

Temperature Fluctuations in a Landfill in Response to Periodic Changes in Surface and Tide-Driven Groundwater Temperatures

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Abstract

In Australia, the concentration of population along the coastal regions has resulted in the construction of landfills near the coastal regions. The wastes buried in these unlined landfills are therefore exposed to tidal influence, often resulting in the dispersion of organic and inorganic pollutants to the surrounding environment. In a project co-sponsored by the Rockhampton Regional Council, a number of processes at a landfill site situated in the flood plains of the Fitzroy River are being investigated. The processes include those in terms of multiphase flow consisting of gas (methane), solute (measured as salts, via EC and pH) and water in a porous media.

In this paper we analyse temperature changes in groundwater and porous media of the landfill which is subject to periodic surface and tide-driven temperatures. The heat equation is solved, subject to two periodic boundary conditions (BC): the top BC is a periodic surface temperature due to the change in air temperature, and bottom BC is a periodic function to account for the changes in groundwater temperature induced by tides. The methods can be used to locate key parameters and variables of concern in the porous media, and to forecast their variability with time, using publicly available air temperature and tide data.

Keywords: Phytocapping; Soil temperature; Groundwater temperature; Landfill

Introduction

The waste sector in Australia has advanced over the last decade due to developments in technology. This has introduced Alternative Waste Technologies (AWT) and Energy from Waste (EfW) technologies. In addition, greater emphasis has been placed over recycling, waste diversion and landfill remediation strategies. Despite problems associated with landfills, they are still being built due to their lower capital cost and being the easiest means of disposing waste globally and in Australia [1,2]. Landfilling is particularly common in regional areas due to low population density and high cost of transporting wastes to cities where other methods of disposing or recycling waste have been well established. Due to increased generation of wastes, Local Governments who own and run most of the landfills have concerns over environmental problems arising from these landfills. Landfills built prior to 1993 in Australia do not have liners [3] and have become a major threat to the environment [4]. At present, more than 600 landfills are in operation in Australia [5,6] and most of the small and medium sized landfills in regional Australia still operate with bare minimum infrastructure, despite making landfill capping mandatory for all landfills; big or small.

Local Governments are responsible for municipal solid waste management; including collection, storage, treatment and disposal. In Australia, it is mandatory to obtain a license to operate and maintain landfills. These licenses specify types of waste to be accepted, means of managing environmental pollution (dust, air, odour and water), landfill design criteria and post closure management and monitoring. Every Local Government organisation that owns and operates a landfill is required to abide by the license condition to reduce environmental impacts. However, ongoing maintenance and operating costs of landfills are significantly higher for small and medium sized councils (population <200,000) than for large councils. Some regional councils in Australia operate more than 10 landfills/waste transfer stations (WTS) and maintenance of these landfills is becoming difficult and expensive.

Operational and closure costs of landfills have escalated due to increasing environmental awareness and stringent regulations of the Environmental Protection Authority (EPA). The most popular practice in Australia is the use of a compacted clay cap [7]. Costs of construction, operation and maintenance of clay caps, as specified by State Governments, are very high depending on size of landfill and local availability of clay material. Studies in the past demonstrate that many medium and small types of council have not budgeted for landfill capping. In most cases waste disposal fees and charges do not include landfill capping expenses. Furthermore, mandatory monitoring of landfill's environmental performance, and managing integrity of clay caps for up to 30 years would create another difficulty for many councils.

Lakes Creek Road Landfill was constructed in 1981 and is the largest (45 ha) landfill currently operated and managed by the Rockhampton Regional Council. It is located within the Fitzroy River flood plain, at approximately 1 km from the Fitzroy River. The landfill site is located

adjacent to residential properties to the North of Rockhampton City, a water body to the West, and a mangrove dominated creek to the South and East. Once filled, this landfill site will have to be capped as per the Department of Environment and Heritage Protection (DEHP); previously known as the Department of Environment and Resource Management (DERM) guidelines.

Rockhampton is situated on the Tropic of Capricorn (23.5°S). It receives rain mostly between November to March with a winter rainfall received during June and September. Rockhampton's average rainfall is 780 mm yr⁻¹ (average of 47 years) with a Potential Evapotranspiration (PET) rate of 1632 mm yr⁻¹. The daytime temperature ranges between 32°C (max) to 22°C (min) during summer (wet season) and 23°C (max) to 9°C (min) during winter (dry season).

The landfill site is entirely unique from other landfill sites in Queensland due to its topographic conditions, tropical climate, where PET is greater than annual rainfall by 2 fold, rainfall distribution, depth of the ground water (approx. 3.8 to 4 m from the surface of daily cover, depth of the buried waste (5 to 6 m) which is influenced by tidal fluctuations. Variation in the depth of groundwater table is greatly influenced by the distance of that site from the river [8].

In Australia, coastal zones are heavily urbanised. As a result many landfills in have been constructed in mangrove habitats making it even more harmful to the surrounding environment. It is therefore important to understand the complex nature of groundwater containing nutrients and heavy metals [9]. The fluctuation in ground water levels due to tidal flux is critical due to its impact on the buried waste and methane emission into the atmosphere. Tidal fluctuations can affect groundwater behaviour up to a distance ranging from 21 m (lateral) [9-11] up to 1 km (lateral) [12] with a certain time lag [11,13-15].

Tidal fluctuations are important as they may be linked to ground water discharge [14]. Groundwater may contain heavy metals and ion from landfills and reclaimed land [9]. Piezometers [16] and level sensor (PS21000) manufactured by Green Span (Australia) were used in study to understand the influence of tides on the groundwater.

Experimental setup

The tidal fluctuations were monitored as part of a research conducted on Phytocapping; an alternative capping technology to reduce waste percolation into buried waste. Piezometer wells were installed at the site - 3 wells x 2 replications. One set of 3 wells were installed near the trial plot at the eastern end and a second set of 3 wells were installed 100 m away from the plots (towards the Fitzroy River). Piezometers at each location were installed at 2 m, 5 m and 9 m depths. During the installation process, the ground surface was drilled to the desired depth (e.g. 2 m, 5 m, 9 m) and piezometer wells were installed (Figure 1).

While drilling the 9 m piezometer well, soil samples were collected from various depths to determine moisture content and composition of soil material (Table 1). Samples were collected to a depth of 9 m at 0.5 m increments (Figure 2).

Each piezometer well was capped at the top end and was insulated with a screen or a mesh cloth at the bottom end for protection from clogging. Then, wells were insulated by sand and bentonite [17]. After installation, the wells were covered and protected by a metallic tube with a lid and a lock (Figure 3) to protect wells from external environment. During installation, a temperature sensor was also attached to the bottom of the well to observe variations in water temperature. Temperature was recorded using the smart logger (Figure 3) which was used for sap flow measurements.



Figure 1: Drilling of piezometer wells.



Figure 2: Wet waste samples from 6 m depth.

Depth (m)	Plot 1	Plot 2
1	soil + stones	soil + stones
2	soil + dry waste + Stones	soil + dry waste + stones
3	soil + stones + dry waste	soil + stones + dry waste
4	soil + dry waste	soil + dry waste
5	wet waste	wet waste
6	wet waste	wet waste
7	wet waste	wet waste
8	wet waste	clay water (7.8 m)
9	clay water (8.5 m)	clay water

Table 1: Composition of the landfill material at various depths.



Figure 3: Piezometer tube completely protected with metal casing.

Meteorological Data

Monthly micro-climatic data was gathered from the Bureau of Meteorology (BOM) site at Rockhampton and from a weather station that was installed at the landfill site. Hourly, daily, monthly and yearly temperature, relative humidity, wind direction, radiation, evaporation wind

velocity, rainfall, rainfall duration and rainfall intensity data were obtained for the duration of the study. This data was required to evaluate the performance of the phytocaps for methane emission and species transpiration rates and canopy rainfall interception potential. This data was also used in simulating the site water balance using HYDRUS 1D. Tidal information was obtained from the Queensland Maritime Safety (QMS) Office for Fitzroy River.

Results and Discussion

It is well known that the soil temperature is influenced both by the fluctuating air temperature and by the tidal temperatures. The measured temperatures of the air and the soil are shown in Figure 4.

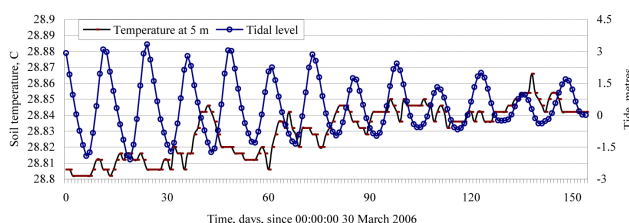


Figure 4: Soil temperature changes in response to changes in tidal height.

It is evident from Figures 4 and 5 that the changes in soil temperature do not strictly follow neither the air temperature nor the tidal heights (and hence the temperature). A combination of these might influence the soil temperature in the landfill. Thus, the combinations of air temperature and the ground water temperature influence the soil temperature under the landfill. As a consequence, we need to incorporate the two effects in the analysis shown below, which in mathematical terms, can be interpreted as two periodic boundary conditions.

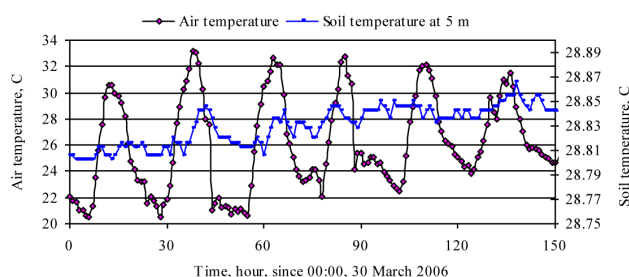


Figure 5: Effect of air temperature on the soil temperature.

Mathematical Formulation for Heat Transfer in Soils

When the groundwater temperature is affected both by the fluctuating air temperature from the surface and tidal temperature from the bottom, the temperature in the groundwater will be an integrated response to both the air temperature and tidal temperature accordingly. For such a problem, the mathematical formulation becomes a classic mixed time-dependent initial and boundary problem, which can be written as [18],

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) \quad (1)$$

$$T(z, t) = \phi_1(t) \quad z = 0 \quad (2)$$

$$T(z, t) = \phi_2(t) \quad z = D \quad (3)$$

$$T(z, t) = f(z) \quad t = 0 \quad (4)$$

Where T is the temperature ($^{\circ}\text{C}$);

z is the vertical space coordinates (L, e.g., cm);

t is time;

$f(z)$ is the initial temperature distribution with depth;

k is the thermal diffusivity (usually in units of cm^2/h), and

$$k = \frac{\lambda}{\rho c} \quad (5)$$

With λ the thermal conductivity (in units of m/h);

ρ the gravimetric density of soil particles (kg/m^3);

c the specific heat capacity of the soil (kJ/kgK).

Normally, the term ρc is called the volumetric heat capacity ($\text{kJ}/\text{m}^3\text{K}$). Marshall et al. [19] suggested that a weighted mean of the volumetric heat capacity, $\bar{\rho c}$, is used to account for the constituency of the soil, i.e.,

$$\bar{\rho c} = \sum_{i=1}^n \theta_i (\rho c)_i \quad (6)$$

Where i the counter of constituents, $i=1,2,\dots,n$, and θ_i is the content of constituent i expressed as a volumetric fractions of the soil.

$\varphi_1(t)$ and $\varphi_2(t)$ are respectively the time-dependent functions on the surface such as air temperature, and tide temperature, and both of which can be conveniently expressed as periodic functions. The air temperature can be written as

$$\varphi_1(t) = A_1 \sin(\omega_1 t - \phi_1) \quad (7)$$

and the tidal temperature can be written as the following [20], Eq. (34), due to tidal movement,

$$\varphi_2(t) = A_2 \cos[\omega_2 t + m \sin(\omega_m t - \phi_2)] \quad (8)$$

Where A_1 and A_2 are the amplitudes of air and tide, respectively;

ω_1 and ω_2 are the frequencies of air and tide, respectively;

ω_m and m is the frequency of tidal modulation and modulation index, respectively;

$$\omega_1 = \frac{2\pi}{p_1} \quad (9)$$

$$\omega_2 = \frac{2\pi}{p_2} \quad (10)$$

ϕ_1 and ϕ_2 are the phase shifts of air and tide temperatures, respectively; and

p_1 and p_2 the wavelengths of air and tide temperatures, respectively.

Equation (1) and its initial and boundary conditions are clear, and we solve it following the work of Carslaw and Jaeger who regard T as a linear combination of two separate components [18] i.e.,

$$T = u + w \quad (11)$$

with

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial z} \left(k \frac{\partial u}{\partial z} \right) \quad 0 < z < D \quad (12)$$

$$u(z, t) = T_a \quad z = 0, z = D \quad (13)$$

$$u(z, t) = f(z) \quad t = 0 \quad (14)$$

and

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial z} \left(k \frac{\partial u}{\partial z} \right) \quad 0 < z < D \quad (15)$$

$$w(z, t) = \phi_1(t) z = 0 \quad (16)$$

$$w(z, t) = \phi_1(t) z = D \quad (17)$$

$$w(z, t) = 0 t = 0 \quad (18)$$

Carslaw and Jaeger presented closed-form solutions of Eq. (1) using by expanding the fundamental solution in a sine series. However, a visual analysis of Carslaw and Jaeger's solution shows that a cosine series expansion is physically realistic and appropriate [18]. With the cosine series expansion, the solution of Eq. (1) subject to (2) to (4) is given as

$$T(z, t) = \frac{2}{D} \sum_{i=1}^n \exp\left[-\left(\frac{n\pi}{D}\right)^2 kt\right] \cos\left(\frac{n\pi z}{D}\right) \left[\int_0^D f(z') \cos\left(\frac{n\pi z'}{D}\right) dz' + \frac{nk\pi}{D} \int_0^t \exp\left[\left(\frac{n\pi}{D}\right)^2 k\tau\right] \left[A_1 \sin(\omega_1 \tau - \varphi_1) - (-1)^n A_2 \cos(\omega_2 \tau - \varphi_2) \right] d\tau \right] \quad (19)$$

Equation (20) is a complete solution, and can be simplified for applications. In practice, a few terms (one or two terms) will be sufficient to approximate the full solution. Here we use only one term as demonstration,

$$T(z, t) = \frac{2}{D} \exp\left[-\left(\frac{\pi}{D}\right)^2 kt\right] \cos\left(\frac{\pi z}{D}\right) \left[\int_0^D f(z') \cos\left(\frac{\pi z'}{D}\right) dz' + \frac{k\pi}{D} \int_0^t \exp\left[\left(\frac{\pi}{D}\right)^2 k\tau\right] \left[A_1 \sin(\omega_1 \tau) + A_2 \cos(\omega_2 \tau) \right] d\tau \right] \quad (20)$$

The further integration of Eq. (19) or (20) can be easily completed when the initial distribution of temperature, $f(z)$, is specified. Under the natural conditions, any temperature profile regarded as an initial distribution is a periodic temperature at a particular time, i.e., the initial temperature is also a function of a periodic function. We use a cosine function, to represent the initial value, i.e.,

$$f(z) = A_0 \cos\left(\frac{\pi z}{D} + \varphi_i\right) + B_0 \quad (21)$$

with A_0 the amplitude, φ_i the phase shift, and B_0 a constant accounting for the background value.

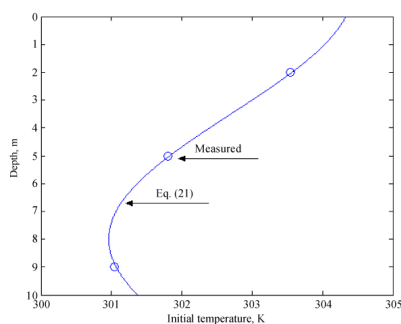


Figure 6: The initial temperature (00:00, 30 March 2006) function and measured values.

It can be seen from Figure 6 that Eq. (21) yields a perfect fitting to the data. Fitting Eq. (21) fitted to the data yields $A_0 = -1.738(K)$, $\varphi_i = -1.738(K)$, and $B_0 = 302.7(K)$.

With Eq. (21), Eq. (20) can be fully completed for two cases: $\omega \neq \pi$ and $\omega = \pi$, and the case for $\omega = \pi$ is physically relevant. In the case of $\omega = \pi$, we have Gradshteyn [21],

$$T(z, t) = \frac{\cos(az)}{\exp(bt)} \left[K_0 + \frac{2k\pi}{D^2} \left\{ K_1 \left\{ \exp(bt) \left[b \sin(\omega_1 t) - \omega_1 \cos(\omega_1 t) \right] + \omega_1 \right\} + K_2 \left\{ \exp(bt) \left[b \cos(\omega_2 t) - \omega_2 \sin(\omega_2 t) \right] - b \right\} \right\} \right] \quad (22)$$

with

$$a = \frac{\pi}{D} \quad (23)$$

$$b = a^2 k \quad (24)$$

$$K_0 = A_0 \left[\cos(\varphi_i) + \frac{\sin(2aD + \varphi_i) - \sin(\varphi_i)}{2aD} \right] - \frac{2B_0 \sin(aD)}{aD} \quad (25)$$

$$K_1 = \frac{A_1}{b^2 + \omega_1^2} \quad (26)$$

$$K_2 = \frac{A_2}{b^2 + \omega_2^2} \quad (27)$$

Equation (22) is complex, and it describes a periodic temperature across the soil subject to the two periodic boundary conditions. Once all the values of the parameters are given, Eq. (22) can be used for predictive and design purposes.

Application of the Model

In the following section, we briefly illustrate the use of the approach presented above in simulating the changes in soil temperature in response to the temperatures of the air and the tide-induce groundwater. The simulated monthly soil temperatures are shown in Figure 6 for different depths.

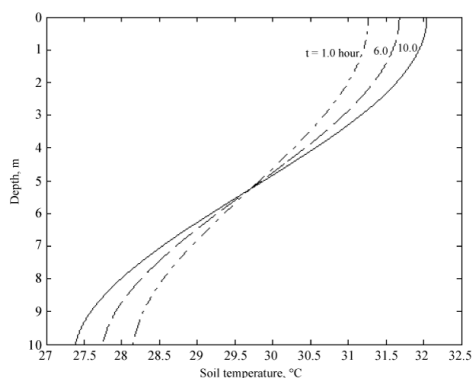


Figure 7: Changes in soil temperature with depth (A) and time (B).

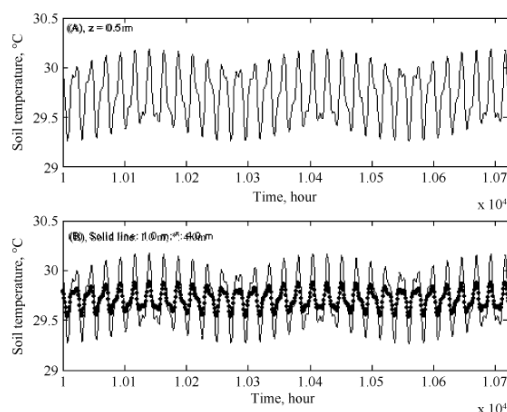


Figure 8: Changes in soil temperature on a monthly scale with a daily resolution.

It can be seen from the above figures that with the procedures described above the complex periodic variations in soil temperature can be simulated satisfactorily.

When simulating the soil temperature using the above methods, two points should be made clear:

[1] An extended “warming up” time is required for the solution to attain an equilibrium state, and the time indicated in Figure 6 is about 10,000 hours;

[2] An average soil temperature, a number equivalent to B_0 , is added to the solution to obtain the above Figures 7 and 8.

Conclusion

The above analysis shows that the variation in soil temperature in response to two periodic boundary conditions is very complex. The closed-form solution is very useful for analysing the changes of soil temperature with depth and time as illustrated.

Most of the data used in the illustration are from measurements, and one of the key parameters for the soil is the thermal conductivity, k , which was calibrated using the data since its measurement is impossible given the nature of the wastes.

Further work is needed to acquire various types of data, particularly the thermal conductivity, k (a value of 0.005 used here) to reveal temperature patterns at different layers. Further analyses can also be carried out to use Eq. (22) for predictive and design purposes.

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