inner PVC tube inside a steel pipe, working with two different fluid velocities.

3.1 Geometry

On account of the axial symmetry of both the ATRT system geometry and the initial and boundary conditions, a 2D axisymmetric model with a cylindrical coordinate system (r, z) was employed, as sketched in **Figure 1**. The ATRT system and the surrounding MSW fill within a 5.0 m radius (R) were included in the computational domain, which represents a cylindrical object along with the ATRT apparatus. The landfill was modelled using eight different layers with two further intermediate layers to improve the convergence of the system. The solid phases (MSW and other layers) were modelled as a porous medium with a constant porosity (0.25). It is well known that there is a linear variation of the thermal properties with depth, layer by layer, which was considered in this study. The ATRTs modelled had length (maximum depths) of 23.35 m, and the real 3D unsteady conditions of the heat transfer process were considered. The model geometry also included a 1.6 m thick layer of a MSW and a 3.5 m thick layer of till underlying the ATRT apparatus.

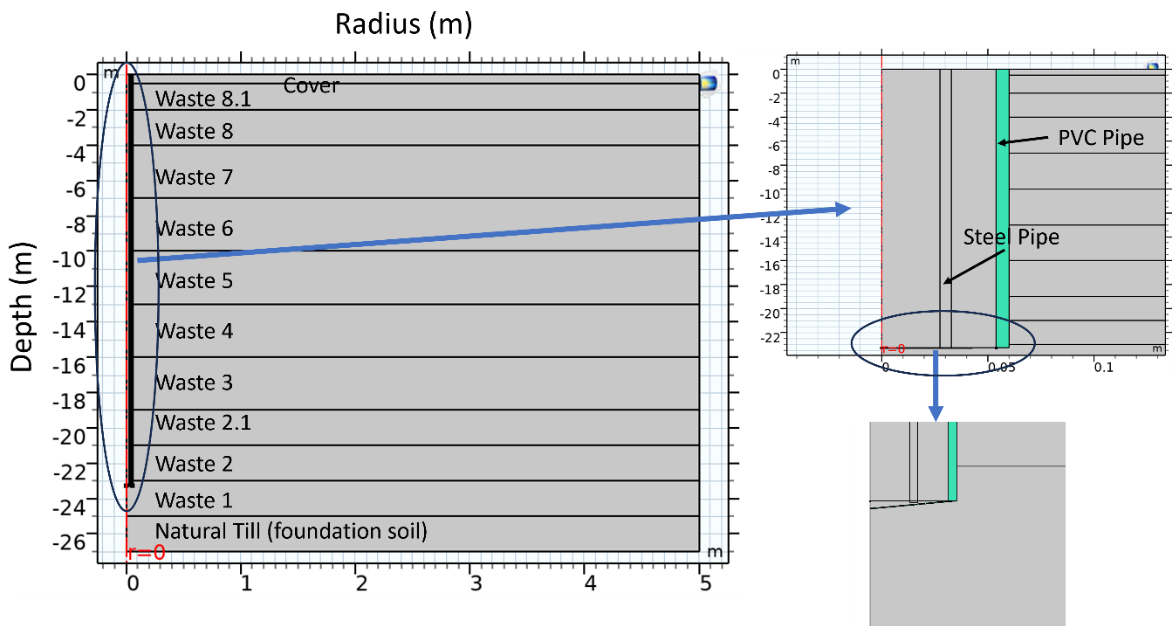


Figure 1 Geometry of MSW landfill and ATRT test model

3.2 Hydraulic model

To understand the spatial distribution of thermal properties within landfills, it is crucial to model the fluid flow within the BHE and its surrounding system. This study utilizes a coupled flow model that integrates the dynamics of liquid movement and heat exchange. The hydraulic model employs the turbulent flow Algebraic yPlus (spf) interface, which simulates high Reynolds number, incompressible fluid flows. This is achieved using advanced Multiphysics software that provides a cross-platform finite element analysis solver, enabling the modeling of complex physics-based systems and coupled partial differential equations.

3.3 Thermal model

Heat transport within a landfill mainly occurs through heat conduction through waste constituents and convective heat transport from both liquid and gas flows through the pore spaces within the waste (Yesiller et al., 2005). In this study, it is assumed that the heat transfer in the ATRT model occurs solely due to conduction and the effects of convection can be neglected. Heat transport in the model is described by the transient heat conduction equation plus convection term (Equation 1) which is derived from the law of conservation of energy (heat) and Fourier's law of heat transport.

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot q = Q + Q_p \quad (1)$$

$$q = -k\nabla T \quad (2)$$

where ρ is fluid density (kg/m^3),

C_P is heat capacity at constant pressure (J/kg*K), k is thermal conductivity (W/m*K), and Q is the general heat source. Q_P can be added to the right-hand side of the equation by enabling the pressure work.

According to (Bonany et al., 2013), the heat transfer within frozen solid waste is governed by conduction. The coefficient of thermal conductivity, k, was assumed to be a linear function of the temperature by authors such that.

$$k = \begin{cases} k_{fro} & T < 0°C \\ k_i + k_s T & T > 0°C \end{cases} \quad (3)$$

Where k_{fro} and k_i are the coefficients of thermal conductivity for frozen and unfrozen material respectively, k_s= 0.001[W/(m*K)] (calibrated as part of this model), and k_s is the coefficient analyzed in order to simulate the thermal response.

As the temperature domain of the model contains both positive and negative temperatures the effects of freezing and thawing, the latent heat of fusion, must also be considered. The formulation for the latent heat for phase change was taken from (Bonany et al., 2013):

$$C_p = \begin{cases} C_s, & T < -1.6\,°C \\ \frac{L}{\Delta T}, & -1.6\,°C < T < -0.6\,°C \\ C_l, & -0.6\,°C > T \end{cases} \quad (4)$$

where C_s is the specific heat for frozen waste (J/kg°C); L: (330 [kJ/kg]) latent heat fusion for the pore fluid in the MSW layers(J/kg), and C_l: specific heat for unfrozen waste (J/kg°C).

3.3.1 Heat generation rate

The heat generation rate (HGR) within a landfill is known to be a function of temperature and volumetric water content, but in this study, for simplicity of the model, the HGR was assumed to only be affected by temperature.

The HGR functions were developed empirically using a sigmoidal relationship between temperature and HGR, analogous to mathematical form to the better-known van Genutchen's function (Equation 5). This sigmoidal relationship was bounded by a minimum HGR (HGR_{min}) at a $T \geq 5$ °C and a maximum HGR (HGR_{max}) at $T \leq 30$ °C. According to (Hanson et al., 2013) and Liu (2007) the HGR functions will vary with the age, having higher HGR values for younger waste and lower HGR values for older waste. Thus, different heat generation rates were predicted for each waste layer in the model. The HGR were developed to be consistent with both the range of values measured in the literature (Hanson (2013); Yoshida et al., 2003; Yeşiller et al., 2005) and site-specific field data gathered by Hucl (2021).

$$HGR(T) = HGR_{min} + \frac{HGR_{max} - HGR_{min}}{[1 + (\alpha T)^n]^{\left(1 - \frac{1}{n}\right)}} \quad (5)$$

Where HGR_{min} and HGR_{max} are the minimum and maximum values of heat generation rate for each layer and α and n are constant calibrated with the expression.

The exact implementation of the different HGR curves can be seen in Appendix B. According to Appendix B, an increase in temperature correlates with an increase in HGR. However, in the older (and therefore deeper) layers of the landfill, where the HGR has already peaked, the variation in HGR with temperature is minimal, as anticipated.

3.4 Material properties

The material groups simulated in this model are the cover soil, underlying glacial till, thermal pumping fluid, steel pipe, PVC pipe, and surrounding MSW. As mentioned above in 3.3.1 both the thermal conductivity and heat capacity for each layer of MSW were calibrated individually. The material properties for the thermal pumping fluid were obtained from the manufacturer. The unit weights of the MSW layers used in this study were determined based on the work of Hucl (2021). This author conducted a comprehensive analysis of the MSW layers using continuous core samples that were carefully extracted for this purpose. Finally, the physical properties of the underlying tills (as reported by Hucl (2021)) and the thermal properties for steel and PVC were determined using data from technical literature. The exact material properties used, can be found in the Appendix C.

3.5 Initial condition

The initial conditions used in this landfill heat transfer model were separated based on their source as seen below:

3.5.1 Solid waste

The initial temperature condition for all the modeled layers, including the underlying till and clay cover can be seen in Table 1.

Table 1 Initial temperature values of all simulated MSW layers including cover and underlying Till.

Waste Layers	Depth (m)	Summer (°C)	Winter (°C)
Waste 1	23.0-25.0	19.4	19.7
Waste 2	21.0-23.0	23.0	24.5
Waste 2.1	19.0-21.0	25.5	26.2
Waste 3	16.0-19.0	28.6	28.8
Waste 4	13.0-16.0	29.8	30.3
Waste 5	10.0-13.0	31.0	30.8
Waste 6	7.0-10.0	27.0	29.5
Waste 7	4.0-7.0	16.0	20.0
Waste 8	2.0-4.0	18.5	13.4
Waste 8.1	0.5-2.0	15.5	5.0
Cover (Till compacted)	0.0-0.5	20.0	6.0
Till natural	25.0-26.0	16.0	16.0

3.5.2 ATRT device

The mean initial temperature of each thermistor inside the annular BHE pipe was measured before starting ATRT. These readings provided a useful initial temperature profile with depth that can be in Table 2. These temperatures were assumed to be valid for both steel pipe and the pvc pipe.

Table 2 Boundary conditions of temperature in the ATRT device.

Depth(m)	Summer Temp. (°C)	Winter Temp. (°C)
0	27.7	-8.2
2	17.8	5.6
9	23.3	26.9
14	27.3	32.2
21	25.1	26.0
23	21.6	22.4

3.6 Boundary conditions

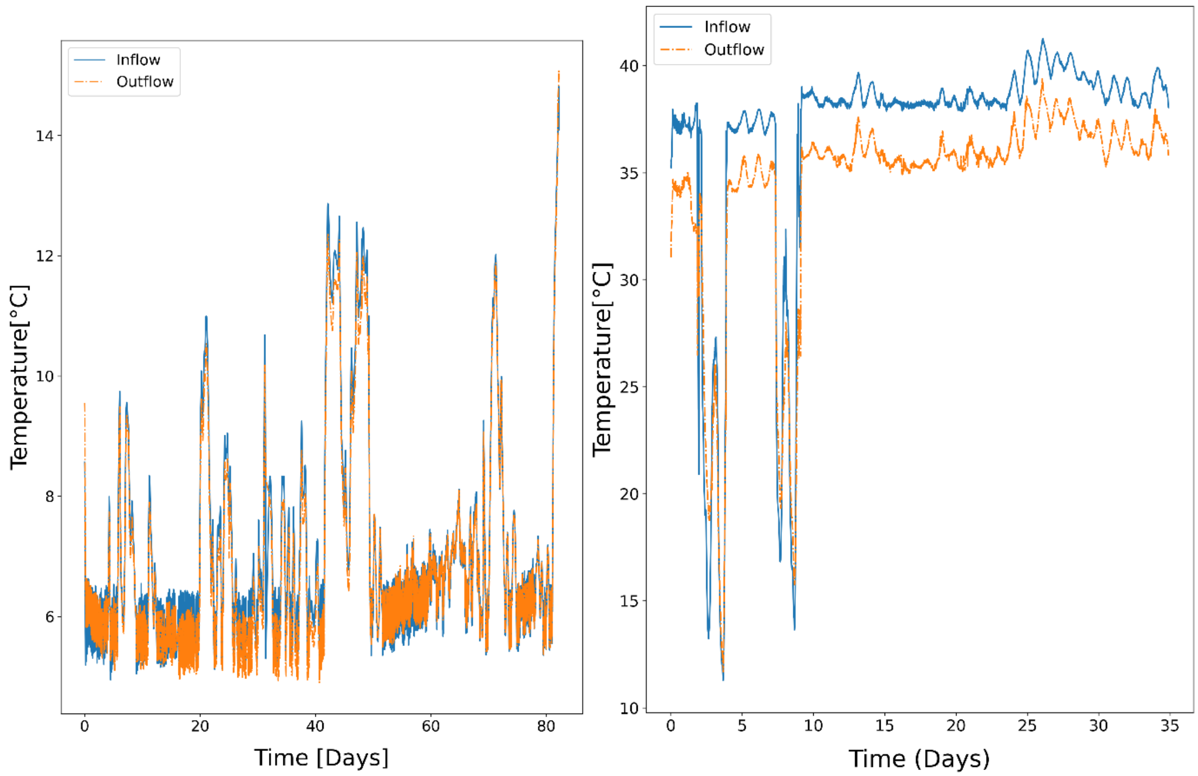
An essential part of any simulation is the determination of the boundary conditions so for this model both hydraulic and heat transfer boundary conditions were established.

3.6.1 Flow

Mean flowrate were measured during the first field trail and hence mean velocity and Reynolds number were calculated for both in the inner PVC pipe and the outer annular passage. The fluid flows in the inner and annular spaces were always turbulent, even with the lowest flow rate, during both summer and winter tests. The velocities for the second ATRT were calculated based on the flow rates of 15.9 L/min for the first 16 days, and 32.2 L/min for the remainder of the test. The variable flowrate was only required for the second ATRT, whereas the flow velocity was constant during the first ATRT. These flows were applied as the inlet data to the circulating fluid system (between steel and inner PVC pipe) input whereas outlet values (inner PVC pipe) were controlled by pressure.

3.6.2 Temperature response due to flow fluid

The temperature boundary applied to the incoming fluid flow was based upon the measured inflow and outflow temperatures as shown in Figure 2. These temperature plots also show the magnitude of daily temperature fluctuations and the effects of the cooling issues noted in section 2.4.



a b

Figure 2 Circulation Fluid TRT Measurements a) Winter test b) Summer Test

3.6.3 Boundary condition on the surface

The surface temperature boundary was established based on the measured annual average surface temperature, obtained from multiple thermistors located on the surface of the site. Two fundamental types of boundary conditions are always considered: specified temperature and specified heat flux. The specified temperature condition directly prescribes the temperature on a boundary. To more accurately simulate the atmospheric effects on the landfill, a Neumann boundary condition was applied (specified heat flux). This condition accounts for the climatic factors of the region, including wind, radiation, and convection.

The Neumann boundary condition specifies the inward heat flux, represented by the following equation:

$$-n * q = h * (T_{ext} - T) \quad (6)$$

The inward heat flux, q_0, is often a sum of contributions from different heat transfer processes (for radiation and convection). A common type of heat flux boundary conditions is one for which $q_0 = h*(T_{ext} - T)$, where T_{ext} is the temperature far away from the modeled domain and the heat transfer coefficient, h, represents all the physics occurring between the boundary and far away. Also, h represents the effect of an exterior fluid cooling or heating the surface of a solid, a phenomenon often referred to as convective cooling or heating.

According to (Hanson et al., 2006), the temperature of waste at the time of placement influences the heat generated in a landfill, particularly the surface temperature in a landfill. The model produced here did not account for the seasonal variation of incoming waste temperature as the waste layers modeled were already deposited prior to field testing.

4. Results

The effect of thermal flow inside the pipe was analyzed, working with two different fluid flow rates (only for winter test), with the inner tube's material constituents: PVC. Once the effects of fluid flow through the BHE were established, the coupled heat flow effect due to fluid flow was also investigated.

4.1 ATRT system hydraulic analysis

Figure 3a shows the results for the fluid velocity field in 3D, with a flow rate of 30.67 L/min. **Figure 3**a was produced using a 3D model to demonstrate the shape of the pipes and the velocity field distribution, both vertically and longitudinally, showing that the highest velocities occur towards the center of the PVC pipe and decrease to zero towards the edges. The 3D axisymmetric model represented in **Figure 3**b shows the temperature variation between the different materials simulated for a given time (Time=82 days). It should be noted that the test represented here is the winter test, and that day 82 marks the end of the heat extraction test and the beginning of the recovery phase.

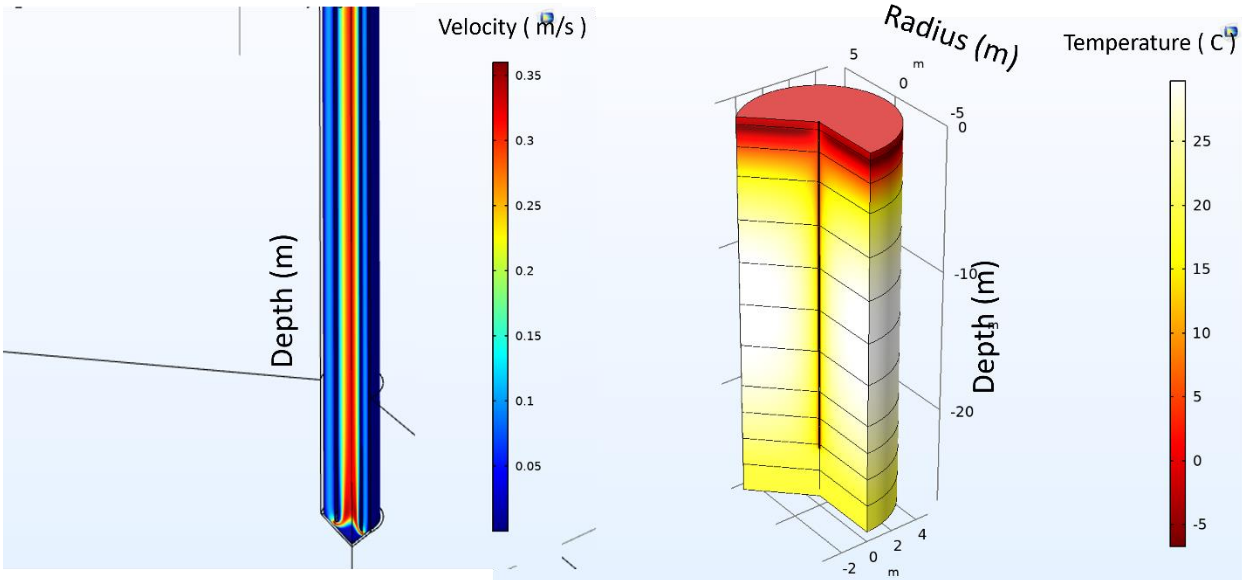


Figure 3 a) Velocity fields for a flow rate of 30.67 L/min in 3D analysis in the BHE system, b) Temperature fields for a flow rate of 30.67 L/min. Time=82 days in the computational domain.

4.2 Thermal analysis

Figure 4, Figure 6 and Figure 6 illustrate the model calibrations when compared to field data. As a first step, the field values obtained for the BHE (radius 0.0 m) were used to calibrate the heat flux from the water flux as shown in **Figure 4**. Once these heat fluxes were calibrated, the model was further calibrated using the data from the monitoring well located at a 1.8 m radial distance from the BHE, as depicted in **Figure 5** and **Figure 6**. A suitable fit is evident in most of the curves in both figures showing the reading of temperature over time.

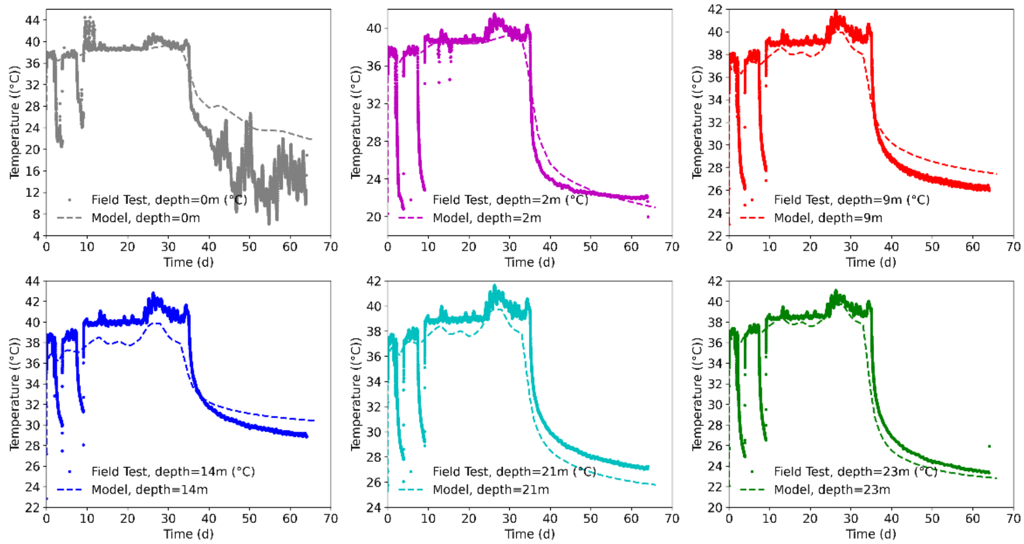
The numerical model simulations of the two field tests were run for the respective duration of the experiments reported earlier. The results obtained from the model are compared with the data during the field tests and are discussed in the following section.

4.2.1 Summer test

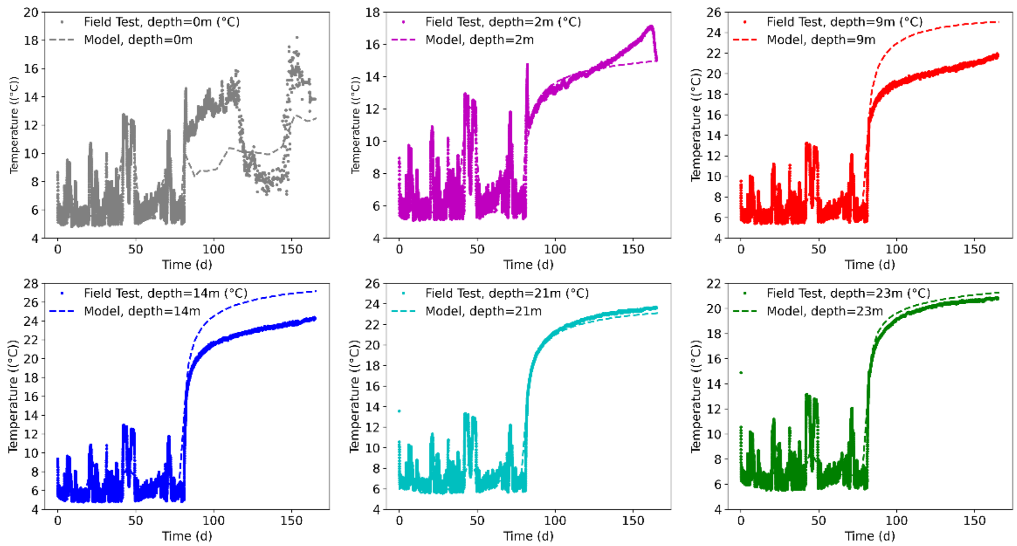
Both the modeled results and measured field response data for both the summer and winter ATRT can be seen in **Figure 5** and **Figure 6** for all measured depths. The trends in predicted and measured temperatures show good agreement at the different MSW fill depths compared, and it is apparent that there was a noticeable thermal response at the TH19-02A thermistor string (r = 1.8 m) for both tests.

Figure 5 shows the comparison of the model predictions with the field data for the summer ATRT at a radius of 1.8 m. The plots in **Figure 5** show that the thermal response stabilized from 50 days onwards in the majority of cases, except at 1.0 and 3.0 m depths, which is to be expected since MSW fill temperatures continued to increase until approximately 10 days into the recovery stage (namely, day 45). After this time, temperatures at each depth remained relatively constant and did not show any indication of decreasing to their initial temperature value. It was also observed, that at a depth of 24 m, the response was lower, as compared to those at depths of 10 m, 15 m, and 20 m.

Owing to the substantial influence exerted by extreme temperature variations at the surface, the response observed following the surface-level model do not exhibit good agreement with the field tests. This inadequacy can be attributed to the fact that the model is not capable of fully capturing the inherent sensitivity to these fluctuations.



(a)



(b)

Figure 4 Temperature reading over time at various depths and radius 0.0m from a) Summer Test, b) Winter Test

4.2.2 Winter test

The predicted temperatures in the winter test were generally within ±2 °C of measured temperatures throughout the entire depth of the landfill, with most of the model predictions within + 0.5 °C of measured temperatures as shown in **Figure 6**. Although there was a good fit in most of the curves, the greatest thermal response was observed at depths less than 10 m (namely, 1 m, 3 m, and 5 m), which is most likely due to atmospheric effects. The influence of atmospheric effects between 6 m and 8 m in depth has been noted at various other landfills in North America (Yesiller et al., 2005) and atmospheric effects between 5 m and 10 m in depth have been noted at the Loraas Northern Landfill Hucl (2021). These atmospheric effects can be observed at depths of 0.0 m and 2.0 m (Figure 4) at a radius of 0 m and depths of 1.0 m, 3.0 m, and 5.0 m depths at the TH19-02A thermistor string, r = 1.8 m (**Figure 6** and **Figure 6**).

It was observed that the thermistor located at a 10 m depth shows thermal responses more akin to those observed at the 5 m depth. According to (Hanson et al., 2022), the influence of the HES is more pronounced towards the middle of the waste depth. Thus, the thermistor at 10 m can be interpreted as transitioning towards the depths of 15 and 20 m, which exhibit distinct thermal responses.

In an attempt to verify the fitted model results from **Figure 5** and **Figure 6** the thermal parameters from both data sets (summer and winter) were compared in **Figure 7** which shows the thermal conductivity and volumetric heat capacity with depth for both tests. Most of the fitted model values from the summer and winter tests seem to be in close alignment with each other. It is worth noting that the values of thermal conductivity and heat capacity seem to differ significantly between the two data sets for depths between 10 and 20 m. These differences specifically at this depth range are most likely due to unideal test conditions during the earlier summer test which were corrected during the second winter test. The overall temperature gradient between the waste temperature at depths between 10 – 20 m and the inlet temperature for the summer tests was relatively small 29.5 and 25.4 °C respectively. This decrease in gradient exaggerated the effect of noise in the results and decreased the quality of the model fit for those depths for the summer trial. In the winter Trial the temperature gradient was much higher, and the test duration was much longer, both factors minimized this issue during the analysis of the winter results.

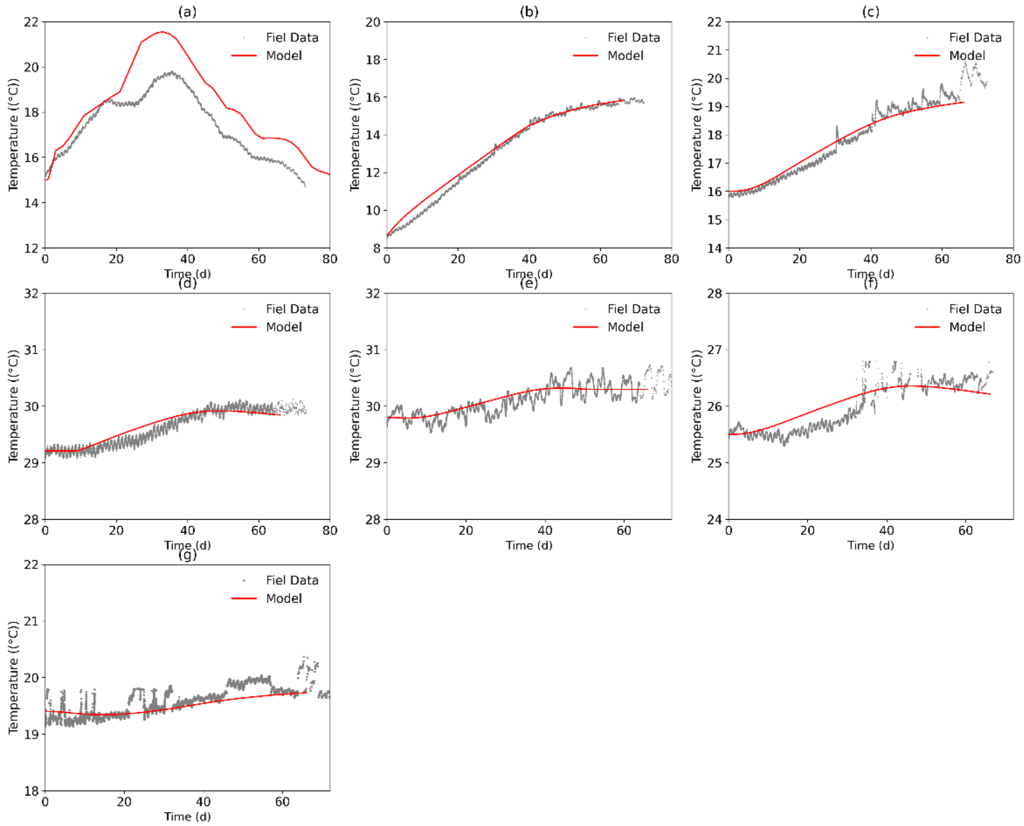


Figure 5 Temperature readings of over time for depths in summer test at radius 1.8m and a) 1.0m, b) 3.0m, c) 5.0m, d) 10.0m, e) 15.0m, f) 20.0m, g) 24.0m

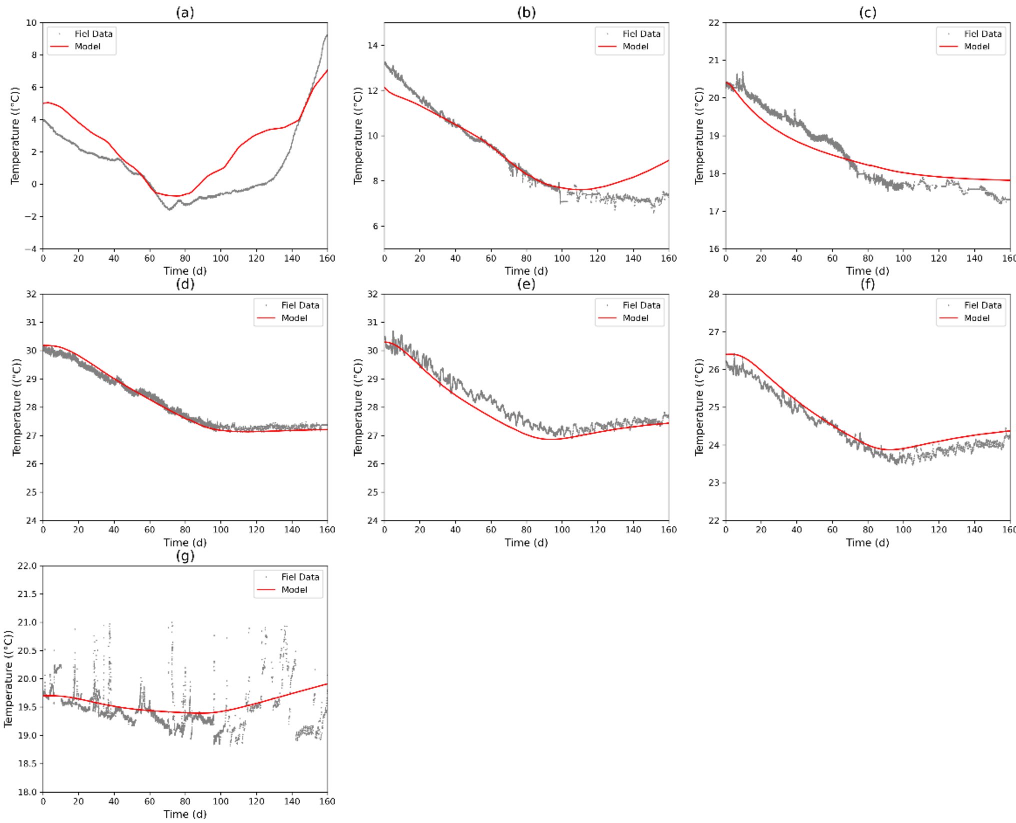


Figure 6 Temperature readings of over time for depths in winter test at radius 1.8m and a) 1.0m, b) 3.0m, c) 5.0m, d) 10.0m, e) 15.0m, f) 20.0m, g) 24.0m

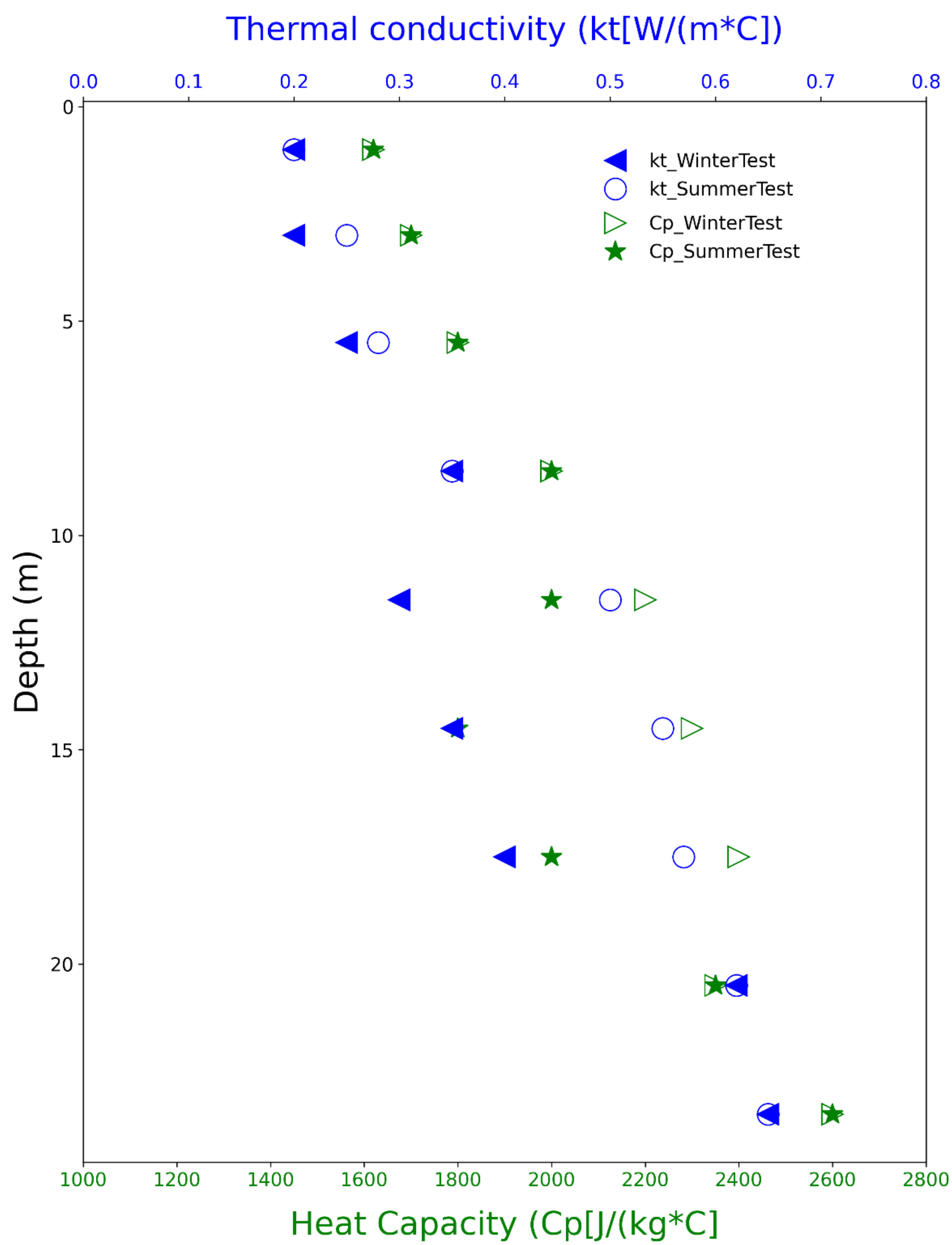


Figure 7 Variation with depth for both tests thermal conductivity volumetric heat capacity

5. Discussion and conclusion

A hydro-thermal (HT) model was developed with the aim of improving the simulation results of the ATRT process in MSW landfills, specifically by determining the thermal parameters of the landfill. To verify and calibrate the model, data from two ATRTs conducted in a medium-sized cold-weather landfill were simulated. The first ATRT (summer test) involved a 35-day heat injection test, followed by 25 days of recovery, while the second ATRT (winter test) consisted of 82 days of heat extraction, followed by 83 days of recovery. Based on the numerical simulations of these field tests, several conclusions were drawn.

The predictions of the proposed HT model were able to closely and, in some cases, accurately capture the field data curve in the majority of cases. The typical temperature profile with depth in MSW landfill depth was demonstrated by the ATRT test, which showed elevated temperatures in the center and decreasing temperatures as depth increased. On the other hand, landfill surface temperatures are influenced by the area's climatic conditions.

The results of the summer test showed stabilization beginning on day 50, approximately 15 days after the injection ended. However, it is important to note that temperatures at depths of 15 and 20 m did not increase in this case. In the winter test, equilibrium was reached at all depths except for 1 m after 100 days (as shown in Figures 5(a) through 5(g)). Specifically, it took 18 days for stabilization to occur, with a slight but gradual increase in temperature at depths of 15 and 20 m (as shown in Figures 5(e) & 5(f)). Interestingly, the 15 and 20 m depths did not reach equilibrium; instead, a rebound effect was observed. This can be attributed to the fact that these layers were more thermally active due to their higher initial temperatures. In contrast, the fluctuations at lower depths with lower temperatures were minimal.

In both the winter 2021 and summer 2020 tests, the temperature change at 24 m is significantly lower than that at other depths. This may be a result of the layer being placed years earlier, which may have already generated the vast majority of the heat it will produce. Therefore, the waste at

24 m depth had a lower temperature than the overlaying layers of MSW fill, and it was also very close to or in contact with the underlying Till, which was at a lower temperature.

The HGR was considered in the finite element analysis. However, given that the test was conducted over a short-term period, the temperature variation between the minimum and maximum values did not exceed 4 °C, thereby the increase in HGR rates is not that significant. This suggests that, in this context, the HGR parameter has a negligible effect on heat transfer.

The thermal parameters of the simulated MSW layers for the summer and winter simulations were compared at each thermistor depth. It was found that the predictions of both thermal conductivity and heat capacity aligned very closely for most depths. The only significant differences in thermal properties between the two simulations occurred at depth between 12 m – 20 m. Although these differences may be explained by an insufficient thermal gradient across the BHE at these depths during the summer heat injection test, which lead to difficulties in fitting the thermal parameters at these depths in the summer simulation of the HT model. These issues were noted, and a higher thermal gradient was used during the winter 2021 test to induce a more pronounced thermal response, along the whole BHE including the depths of 12 m to 20 m.

The increase in heat capacity with depth can be attributed to the higher liquid content of the predominant materials found at greater depths compared to shallower depths.

Going forward, there are still a few improvements that could be brought into the model. One of them is to consider the effect of the convection on the thermal flow. Also, infiltration of snow as it thaws to predict thermal response at shallow depths.

CRediT authorship contribution statement

Vladimir Buelvas: Conceptualization, Methodology, Software, Validation, Writing - original draft, Visualization. Logan Morhart: Field test. Tyler Casavant: Field test and writing. Ian Fleming:

Conceptualization of this study, Writing - review & editing, Supervision. Claudio Mahler: Final revision.

Acknowledgments

Much of the study research was supported by Loraas Disposal Service Inc, Saskatoon Canada.

Funding

This research project was funded by the University of Saskatchewan and Loraas Disposal Service Inc, Saskatoon. The corresponding author would like to acknowledge the financial support of Pasaporte a la Ciencia "ICETEX-Colfuturo, Canadian Federal Government's ELAP programme as well as Colciencia regiones.

6. References

1. Berquist, C., 2017. The Impacts of Temperature and Thermal Properties on Municipal Solid Waste Stabilization. Ph.D. thesis.
2. Bonany, J.E., Van Geel, P.J., Burak, H., Burkan, I.O., 2013. Heat budget for a waste lift placed under freezing conditions at a landfill operated in a northern climate. Waste Manag. 335, 1215–1228. https://doi.org/10.1016/j.wasman.2013.01.020.
3. Faitli, J., Magyar, T., Erdélyi, A., Murányi, A., 2015. Characterization of thermal properties of municipal solid waste landfills. Waste Manag. 36, 213–221. doi: 10.1016/j.wasman.2014.10.028.
4. Hanson, J. L., Onnen, M. T., Yeşiller, N., & Kopp, K. B. (2022). Heat energy potential of municipal solid waste landfills: Review of heat generation and assessment of vertical extraction systems. Renewable and Sustainable Energy Reviews, 167, 112835. https://doi.org/10.1016/j.rser.2022.112835
5. Hanson, J., Yeşiller, N., Howard, K., Liu, W.L., Cooper, S., 2006. Effects of placement conditions on the decomposition of municipal solid wastes in cold regions, in: Proceedings of 13th International Conference on Cold Regions Engineering.
6. Hanson J., Yesiller N., Liu W., Oettle N., Marinos J. 2013. Development of numerical model for predicting heat generation and temperatures in MSW landfills. Waste Manag. 1993-2000, 33(10).
7. Hucl, G.B. 2021. *Derivation of first-order decay heat generation function and prediction of thermal energy potential for a municipal solid waste landfill.* Master Thesis. University of Saskatchewan.
8. Liu, Wei-Lien. 2007. *Thermal Analysis of waste landfill*. PhD Thesis.

9. Lu S. and Feng S. 2020. Comprehensive overview of numerical modeling of coupled landfill processes. Waste Manag. 161-179, 118.
10. Megalla, D., 2015. *Heat transfer model for an engineered landfill in Sainte- Sophie, Quebec, Canada*. MA Sc. Ph.D. thesis. Thesis, Ottawa, Canada. https://curve. Carleton. ca/system/files/etd.
11. Megalla, D., Van Geel, P.J., Doyle, J.T., 2016. Simulating the heat budget for waste as it is placed within a landfill operating in a northern climate. Waste management 55, 108–117.
12. Morhart, L. J. 2022. *Evaluation of low-grade geothermal energy recovery from a cold climate municipal solid waste landfill.* Master Thesis. University of Saskatchewan.
13. Nocko, L.M., Botelho, K., Morris, J.W.F., Gupta, R., McCartney, J.S., 2020. Thermal conductivity of municipal solid waste from in situ heat extraction tests. J. of Geotechnical and Geoenviron. Engineering 146, 04020077. doi:10.1061/(ASCE) gt.1943-5606.0002325.
14. Rowe, R.K., Hoor, A., Pollard, A., 2010. Numerical examination of a method for reducing the temperature of municipal solid waste landfill liners. J. of Environ. Engineering 136, 794–803. doi:10.1061/(ASCE)EE.1943-7870.0000212.
15. Shi, J., Zhang, T., Zhang, J., Ai, Y., Zhang, Y., 2018. Prototype heat exchange and monitoring system at a municipal solid waste landfill in China. Waste Manag. 78, 659–668. doi: 10.1016/j.wasman.2018.06.036.
16. Yesiller, N., Hanson, J., Liu, W.L., 2005. Heat generation in municipal solid waste landfills. Journal of Geotechnical and Geoenvironmental Engineering 131, 1330.
17. Yeşiller, N., Hanson, J.L., Kopp, K.B., 2016a. The design and installation of a prototype

heat extraction system at a municipal solid waste landfill, in: Geo-Chicago 2016, pp. 111–120.

18. Yeşiller, N., Hanson, J.L., Kopp, K.B., Yee, E.H., 2016b. Heat management strategies for MSW landfills. Waste Management 56, 246–254. doi:10. 1016/j.wasman.2016.07.011.

19. Yeşiller, N., Hanson, J.L., Yee, E.H., 2015. Waste heat generation: A comprehensive review. Waste Manag. 42, 166–179. doi:10.1016/ j. wasman.2015.04.004.

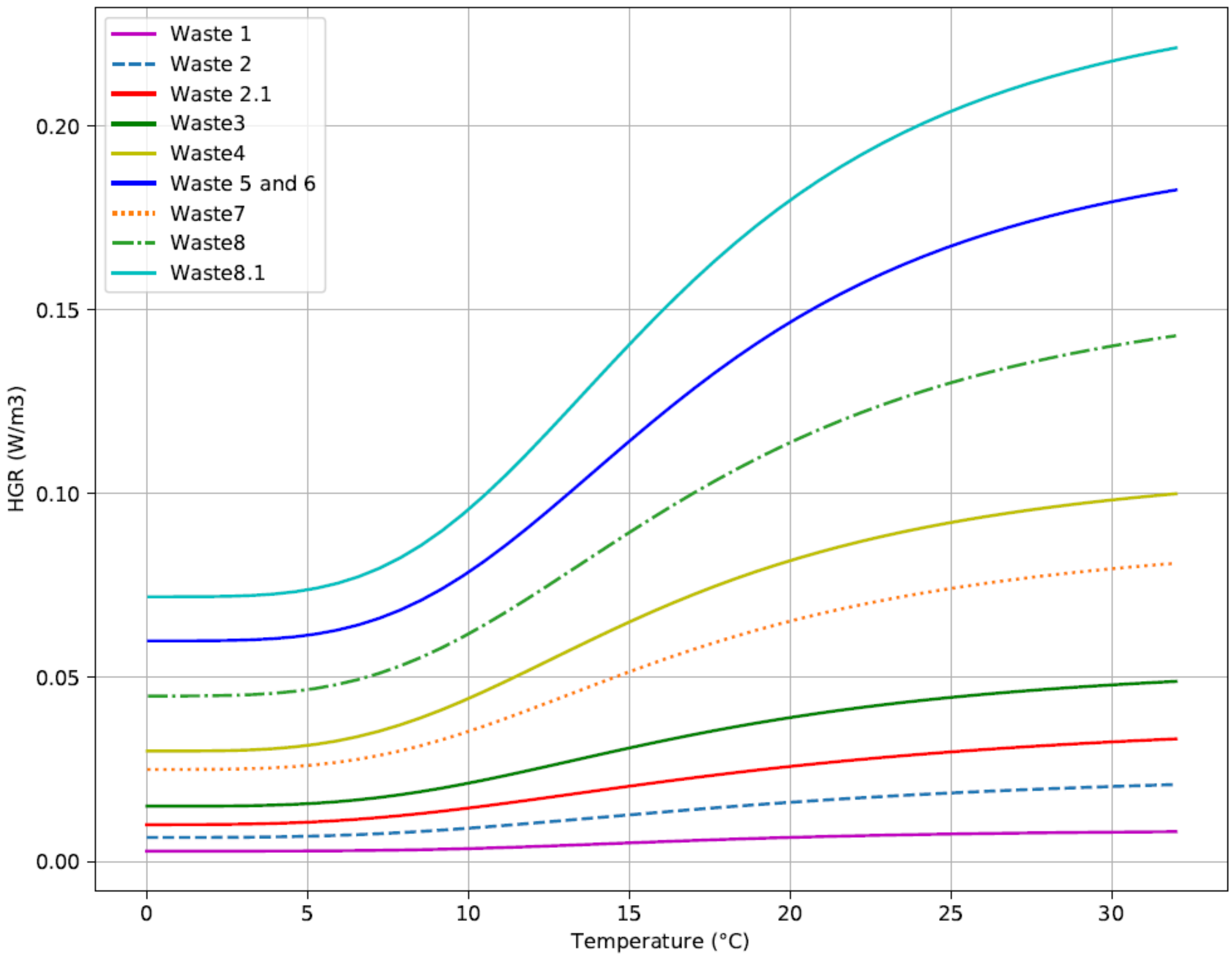
20. Yoshida, H., Rowe, R.K., 2003. Consideration of landfill liner temperature, in: Proceedings Sardinia, pp. 6–10.

21. Zanchini, E., Lazzari, S., Priarone, A., 2010. Improving the thermal performance of coaxial borehole heat exchangers. Energy 35, 657–666. doi: 10.1016/j.energy. 2009.10.038.

7. Appendices

Appendix A. Cross-section of installed BHE including thermistors and backfill material.

Appendix B. Heat generation in function of temperature for each layer**.**



Appendix C Material thermal properties.

MATERIAL	Thick (m)	Density (kg/m^3)	Thermal conductivity, k_t (W/mK)	Heat Capacity, C_p (MJ/m^3K)	Dynamic viscosity (Pa.s)
Cover	0.5	2400	3.7	3.5	NA
Annular A53 Steel	NA	7850	51	3.6	NA
PVC	NA	1760	0.1	1.6	NA
Glicol	NA	1020	0.3	4.5	0.042
Till Natural	2.0	2200	3.7	3.1	NA