Storm Driven Seasonal Variation in the Thermal Response of the Streambed Water of a Low-Gradient Stream

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Abstract: Storm events strongly influence water temperatures in the saturated substrate underlying stream channels, or the hyporheic zone (HZ). The goal of this study was to evaluate the impacts of storm events on thermal transport in the HZ. A year of temperature data were collected from six (6) multi-level samplers at multiple depths (30 cm, 60 cm, 90 cm and 150 cm) and were categorized into seasonal storm events. Analysis of the HZ temperature profiles revealed a seasonal reversal in the post-storm temperature change ($\Delta T$) in the substrate. Increases in the $\Delta T$ were observed in the warm period (summer), whereas decreases occurred during the cold period (winter); both were associated with the direction of the pre-storm thermal gradient between the stream and substrate temperatures. The amplitude of $\Delta T$ became muted with increasing depth. Two-sample t-test analyses showed statistically significant differences between the pre- and post-storm temperatures at all depths during the warm period and at all depths except 150 cm in the cold period. Upwelling groundwater moderates the thermal response. There were no statistically significant differences in the pre- and post-storm stream temperatures during both the cold and warm periods.

Keywords: hyporheic zone; thermal transport; storm-events; groundwater/surface-water interaction; thermal conditions

1. Introduction

Heat is an important nonreactive, naturally occurring, robust tracer [1] that can be used to track water movement [2,3], to quantify groundwater fluxes and aquifer hydraulic properties [4–8] and to delineate losing and gaining reaches of a stream [3,9–18]. The development of various research techniques has made temperature an accurate and cost-effective method of analyzing groundwater-stream interactions [19–22].

The interface below the streambed where groundwater and surface water mix and the area where surface water infiltrates into biologically active near stream sediments has been defined as the hyporheic zone [23–25]. As a mixing zone, the hyporheic zone has been reported as a critical heat source/sink affecting the overlying water channel [26,27] with the streambed temperature profile reflecting the nature and extent of groundwater-surface water interactions [28,29]. Within stream systems, survival of aquatic organism is controlled by water temperature [30]. Thermal stability with the hyporheic zone provides a thermal refuge for stream biota and greater overall ecosystem stability [31–35]. Subsequently, the stable thermal conditions contribute to the hyporheic zone serving as a hatchery for fish and invertebrate eggs [36,37], as a refuge for invertebrates and larval fish during high flows [38,39] and as an important zone for stream ecosystem metabolism [30,40–44]. The importance of thermal dynamics to aquatic stability within the hyporheic zones during high flows...
cannot be overemphasized. Acute temperature changes, specifically the increase in water temperature stress organisms and may result in mortality [43,44].

Consequently, if temperature plays such an important role in ecologic stability and in understanding groundwater and surface water interactions, then factors controlling temperature, must be of importance to all these research works. One major factor that affects hyporheic zone temperature is storm (high-flow) events. Storm events generate thermal spikes, either increases or decreases in temperature, that overwhelm a system, thereby perturbing the thermal equilibrium of a system [8,45]. In alpine streams, thermal spikes were measured in the streambed, with the thermal response diminishing with depth [46]. How storm events influence the thermal regime of the hyporheic zone is not well reported. This work examines the impacts of storm events on thermal variations within the hyporheic zone of a low-gradient, sand and gravel bedded stream. The following research questions are explored: (1) How does after-storm thermal response vary with increasing substrate depth? and (2) are there seasonal differences in substrate response after a storm event? Given the importance of thermal stability to the survival of aquatic organisms [30], understanding how storm events disturb the thermal stability of the hyporheic zone is critically important to aquatic resource management. Similar studies have been done in other environments. In a karst stream, Dogwiler and Wicks [45] observed after-storm temperature spikes between 0 to 5 °C in the substrate, that decreased with increasing depth during the summer. They discovered a dramatic drop in after-storm substrate temperature during the winter, which was due to the influx of very cold water into the substrate system. Brown and Hannah [46] observed spatial and temporal differences in after-storm water and substrate thermal responses in an alpine stream during the summer. They reported a dampening after-storm substrate response with increasing depth. However, limited information is known of storm-induced events on thermal variations in the hyporheic zone of low gradient sand and gravel bedded streams.

2. Materials and Methods

2.1. Study Locality

A 25 m straight stretch along a third-order, low-gradient (0.002 m/m), sand and gravel bedded stream located in central Illinois, USA was selected for the purposes of this investigation (Figure 1). The stream, Little Kickapoo Creek (LKC) has been extensively studied, with detailed descriptions of the stream [47–54]. For reference, a brief description is provided here. The stream channel runs along the contact between an alluvial floodplain deposit, the Cahokia Formation, and an underlying poorly-sorted gravel and sand unit, the Henry Formation. With a thickness that ranges from 5 to 7 m, the Henry Formation serves as a minor aquifer with an average hydraulic conductivity of 10 m/day. Interaction between the aquifer and stream has been well documented, with the aquifer providing a constant source of water to the stream [51–53]. The overlying 2 m of Cahokia Formation is not considered a confining unit because of the presence of macro porosity and high level of connectivity between LKC and the Henry Formation.

With a humid continental climate, central Illinois experiences cold winters (−1 to −10 °C) and warm summers (20 to 30 °C). Within the period of 1950 to 2002, the annual mean temperature was 11.2 °C. July is the warmest month of the year with an average temperature of 24 °C, while January is the coldest month with an average temperature of −5.3 °C. During the summer, temperature variations between night and day range ±6.1 °C, and a greater variation between night and day temperatures during winter with an average difference of ±7.8 °C. Annual precipitation is 953 mm with the wet season occurring in the spring and summer, when average monthly rainfall is greater than 90 mm, and the dry season occurring during the winter, when average monthly rainfall is less than 75 mm.
2.2. Data Collection

An array of six multi-level samplers (W1, W2, W3, W4, W5 and W6) were installed along the thalweg at the study site (Figure 1). Each multi-level sampler had openings at depths of 30 cm, 60 cm, 90 cm and 150 cm below the streambed (Figure 2). Temperature loggers (Onset Pendant Data Loggers with accuracy: $\pm 0.53 \, ^\circ C$; resolution: $0.14 \, ^\circ C$ at $25 \, ^\circ C$) at each depth were isolated using foam sealant as packing. Thus, temperatures measured in each chamber were determined only by water temperature over the associated screened depth interval in the stream substrate. Additional temperature loggers were attached to W1 and W6 to record upstream and downstream surface water temperatures, respectively. Along the bank of the stream in line with W2 (Figure 1), a stilling well (SW) housing a Solinst Levelogger® (Solinst, Georgetown, Ontario, Canada) (temperature accuracy $\pm 0.05 \, ^\circ C$ and a resolution 0.01 °C at 20 °C, and water level resolution of 0.002 m) was installed to record the stream stage. All temperature loggers and pressure transducers recorded temperatures at 15-min intervals, and data were collected from February 2009 until March 2010. Forty (40) storms were recorded during this period; 25 storms occurred during the warm period (later spring to early autumn) and 15 storms occurred during the cold period (later autumn to early spring).
2.3. Data Reduction

Storm events were identified by comparing stream stage data with precipitation data collected from the US weather service. Thermographs for all loggers, all multi-level samplers at the various depths and for the stream, were generated and compared to the hydrographs to identify the streambed and stream thermal responses associated with each storm pulse. The amplitudes of the streambed and stream thermal pulses due to the storm pulse were determined by subtracting the pre-storm temperature from the peak-storm temperature, the maximum or minimum temperature observed during the storm, to get the post-storm thermal change (ΔT). The mean response of the substrate at different depths was assessed by averaging the ΔT at each depth across all multi-level samplers, thus ignoring within-site spatial variability for the purposes of this study.

2.4. Temperature Comparisons

To study the seasonal variations, the averages of the ΔT for each depth from all the storms were separated into warm period (21 March to 21 September) data and cold period (21 September to 21 March) data, which are similar to the categorizations used by Beach and Peterson [55] and Dogwiler and Wicks [45]. There was no categorization of the storm magnitude in the analyses; all storm events that produced an increase in stage were included. To test for the after-storm temperature change (ΔT) with depth, the difference between the pre-storm and peak-storm temperatures were calculated and averaged for each depth. These mean values quantified the vertical change in the amplitude of after-storm temperature response from the shallow substrate into the deeper substrate. One-tailed two-sample t-test for equality of means at a significance level of α = 0.05 were conducted between the pairs of pre- and post-storm temperatures to test for statistically significant impact of the storm event on after-storm temperatures in the stream and substrate. We also performed the t-test between the pairs of 30 cm and stream, 30 cm and 60 cm, 30 cm and 90 cm and 30 cm and 150 cm depths to test for statistically significant differences in the vertical amplitude of change from the shallow substrate to the deeper substrate. We performed t-test instead of z-test due to the small sample size (about 15 and 25 samples for the cold and warm periods, respectively).

3. Results

The distribution of substrate temperatures showed opposite thermal gradients during the cold and the warm months. Specifically, throughout the cold periods, the temperatures increased with depth in the substrate, with the warmest temperatures recorded at 150 cm (Figure 3). For the warm period, temperatures declined at depths below the stream-bed interface, with the lowest temperatures measured
at 150 cm and warmest temperatures at 30 cm. The patterns reflect the influence of upwelling groundwater on the system, which has been reported as $10^{-1}$ to $10^{-2}$ m/day [48,51]. In the area, the mean annual groundwater temperature is 11.2 °C [48,52] and exhibits a sinusoidal temperature signature with the warmest temperatures in October and November and coolest temperatures in April [51,52].

Analysis of thermographs of all substrate after-storm responses indicated that the thermal response within the substrate was similar among the storms for the given periods. During the warm periods, substrate temperatures increased, while in the cold periods, the substrate temperatures decreased (Figures 3 and 4). All warm period ΔT values were positive, above the 0 °C reference line (Figure 3c). The average substrate after-storm temperature increased 1.69 °C, with a standard deviation of 0.99 °C during the warm (Figure 4). The converse occurred during the cold period when the ΔT values were negative, below the 0 °C reference line (Figure 3c), with an average decrease of −1.31 °C and a standard deviation of 1.09 °C (Figure 4). The distributions of ΔT values for the two periods represented two different distributions ($p < 0.001$) and were, thus, treated separately (Figure 4).

![Figure 3](image_url)

**Figure 3.** Box plots of pre- and peak-storm temperatures for stream and average of substrate depths for all multi-level samplers: (a) Cold periods, (b) warm periods and (c) post-storm thermal change (ΔT) at substrate depths for all multi-level samplers. The box represents the middle 50% of the data (interquartile range). The lower and upper edges of the box represent the 25th and 75th percentiles, respectively. The solid line represents the median, and the dotted line is the mean. The upper and lower whiskers represent the 10th and 90th percentiles. The points represent outliers. The asterisks (*) in (a,b) indicate statistically significant difference between pre- and post-storm temperatures.

Figure 5 presents examples of typical after-storm substrate thermal responses during both the cold and warm periods selected from W3. A typical cold after-storm substrate thermal response was
recorded at both the 30 cm and 60 cm depths almost simultaneously with the onset of rising after-storm stream stage (Figure 5a), with different amplitudes of response, i.e., approximately −1.65 °C and −1.38 °C (Figure 3c; Table 1), respectively. While the 90 cm depth response lagged the reactions at 30 cm and the 60 cm depths by ~3 h, the amplitude of response was comparable to that at 60 cm, i.e., −1.37 °C. The response at the 150 cm depth, in contrast, was smaller i.e., −0.35 °C (Figure 3; Table 1) and lagged the response at the 90 cm by ~4 h (e.g., Figure 5a). The 30 cm and 60 cm substrates responded instantaneously to the onset of rising after-storm stream stage, including the onset of thermal recovery at the 30 cm and 60 cm immediately after the peak-storm stage (Figure 5a), suggesting a better hydraulic connectivity of the stream with the substrate up to the 60 cm depth during the cold periods.

Figure 4. Box plot of post-storm thermal change (ΔT) within the substrate among all the multi-level samplers. The box represents the middle 50% of the data (interquartile range). The lower and upper edges of the box represent the 25th and 75th percentiles, respectively. The middle band of the box represents the median and the upper and lower whiskers represent the maximum and the minimum data values, respectively.

Figure 5. Representative after-storm substrate temperature response during the: (a) Cold period and (b) warm period.
Despite a positive $\Delta T$ in the stream temperature of $\sim 0.29 \, ^\circ C$ (Table 1), the thermal changes in the substrate were all negative (Figure 3c), indicating that the storm water was warmer than the pre-storm stream water and colder than the substrate water. Analyses of the equality of mean of the pre-storm and post-storm temperatures indicated statistically significant differences for the 30 cm, 60 cm and 90 cm depths (Figure 3; Table 1). The null hypothesis of equality of mean of the pre- and post-storm temperatures could not, however, be rejected for the stream and 150 cm depth (Table 1). Note, $p$-values less than the significance level ($\alpha = 0.05$) indicate statistically significant difference.

During the warm periods, the warm storm events introduced warmer waters into the stream, raising the stream temperatures ($\Delta T$) on average $1.47 \, ^\circ C$ (Figure 3c; Table 2). Concomitant with the warming stream waters, the downwelling thermal flux increased the substrate temperatures. A typical warm season thermal response produced similar magnitude changes at the 30 cm, 60 cm and 90 cm depths, $2.14 \, ^\circ C$, $2.01 \, ^\circ C$ and $2.04 \, ^\circ C$, respectively, at nearly the same lag time after the storm event (Figure 5b). The 150 cm depth, however, responded 1 h after the temperature began to change at the 30 cm, the 60 cm and the 90 cm depths and had a smaller amplitude of response, $1.58 \, ^\circ C$ (Table 2).

Analyses of the pre-storm temperatures revealed a dampening of $\Delta T$ with increasing depth during the warm period. There were statistically significant differences in the pre- and post-storm temperatures at all depths, whereas the null hypothesis of equality of means of post- and pre-storm stream temperatures could not be rejected (Figure 3; Table 2).

Unlike the cold period during which the substrate responded instantaneously to the storm event up to the 60 cm depth, during the warm period, the instantaneous penetration was up to the 90 cm depth (Figure 5), indicating a deeper hydraulic connectivity (advection-driven flow) between the stream and the substrate during warm periods. This observation was also corroborated by the t-test hypotheses testing in which there were statistically significant alterations of post-storm temperatures up to the 150 cm depth during the warm periods compared to the statistically significant change up to 90 cm during the cold periods (Figure 3c and Tables 1 and 2). Overall, there were no statistically significant differences between pre- and post-storm stream temperatures during both the cold and warm periods, which is plausibly due to thermal equilibration between pre-storm air and stream temperatures.

For both cold and warm periods, with the exception of the 150 cm depth during the cold period, there were no statistically significant differences in the amplitude of change between the pairs of 30 cm and 60 cm, 30 cm and 90 cm, and 30 cm and 150 cm (Figure 3c and Tables 1 and 2). There were, however, statistically significant differences in the amplitude of change between the substrate and stream during both cold and warm periods.
Table 1. Summary statistics of cold pre- and peak-storm temperatures and after-storm thermal amplitude change (ΔT).

| Location | Sample Size | Pre-Storm Temperature (°C) | Peak-Storm Temperature (°C) | Paired t-Test: Pre- vs. Peak-Storm T | ΔT (°C) | Paired t-Test: ΔT 30 cm vs. Other Depths |
|----------|-------------|----------------------------|----------------------------|-------------------------------------|---------|----------------------------------------|
|          | (n)         | Mean ± Standard Deviation  | Mean ± Standard Deviation  | p Value | Mean ± Standard Deviation | p Value |
| Stream   | 15          | 6.32 ± 2.71                | 6.61 ± 3.03                | 0.39     | 0.29 ± 1.11               | <0.05   |
| 30 cm    | 15          | 8.11 ± 1.46                | 6.46 ± 1.7                | <0.05    | −1.65 ± 1.06             | 1.11    |
| 60 cm    | 15          | 9.05 ± 1.26                | 7.67 ± 1.24                | <0.05    | −1.38 ± 1.11             | 1.11    |
| 90 cm    | 14          | 9.55 ± 1.09                | 8.18 ± 1.17                | <0.05    | −1.37 ± 1.20             | 0.25    |
| 150 cm   | 14          | 10.11 ± 1.18               | 9.76 ± 1.32                | 0.23     | −0.35 ± 0.40             | <0.05   |

Table 2. Summary statistics of warm pre- and peak-storm temperatures and after-storm thermal amplitude change (ΔT).

| Location | Sample Size | Pre-Storm Temperature (°C) | Peak-Storm Temperature (°C) | Paired t-Test: Pre- vs. Peak-Storm T | ΔT (°C) | Paired t-Test: ΔT 30 cm vs. Other Depths |
|----------|-------------|----------------------------|----------------------------|-------------------------------------|---------|----------------------------------------|
|          | (n)         | Mean ± Standard Deviation  | Mean ± Standard Deviation  | p Value | Mean ± Standard Deviation | p Value |
| Stream   | 25          | 17.39 ± 2.94               | 18.68 ± 3.01               | 0.07     | 1.47 ± 1.06               | <0.05   |
| 30 cm    | 25          | 14.50 ± 3.19               | 16.49 ± 4.09               | <0.05    | 2.14 ± 1.36               | 0.38    |
| 60 cm    | 25          | 13.73 ± 2.72               | 15.58 ± 3.63               | <0.05    | 2.01 ± 1.56               | 0.42    |
| 90 cm    | 25          | 13.01 ± 2.39               | 14.80 ± 3.41               | <0.05    | 2.04 ± 1.94               | 0.07    |
| 150 cm   | 23          | 12.07 ± 1.93               | 13.57 ± 2.50               | <0.05    | 1.58 ± 1.24               | 0.24    |
4. Discussion

The thermal response observed in the stream substrate varied between the cold period and the warm period. During the warm period, warmer stream waters were transported into the substrate; all depths experienced elevated temperatures that were statistically warmer than the pre-storm temperatures. Cold period storms generated an opposite response, with the substrate temperatures cooling. While statistically significant changes in temperature were observed at all depths (30 cm, 60 cm, 90 cm and 150 cm) during the warm period, the 150 cm depth did not experience a significant change during the cold period. The observed thermal responses at depth were consistent with the works of White, et al. [56], Dogwiler and Wicks [45], and Brown and Hannah [46].

Cold air temperatures in the cold period produced surface water temperatures that hovered near 0 °C. During the cold season, the mean pre-storm stream temperature was colder than the mean pre-storm substrate temperatures (Figure 3a; Table 2). Within the substrate, the pre-storm temperatures increased with increasing depth, as was similarly observed by Constantz and Thomas [57]. A strong connection between the stream and the upper substrate kept the upper substrate relatively colder during the cold period. Deeper in the substrate, the upwelling groundwater, which was warmer than the stream temperature in the cold period, regulated the deeper substrate temperatures [58]. The flux of warmer groundwater caused the pre-storm substrate temperatures to increase with increasing depth during the cold period. At baseflow, Bastola and Peterson [48] reported the influence of surface water temperature did not extend beyond 90 cm. In contrast, storm-driven thermal flux extended beyond 90 cm, with modified temperatures recorded at 150 cm depths. For 150 cm, the ΔT values during the cold period, −0.35 °C, and warm period, 1.58 °C, only the warm period ΔT value was statistically significant (Tables 1 and 2). The magnitude of the change was smaller than those measured at 90 cm. The smaller magnitude documented the dissipation of heat as the pulse migrated through the substrate as well as the influence of upwelling water. Regardless, the storm events generated a thermal perturbation to a depth of 150 cm.

The pre-storm temperatures in all the multi-level samplers during the cold period were above 8 °C (Figure 3c). After the storm, substrate temperatures dropped to below/about 8 °C. The drop in the after-storm substrate temperature is due to the increase vertical hydraulic gradient during high hydrologic flow, which increases the vertical hydraulic head and increases the flux of the stream water into the streambed. As the relatively colder stream water inundates the substrate, there is mixing and thermal homogenization of the colder stream water with the relatively warmer substrate water. For there to be thermal equilibrium during the mixing of the warmer pre-storm substrate temperature with the incoming colder stream temperature, the substrate temperatures will have to drop, which explains the observed drop in the ΔT during cold season.

Similarly, during the warm season, the mean pre-storm stream temperature was higher than the mean pre-storm substrate temperatures (Figure 3b; Table 2). The pre-storm substrate temperatures decreased with increasing depth during the warm season, which is consistent with the other published work [57,59]. The warmer pre-storm stream water is due to diurnal heating of the stream water by solar radiation and the warmer air [60]. Numerous works (e.g., [61–64] have shown a direct relationship between air temperature and stream temperature, helping to account for the observed contrast of the after-storm substrate temperature response between the cold and warm seasons. A strong interaction between the stream and the upper 60 cm allowed the transmission of heat, which makes the upper substrate relatively warmer than the 90 and 150 cm depths. At the deeper substrate depths, upwelling groundwater that was colder than the stream water controlled the temperatures, dampening the effects of the surface heat [58].

Previous works have revealed that vertical heat transfer into the streambed is controlled predominantly by advective transport and to a lesser extent by conductive transport [13,65–67]. Figure 5 illustrates the extent of the storm water flux into the streambed. During the cold period, the vertical flux of the cold stream water rapidly cooled the substrate to the 60 cm depth, an indication of advection dominated heat transfer (e.g., [57,59]. The sharp temperature change at the 60 cm depth
creates a high thermal gradient between the 60 cm and the deeper substrate. The small amplitude of
response and the longer lag time for the 90 cm depth was due the conductive mode of heat transport
into the deeper substrate. In contrast, advective dominated heat transport to the 90 cm depth during
the warm period was observed, with a muted response at 150 cm that implies conduction dominated
heat transfer.

A dampening of after-storm substrate thermal response with increasing substrate depths occurred
following both cold and warm season storms (Figure 3c), which is consistent with the findings of
Dogwiler and Wicks [45] and Brown and Hannah [46]. The dampening of thermal response with
increasing depth occurred because the after-storm substrate response was controlled by the thermal
gradient between the pre-storm stream water and pre-storm substrate temperatures. The steeper the
thermal gradient, the larger the amplitude of the $\Delta T$ during mixing and thermal homogenization of
the stream water with the streambed water. As the initial stream water advanced into the substrate, at
the 30 cm depth (upper substrate) there is a steeper thermal gradient, and the heat exchange required
to thermally equilibrate the substrate with the stream water was greater. The streambed sediments
acted as a mechanical filter to the surface thermal inputs [68]. The stream water that migrated to the
60 cm depth had depleted thermal energy. Thus, the 60 cm depth experienced a smaller spike during
mixing and thermal equilibration with the stream water. The same thermal exchange occurred between
the 60 cm and the 90 cm and between the 90 cm and the 150 cm. The muted thermal gradient with
increasing substrate depth accounted for the dampening $\Delta T$ with increasing substrate depth.

Test of equality of means from the 30 cm to the 150 cm depths for both cold and warm seasons
were conducted to help further assess the significance in the variations of $\Delta T$ with increasing depth.
Though there was dampening of $\Delta T$ with increasing depth, the $p$-values reveal that there were no
significant differences in the warm period $\Delta T$ from the 30 cm to the 150 cm depths. During the
cold period, significant difference was observed at the 150 cm depth with the 30 cm depth response.
The similarity in the warm period $\Delta T$ with increasing depth as compared to the cold period may be a
result of advective heat transfer. The ability and time lag of a storm pulse penetrating the hyporheic
zone is dependent on the strength and direction of the vertical gradient in the underlying groundwater
system [69]. Gradients were not measured for this work, but the hydraulic gradient during both
periods drives upwelling of groundwater [51]. In the short-term, storm events reverse the gradient;
with the gradient observed in the winter suggest greater downwelling [70]. However, the data suggest
greater downwelling in the summer. As a function of fluid velocity, advection transfer is dependent
on hydraulic conductivity. Temperature controls the fluid density and dynamic viscosity; variables
that govern hydraulic conductivity, resulting in muted thermal responses and greater lag times [71].
In substrates with warmer water, elevated flux rates were attributed to higher temperatures [72,73].
A similar effect may have been observed the LKC substrate. Assuming the permeability of the substrate
remained constant despite mobility of the top 30 cm [74], the hydraulic conductivity in the warm
period with surface water temperature of 18 °C, would have been 40% larger than during the cold
period with surface water temperature of 6 °C. The higher hydraulic conductivity would allow for
greater advection and transport of heat. The difference in the thermal response between the cold period
and warm period may also be a result of conduction, which is more important in the summer [75].
At baseflow, Bastola and Peterson [48] observed heat exchange occurred deeper in the substrate during
the summer than the winter.

5. Conclusions

The aim of this study was to assess the impact of storm events on thermal anomalies in the
streambed. Various aspects of pre- and post-storm temperature responses and amplitude of after-storm
response ($\Delta T$), such as seasonal and vertical variations were investigated to meet the object of this study.
In totality, there were seasonal differences in the $\Delta T$ with the substrate cooling on the average of 1.2 °C
in response to cold period storm events and warming on the average of 2.0 °C in response to warm
period storms. The seasonal reverse in response will inform resource managers as to the degree in
temperature changes to expect in the substrate after a storm event given a particular season. The depth of thermal front of a storm event determines the depth to which advective transport controls thermal transmission into the substrate. While advective transport dominates up to the 90 cm depth during warm period storms, advective mode of heat transport is limited to about 60 cm during cold period storms. The sharp temperature change at the depth of the thermal front creates a steep thermal gradient, which induces conductive transport that further propagates heat slowly with muted amplitude into the deeper substrate. Overall, the amplitude of the vertical responses dampens with increasing depth. There are, however, no significant differences in the dampening responses with increasing depth in the warm period. The cold response, however, showed significant difference at 150 cm depth at 0.05 level of significance.

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