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Article

Modeling the Effectiveness of Cooling Trenches for Stormwater Temperature Mitigation

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Abstract: Due to elevated runoff stormwater temperatures from impervious areas, one management strategy to reduce stormwater temperature is the use of underground flow through rock media termed a cooling trench. This paper examines the governing equations for the liquid phase and media phases for modeling the temperature leaving a cooling trench assuming that changes in temperature occurred longitudinally through the cooling trench. This model is dependent on parameters such as the media type, porosity, media initial temperature, inflow rate, and inflow temperature. Several approaches were explored mathematically for evaluating the change in temperature of the water and the cooling trench media. Typical soil–water heat transfer coefficients were summarized. Examples of predictions of outflow temperatures were shown for different modeling assumptions, such as well-mixed conditions, batch mixing and subsequent release, and steady-state and dynamic conditions. Several of these examples evaluated how long rock media would cool following a stormwater event and how the cooling trench would respond to multiple stormwater events.

Keywords: stormwater; stormwater temperature; temperature modeling; cooling trench; rock crib; stormwater cooling

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1. Introduction

One of the problems of stormwater runoff from impervious surfaces is the heat absorbed in the stormwater and its effect on receiving water streams [1]. Excessive heat loads from stormwater runoff into natural water bodies impact fish and aquatic organism survivability [2,3]. Particularly sensitive are urban areas with their large impervious areas creating elevated stormwater temperatures after a runoff event. Impervious areas absorb heat and then transfer it to stormwater during runoff events [4]. Gulliver et al. [5] showed that the largest runoff temperatures occur for smaller storm events or at the beginning of larger storm events and that this runoff temperature is affected by (1) the rainwater temperature and (2) the heating and cooling processes between the runoff and the land surface.

To reduce the impact of this elevated temperature on receiving streams, DiGennaro [6] studied temperature-related stormwater Best Management Practices (BMPs) and showed that infiltration of stormwater was more advantageous than surface stormwater BMPs such as ponds. This occurred since infiltration into the subsurface eliminated surface heat transfer and took advantage of the cooling with the underground substrate. Some have termed these infiltration BMPs cooling trenches or rock cribs. Hathaway et al. [7] showed that subsurface drainage infrastructure in urban areas tended to moderate elevated stormwater runoff temperatures.

Sabouri [8] evaluated data from cooling trenches or rock cribs ranging in size from 50 to 100 m. Sabouri found that the cooling trench effectiveness was very dependent on the initial media or rock temperature and the temperature of the stormwater and that increasing the length of the cooling trench also led to improved cooling.

Roseen et al. [3] reviewed temperature field data from stormwater infiltration systems and showed that these systems can reduce runoff temperatures by thermal exchange with subsurface media in contrast to surface systems for treating stormwater that can continue to elevate runoff temperatures.

Thompson et al. [9] modeled the effect of a rock crib on stormwater runoff temperatures. They also evaluated the cooling effectiveness of a rock crib in laboratory studies. They assumed in their modeling approach that the influent water was immediately mixed with the water in the crib and that heat conduction occurred between the water and rock. They mixed a fraction of new incoming water with the exiting water in the crib to account for the temporal variation of water temperature inside the crib. This modeling approach did not consider any longitudinal variation in temperature of the water nor of the rock.

The objective of this paper is to develop a mathematical model for heat transfer in a cooling trench accounting for longitudinal variation of the temperature of the water and cooling trench media or rock. Several different solutions and examples are shown illustrating the use of the mathematical solutions.

2. Model Assumptions

For a conceptual model shown in Figure 1, the cooling trench is a porous matrix composed of rock or other media and stormwater. The major processes for heat transfer shown in Figure 2 are rock–water conduction, advective transport of heat in water, and diffusive transport of heat in water and sediment. The governing mathematical equations for the liquid and solid phases are based on the following assumptions:

- There is heat flux between the media and water and between the media and the surrounding soil as shown in Figure 2. All heat loss/gain for the fluid is through contact with a solid phase, such as rocks, there are no other sources/sinks such as groundwater inflow or outflow or radiation;
- There is no vertical or lateral variation in water temperature or solid temperature;
- There is no temporal or longitudinal variation of water diffusivity coefficient (E);
- There is no temporal of spatial variation of the solid–solid heat diffusivity coefficient (D).

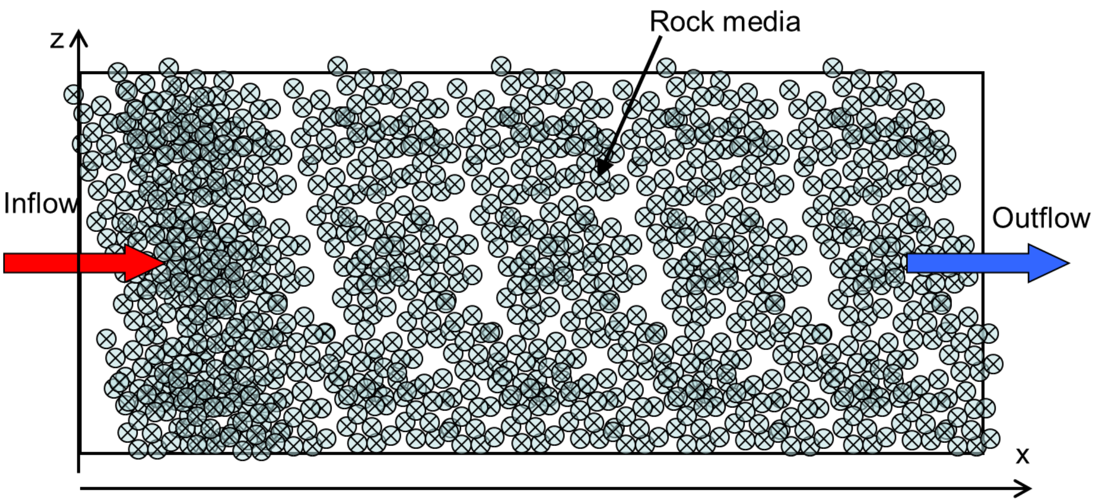

Figure 1. Flow of stormwater into and out of a rock crib or cooling trench with rock media.

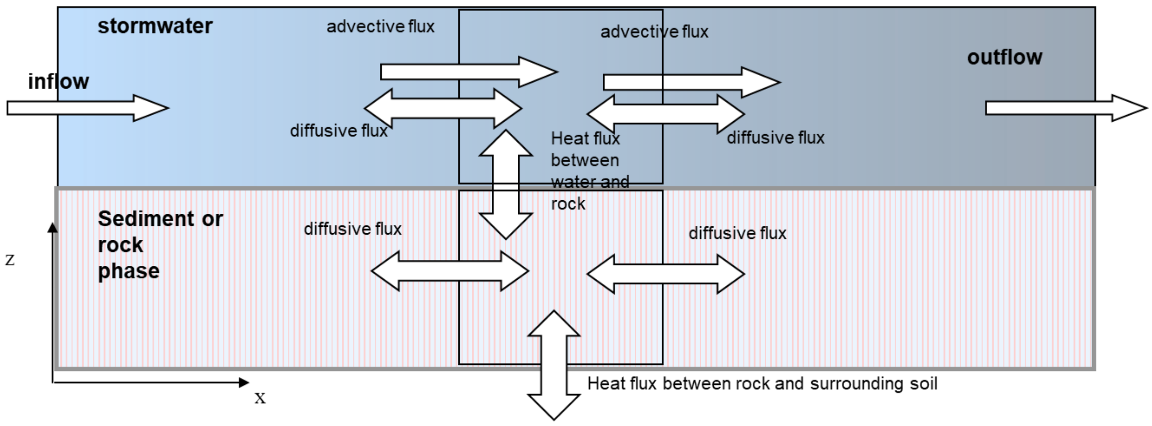

Figure 2. Temperature conceptual model.

The liquid phase and solid phase governing equations can then be described as follows:

Liquid Phase

$$\frac{\partial T}{\partial t} = E\frac{\partial^2 T}{\partial x^2} + \frac{A_{surface}k(T_s - T)}{\rho c_p V\delta} - u\frac{\partial T}{\partial x} \quad (1)$$

subject to an initial condition and boundary conditions:

Initial condition

$T = T_o(x)$

Boundary conditions

$x = 0$, $T = T_{in}(t)$

$$E\left.\frac{\partial T}{\partial x}\right|_{x=L} = 0$$

$x = L$,

<u>Rock Phase</u>

$$\frac{\partial T_s}{\partial t} = \frac{k}{\rho_s c_{ps}}\frac{\partial^2 T_s}{\partial x^2} - \frac{kA_{surface}(T_s - T)}{\rho_s c_{ps} V_s \delta} - \frac{kA_{contact}}{\rho_s c_{ps} V_s}\frac{(T_s - T_{outside})}{\delta_{s-o}} \quad (2)$$

subject to an initial condition and boundary conditions:

Initial condition

$T_s = T_{so}(x,z)$

Boundary conditions

$\left.\frac{\partial T_s}{\partial x}\right|_{x=0} = 0$

$\left.\frac{\partial T_s}{\partial x}\right|_{x=L} = 0$

where T: water temperature (°C);

T_s: rock or sediment temperature (°C);

T_o: initial temperature of water in cooling trench (°C);

T_{so}: initial temperature of rock in cooling trench (°C);

T_{in}: inflow temperature of stormwater (°C);

$T_{outside}$: temperature of surrounding soil outside the cooling trench in contact with the substrate rock (°C);

E: longitudinal dispersion coefficient for heat ($m^2 s^{-1}$);

L: length of cooling trench (m);

$A_{surface}$: surface area of contact between stormwater and rock (m^2);

$A_{contact}$: surface area of contact between rock and surrounding soil matrix (m^2);

k: thermal conductivity of the rock (Joule $m^{-1}s^{-1}$ $°C^{-1}$);

δ: length scale for thermal gradient in rock controlling the heat diffusion process (m);

δ_{s-o}: controlling length scale for thermal gradient in rock to the surrounding soil matrix (outside) (m);
ρ: density of stormwater (kg m^{-3});
ρ_s: rock density (kg m^{-3});
c_p: specific heat of water at constant pressure, 4182 J/(kg °C). (Joule kg^{-1} $°C^{-1}$);
c_{ps}: specific heat of rock at constant pressure (Joule kg^{-1} $°C^{-1}$);
V: volume of voids or liquid = $V_{total}\varepsilon$ (m^3);
V_{total}: total volume of trench (m^3);
V_s: volume of rocks or sediment = $V_{total}(1\text{-}\varepsilon)$ (m^3);
ε: porosity (-);
u: velocity of stormwater through trench = $Q/(A\varepsilon)$ (m s^{-1});
Q: flow rate (m^3 s^{-1});
A: cross-sectional area of trench (m^2);
D: Thermal diffusivity of rock = $k/(\rho_s\ c_{ps})$ (m^2 s^{-1}).

The following additional assumptions were made to facilitate solution of the governing equations:

The contact area of the rocks and the water, $A_{surface}$, was computed by assuming an average spherical diameter of the rocks, d_{rock}, such that

$$A_{surface} = \frac{V_{total}(1-\varepsilon)}{\left(\frac{4}{3}\pi\frac{d^3{}_{rock}}{8}\right)}\pi d^2_{rock}$$

This area was reduced by a factor, f, because the water is not in contact with 100% of the surface area of the rock.

The contact area between the rocks and surrounding soil was computed as the surface area of the trench multiplied by the porosity, such as

$$A_{contact} = (2LW + 2LH)\varepsilon$$

where L, W, and H are the length, width and depth of the trench, respectively.

The length scale for thermal conductivity in the rock, δ, and the length scale for thermal gradient in rock to the surrounding soil matrix (outside), δ_{s-o}, was approximated by half the diameter of the rock media.

These equations were solved for T and T_s as a function of t and x given constant inflow conditions.

The physical properties of the rock or sediment are an important consideration in modeling the thermal transfer between the water and sediment. There have been many studies performed on heat transfer between sediment and water in streams. A summary of several of these studies and their parameter values are shown in Table 1 using the original units of each study.

Table 1. Model parameters for sediment heating.

Reference	Thermal Diffusivity of Sediment, D: $D = \frac{k}{\rho_s c_{ps}}$	Bed Thermal Conductivity, k	$\rho_s c_{ps}$ for Sediment	c_{ps} for Sediment	Description
Fang and Stefan [10]	0.035 m^2/d		2.3×10^6 $J/m^3/°C$		Lake sediment study, determined by calibration
Fang and Stefan [10]	0.01–0.11 m^2/d		1.4×10^6–3.8×10^6 $J/m^3/°C$		Literature reported range and is a function of sediment composition
Silliman et al. [11]	0.0046 cm^2/s	0.0023 cal/cm/s/°C	0.5 $cal/cm^3/°C$		Taken from Carslaw and Jaeger [12]
Jobson [13]	0.01 cm^2/s (range of 0.006 to 0.2 cm^2/s not found to be sensitive to model results)		0.55 $cal/cm^3/°C$		Concrete lined channel, study length 16 miles
Jobson [13]	0.0077 cm^2/s		0.68 $cal/cm^3/°C$		Sand bed study length 17 miles
Chen et al. [14]	1.18×10^{-6} m^2/s or 0.0118 cm^2/s		1.491×10^6 $J/m^3/°C$		Homogeneous rock, study length 9.3 miles
Kim and Chapra [15]	3×10^{-7} m^2/s			795.2 J/kg/°C	Sand–dry, density of dry sand was 1750 kg/m^3, study length 8.5 miles, penetration depth of heat was about 0.25 m for the diurnal case
Kim and Chapra [15]	9×10^{-7} m^2/s			799.8 J/kg/°C	Stone–dry, density of dry sand was 2500 kg/m^3
Pluhowski [16]		0.00394 cal/cm/s/°C			Water saturated sands and gravel mixtures, study length 0.94 miles

3. Model Simplifications

Oftentimes, planners of stormwater BMPs are using screening tools to evaluate the effectiveness of a treatment strategy. In that case, further simplifications to those made in the development of Equations (1) and (2) can be used to evaluate how an alternative may perform. Table 2 shows a series of simplifying assumptions and governing equations that could be evaluated to assess the potential for a cooling trench to mitigate stormwater temperatures.

Table 2. Governing equations for infiltration gallery based on given assumptions.

Governing Water Temperature Equation	Governing Sediment Temperature Equation	Assumptions	Equation
$\frac{\partial T}{\partial t} = E\frac{\partial^2 T}{\partial x^2} + \frac{A_{surface}k(T_s - T)}{\rho c_p V\delta} - u\frac{\partial T}{\partial x}$	$\frac{\partial T_s}{\partial t} = -\frac{A_{surface}k(T_s - T)}{\rho_s c_{ps} V_s \delta}$	1. No heat transfer between the rock media longitudinally 2. Rock mass insulted from the surrounding soil matrix and hence no flux of heat to the surrounding soil	(3)
$\frac{\partial T}{\partial t} = \frac{A_{surface}k(T_s - T)}{\rho c_p V\delta} - u\frac{\partial T}{\partial x}$	$\frac{\partial T_s}{\partial t} = -\frac{A_{surface}k(T_s - T)}{\rho_s c_{ps} V_s \delta} + \frac{A_{contact}k(T_{outside} - T_s)}{\rho_s c_{ps} V_s \delta_{s-o}}$	1. No heat transfer between the rocks longitudinally 2. No diffusive or dispersive flux in the water phase 3. Plug flow assumed for the stormwater	(4)
$\frac{\partial T}{\partial t} = \frac{A_{surface}k(T_s - T)}{\rho c_p V\delta} - \frac{Q(T_{in} - T)}{V}$	$\frac{\partial T_s}{\partial t} = -\frac{A_{surface}k(T_s - T)}{\rho_s c_{ps} V_s \delta}$	1. No heat transfer between the rocks longitudinally 2. No diffusive or dispersive flux in the water phase, i.e., plug flow assumed for the stormwater 3. No spatial gradients in sediment media or stormwater, i.e., both rock and fluid assumed to be well-mixed 4. Rock mass insulted from the surrounding soil matrix	(5)
$\frac{\partial T}{\partial t} = \frac{A_{surface}k(T_s - T)}{\rho c_p V\delta}$	$\frac{\partial T_s}{\partial t} = -\frac{A_{surface}k(T_s - T)}{\rho_s c_{ps} V_s \delta}$	1. Batch reactor with no inflow or outflow 2. Both water and solid phases well-mixed 3. Rock mass insulted from the surrounding soil matrix	(6)
$\frac{\partial T}{\partial t} = \frac{A_{surface}k(T_s - T)}{\rho c_p V\delta} - \frac{Q(T_{in} - T)}{V}$ Steady-state solution: $T = \frac{\frac{Q}{V}T_{in} + \frac{A_{surface}k}{\rho c_p V\delta}T_s}{\frac{Q}{V} + \frac{A_{surface}k}{\rho c_p V\delta}}$	T_s = constant	1. No spatial gradients in sediment or stormwater – treated as well mixed vessel with inflow and outflow 2. Rock temperature constant There are both steady-state and time dependent solutions for water temperature.	(7)
$T_{mix} = \frac{\rho_s c_{ps}(1-\varepsilon)T_s + \rho c_p(\varepsilon)T}{\rho_s c_{ps}(1-\varepsilon) + \rho c_p(\varepsilon)}$	$T_{mix} = \frac{\rho_s c_{ps}(1-\varepsilon)T_s + \rho c_p(\varepsilon)T}{\rho_s c_{ps}(1-\varepsilon) + \rho c_p(\varepsilon)}$	1. Complete mix of water and sediment 2. Steady-state heat balance 3. The rock mass insulted from the surrounding soil matrix	(8)
$\frac{\partial T}{\partial t} = \frac{A_{surface}k(T_s - T)}{\rho c_p V\delta} - \frac{Q(T_{in} - T)}{V}$	$\frac{\partial T_s}{\partial t} = -\frac{A_{surface}k(T_s - T)}{\rho_s c_{ps} V_s \delta} + \frac{A_{surface}k(T_{outside} - T_s)}{\rho_s c_{ps} V_s \delta_{s-o}}$	1. No longitudinal heat transfer between the rocks 2. Plug flow through the infiltration gallery for the stormwater 3. No spatial gradients in stormwater nor in the rock media, i.e., well-mixed	(9)

4. Model Examples

To show how these model solutions can be used, a set of physical parameters were chosen in Table 3 for use in model examples. All the model examples were solved using a FORTRAN computer code even though they can be computed in a spreadsheet.

Table 3. Input parameters and constants for the cooling trench model.

Parameter	Value	Units
L, length of infiltration gallery	25	m
H, height or depth of infiltration gallery	4	m
W, width of infiltration gallery	2	m
ε, porosity	0.35	(-)
V_{total}, total volume of infiltration gallery	200	m^3
Rock or solid media volume	130	m^3
ρc_p density times specific heat of fluid	1	$cal/cm^3/°C$
$\rho_s c_{ps}$ density times specific heat for solid media	0.4	$cal/cm^3/°C$
k, Thermal conductivity of rock	0.004	cal/s/cm/°C
D, Thermal diffusivity, $k/(\rho_s c_{ps})$, of rock	0.01	cm^2/s
d_{rock}, Average diameter of stones	0.08	m
δ, B/L thickness (assume 50% of stone diameter)	0.04	m
$\delta_{s\text{-}o}$, B/L thickness for stone to outside soil heat diffusion (assume 50% of stone diameter)	0.04	m
$A_{surface}$, Surface area - contact area	9750	m^2
$A_{contact}$, Surface area - contact area for rock and surrounding soil	105	m^2
f, Factor to decrease contact area between rocks and water	0.5	(-)
$fA_{surface}$, Actual surface area used in model	4875	m^2
Inflow temperature of water coming into trench	30	°C
Initial temperature of stones	10	°C
Temperature of surrounding soil $T_{outside}$	10	°C
Initial temperature of water in trench	10	°C
E, dispersion coefficient for water	0.1	m^2/s

4.1. Base Case Example

The temperature of the water and solid media as a function of time and longitudinal distance through the domain can be computed using a finite difference form of Equations (1) and (2). An example of this calculation using the parameters in Table 3 and an inflow flow rate of 0.03 m^3/s is shown in Figure 3 for water temperature and Figure 4 for media temperature. With a water detention time of about 30 min, there was significant cooling over this period, but the cooling trench exit temperature warmed considerably within two detention times. This implied that longer stormwater flush events did not benefit from the underground cooling directly even though they would benefit from being shielded from solar radiation if this were a daytime event.

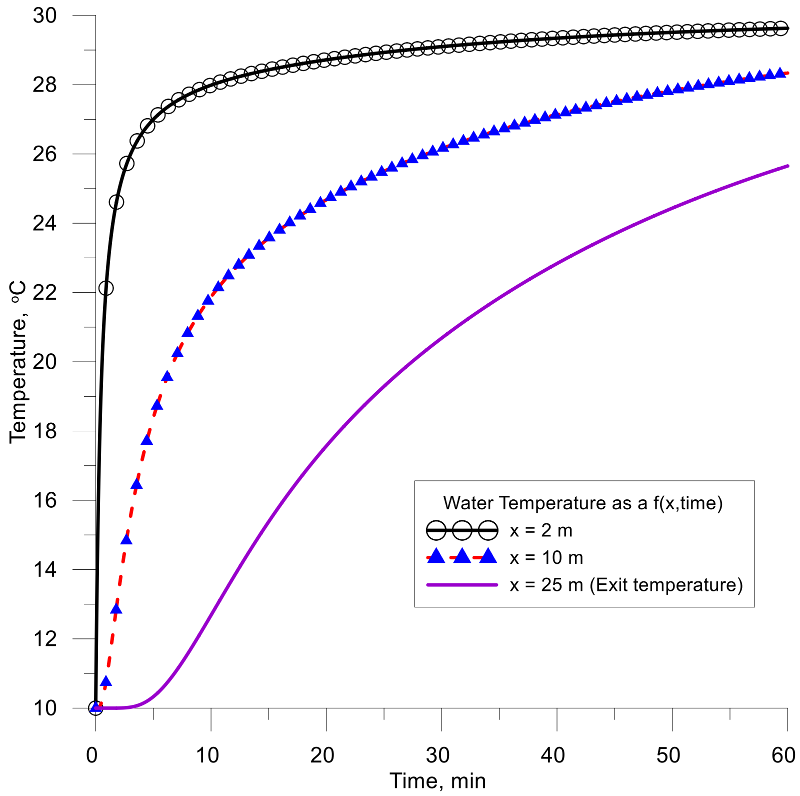

Figure 3. Predictions of temperature of the water at three locations in the infiltration gallery as a function of time for the solution of Equation (1) and (2) for a flow rate of 0.03 m^3/s.

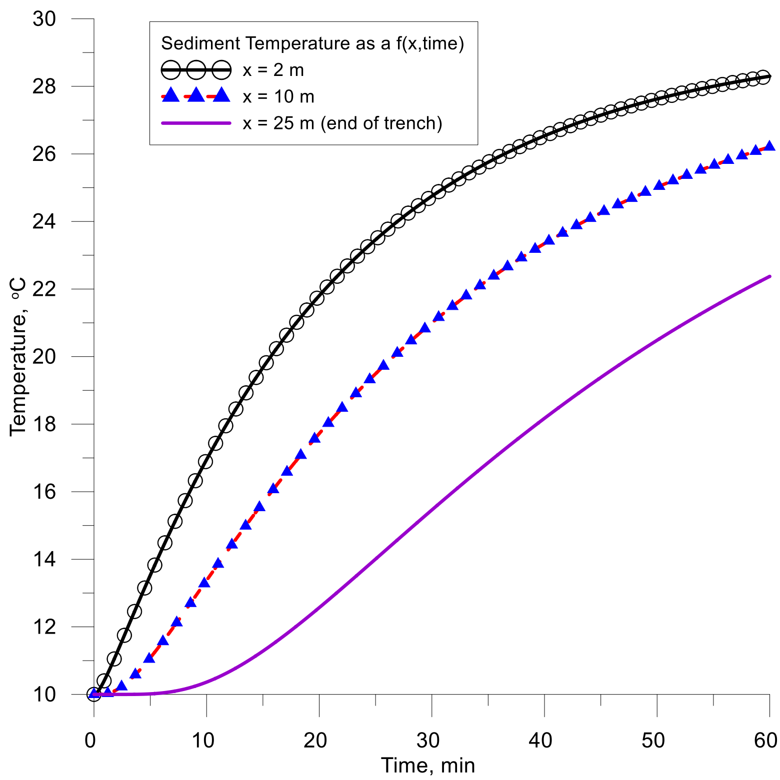

Figure 4. Predictions of sediment or rock media temperature at three locations in the infiltration gallery as a function of time for the solution of Equation (1) and (2) for a flow rate of 0.03 m^3/s.

How long does it take to cool the infiltration trench media in contact with the outside soil? Assuming the outside soil is not affected by the rock media heating up during a storm water event (which is not conservative), Figure 5 shows the rock media temperature during a storm event that lasts 60 min and then stops. The rock media gradually cooled to the surrounding ground temperature very slowly approaching the soil temperature within about 2 days after the stormwater event.

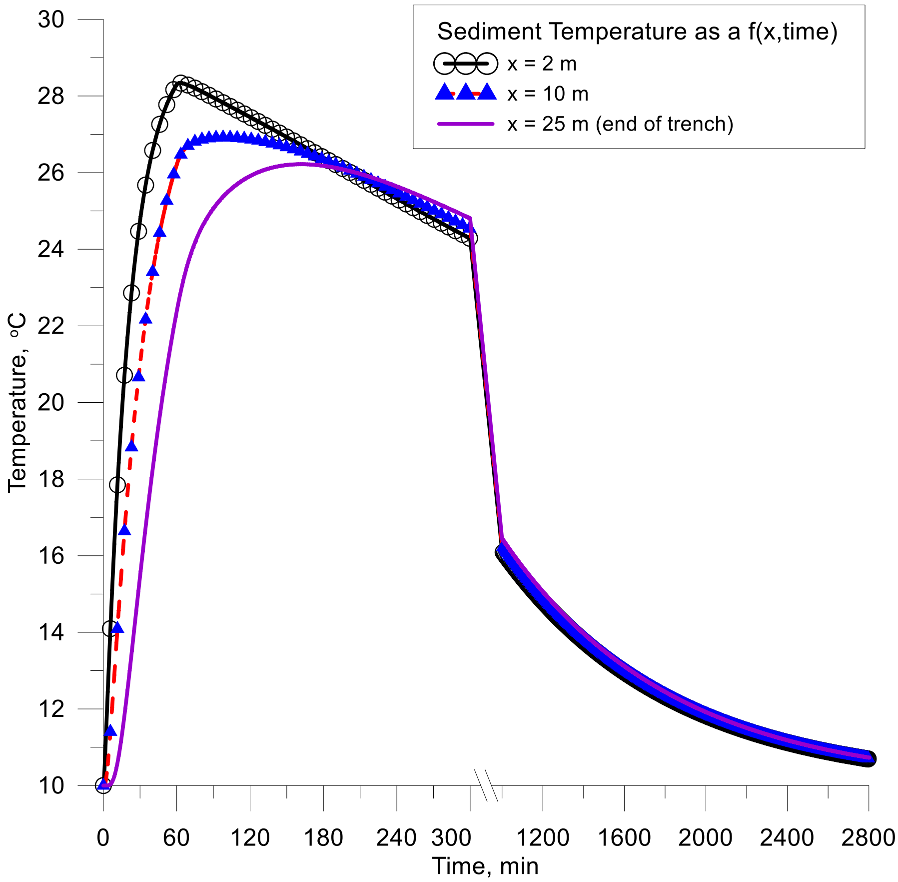

Figure 5. Rock media temperature as a function of position in the cooling trench during and after a storm event ends after 60 min using Equation (2).

4.2. Steady-State Mixing of Stormwater and Media in a Batch Operation

Using Equation (8) in Table 2, the mixed temperature of the rock and water can be computed. This is comparable to infiltrating stormwater (at 30 °C) into rock media (initially at 10 °C) and then letting them reach an equilibrium temperature. The resulting temperature is shown in Figure 6 as a function of porosity. Note that this result is not a function of the dimensions of the cooling trench and that the more media available (lower porosity) the cooler mixed temperature of the water and solid.

4.3. Dynamic Mixing of Stormwater and Media in a Batch Operation

How quickly the water and rock media temperature change if the water and rock were in a well-mixed (batch) reactor can be described by Equation (6) in Table 2. This equation can show the ultimate capacity of the rock thermal mass to cool a specific volume of water. Figure 7 shows a solution using the parameters values in Table 1 where after about 30 min the rock and water have reached an equilibrium. With a volume of the water of about 70 m^3 and a volume of rock of about 130 m^3, the mixed temperature approached 21.5 °C based on Equation (8).

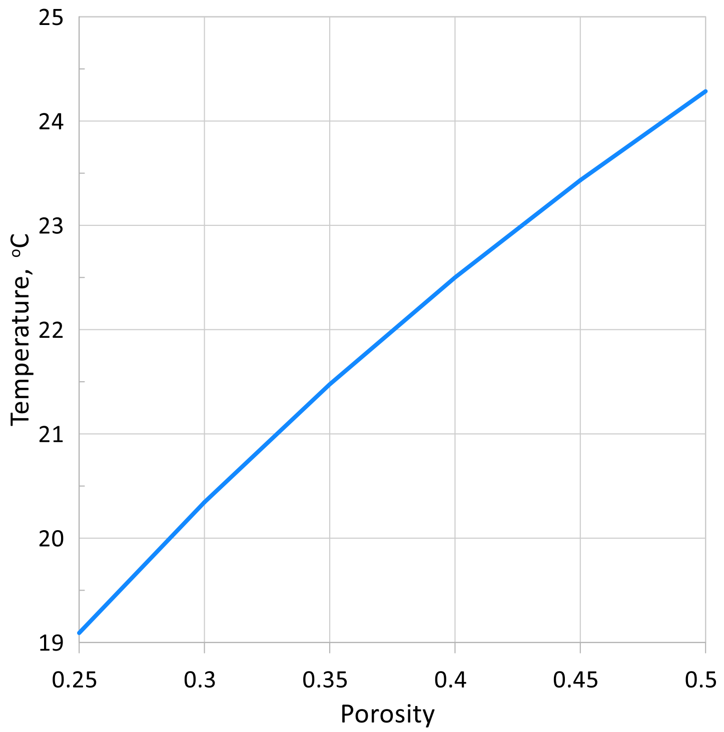

Figure 6. Equilibrium temperature of the stormwater and rock in a batch cooling trench as a function of porosity (Equation (8) in Table 2) with stormwater initially at 30 °C and rock media at 10 °C.

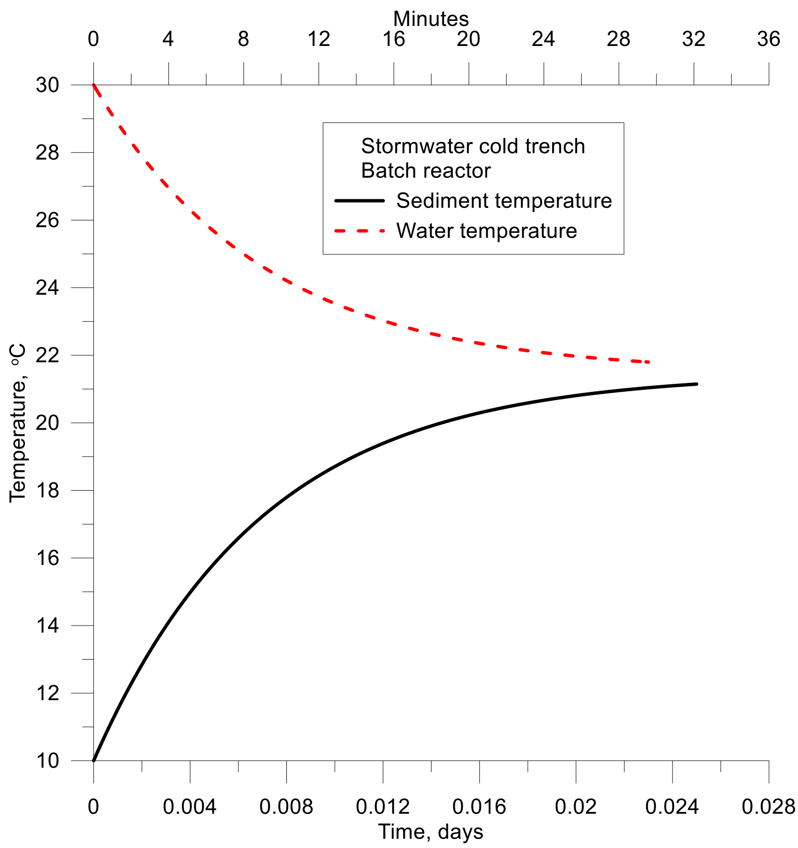

Figure 7. Equilibrium temperature for rock and water for a batch reactor (Equation (6) in Table 2). The initial rock media temperature was 10 °C and the initial stormwater temperature was 30 °C.

4.4. Dynamic Well-Mixed Stormwater and Media with Inflow and Outflow

Equation (5) in Table 2 was used to explore the impact of dynamic flow through the cooling trench assuming the media and water were well-mixed. In this case a range of flow rates were chosen. The flow rates and their detention times are shown in Table 4.

Table 4. Flow rates and detention times of infiltration gallery based on dimensions in Table 2.

Q, m^3/s	Detention Time, days	Detention Time, min
0.03	2.1×10^{-2}	30
0.52	1.3×10^{-3}	1.8
2.72	2.4×10^{-4}	0.3

At the start of the simulation, t = 0 days, the water in the trench was in equilibrium with the rock, i.e., the water initial temperature was the temperature of the rock media. Model predictions of exit temperatures for these flow rates are shown in Figure 8 assuming a constant inflow flow rate and stormwater inflow temperature. These results show that within about twice the detention time of the flow rate the effectiveness of the cooling trench was reduced since exit temperatures significantly approach the inflow temperature. Hence, design volume impacts cooling effectiveness and should be based on the storm event that is being mitigated.

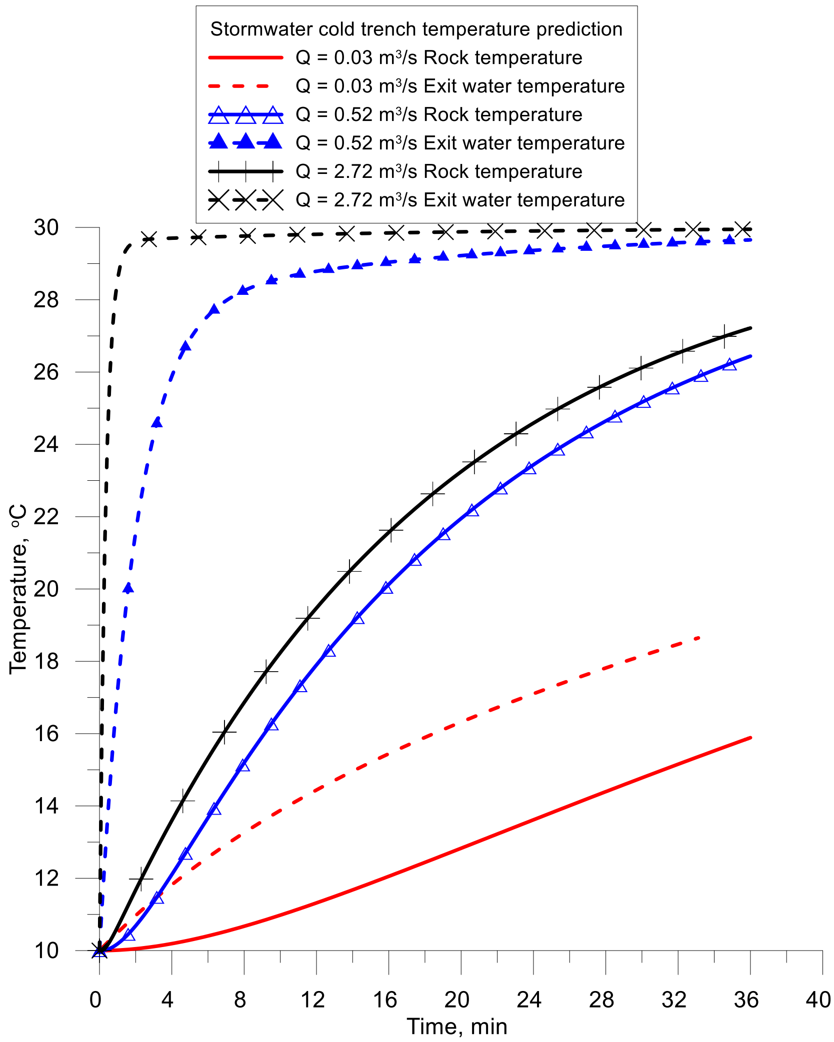

Figure 8. Temperature of rock and water for a well-mixed flow through reactor at flow rates of 0.03, 0.52, and 2.72 m^3/s (Equation (5); Table 2).

4.5. Dynamic Inflow-Outflow Plug Flow with Spatially Variable Water Temperature

Using Equation (4) in Table 2 (except that the soil temperature was assumed equal to the rock temperature, i.e., no impact of stormwater heating the surrounding soil matrix) for a flow rate of 0.03 m^3/s (about a 30 min detention time), the spatial and temporal variation of temperature is shown in Figure 9. The change in temperature of the sediment as a function of position for the same conditions is shown in Figure 10. For both the rock matrix and water, longitudinal diffusion was assumed to be negligible.

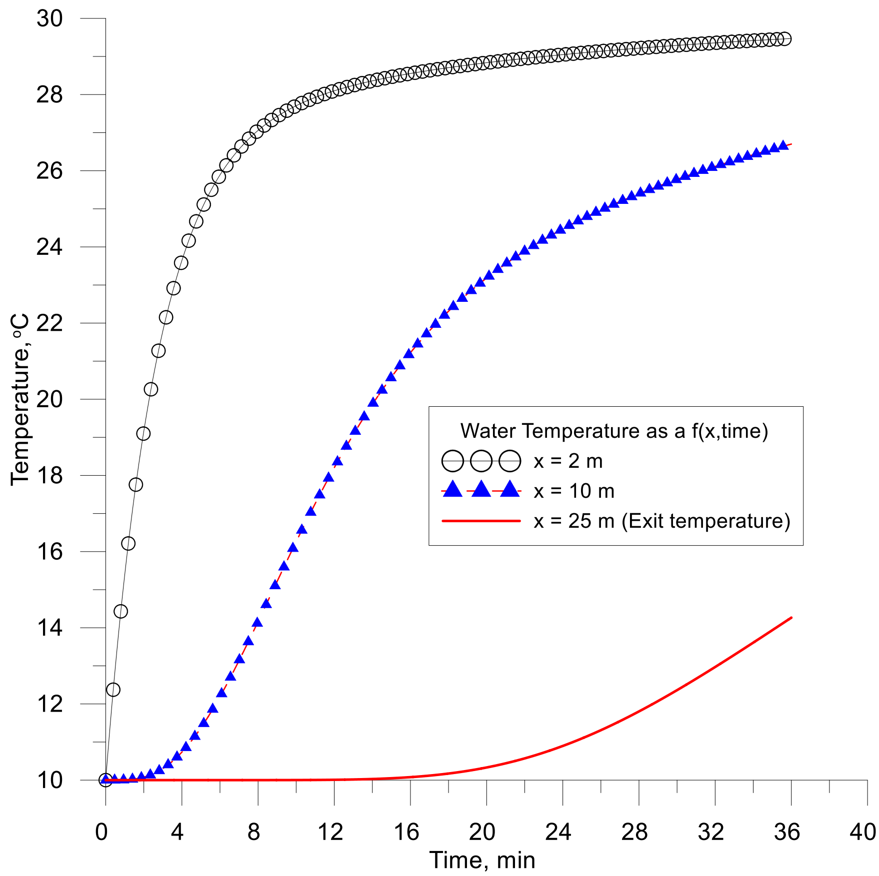

Figure 9. Variation of stormwater temperature as a function of position through a 25 m long cooling trench with an inflow flow rate of 0.031 m^3/s (Equation (4) in Table 2).

After the detention time of the inflow, the exit temperatures were still well-below inflow temperatures. However, the cooling effectiveness of half of the cooling trench has already been depleted.

Using Equation (4) in Table 2 for the case of a flow through the cooling trench of 0.52 m^3/s (about a 2 min detention time), the spatial and temporal variation of temperature is shown in Figure 11. The change in temperature of the sediment as a function of position for the same conditions is shown in Figure 12. Here, after about two detention times, the effectiveness of the cooling trench was compromised.

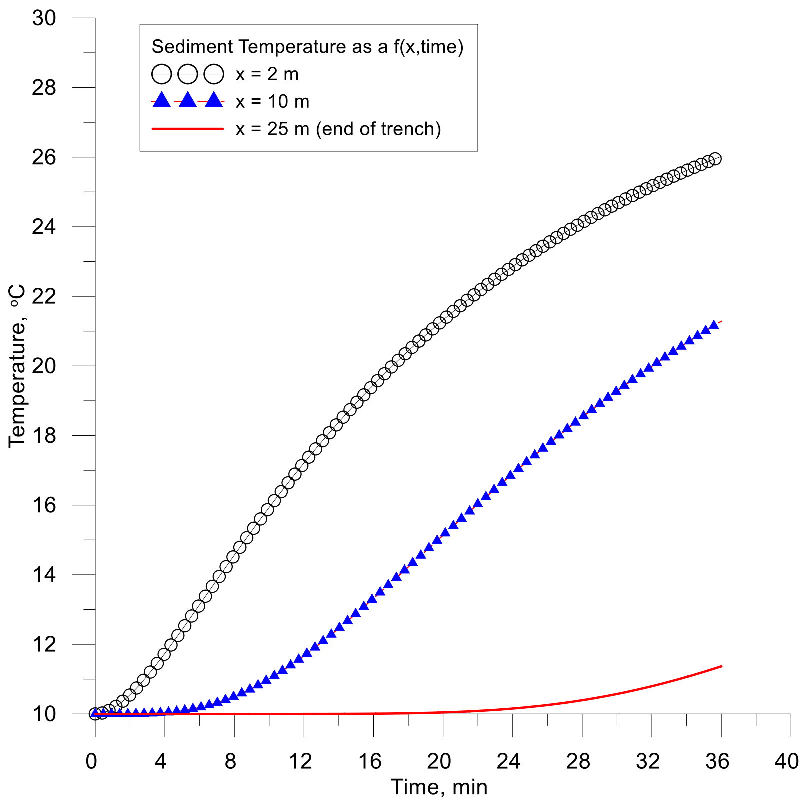

Figure 10. Variation of rock temperature as a function of position for a stormwater inflow flow rate of 0.031 m^3/s through a 25 m long cooling trench (Equation (4) in Table 2).

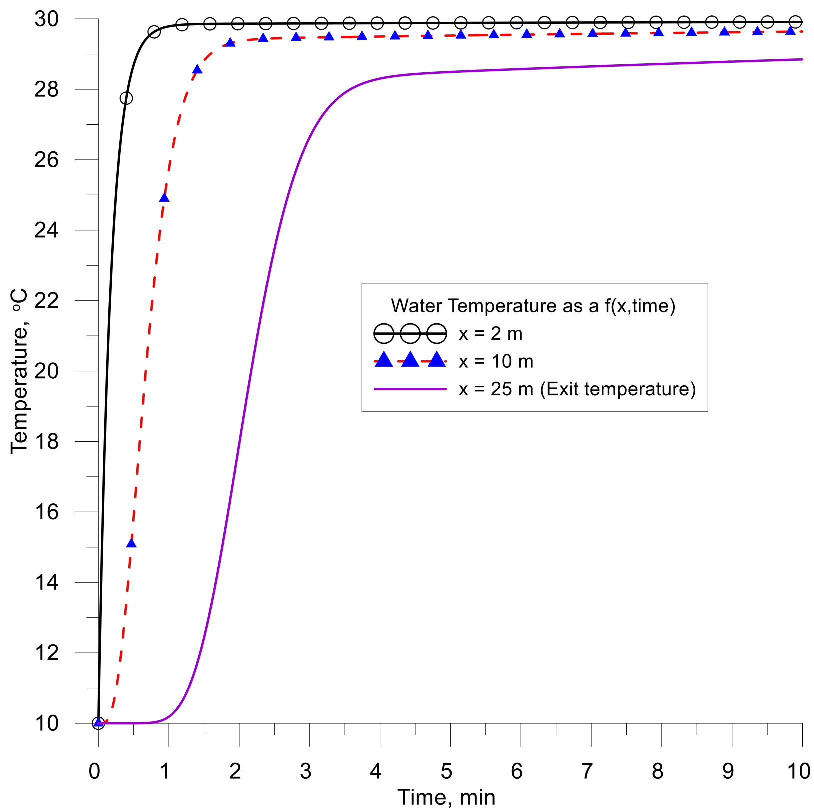

Figure 11. Variation of stormwater temperature as a function of position through a 25 m long cooling trench for a flow of 0.52 m^3/s (Equation (4) in Table 2).

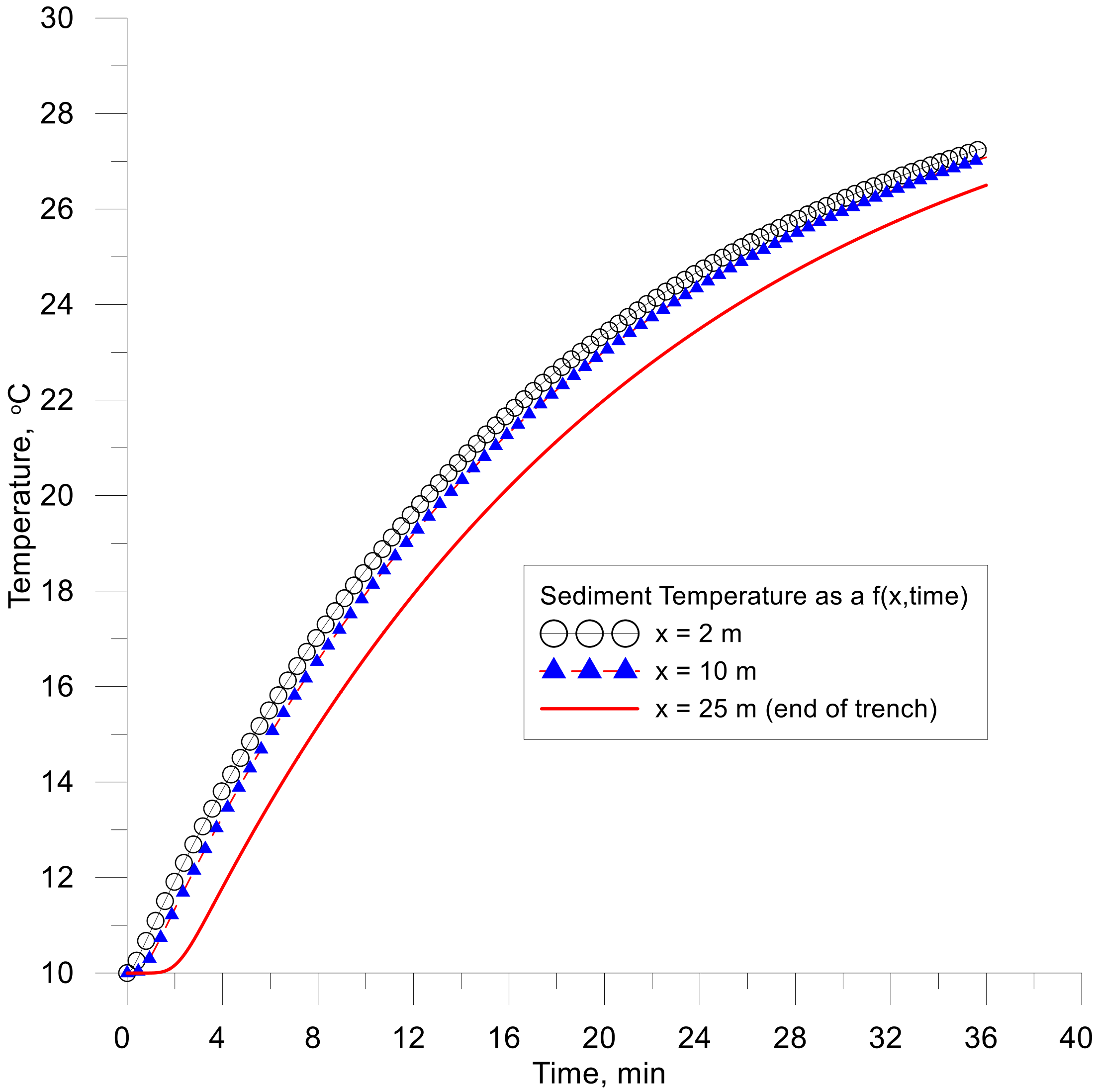

Figure 12. Variation of rock temperature as a function of position for a stormwater flow of 0.52 m^3/s through a 25 m long infiltration trench (Equation (4) in Table 2).

4.6. Dynamic Well-Mixed Stormwater and Media with Inflow and Outflow with Soil Cooling

This case is similar to that in Section 4.4 but with soil cooling between storm events. A storm event was assumed to occur every 2 days, and the first 10 minutes of the summer storm was directed into the cooling trench. Once the trench was filled, the stormwater bypassed the cooling trench. Equation (9) from Table 2 was used for this analysis. This simulation includes the cooling potential of the surrounding soil lowering the temperature of the rock between summer storms. Figure 13 shows the temperature over a period of 10 days for both the water and the rock media. This shows that the storm with 30 °C water approached equilibrium with the rock media but cooled over time due to the effect of the surrounding soil. After each successive storm, the maximum rock media temperature increased from 17.7 °C (for the first storm) to 19.9 °C (for the last storm) as the impact of successive storms on the rock media did not allow it to reach its initial temperature of 10 °C at the beginning of each storm. The stormwater release temperature also increased from 21.7 to 23.5 °C at the end of the successive storms. In both the rock media and water, the maximum temperatures after a storm event did not continue to increase but reached an equilibrium.

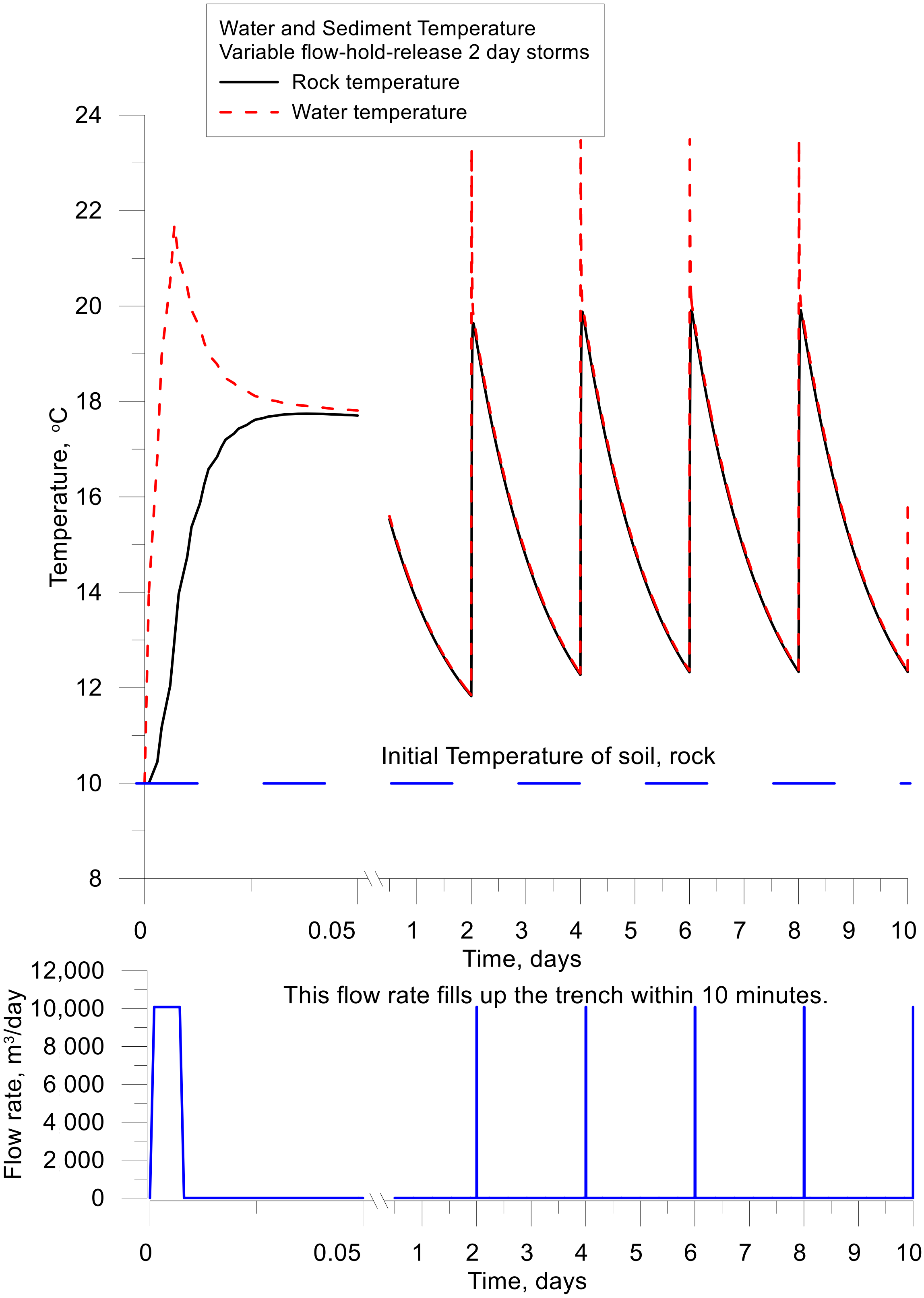

Figure 13. Water and rock temperature within cooling trench with a flow rate of about 10,080 m^3/day over a 10 min period every 2 days assuming cooling by soil in contact with the cooling trench (Equation (9) Table 2).

Considering that the volume of stormwater placed in the cooling trench is 70 m^3 over 10 minutes (0.12 m^3/s), if this water (at 30 °C) bypassed the cooling trench and was mixed directly with a stream flow with a flow rate of 4 m^3/s with a temperature of 15 °C, the final mixed temperature would be only 15.4 °C. With the average release temperature from the cooling trench over the 10 min period of release of 17 °C (for the first storm event), the average stream temperature with the stormwater input would be 15.1 °C. Hence, bypassing this flow provided a 0.3 °C improvement in stream temperatures for this event.

To illustrate how long the surrounding soil would take to equilibrate with the temperature of the rocks in the cooling trench, Figure 14 shows that after about 5 days the soil and rock in the trench reach the same equilibrium temperature.

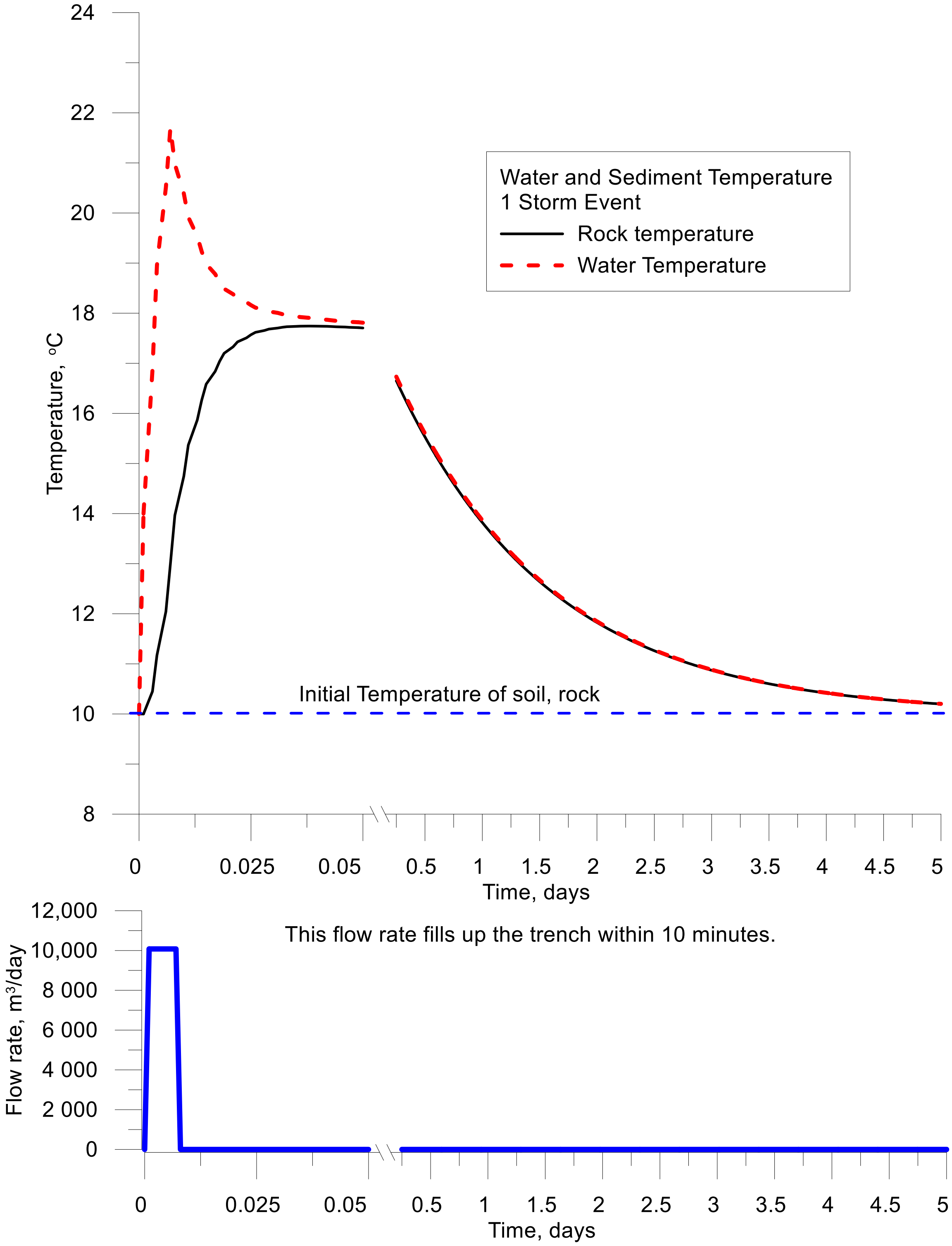

Figure 14. Water and sediment temperature in cooling trench after 1 storm event (Equation (9) Table 2).

Additionally, this analysis assumed that the surrounding soil stayed at a constant temperature and did not heat up because of the heat introduced from the storm water.

5. Summary

The mathematical basis for evaluating a cooling trench was explored. Physical constants necessary to determine properties to model the impacts of rock heating in a cooling trench were obtained from references based on sediment temperature heating.

A series of computations were made to evaluate typical heating impacts of the cooling trench for the following conditions:

- Dynamic changes in water and rock media temperatures along the axis of the cooling trench with cooling from surrounding soil;
- Equilibrium temperature of a batch reactor of rock and stormwater as a function of porosity;
- Dynamic temperature change of rock and stormwater in a batch reactor;
- dynamic changes in temperature of stormwater and rock in cooling trench conceptualized as a complete-mix, continuous flow reactor;
- Dynamic changes in temperature of stormwater and rock in cooling trench conceptualized as a plug-flow, continuous flow reactor;
- Dynamic changes in temperature of stormwater and rock in cooling trench conceptualized as a complete-mix, continuous flow reactor with cooling from the surrounding soil.

In several of these simulations, the primary conservative assumption was that the cooling trench was insulated from the surrounding soil. The models did not consider changes in the cross-section of the cooling trench assuming that these were negligible. This assumption is largely based on assuming that the longitudinal length scale is much larger than the cross-sectional length scale.

The time scale for cooling due to conduction between the rock media and the warm stormwater is based on Equation (1) and is

$$T_{cooling} \sim \left(\frac{A_{surface} k}{\rho c_p V \delta} \right)^{-1}$$

This gives a time scale for how long significant cooling can occur between the rock media and the stormwater. For the parameters of Table 3 the time scale is computed to be about 24 min. Hence, this gives planners an idea of how long the cooling due to conduction may be effective during a stormwater event.

To compare the temperature impact of a cooling trench or rock crib, one needs to compare the heating/cooling potential of ponds and other stormwater BMPs. A pond during the day will be subjected to surface heat transfer including solar radiation, longwave atmospheric radiation, conduction with the air temperature, evaporation, and longwave back radiation. During a first stormwater flush from an impervious area, a cooling trench may result in cooler temperatures not only from the cooling from the rock media but also from being shielded from the solar radiation during the day.

To further advance this research topic, comparison of field data to the mathematical framework presented in this paper and exploring the impact of water loss from the infiltration system into the groundwater would prove useful.

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References

1. Haq, R.U.; James, W. Thermal Enrichment of Stream Temperature by Urban Storm Waters. In Proceedings of the Ninth International Conference on Urban Drainage (9ICUD), Portland, OR, USA, 8–13 September 2002; American Society of Civil Engineers: Portland, OR, USA, 2002. [CrossRef]
2. Jenkins, P. *Methods to Reduce or Avoid Thermal Impacts to Surface Water: A Manual For Small Municipal Wastewater Treatment Plants*; Ecology Publication 07-10-088; Washington Department of Ecology Water Quality Program: Olympia, WA, USA, 2007; 109p.
3. Roseen, R.M.; DiGennaro, N.; Watts, A.; Ballestero, T.P.; Houle, J. Preliminary Results of the Examination of Thermal Impacts from Stormwater BMPs. In Proceedings of the World Environmental and Water Resources Congress 2010, Providence, RI, USA, 16–20 May 2010; American Society of Civil Engineers: Portland, OR, USA, 2012. [CrossRef]
4. United States Environmental Protection Agency (USEPA). *Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act*; No. EPA 841-B-09-001; United States Environmental Protection Agency, Office of Water: Washington, DC, USA, 2009.
5. Gulliver, J.S.; Erickson, A.J.; Weiss, P.T. Stormwater Treatment: Assessment and Maintenance. Available online: http://stormwaterbook.safl.umn.edu/ (accessed on 30 January 2021).
6. DiGennaro, N. Examination of thermal impacts from stormwater BMPs. Master's Thesis, University of New Hampshire, Durham, NH, USA, May 2010.
7. Hathaway, J.M.; Winston, R.J.; Brown, R.A.; Hunt, W.F.; McCarthy, D.T. Temperature Dynamics of stormwater runoff in Australia and the USA. *Sci. Total Environ.* **2016**, *559*, 141–150. [CrossRef] [PubMed]
8. Sabouri, F. Dissipation of Thermal Enrichment of Stormwater Management Ponds. Ph.D. Thesis, The University of Guelph, Guelph, ON, Canada, December 2013.
9. Thompson, A.M.; Vandermuss, A.J.; Norman, J.M.; Roa-Espinosa, A. Modeling the Effect of a Rock Crib on Reducing Stormwater Runoff Temperature. *Trans. ASABE* **2008**, *51*, 947–960. [CrossRef]
10. Fang, X.; Stefan, H. Temperature variability in lake sediments. *Water Resour. Res.* **1998**, *34*, 717–729. [CrossRef]
11. Silliman, S.E.; Ramirez, J.; McCabe, R.L. Quantifying downflow through creek sediments using temperature time series: One-dimensional solution incorporating measured surface temperature. *J. Hydrol.* **1995**, *167*, 99–119. [CrossRef]
12. Carslaw, H.C.; Jaeger, J.C. *Conduction of Heat in Solids*, 2nd ed.; Oxford University Press: Oxford, UK, 1959.
13. Jobson, H.E. Bed Conduction Computation for Thermal Models. *J. Hydraul.* **1977**, *103*, 1213–1217.
14. Chen, Y.; Carsel, R.; McCuthcheon, S.; Nutter, W. Stream Temperature Simulation of Forested Riparian Areas: I. Watershed-Scale Model Development. *J. Environ. Eng.* **1998**, *124*, 304–315. [CrossRef]
15. Kim, K.; Chapra, S. Temperature Model for Highly Transient Shallow Streams. *J. Hydraul. Eng.* **1997**, *123*, 30–39. [CrossRef]
16. Pluhowski, E.J. *Urbanization and Its Effect on Temperature of the Streams on Long Island, New York*; Geological Survey Professional Paper 627-D; The United States Geological Survey (USGS): Reston, VA, USA, 1970; p. 110.