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Bank thermal storage as a sink of temperature surges in urbanized streams

Abstract

A poorly-studied benefit of bank storage is the ability of the streambed to act as a thermal sink to streams influenced by urban runoff (e.g. bank thermal storage). Headwater streams, with their low thermal iner-tia, are particularly susceptible to thermal pollution. We utilize numerical modeling to quantify the amount of heat exchanged with the subsurface during temperature surges, which we define as greater than a 1 C stream temperature increase in 15 min. We base our study on Boone Creek, a low-order stream in northwestern North Carolina with stream discharge and temperature data dating to March 2006. The catchment is heavily urbanized, and although the stream is of moderate gradient, it is fed by tributaries that lose up to 200 m/km. The combined effect of urbanization and steep gradient produces a flashy response: stream discharge averages 0.10 m^3/s, but may increase up to two orders of magnitude during storm events. These events also affect stream and streambed temperatures. Four summers of monitoring (2006—2008, 2010) indicate that 71 temperature surges occurred with a mean temperature increase of 2.39 C and a maximum increase of 6.36 C.

We model generic storm events based on typical Boone Creek storms and streambed hydrogeology with the U.S.G.S. finite-difference groundwater flow and heat transport code VS2DH. The one-dimen-sional model domain includes a diurnally-oscillating stream temperature and specified head at the upper boundary, a constant streambed temperature and head at the lower boundary, and gaining stream conditions. Reference storm simulations use a temperature increase of 3.66 C and a stream stage increase of 0.66 m. Simulations show that at a depth of 4.5 cm, nearly half of the temperature-surge signal has dissipated and lag times are 30 min. By a depth of 9.5 cm, however, peak temperatures are only one-third of storm levels and lag times are 2 h. At depths beyond 49.5 cm, the perturbation is less than 0.1 C and lags the storm event by more than 17.5 h. Storm influence extends to a depth of 2 m and persists for days. Sensitivity simulations suggest that hydraulic conductivity, sediment heat capacity, and thermal conductivity are the most sensitive model parameters. Calculations show that temperature-surge induced heat storage in the simulated streambed is 72% of the heat storage in the stream.

1. Introduction

The urbanization of watersheds, a process which involves the removal of riparian vegetation and the replacement of natural land cover with pavement, buildings, and urban infrastructure (e.g. stormwater systems), has long been described as a detriment to stream water quality, one component of which is stream temperature (Webb et al., 2008). Much of the literature on watershed urbanization describes long-term trends in water-quality degradation such as an increase in average stream temperatures due to urban infrastructure (Wang and Kanehl, 2003; Nelson and Palmer, 2007) and the lack of riparian vegetation (Moore et al., 2005; Nelson and Palmer, 2007), but also variations induced by climate change (Webb, 1996; Mohseni et al., 1999) and the decline in baseflow because of reduced infiltration (Wang et al., 2003). These factors affect stream habitats because of compromised water quality (Wang et al., 2003; Wang and Kanehl, 2003).

Several studies in the literature look at the direct effects of urbanization on stream temperatures. A study of the effects of urbanization on stream temperatures using a process-based thermal energy balance finds that the most important factors are shading from riparian vegetation, baseflow to the stream, and stream width (LeBlanc et al., 1997). There is a need for studies of low-order urban streams because we lack long-term datasets for this stream class, most notably due to the difficulty in maintaining monitoring sites in flashy streams (Nelson and Palmer, 2007). They address the importance of this type of study because of the influence of heated runoff from the urban infrastructure, which they acknowledge will have a strong influence on stream temperature due to the small thermal inertia of low-order streams. Another study of the effects of the urban infrastructure on the thermal regime of streams finds that in addition to the factors of LeBlanc et al. (1997), urbanization is an important factor in habitat loss (Herb et al., 2008). Their study also utilizes a process-based model of thermal energy balance; however, they use it to model runoff temperatures during typical storm events. Their modeling results demonstrate that 34% of the studied precipitation events produce runoff temperatures greater than 20 °C, with maximum runoff temperatures approaching 33 °C. A study involving a process-based model of runoff from a paved surface tests the model using measured and modeled runoff temperatures from a small asphalt parking lot that exceed 34 ° C (Janke et al., 2009). Another study of the mitigation effects of stormwater detention finds that while overall daily-average stream temperatures with pond storage increase slightly (0.03 ° C) above unrestricted runoff conditions, the overall daily maximum stream temperature declines by 0.15 °C with detention (Herb et al., 2009).

Few studies in the literature describe the effects of urbanization on stream and streambed temperatures at short temporal scales. Rapid increases in stream temperature during storm events in urban landscapes, known as temperature surges, have detrimental effects on cold-water stream habitats (Wang et al., 2003; Wang and Kanehl, 2003; Quigley and Hinch, 2006). Nelson and Palmer (2007) classify temperature surges as a greater than 2 ° C increase in stream temperature within 30 min, which was their stream temperature monitoring interval. Their data, collected in watersheds with a range of land coverage classifications in central Maryland, USA, suggest that relatively undisturbed monitoring locations such as agricultural sites do not experience temperature surges, whereas urbanized monitoring locations experience temperature surges up to 10% of the monitored days. Temperature surges at their urbanized monitoring locations averaged 3.7 °C with temper-atures returning to normal diurnal oscillations within an average of 2.8 h.

Here, we study the temperature surge phenomenon with a process-based model of streambed heat transport in the context of groundwater–surface water interactions in a gaining stream. We use data collected over a four-year period (2006–2008, 2010) to guide a generic modeling study of storm influence on stream and streambed temperatures. The stream was not monitored in 2009. Lautz (2010) notes that groundwater–surface water interactions increase stream residence times, thereby initiating contact between groundwater and solutes, microbes, and reactive sediments. We extend this suggestion to the exchange of heat between water flowing into the alluvial aquifer during flood events and the streambed sediments. Thus, our goal is to assess the ability of the streambed to act as a thermal capacitor during temperature surge events. In other words, can process-based groundwater flow and heat transport models recreate the streambed temperatures that we have measured in the field? We provide our dataset as a contrast to the Nelson and Palmer (2007) study conditions: the stream upon which we base our study has a smaller mean annual discharge and a higher gradient, thus providing a study stream with a low thermal inertia and a high likelihood of temperature surge effects. In this paper we demonstrate that stream temperature surge effects, although relatively short in duration, cause elevated streambed temperatures at depth that lag in time. It is our hope that this paper will prompt further research into quantifying the amount of heat that a streambed may store in the aftermath of temperature surge events, and the effect that this storage may have on stream temperatures both during and after the storm event.

2. Site description

Boone Creek flows through the Town of Boone and the Appalachian State University campus in the Blue Ridge Mountains of northwestern North Carolina, USA (Fig. 1). Four previous studies of the stream have documented (1) estimates of runoff tempera-tures during storm events (Anderson et al., 2007a), (2) basic water quality conditions (Anderson et al., 2007b), (3) the influence of baseflow on stream temperatures (Anderson et al., 2010), and (4) the influence of urbanization on stream temperature variations along the stream (Rice et al., 2011). Within the relatively small catchment of the study site, which has an area of 5.2 km^2, total relief is approximately 480 m and tributary streams have gradients of greater than 20%; however, the overall gradient of the main stem of Boone Creek is a modest 2% (Anderson et al., 2010). The stream has a mean width of approximately 2.8 m and a mean depth of 20 cm in the vicinity of monitoring site MS-2 (Fig. 1), although this varies with changes in stream stage (Anderson et al., 2010). In gen-eral, the streambed sediments comprise sand and gravel with lar-ger cobbles and boulders with occasional clay lenses.

A previous study of temperature surges in the catchment utilizing a thermal mixing model (Anderson et al., 2007a) suggests that runoff temperatures must exceed 30 °C in order to produce measurable changes in stream temperatures during surge events. This is comparable to the findings of both Herb et al. (2008) and Janke et al. (2009). Anderson et al. (2010) use a modeling study to demonstrate that baseflow to gaining streams of low thermal inertia exerts a strong control on stream temperatures. They also note that restoration of groundwater–stream interaction through the removal of long culverts may reduce stream temperatures. Rice et al. (2011) examine detailed stream temperature records along the length of Boone Creek, noting that the stream–air temperature relationship becomes less correlated with increasing urbanization.

Boone Creek is a headwater stream that has a relatively low mean annual discharge of less than 0.10 m^3/s (Anderson et al., 2010); however, during high-intensity precipitation events, especially those deriving from summer convective thunderstorms, stream discharge may increase by two orders of magnitude within 15 min (Anderson et al., 2007b). Moreover, during the summer months these convective storm events transfer heat stored in the urban infrastructure to runoff, prompting rapid increases in stream temperatures that range from just over 1 °C to greater than 6 °C. We define temperature surges for this study as an increase of greater than 1 °C within 15 min of monitoring. We use a smaller change in temperature over a shorter time interval to define temperature surges in Boone Creek than that of Nelson and Palmer (2007) to reflect our smaller sampling interval.

Rice et al. (2011) document the effects of urbanization on stream temperatures in Boone Creek with distance downstream. They describe an increase in urbanization within the watershed from 13.7% impervious surface coverage (ISC) in the headwater portion of the stream up to 24.3% at downstream points within a distance of less than 1.6 km. ISC within a 25 m buffer on either side of Boone Creek at locations along the study reach is up to 75%, while ISC at the upstream-most reach is just 1%. The area around the monitoring site has some riparian vegetation, as does much of the stream length upstream of the monitoring site (Anderson et al., 2010).

3. Methods and data

3.1. Data collection

We began monitoring stream temperatures in March 2006 with three monitoring stations (Anderson et al., 2007b), including site

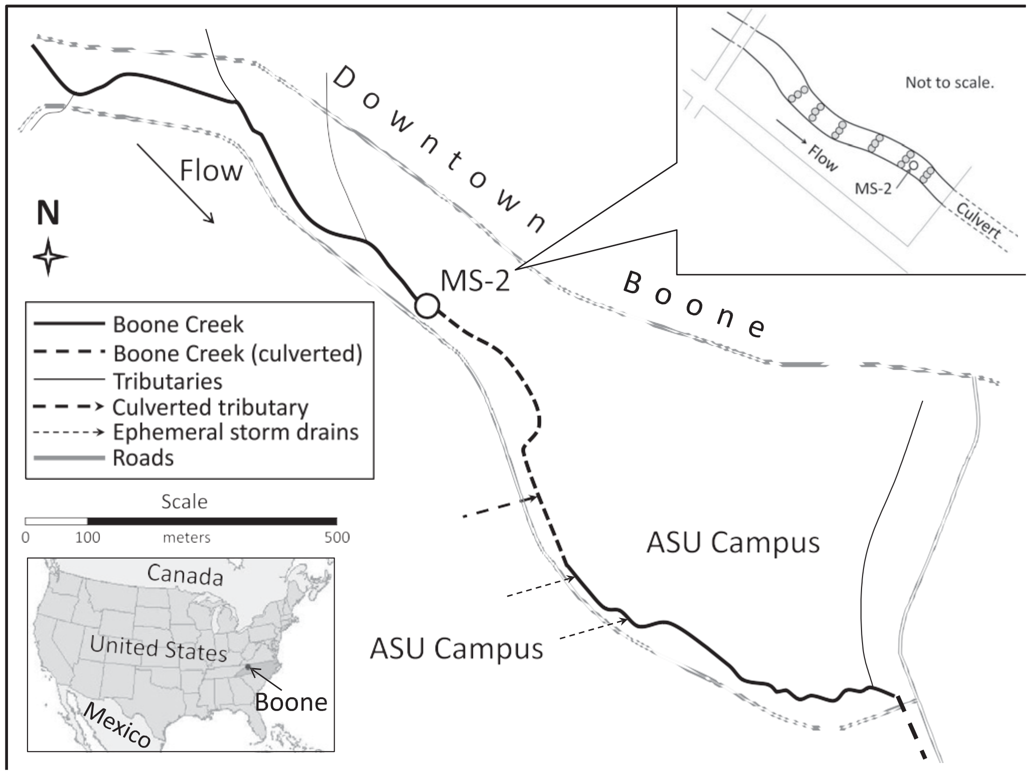

Fig. 1. A map of Boone Creek showing the main stem of the stream (solid line), the main study location of this paper (circle labeled MS-2), the culverted reach of the stream below MS-2 (dashed line), and the approximate location of tributaries, culverted tributaries, and ephemeral storm drains (arrows). The inset shows a drawing of the stream around MS-2, including the layout of the streambed piezometer nests (small gray circles). Modified from Anderson et al. (2010).

MS-2 (Fig. 1). The initial stations were also used to monitor stream stage, which were converted to stream discharge based on rating curves that were developed as part of the initial study (Anderson et al., 2007b, 2010). In subsequent years additional stream temperature monitoring sites were added as well as streambed temperature piezometer nests (approximate locations shown in the inset of Fig. 1 along with their location relative to monitoring station MS-2), which we use to determine daily-average groundwater discharge velocities (Anderson et al., 2010) using the decay of the temperature signal with depth (Hatch et al., 2006; Keery et al., 2007). In total, we have monitored stream temperatures at 15-min intervals at 10 monitoring stations for up to 4 years on the main stem of Boone Creek. The flashy conditions in the stream caused the loss of several of the temperature gauges during the monitoring period; therefore, all of the temperature time-series data have gaps. Still, we have a fairly complete record of stream temperature variations along the length of Boone Creek.

3.2. Numerical modeling with VS2DH

The US Geological Survey two-dimensional finite-difference code VS2DH combines the solution of Richards' equation for fluid flow with the solution for advective–dispersive energy transport (Healy and Ronan, 1996). We employ this model for our numerical experiments because of its ease of use, applicability to our problem, and its prevalence in the literature (see, for example, Constantz, 1998; Hatch et al., 2006; Schmidt et al., 2007; Lautz, 2010; Duque et al., 2010, for studies that utilize VS2DH). Our numerical simulations implement VS2DH in one dimension oriented perpendicularly to the streambed under fully-saturated conditions. The 4 m-high by 1 m-wide model domain utilizes a grid spacing of 0.01 m in the vertical direction (Fig. 2). We assign specified pressure-head boundaries to the top and bottom of the model domain in order to produce the desired groundwater discharge velocity; the upper pressure boundary corresponds to stream stage. We assign higher heads to the lower boundary, forcing upward flow and gaining stream conditions. The resulting gradient produces groundwater discharge velocity equal to the mean of 0.37 m/d reported by Anderson et al. (2010). Specified temperature boundaries are also assigned to the upper and lower boundaries, the upper boundary oscillating with diurnal stream temperature oscillations and the lower boundary fixed at the mean stream temperature of 17 °C. The sides of the model have been designated no fluid flow and no heat flow boundaries. This assumption requires ideal vertical flow. Although purely vertical flow would not necessarily be the norm in most field settings, this assumption provides a conservative estimate of the interaction between stream and groundwater in the hyporheic zone. Given that this is a study that is meant to demonstrate groundwater–surface water interactions during temperature surge events, we think that this assumption is acceptable.

3.2.1. Generic simulations

The main numerical experiment involves simulations of a generic aquifer that we base on conditions exhibited at monitoring station MS-2. We generate initial conditions for the transient simulations using an ideal sinusoid that approximates diurnal stream temperature oscillation with mean stream temperature of 17 °C, amplitude of 1.25 °C, and constant stream stage. This simulation runs for 100 days in order to provide adequate time for the model to stabilize. The transient initial condition simulations vary stream temperature and stage at 30-min intervals, which is similar to the methodology of Lautz (2010). These results then function as initial conditions of pressure head and temperature distribution with depth in subsequent transient simulations.

3.2.2. Sensitivity analyses

We also conduct sensitivity analyses of hydraulic parameters, thermal parameters, and boundary conditions to delineate the

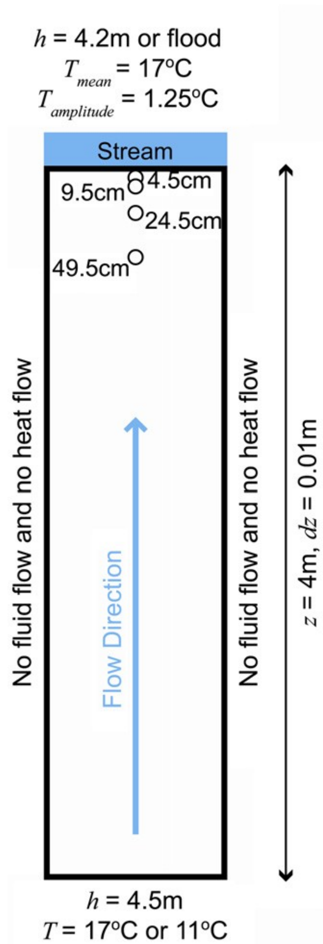

Fig. 2. A drawing of the model domain oriented perpendicularly to the streambed showing temperature boundary conditions in the stream and at the base, no-flow boundaries along the sides, and pressure heads at the upper and lower positions of the model that result in upward flow of groundwater to the stream or gaining conditions. While streambed monitoring locations are shown for a portion of the study, later analyses in the paper utilize monitoring locations at 2 cm spacing, which is too dense to place on this figure.

primary controls on streambed temperature distribution with depth. Hydraulic parameters include hydraulic conductivity, porosity, and storativity. Thermal parameters that we vary include heat capacity of the sediment and thermal conductivity. Given the narrow range of potential heat capacity values of water, we do not perform sensitivity simulations of this parameter. Boundary conditions also have a strong influence on model output. We vary the groundwater discharge velocity, storm stage, storm stream temperature, and model base temperature in an effort to explore the influence of the boundary conditions on model output. We generate initial conditions for each of the sensitivity simulations with the varied parameter and then use these conditions as initial conditions in the subsequent 11-day storm and sinusoidal simulations.

4. Results

4.1. Stream temperatures during storm surges

Over four summers of stream temperature monitoring, a total of 71 temperature surges occurred at the MS-2 monitoring site (Fig. 1), which is 16.4% of the monitored days. These surges averaged 2.39 °C with a maximum change of 6.36 °C in August 2007. It should be noted that the total temperature increase during each event is larger than this value, which only includes the changes in temperature that exceeded 1 °C within 15 min. Taking into account that multiple surges may occur within a period of 1 h, we calculated the mean duration of each surge event. The data show that each surge in temperature of greater than 1 °C lasted an average of 18.6 min and occurred on average at 14:31; the time need for the stream to return to typical diurnal oscillation is on the order of hours. While afternoon convective storms account for a majority of the events, as suggested by the mean time of occurrence, temperature surges may occur at any time: the data show that 10 events occurred between 22:00 and 4:00 during the four summers of monitoring. The temperature surges also may have a period of less than 1 °C rise in the midst of the storm event. Accounting for all positive changes in stream temperature during a surge, where brief intervals of falling temperature may occur during a single, long storm event, our data from the MS-2 monitoring site show that total temperature surges average 2.63 °C and last for 30.4 min.

The total number of temperature-surge events occurring in the basin depends as much on high temperatures as it does on hydrologic conditions. Drought conditions during Summer 2008 limited the number of convective storm events, so only three temperature surges occurred at MS-2. In contrast, record heat during Summer 2010, coupled with a wealth of convective storms, prompted at least 44 temperature surge events at MS-2. This total is likely higher because it does not include at least two events during the last week of May and first half of June when the temperature sensor was lost. Fig. 3 shows stream temperature time-series as measured at monitoring site MS-2 during Summer 2010, including the timing and magnitude of temperature surge events (see location in Fig. 1).

The effect of the temperature surge events can be observed in the streambed as well. Fig. 4 shows streambed temperature time series as measured in 17 piezometer nests during a temperature surge event on July 5, 2008. These are a portion of the streambed temperature data that were used to calculate groundwater discharge velocities in Anderson et al. (2010). The spacing of the shallow and deep observation points at all locations was 25 cm, and the approximate depth of the shallow observation point in each nest was 10 cm. The measured temperature surge in the streambed is damped relative to the stream temperature, and this dampening increases with depth. Peak streambed temperatures also lag the timing of the peak stream temperatures with the lag also increasing with depth. The streambed time series are particularly interesting because of the large variation in storm response between the 17 monitoring sites. This is an indication of the heterogeneity of the streambed sediments (e.g., Conant, 2004; Schmidt et al., 2007).

4.2. Base case simulations

Transient simulations of the flood wave problem run for 11 days utilizing an ideal flood wave that is typical of mean storm conditions (time series of stage and temperature) as measured in Boone Creek (Fig. 5). The storm simulation lasts one day with ideal sinusoidal oscillations that generated the initial conditions returning for the remaining 10 days of simulation. The 10-day length of the sinusoidal oscillation provides adequate time for temperatures in the streambed to return to pre-storm conditions. VS2DH generates model output at 30-s intervals every 2 cm of depth up to 2 m in depth for each of the simulations.

The simulated temperature surge has the properties of the design storm shown in Fig. 5 with a change in stream temperature prompted by the design temperature surge of 3.66 °C and a stream stage increase of 0.63 m. We add the conditions of Fig. 5 to the sinusoidal oscillation of the generic diurnal variations, placing the storm event at 15:00, which is near the mean time of

Fig. 3. Stream temperatures measured at 15-min intervals at monitoring station MS-2 during Summer 2010. Note the temperature surges, which present as a spike in the normal temperature oscillation. The spikes on 08 July, 09 July, and 26 July are particularly good examples of temperature surges.

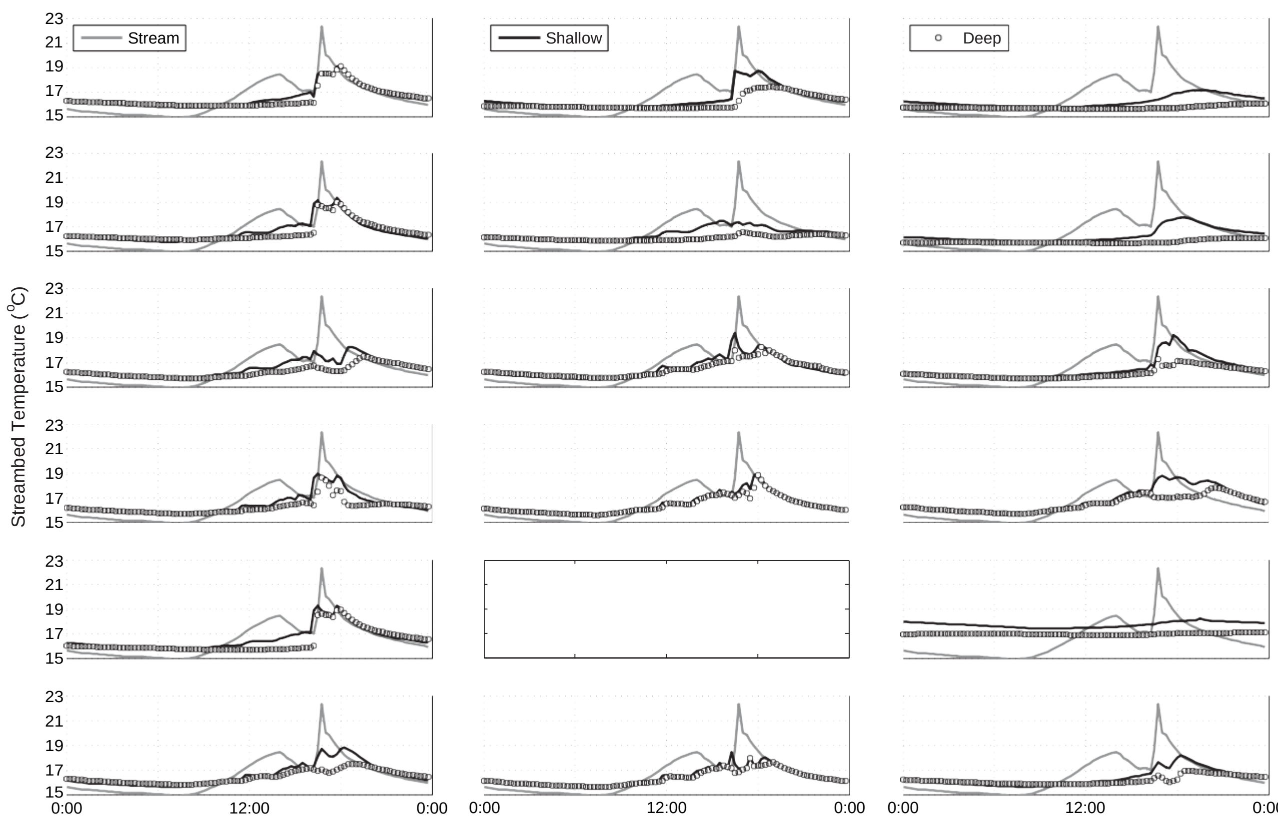

Fig. 4. The influence of a temperature surge of 05 July, 2008 (solid gray line), on measured streambed temperatures at shallow (~10 cm, solid black line) and deep (~35 cm, white circles) locations. The plots are shown in relative orientation in the stream with flow from top to bottom. Note that data from the center of Row 5 were unavailable due to the loss of the probe. The high variability of the streambed response reflects the heterogeneity of the streambed sediments.

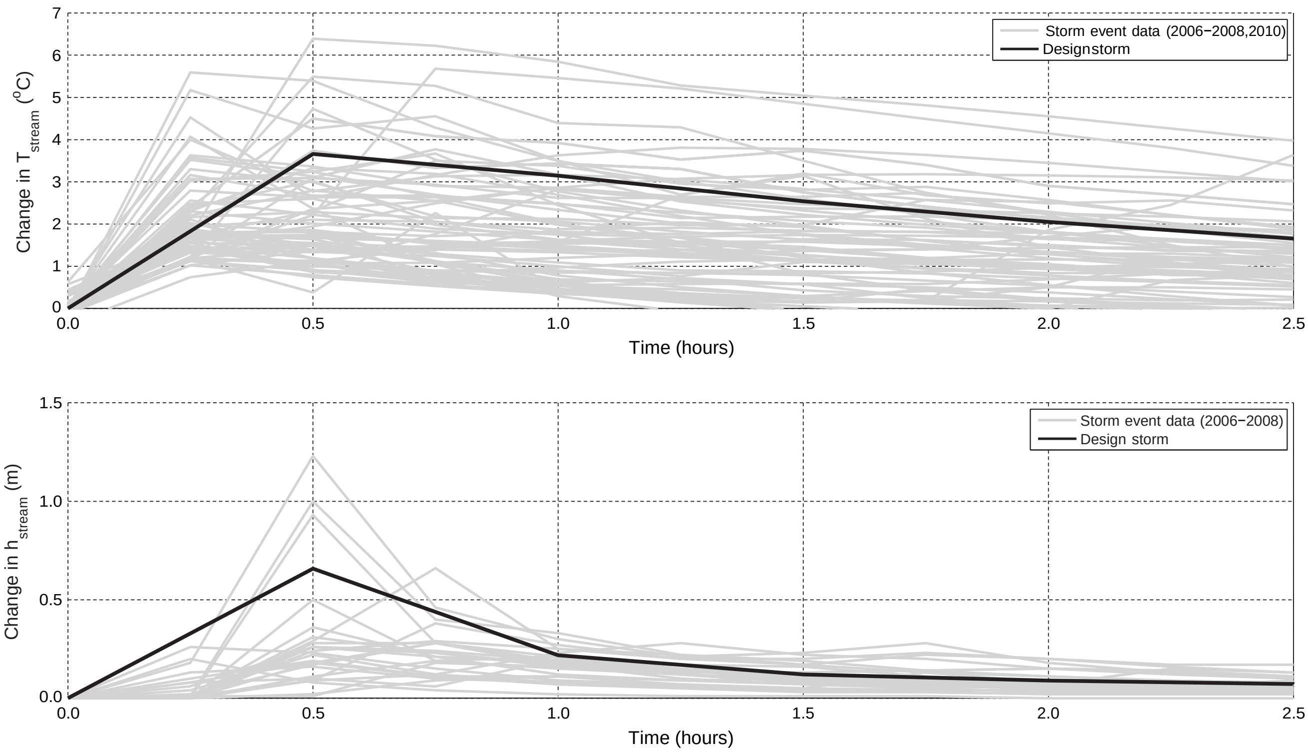

Fig. 5. Storm design for numerical simulations with VS2DH showing (upper panel) all temperature surge field data from monitoring station MS-2 (gray lines) and the design storm (black line), and (lower panel) all measured floodwave data from the same station (gray lines) and the design storm (black line).

occurrence of temperature surges in Boone Creek. Our intent in returning the non-storm stream conditions to the sinusoidal oscillations is to limit the complexity of conditions in the stream and thereby limit the source of perturbations in model output to include only the simulated storm events. Fig. 6 compares flood wave conditions with the ideal sinusoidal oscillations. The generic sinusoidal oscillation has the same mean temperature (17 °C) and amplitude (1.25 °C) as those that generate the initial conditions. Table 1 shows the model parameters for the numerical simulations. We evaluate the influence of the temperature-surge events by comparing the generic sinusoidal simulation output to the storm-influenced output. For each condition we run two transient simulations: (1) a 1-day storm event followed by 10 days of diurnal temperature fluctuation, and (2) 11 days of diurnal temperature fluctuation. We compare the influence of the storm with depth by taking the difference between the two simulations. By doing so, we are able to see the influence of the individual storm event on streambed temperatures. The same methodology applies to the sensitivity analyses.

The base case simulation models aquifer parameter, boundary, and flood-wave conditions that approximate conditions in Boone Creek. Fig. 7 shows the results of these simulations with the upper panel displaying the floodwave simulation output at a range of depths in the streambed (4.5 cm, 9.5 cm, and 24.5 cm) in addition to conditions in the stream, the middle panel showing 11 days of sinusoidal oscillation, and the lower panel displaying the difference between the upper and middle panels at various depths. At a streambed depth of 4.5 cm, nearly half of the temperature-surge signal has dissipated, possibly in response to the high frequency of the perturbation, and lag times between the surface and this depth are approximately 30 min. Thermal dampening is more obvious at a depth of 9.5 cm, where peak temperature is only about one-third of that experienced in the stream and lag times are on the order of 2 h. Dampening and lags continue to increase with depth. At a depth of 24.5 cm into the streambed, the temperature oscillation caused by the storm event is only 10% of that in the stream and lags the actual event by 8 h. By a depth of 49.5 cm, the perturbation is barely noticeable (∼0.1 °C), and this perturbation lags that in the stream by 17.5 h. The simulations suggest that negligible changes in temperature of up to 0.001 °C occur deeper in the streambed, but these would not be detectable with common temperature sensors.

The base case results are analogous to the sample streambed temperature data shown in Fig. 4. While the July 5, 2008 storm event has neither the same thermal signal nor the same change in stage, conditions are comparable to the simulated data. The shallow storm signals, which are all near 10 cm in streambed depth, but may be slightly shallower due to field-necessitated variations in total installation depth, show a range of thermal dampening and lag times. Thermal dampening in the shallow dataset ranges from 50% to 90% of the storm signal. Lag times range from instantaneous response to hours of delayed response. At deeper locations of approximately 35 cm, but again with some variation, thermal dampening ranges from 50% to 100%, and lag times are all greater than 1 h. It should be noted that this is only one storm; however, it does show that the simulations utilize hydraulic and thermal properties and boundary conditions that are a good approximation of the Boone Creek streambed.

4.3. Sensitivity analyses

The sensitivity analyses are undertaken for hydraulic and thermal properties and boundary condition variations in an effort to determine the importance of the various parameters. We display the results of the sensitivity simulations as differential temperature time series, as in the lower panel of Fig. 7, at a simulated depth of 9.5 cm, which is the approximate depth of the shallow sampling in the field data (Fig. 4). Table 2 shows the range of values used in the sensitivity simulations.

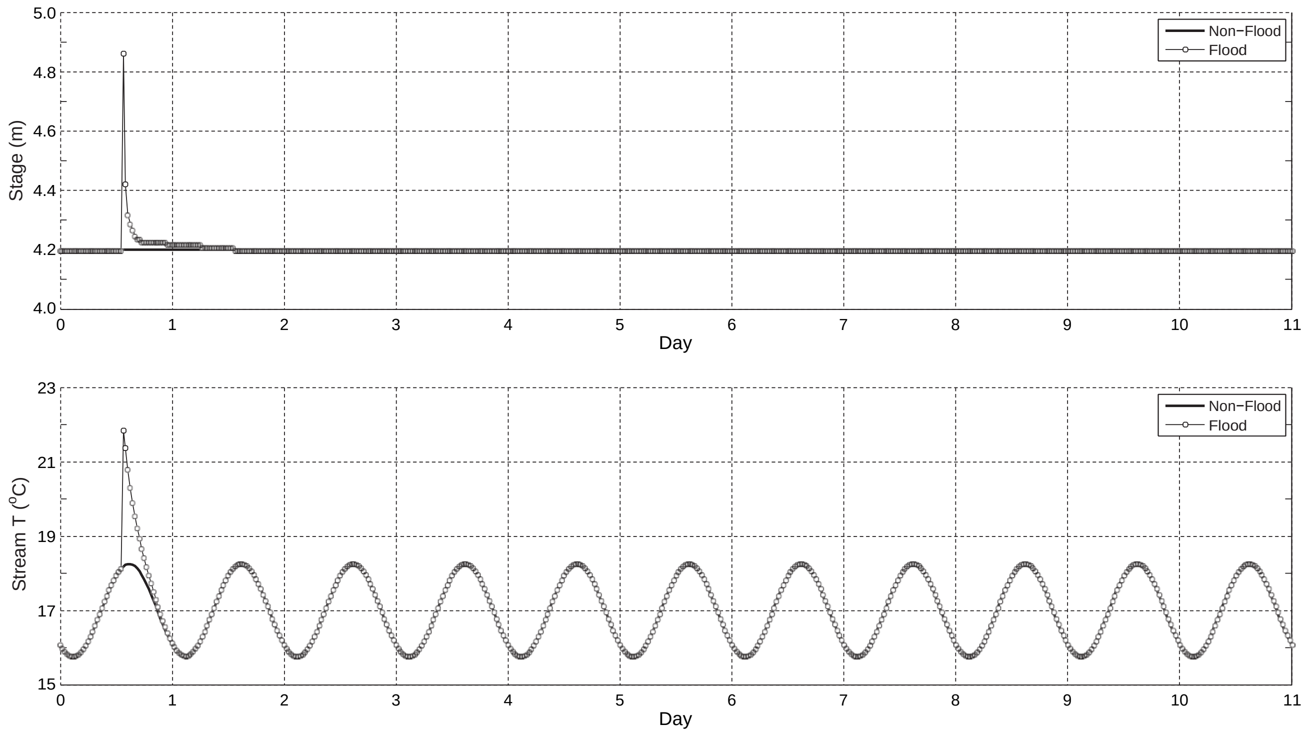

Fig. 6. Plots of the flood (solid line) and non-flood (thin line with white circles) boundary conditions of (upper panel) stream stage and (lower panel) stream temperature. Note that the differences between simulation output of flood and non-flood events will indicate the influence of the temperature surge on streambed temperatures.

Table 1
Hydraulic and thermal property values used in the VS2DH modeling.

Parameter	Value	Units
Saturated hydraulic conductivity @ 20 °C, K	1.2×10^{-5}	m/s
Specific storage, S_s	0.0001	m^{-1}
Porosity, /	0.20	1
Longitudinal dispersivity, a_L	0.10	m
Saturated thermal conductivity, j_T(/)	1.67	J/(s m °C)
Heat capacity of the streambed materials, C_s	2.100×10^6	J/(m^3 °C)
Heat capacity of water, C_w	4.182×10^6	J/(m^3 °C)
Heat capacity of the saturated streambed, $C_{streambed}$	2.516×10^6	J/(m^3 °C)
Density of water, q	1000	kg/m^3

4.3.1. Hydraulic parameters

Fig. 8 shows the influence of variations in streambed hydraulic parameters over a range of values. In the upper panel, we display the modeling output from variations in hydraulic conductivity by an order of magnitude above and below base conditions. In the middle panel, we show the results of variations in model output through variations in porosity of ±0.10. The lower panel shows the effect on model output of variations in storativity by an order of magnitude above and below base conditions. As the results in Fig. 8 indicate, the most sensitive hydraulic parameter is hydraulic conductivity. Increasing hydraulic conductivity by an order of magnitude allows the thermal signal of the stream to more readily penetrate the streambed: more of the thermal signal makes it to the modeled depth of 9.5 cm and the lag time decreases. In fact, nearly twice the thermal signal is able to penetrate to this depth, making it resemble the shallowest time series of the base simulation of the lower panel of Fig. 7. Neither porosity nor storativity variations affect model output over the range of likely parameter values.

4.3.2. Thermal parameters

We examine the influence of variations in thermal parameters in Fig. 9, which in the upper panel shows variations in the heat capacity of the sediments and in the lower panel shows variations in thermal conductivity. In both cases, the thermal parameters are doubled and halved. Model output is sensitive to variations in these parameters in the same manner that model output was sensitive to hydraulic conductivity. In the case of the halving of the heat capacity of the sediment, streambed temperatures at a depth of 9.5 cm rise by nearly 1 °C with a 2-h decrease in lag time. A doubling of the sediment's heat capacity has a less dramatic effect on model output; however, the temperature time series decreases in amplitude and lags 90 min in time. Model output is also sensitive to thermal conductivity, but not at the same level as streambed sediment heat capacity. Halving and doubling of this parameter causes nearly identical increases and decreases in streambed temperature differentials of approximately 0.2 °C. Halving of thermal conductivity relative to the base simulation produces a lag in the temperature signal of 30 min; doubling of thermal conductivity, however, produces an earlier arrival of the temperature signal by 1 h relative to base conditions.

The thermal parameter sensitivity results are not surprising and serve to support the primary tenet of this paper that the streambed acts as a thermal sink to temperature surge events. A decrease in the heat capacity of the sediment in the sensitivity simulation promotes a greater fluctuation in streambed temperatures with depth, while an increase in the heat capacity reduces the streambed temperature fluctuation at various depths. Presumably, a streambed matrix of infinitely high heat capacity would not change temperature as a result of heat transfer into the streambed; conversely, a streambed matrix of zero heat capacity would show nearly the same temperature oscillation as that occurring in the stream. The behavior of the model output with respect to the thermal conductivity is also not surprising as it should behave in much the same manner as hydraulic conductivity. Doubling of the thermal conductivity allows easier conduction of the thermal signal into the streambed than the base conditions; conversely, halving of the thermal conductivity makes it more difficult for the thermal signal to conduct into the aquifer. Additionally, amplitude variations are

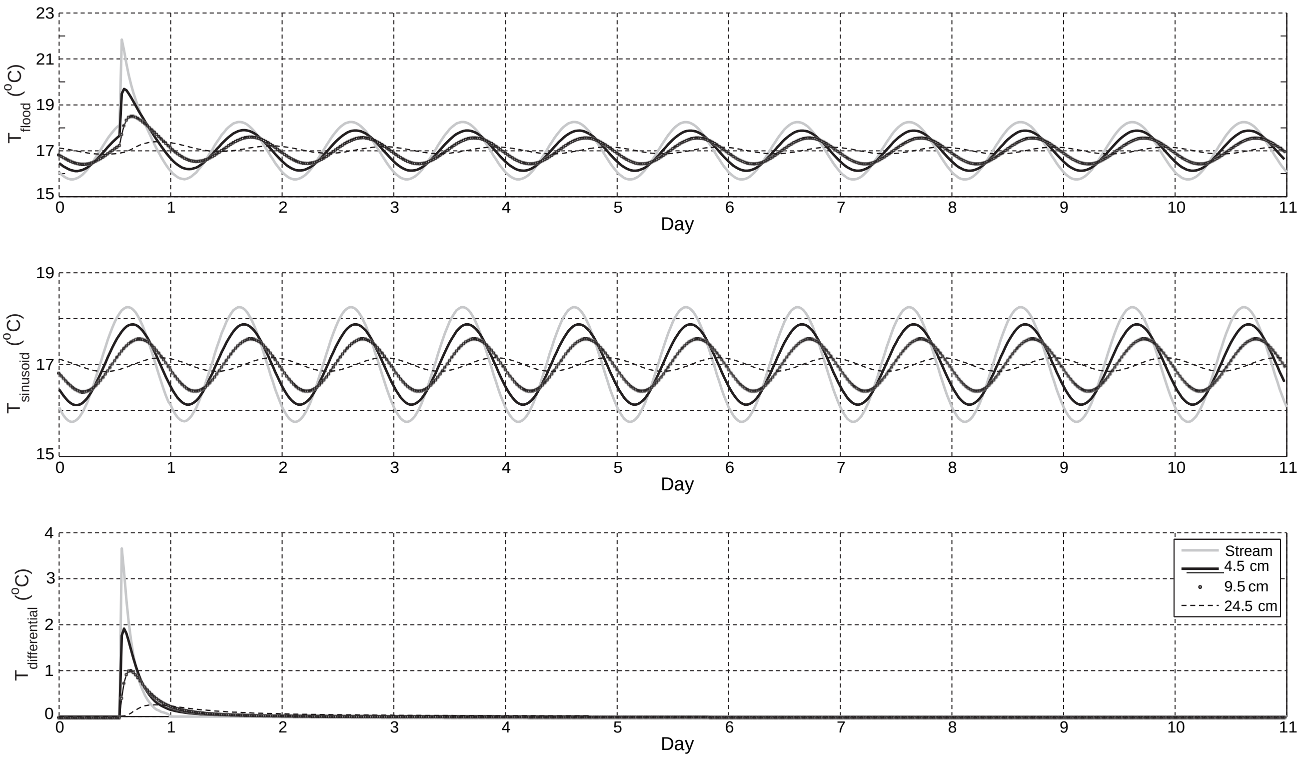

Fig. 7. Simulated stream and streambed temperatures based on base-case simulations of (upper panel) the floodwave and 10 days of sinusoidal oscillations, (middle panel) solely sinusoidal oscillations, and (lower panel) the difference between the upper and middle panels. The stream is shown as a gray line with various depths shown as solid black lines (4.5 cm), solid black lines with white circles (9.5 cm), and dashed lines (24.5 cm).

Table 2
Parameters used in the sensitivity simulations.

Parameter	Base value	Increase	Decrease	Units
Hydraulic parameters				
Saturated hydraulic conductivity @ 20 °C, K	1.2×10^{-5}	1.2×10^{-4}	1.2×10^{-6}	m/s
Porosity, /	0.20	0.30	0.10	1
Specific storage, S_s	0.0001	0.001	0.0001	m^{-1}
Thermal parameters				
Heat capacity of the streambed materials, C_s	2.100×10^{6}	4.200×10^{6}	1.050×10^{6}	J/(m^3 °C)
Saturated thermal conductivity, j_T(/)	1.67	3.34	0.835	J/(s m °C)
Boundary conditions				
Groundwater discharge velocity, v_{gw}	0.37	3.70	0.037	m/d
Storm change in stage, Dh	0.66	1.32	0.33	m
Storm change in temperature, T_{flood}	3.66	7.32	1.83	°C
Model base temperature, T_{bot}	17	–	11	°C

not as high as those produced by variations in hydraulic conductivity and sediment heat capacity because conduction is a slower process and the storm events reflect convection-dominated conditions.

4.3.3. Boundary conditions

We examine the influence of variations in boundary conditions in Fig. 10, which shows the effects on modeled streambed temperatures of variations in groundwater discharge velocity, stream stage, surge temperature, and bottom boundary temperature. Peak surge temperature in the stream during the surge event is the most sensitive of the boundary conditions (lower middle panel). As expected, a doubling of the surge temperature at the upper boundary of the model produces a doubling of the streambed temperature at a depth of 9.5 cm; conversely, halving of the surge temperature cuts streambed temperature by half. This large variation in streambed temperature does not produce a corresponding lag at depth. Modeled streambed temperatures are only moderately sensitive to two other boundary conditions: groundwater discharge velocity and stream stage. Lower groundwater discharge velocity (upper panel) enables the thermal signal of the storm to penetrate further into the streambed; thus, streambed temperatures at 9.5 cm are 0.25 °C higher than those simulated under base conditions and there is no obvious time lag. Higher groundwater discharge velocities, in contrast, cause the thermal signal of the storm event to have a shorter residence time in the streambed. This results in an obvious time lag under this condition and the thermal signal decays at a faster rate. Variations in stream stage (upper middle panel) have minimal effect on lag times. They do, however, have an effect on streambed temperatures, where a doubling of the stream stage raises streambed temperature at 9.5 cm by 0.25 °C and halving of the stream stage lowers streambed temperatures by <0.10 °C. Basal model temperature (lower panel) has no effect on model output.

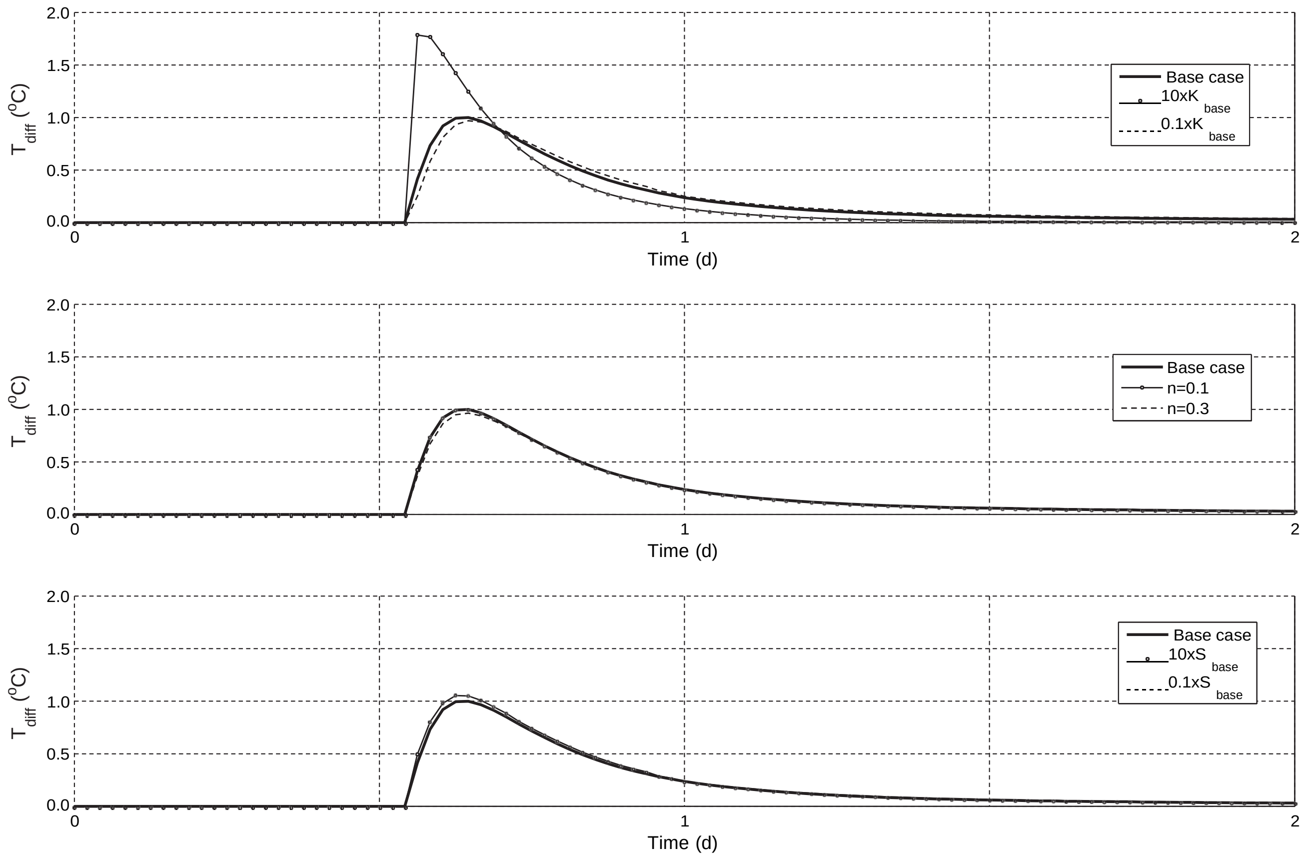

Fig. 8. Sensitivity simulation results at a simulated depth of 9.5 cm for variations in hydraulic parameters. The figure shows model output sensitivity to (upper panel) streambed hydraulic conductivity, (middle panel) porosity, and (lower panel) storativity. In all panels solid black lines represent base case simulations, while solid black lines with white circles and dashed lines represent changes in a parameter.

4.4. Heat storage calculations

We quantify heat flux in the streambed by integrating the streambed temperature differential time series using

$$H_{streambed}(t) = (\rho c)_{streambed} V_{streambed} \Delta T_{streambed}(z,\ t); \tag{1}$$

where $(\rho c)_{streambed} = C_{streambed} = nC_w + (1 - n)C_s$ represents heat capacity of the streambed (J/m^3 °C), n is the porosity, C_w is the heat capacity of water, C_s is the heat capacity of the solids making up the streambed, $V_{streambed}$ is the volume of the streambed influenced by the temperature surge (m^3), and $\Delta T_{streambed}(z, t)$ is the storm-induced streambed temperature differential time series (°C) as a function of depth and time. The volume of the streambed, $V_{streambed}$, consists of a unit length along the channel, a 2.8 m width, which is the stream width at the study site and represents the mean channel width, and a 2.0 m depth, which is the extinction depth of the storm's influence. Note that this is a conservative estimate as it assumes purely vertical flow and disregards stream–aquifer interaction with the stream banks, which is highly probably during temperature surge events. Also note that the quantity $\Delta T_{streambed}(z, t)$ is the temperature differential calculated by subtracting the sinusoidal simulations from the temperature surge simulations (as shown in the bottom panel of Fig. 7). This difference represents temperature variations produced over time in the streambed by the temperature surge itself at depths up to 2 m. Obviously, the amplitude and phase of this differential varies with depth and time. We account for this by quantifying the time series of heat stored in the streambed through integration with depth for each time step of the model output.

We employ a similar methodology to calculate the heat stored in the stream due to the temperature surge event with the following equation

$$\begin{aligned} H_{stream}(t) &= (\rho c)_w \Delta h_{stream}(t) w_{stream} l_{stream} \Delta T_{stream}(t) \\ &= (\rho c)_w \Delta V_{stream}(t) \Delta T_{stream}(t); \end{aligned} \tag{2}$$

where $(\rho c)_w = C_w$ represents heat capacity of water (J/m^3 °C], Δh_{stream} is the change in stage of the stream over the course of the temperature surge event, w_{stream} is the mean width of the stream, or 2.8 m, l_{stream} is a unit length of the stream, or 1.0 m, and ΔT_{stream} is the difference in stream temperature over time between the temperature surge event and the typical diurnal oscillation.

In Fig. 11 we compare bank thermal storage to the heat stored in the stream during the first 24 h following the temperature surge event. The quantities shown in this figure represent heat storage induced by the temperature surge event only. All pre-surge heat storage has been removed. The x-axis in both panels of the figure shows time in hours. In the upper panel we show heat storage in the upper 2 m of the streambed in order to enable it to be viewed in detail. This same quantity is shown in the lower panel as well with a different y-axis scale. Note that the peak heat storage occurs 90 min after the temperature surge and the decay of this heat storage persists well beyond the 24 h that are shown. The lower panel compares heat storage in the stream to that in the streambed. At early times, heat storage in the stream overwhelms that of the streambed. As the heated floodwave subsides after approximately 2 h, however, heat storage in the streambed overtakes that in the stream. Six hours after the temperature surge, heat storage in the

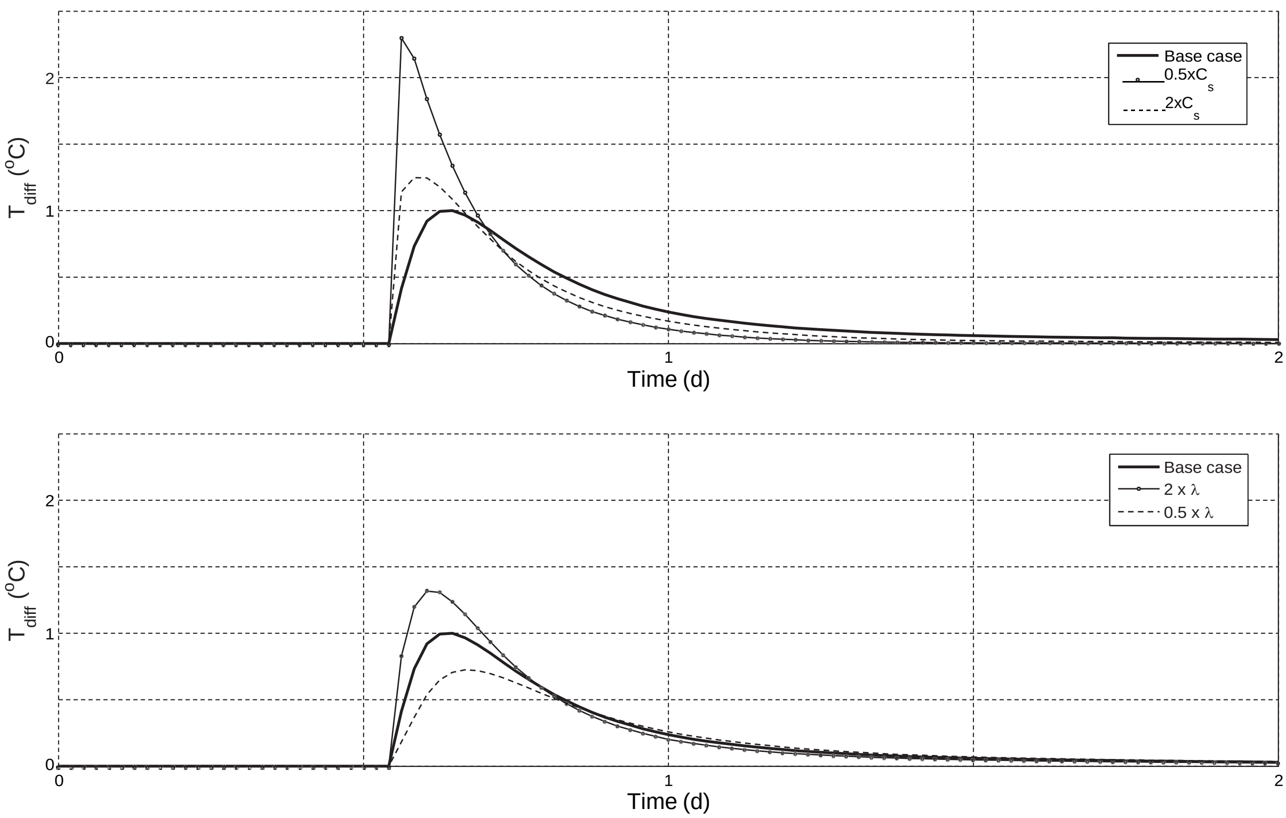

Fig. 9. Sensitivity simulation results at a simulated depth of 9.5 cm for variations in thermal parameters. The figure shows model output sensitivity to (upper panel) sediment heat capacity and (lower panel) thermal conductivity. This figure uses the same line scheme as Fig. 8.

stream is essentially zero. Integration of the two curves in the bottom panel shows that the total heat stored in the streambed due to the temperature surge is 72% of the total heat stored in stream due to the same temperature surge during the first 24 h after the storm.

5. Discussion

The hydraulic and thermal processes that we have discussed in this paper are essential for understanding basic bank storage dynamics in urban stream environments, especially those subject to temperature surge phenomena. Bank storage has been discussed for years as a water storage process during flood events; however, we could find no mention in the literature of the heat storage capabilities of bank storage during flood events, or *bank thermal storage*. We have observed this process in Boone Creek and have based this study in part on these observations.

We have demonstrated with numerical simulations that temperature surges during storm events may be transferred to the streambed in gaining streams as increasing streambed temperatures lagging in time. Furthermore, these temperature surge events affect streambed temperatures even though the events themselves are of relatively short duration. Our simulations demonstrate the changes in streambed temperature that occur; however, there is more to this process than our simulations show. For example, this process occurs due to (1) reversed hydraulic gradients prompted by the passing floodwave, causing convective heat transport into the hyporheic zone; (2) conduction from the hyporheic groundwater to the streambed sediments; and (3) conduction from the stream directly to the streambed sediments. This complex process needs further study with a more detailed model that can quantify the effect that this process has on mitigating stream temperatures.

Convective transport of the stored heat through baseflow ultimately returns the stored heat back to the stream, but the lagging of this release varies with the thermal and hydraulic properties of the streambed. Thus, the response of a particular streambed to a temperature surge will vary in different alluvial aquifer settings. Conduction also plays a role in this process because of reversed thermal gradients that also occur as the floodwave passes. We do not differentiate between convection and conduction in this study, and have solely looked at the phenomenon in terms of the resulting temperature changes at depth in the streambed and simple calculations of heat storage. While the magnitude of the heat stored will not likely offset the large spike in stream heat storage during peak flows at early times, it should help to mitigate stream heat storage, and thus stream temperatures, at later times when streambed heat storage may meet or exceed that in the stream. The precise influence that these interactions will have on stream temperatures will depend on research combining numerical simulations and mixing model calculations with a heat storage time series similar to studies performed by Becker et al. (2004) and Anderson et al. (2010). This type of work is beyond the scope of this paper.

5.1. Bank thermal storage benefits of stream restoration

A potentially more important lens through which to look at bank thermal storage is in terms of the restoration of urban streams to natural conditions. Heavily altered streams that have had their connection with groundwater eliminated, such as those that have experienced extensive installation of culverts, may see improved mitigation of thermal surges with the restoration of groundwater–surface water interaction. Restoration of stream–groundwater interaction through culvert removal will allow for

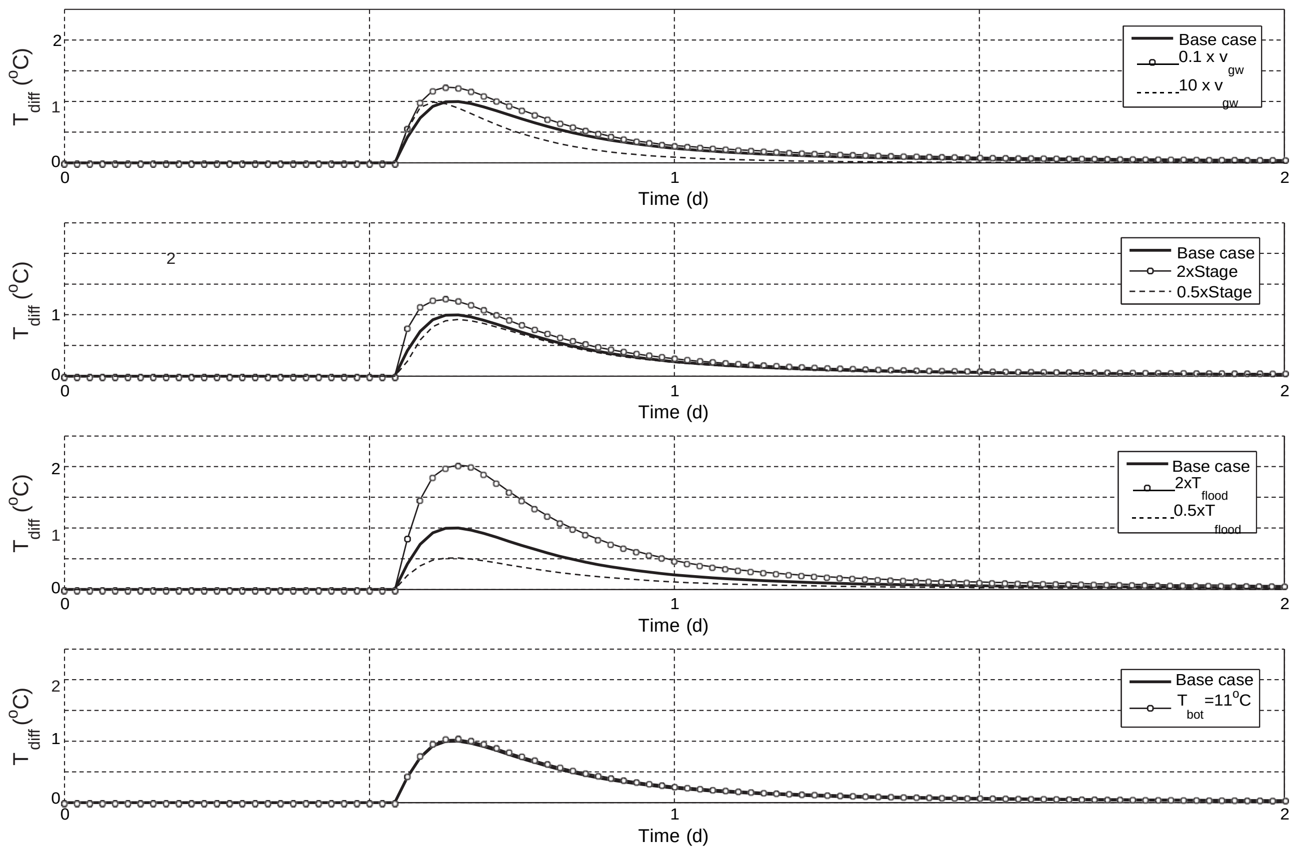

Fig. 10. Sensitivity simulation results at a simulated depth of 9.5 cm for variations in boundary conditions. Model output sensitivity is shown for variations in (upper panel) groundwater discharge velocity, (upper middle panel) stream stage, (lower middle panel) peak surge stream temperature, and (lower panel) model base temperatures. This figure uses the same line scheme as Fig. 8.

additional bank thermal storage during storm events. This restored interaction may help to reduce storm-induced stream temperature surges at locations downstream of the culvert. The increased volume of storage, especially after the removal of long culverts, may play an important role in the mitigation of temperature surge events downstream of the restoration project. It has been demonstrated in the literature (Anderson et al., 2010) that stream–groundwater interactions under baseflow conditions can act to reduce stream temperatures with culvert removal. It is likely that this also applies to temperature surge events at shorter temporal scales. In Boone Creek, for example, a 700 m length culvert exists downstream of the MS-2 monitoring site. Based on this study and our modeling results, which suggest that the depth of storm influence may be up to 2.0 m in streambed depth, removal of the culvert would add approximately 3900 m^3 of streambed for interaction with the bank thermal storage process. This quantity includes the total volume of the streambed. Assuming a porosity of 0.20, this equates with 780 m^3 of groundwater and 3120 m^3 of streambed sediment if applying the conditions of the generic streambed simulations used in this study. The restoration of groundwater–surface water interaction would likely reduce downstream temperatures during post-restoration temperature-surge events because of the added volume available for bank thermal storage, adding more support to the need for culvert removal.

As we have demonstrated in this paper, this process will have similar effects on stream temperatures as does a detention pond (Herb et al., 2009). Restoration of a culverted stream adds aquifer volume to the bank thermal storage process. While this interaction will raise baseflow temperatures at short times after the temperature surge, the effects of the higher baseflow temperatures will be mitigated by the increased lag times that will exist due to thermal capacitance by the streambed sediments and groundwater. Our modeling results demonstrate that streambed sediment and groundwater temperatures increase proportional to the temperature surge, and decay of this signal increases with depth. The increased streambed temperatures, however, are balanced by the lag times that result from the return of this higher-temperature groundwater to the stream as hydraulic and thermal gradients return to pre-storm conditions. So, just as in the case of the detention pond, we suggest that the storage of heat in the streambed means that the heat, although slightly elevated, will persist longer than under culverted conditions. The benefit of culvert removal, though, is that the spike in stream temperature will be reduced.

5.2. Bank thermal storage effects on aquifer hydraulic properties

Another process that occurs in the streambed that we have not taken into account in our modeling with VS2DH is temporal variation in hydraulic conductivity throughout a temperature surge event. Hydraulic conductivity is temperature dependent because it depends on density and dynamic viscosity in the fluid portion of the property. These properties vary with variations in temperature. While VS2DH allows hydraulic conductivity to vary with saturation, it does not allow hydraulic conductivity to vary with changes in temperature, which may add error to our analyses. Constantz (1998) summarizes studies of this phenomenon that suggest that it is less important in gaining streams than in losing streams because the streambed temperatures remain more consistent with time. The fact that temperature surge events cause a rapid change in streambed temperature and the temporary conversion of the stream to a losing stream makes this a potentially important response. In the current study, stream temperatures increase by

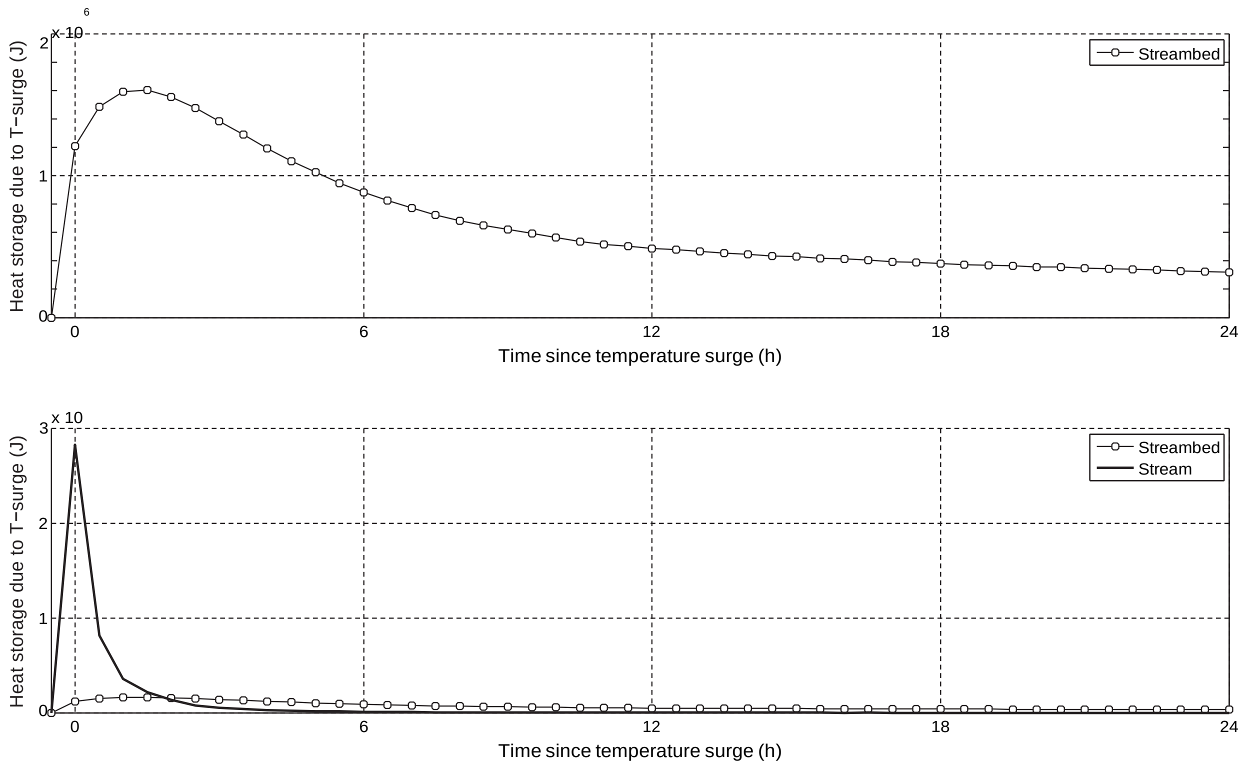

Fig. 11. A comparison of time series showing heat stored in the streambed and the stream in response to a temperature-surge event. Heat stored in the streambed is shown as solid black lines with white circles during the first 24 h following a temperature surge (upper panel). This same quantity and stream heat storage over time is shown as a solid black line (lower panel) with a different *y*-axis scale. Both panels use the same *x*-axis scale.

3.66 °C during the temperature surge event. If we take this as the maximum temperature change, we can calculate the range of hydraulic conductivity that is likely to occur in the streambed during a temperature surge event. Assuming that the pre-storm temperature is 18.25 °C, then the peak temperature in the stream is 21.91 °C. These temperature differentials result in a nearly negligible variation in hydraulic conductivity of only 0.08%. Even using the highest observed change in stream temperature of 6.36 °C, the change in hydraulic conductivity is only 0.14%. Therefore, it is our conclusion that temperature dependence of the streambed hydraulic conductivity is insignificant.

6. Conclusions

Stream temperature surges are extreme events involving a rapid rise of stream temperature in response to heated runoff from urban environments. Despite their potential detrimental effects to riparian habitats, these phenomena are relatively little studied. In fact, we could find only two papers documenting this phenomenon in streams (Nelson and Palmer, 2007; Rice et al., 2011) with most studies focusing instead on the heated runoff itself (Herb et al., 2008, 2009; Janke et al., 2009). Temperature surges as measured at our monitoring station in Boone Creek in North Carolina, USA, averaged 2.39 °C within 15 min of monitoring time; the maximum stream temperature surge recorded at our monitoring station was 6.36 °C. We also detected these temperature surges in the streambed, where we had positioned 17 streambed piezometer nests screened at depths of approximately 10 cm and 35 cm below the streambed surface. The response of streambed temperatures to temperature surges was not uniform, but varied in response to the heterogeneity of the streambed materials. An example case (Fig. 4) in which stream temperatures surged approximately 5 °C caused some streambed piezometer nests to show no response while those positioned in high-permeability sands and gravels showed temperature surges of over 2 °C at shallow depths.

We studied the streambed temperature surge process using numerical simulations performed with the US Geological Survey's two-dimensional finite-difference code VS2DH. Our goals were to document (1) that the process can be replicated in the numerical laboratory, (2) that these events extend well beyond the depth of our piezometer nests, and (3) that these events persist in time and, thus, may potentially mitigate at least some of the detrimental effects of the surge events. We created generic simulations using a homogeneous aquifer and simple sinusoidal and diurnal temperature oscillations; however, we based the simulated temperature surge event and the simulated aquifer properties on our field site in Boone Creek. Our numerical experiments demonstrate that a single temperature surge of 3.66 °C may produce temperature response at depths of up to 2 m. For example, simulated temperature differentials between storm and non-storm conditions show changes of 1.91 °C at a depth of 4.5 cm, 1.0 °C at 9.5 cm, and 0.26 °C at 24.5 cm. These differentials lag the storm in time from 30 min at 4.5 cm up to 8 h at 24.5 cm. Lag times below 49.5 cm are on the order of days.

The simulations show that these relatively quick events have significant impact on streambed temperatures, both in the temperature differentials induced in the streambed and in the persistence of the event in the stream, which may last on the order of days. In addition, our generic simulations show that a streambed having the simulated thermal and aquifer properties may store 72% of the temperature surge-induced heat stored in the stream. Thus, urbanized streams that are still in a relatively natural state in which groundwater–surface water interactions are taking place may be able to buffer these temperature surges with the bank thermal storage process. In many urbanized streams, however, the streambed is not in a natural state because of channelization, the installation of culverts, or the paving of the streambed. Our simulations show that restoration of these altered ecosystems and restoration of groundwater–surface water interaction will enable any gaining stream with a permeable streambed to store at least a portion of the heat generated by a temperature surge. Our simulations are meant to demonstrate this process and cannot be used to quantify the influence that this interaction has on stream temperatures. We see this as the next logical step in the study of the streambed temperature surge phenomenon.

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