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Use of heat to estimate streambed fluxes during extreme hydrologic events

Jeannie R. B. Barlow[1] and Richard H. Coupe[1]

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[1] Using heat as a tracer, quantitative estimates of streambed fluxes and the critical stage for flow reversal were calculated for high-flow events that occurred on the Bogue Phalia (a tributary of the Mississippi River) following the 2005 Hurricanes Katrina and Rita. In June 2005, piezometers were installed in the Bogue Phalia upstream from the stream gage near Leland, Mississippi, to monitor temperature. Even with the hurricanes, precipitation in the Bogue Phalia Basin for the months of June to October 2005 was below normal, and consequently, streamflow was below the long-term average. Temperature profiles from the piezometers indicate that the Bogue Phalia was a gaining stream during most of this time, but relatively static streambed temperatures suggested long-term data was warranted for heat-based estimates of flux. However, the hurricanes caused a pair of sharp rises in stream stage over short periods of time, increasing the potential for rapid heat-based modeling and for identification of the critical stage for flow reversal into the streambed. Heat-based modeling fits of simulated-to-measured sediment temperatures show that once a critical stage was surpassed, flow direction reversed into the streambed. Results of this study demonstrate the ability to constrain estimates of streambed water flux and the critical stage of flow reversal, with little available groundwater head data, by using heat as a tracer during extreme stage events.

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1. Introduction

[2] Surface-water and groundwater exchanges are dynamic processes that can be difficult to quantify, due to an array of challenges in monitoring spatial and temporal hydrologic properties necessary to determine exchange rates. Differential-discharge measurements (seepage runs) are laborious, and result in one value over the entire reach of interest. Measurement of hydraulic values of head and conductivity necessary to directly calculate Darcy flux exchanges are also laborious, and there is considerable uncertainty associated with the derived hydraulic conductivity values. Introduced chemical tracer tests can be effective, but have extensive regulatory and manpower requirements, and can create adverse public perceptions about the test. Natural tracer tests avoid this perception issue, though may be problematic due to reactions, transformations, and the general non-conservative properties of many natural tracers. The use of heat as a natural tracer has proven to be an effective method for identifying and quantifying ground- and surface-water interactions [*Lapham*, 1989; *Stonestrom and Constantz*, 2003; *Anderson*, 2005; *Burow et al.*, 2005]. Although heat is also a non-conservative tracer, the physics of heat and water transport through sediments is well defined and predictable for a range of hydrologic settings [*Blasch et al.*, 2007]. In addition, temperature data are relatively easy to collect and provide insight into streambed processes, such as infiltration rates and groundwater discharge into the stream. The theory behind using heat as a tracer is based on Darcy's law and Fourier's law, which govern the movement of fluids and conductive movement of heat, respectively. Additionally, numerical models, such as VS2DH used in this analysis, utilize a form of the advection dispersion equation to simulate energy transport. [*Healy and Ronan*, 1996]. VS2DH is a modification of VS2DT [*Healy*, 1990], which was developed for simulating solute transport in variably saturated porous media such as ephemeral streambeds or through the vadose zone [*Blasch et al.*, 2006; *Constantz et al.*, 2001]. Recent studies have also shown the effectiveness of using heat to model energy transport in order to derive hydraulic properties of alluvial aquifers and wetlands [*Su et al.*, 2004; *Burow et al.*, 2005].

[3] Use of heat as a tracer is routinely applied to short duration data sets derived from strongly gaining or losing streams to estimate streambed hydraulic conductivities and fluxes. For stream environments with low hydraulic conductivities and hydraulic gradients, low fluxes generally yield subtle diurnal variations in streambed sediment temperature, such that longer duration data sets are desirable for matching simulated to observed streambed temperatures. Though simulations can match the static temperature pattern created by low fluxes, dynamic patterns created by higher fluxes are desirable to verify that thermal and hydraulic parameters in the model are good approximations of those in the actual streambed. The site investigated in this study generally showed low streambed fluxes during base flow conditions or small storm events, but relatively high stream-

[1] Water Resources Division, U.S. Geological Survey, Jackson, Mississippi, USA.

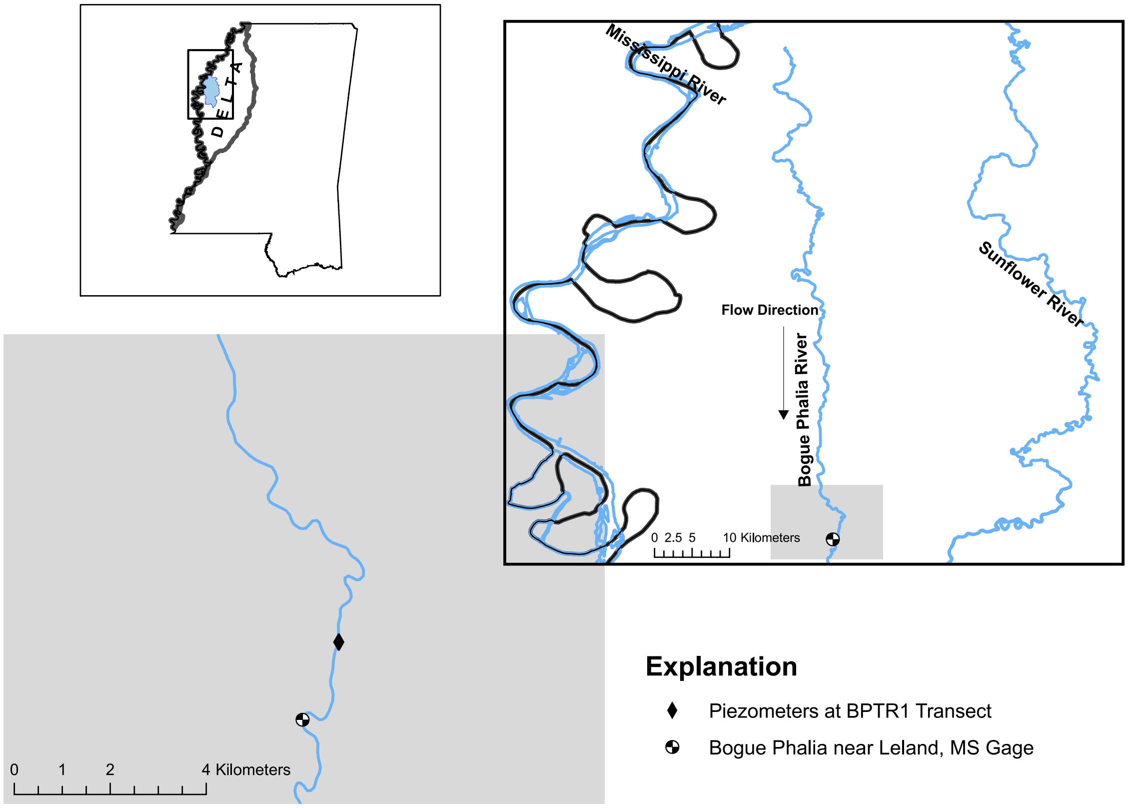

Figure 1. Location of the study area within the Bogue Phalia Basin in northwestern Mississippi.

bed fluxes were observed throughout both hurricanes. This study examines the value of using heat tracing methods for data from extreme hydrologic events to estimate hydraulic conductivity, fluxes, and critical stage estimates.

2. Background

[4] The Bogue Phalia Basin is located in northwestern Mississippi in the Mississippi Alluvial Plain, locally referred to as the Delta (Figure 1). The principal aquifer of interest in this region is the Mississippi River alluvial aquifer (alluvial aquifer). This aquifer is considered to be a confined aquifer, with the confinement penetrated locally by streams. The piezometers in this study are located in an area where the stream cuts through the surficial clay layer, and is hydraulically connected to the alluvial aquifer. Streambed sediments in this area consist of loamy clays with some loess at the surface grading into fine to medium sands about 2 m below the surface. During normal stream stage, groundwater heads are generally higher than the stream stage and the reach is a gaining reach. The site was chosen on the basis of boat accessibility, observed groundwater seepage along the stream banks, and a nearby USGS real-time gage (approximately 2.3 km downstream).

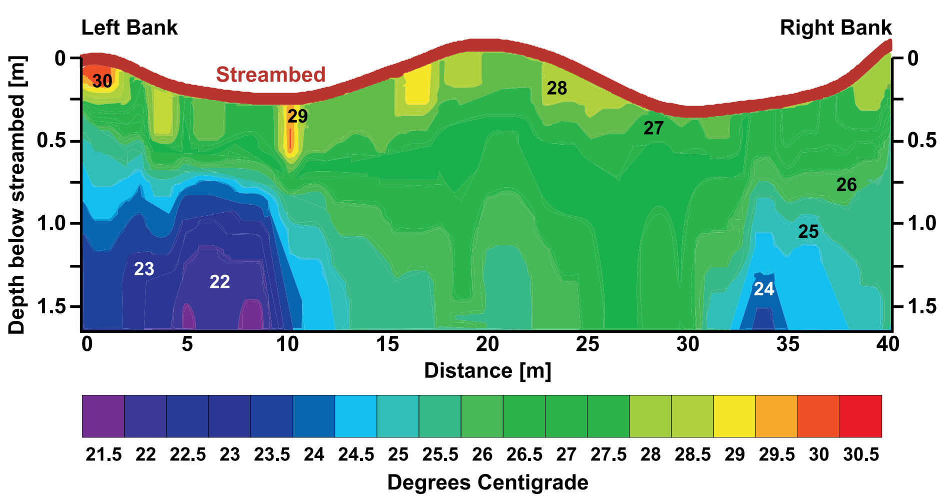

Figure 2. Temperature cross-sections for BPTR1 transect. Contours generated using measurements made by temperature probes.

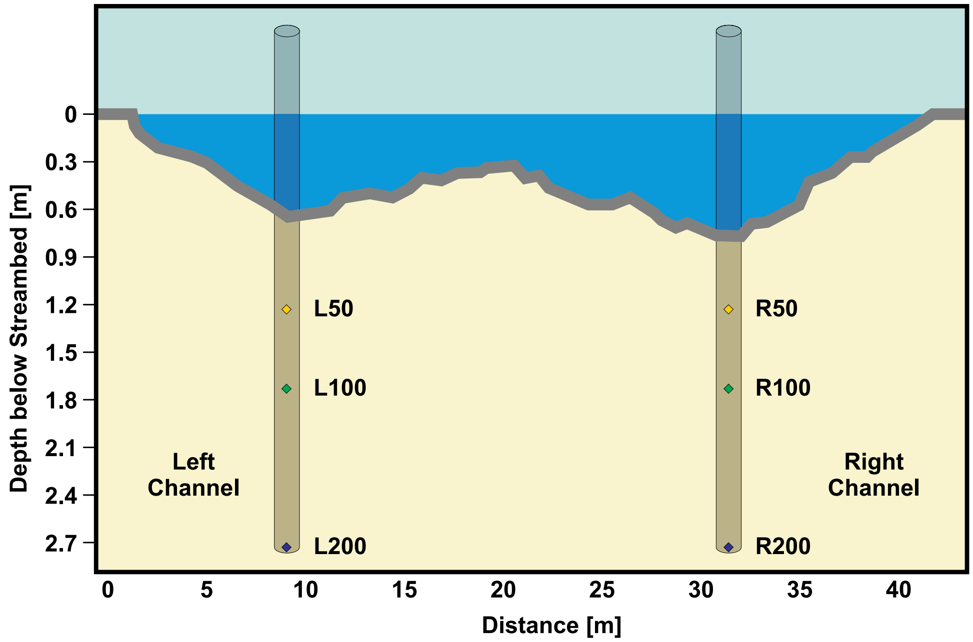

Figure 3. Study design schematic of piezometers across BPTR1.

[5] Data collection began in the summer of 2005 on the Bogue Phalia, a perennial stream located in northwestern Mississippi. The Bogue Phalia flows from north to south, to its confluence with the Sunflower River, which ultimately discharges into the Mississippi River (Figure 1). The overall objective of the study is to examine the ground- and surface-water interaction of the Bogue Phalia and how that relates to the fate and transport of agricultural contaminants, as part of the U.S. Geological Survey's (USGS) National Water-Quality Assessment Program (NAWQA). As part of a reconnaissance effort, three piezometers were installed across a transect of the Bogue Phalia, and an array of continuous temperature recorders were set at different depths within each piezometer. For the purpose of this study, only data from the right and left channel piezometers were considered. The temperature recorders were deployed between June and November 2005. During this time two major hurricanes, Katrina and Rita, made landfall and produced heavy rainfall in the Bogue Phalia Basin. As a result of the rainfall produced by hurricanes Katrina and Rita, stage in the Bogue Phalia peaked at 5.3 m and 7.13 m, respectively. Exceedance values for each stage ranged from 1.5 (7.13 m) to 10.5 (5.3 m) percent. Temperature data from the piezometers and surface water, along with stage data were used to estimate the flux into and out of the streambed, as well as validate that during periods of high stage, the stream reverses from a gaining to a losing stream. The reversal of flow from a gaining to a losing reach suggests the potential for enhanced groundwater recharge, chemical transport into the groundwater system, and increased bank instability during flood events.

3. Methods

[6] In late June 2005, piezometers were installed along a transect in the Bogue Phalia (BPTR1) to depths of about 2 m below the bottom of the stream. Piezometers were made from poly vinyl chloride (PVC) with an inner diameter of 5.20 cm and a 15.24-cm screen. During normal operations, the piezometers were capped and sealed to prevent surface-water infiltration during high flow. The piezometers were accessible only at low flow.

[7] Temperature data loggers were installed at fixed depths within the piezometers and recorded temperature every 15 minutes from 05 June to 05 November (Figure 2). A temperature data logger was also placed in the stream to record surface-water temperatures. According to the manufacturer's specifications, the temperature data loggers have an accuracy of ±0.2°C; they were also validated in the laboratory according to the manufacturer's specifications (Onset StowAway Tidbit data Logger).

[8] The stream water-level gage, Bogue Phalia near Leland, MS (USGS station number 07288650), located downstream approximately 2.3 km, measured stream stage every 15 minutes.

[9] The streambed flux at each piezometer was modeled individually for two time periods corresponding to Hurricane Katrina and Hurricane Rita using the numerical model VS2DHI. Each model was set up as a one-dimensional model, and only flow in the vertical direction was simulated to simplify the boundary conditions. This process is valid for determining ground- and surface-water exchange at the streambed interface, but not for determining lateral flow and bank storage. The streambed flux at each piezometer was modeled with a 1-m (width) by 2-m (length) domain using a uniform grid having a 0.11-m width and 0.04-m length. Each simulation was calibrated by matching the simulated temperatures with observed temperatures. Temperature, head differences (dh), and stream water levels at each piezometer (h_{top}) were used as boundary conditions for the model and were determined for each 15 minute time-step throughout the simulations. VS2DHI simulations were conducted for approximately 1-month time periods for each hurricane. Values for hydraulic conductivity varied for each

Table 1. Description and Source for Variables Used to Develop Model Boundary Conditions

Variable Symbol	Variable Description	Boundary Condition Component (Flow)	Source
dh	Head difference between the stream and piezometer	Derivation of specified head for bottom boundary	Derived from a linear relation between the gage height and head differences measured at low stage
h_{top}	The height of water in the stream above the streambed	Specified head for top boundary	Derived from a linear relations between the gage height and in-stream water-level measurements
G_h	Stream stage	Specified head for top boundary and derivation of dh	Recorded every 15 min
h_{bot}	The height of water in the piezometer above the streambed	Specified head for bottom boundary	Calculated by adding h_{top} to dh. When dh is negative, $h_{top} > h_{bot}$ indicating movement of surface water into the alluvial aquifer

piezometer but were held constant through each simulation. Thermal parameters used in the model were taken from literature (Table 1).

[10] In order to estimate d*h,* the water level in each piezometer (h_{bot}) along with the stream water level at each piezomter (h_{top}) were estimated on the basis of a linear regression analysis between the measured water levels at each piezometer during low flow and the recorded water level at the stream gage. The Bogue Phalia is a channelized, low-gradient stream. Stream morphology is consistent between the gage and the piezometer transect at BPTR1. Additionally, surface-water levels were measured just upstream of the piezometers and compared to the stage at the stream gage (data not shown). The comparison indicates that, although the water level is consistently higher upstream (to be expected) and becomes more pronounced at higher stages, using water level data from the gage to estimate the water level at the piezometers is reasonable.

[11] For the regression analysis, it was necessary to estimate the stage equilibrium value at which d*h* equals zero, or the point at which h_{top} equals h_{bot}. From an examination of the temperature data, it appears that at a stage above 3 m, a temperature reversal, or the warming of ground water due to surface-water infiltration, commonly occurred at each measured interval within each piezometer. This temperature reversal indicates a reversal in flow direction, or the point at which surface water begins to recharge the alluvial aquifer. On the basis of this assumption, 3 m was initially assumed to be the stage equilibrium at which d*h* equals zero and was used as the y-intercept to derive a linear equation with which to relate d*h* to h_{top}. This value was used as an estimate of stage equilibrium to begin the model simulation; and is valid only for this set of conditions, (i.e., groundwater level and perhaps also the sharp rise in river stage).

[12] Temperature measurements of the streambed sediments were made across the BPTR1 transect using a temperature probe consisting of a thermistor at the end of a 2-m rod. Temperature profile measurements were made at 1-m intervals across the transect, and temperature was recorded every 20 cm down to 1 m at each interval. The temperature probe was allowed to equilibrate at each point before recording the temperature.

[13] As part of the sensitivity analysis, the correlation coefficient (r) and the efficiency coefficient (E) by *Nash and Sutcliffe* [1970] were calculated for each trial in order to compare simulated and observed temperature values. The correlation coefficient measures the co-variance between the simulated results from each scenario and the observed results recorded by the temperature recorders [*Helsel and Hirsch*, 1992]. The Nash-Sutcliff efficiency coefficient measures how well each scenario modeled is able to predict the observed temperature by comparing the differences between the two [*Nash and Sutcliffe*, 1970]. A perfect model is indicated by a coefficient value equal to 1 in both cases.

4. Results

4.1. Field Observations and Raw Data

[14] Temperature measurements of streambed sediments were used to create a temperature cross section of the piezometer transect. The streambed temperature profile (Figure 3) shows an uprising of cold water on the right and left sides of the steam channel, with the coldest water on the left side of the channel at a depth of 1 m. Temperature values on the left and right channel ranged from 21.5 to 30.5°C and from 23 to 28°C, respectively. A clay mound in the center of the transect appears to impede the discharge of ground water into the stream; temperature values range from 25 to 29°C and remain static at about 27°C to a depth of 1 m below the streambed surface.

[15] Figure 4 shows temperature and stage data for the study period. At lower stages (<3 m) surface-water temperature varies diurnally and groundwater temperature remains relatively constant at a depth of 0.5 to 2 m. Alternatively, during periods of higher stage (>3 m), surface-water temperature decreases because of the cooler rainfall as the groundwater temperature increases because of the movement of surface water into the alluvial aquifer.

4.2. Estimates of Stage Equilibrium and Hydraulic Conductivity

[16] A sensitivity analysis was conducted to ascertain the model's dependency on input parameters and determine the "best" estimates for these input parameters. The input parameters of interest are the stage equilibrium values (the stage value at which dh = 0 or $h_{bot} = h_{top}$) and the hydraulic conductivity (K). Both of these parameters are estimated values, and both are needed to obtain the gradient and flux of water moving into and out of the streambed. The stage equilibrium value is not constant, and changes in response to groundwater levels. It represents the critical stage at which fluxes reverse from gaining to losing conditions. The sensitivity analysis was conducted as described by *Lenhart et al.* [2002], where only one input parameter

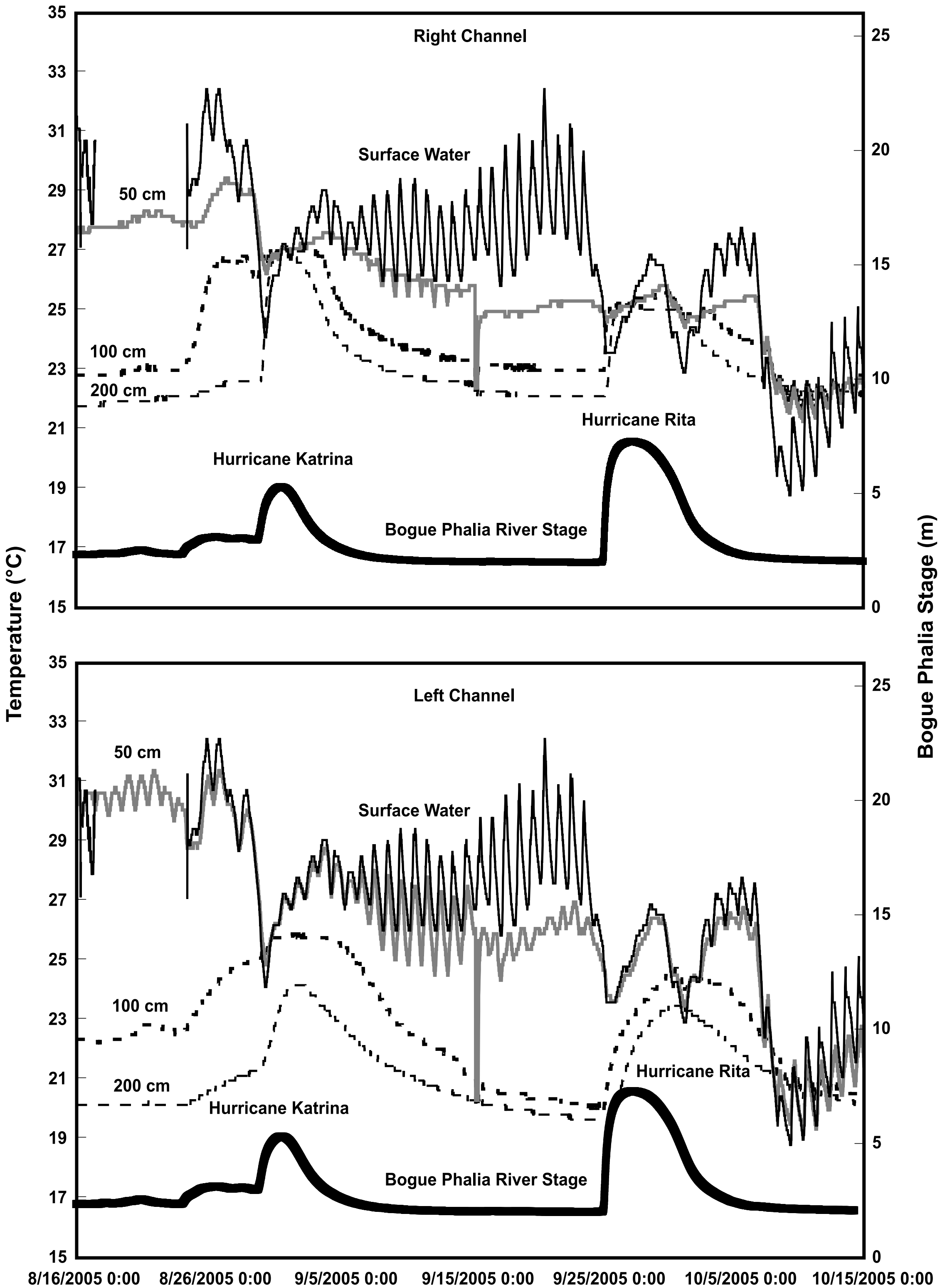

Figure 4. Temperature and stage data for the right and left channel at BPTR1. Stage data recorded by downstream gage on the Bogue Phalia River. Surface-water temperature data recorded by thermistor located under a bridge near BPTR1. Streambed temperature data (50, 100, and 200 cm) recorded by thermistors installed in right and left channel piezometers at each depth.

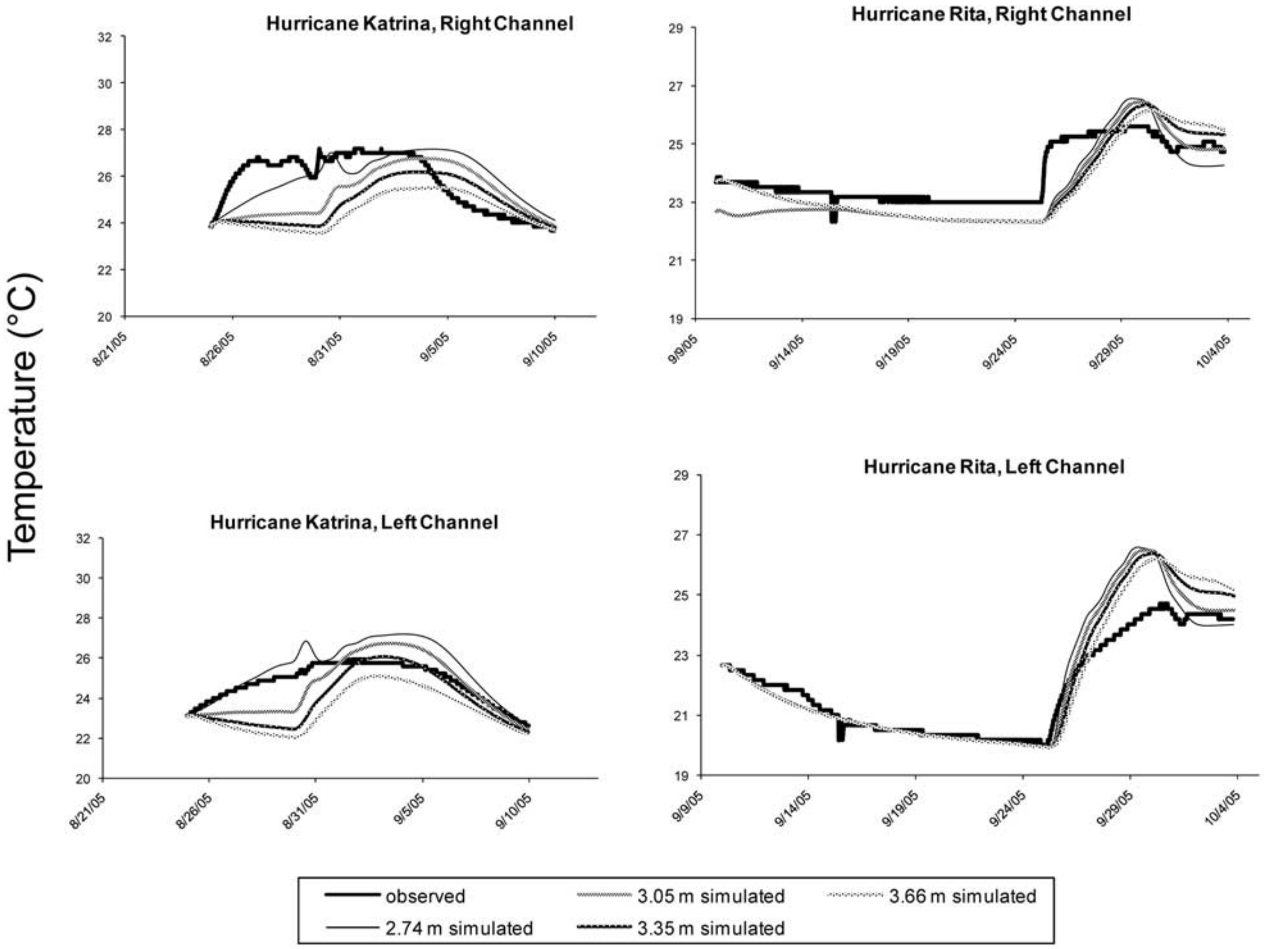

Figure 5. Graphs comparing the simulated and observed temperatures for each stage variation.

varies at a time while the other is kept constant. Initially, stage equilibrium was assumed to be 3 m based on qualitative analysis. A good match of the modeled and observed results was determined by trial and error with a resulting K value equal to 8.1e-6 m s^{-1}.

4.2.1. Stage Equilibrium Sensitivity Analysis

[17] A sensitivity analysis was conducted to determine the response of the model to a variation of the stage equilibrium, keeping the K = 8.1e-6 m s^{-1} constant. Simulations for both right and left channel piezometers during each event were run using stage equilibrium values of 2.74, 3.05, 3.35 and 3.66 m (Figure 5). The range of candidate values for the stage equilibrium were bounded by the measured dh on the low end and calculated dh on the high end. Table 2 shows that at a stage of 2.47 m at the gage downstream, head differences between ground and surface water were positive, indicating upward flow. Therefore it is not possible for dh to be equal to zero for a stage of 2.47 m. On the other hand, a stage equilibrium value above 3.66 m results in dh calculations such that at the onset of an event, temperature reversal occurs before head reversal. Calculations of dh using a stage equilibrium value of 3.66 m yields a lag time between the increase in sediment temperature and head reversal of only 15 minutes, even with an unrealistically high K value.

[18] Figure 6 shows the r and E for each stage equilibrium value scenario modeled. Results from Hurricane Rita data show little sensitivity to changes in the stage equilibrium value, whereas results from Hurricane Katrina show considerable sensitivity to changes in the stage equilibrium value. This difference in sensitivity is most likely due to the more rapid stage increase during Hurricane Rita than the stage increase during Hurricane Katrina. The recording increment of 15 minutes for the gage and temperature was insufficient to capture the specific dynamics of the flow reversal for Hurricane Rita. However, the r and E results from Hurricane Katrina indicate that a stage equilibrium value of 2.74 m provides the best fit.

4.2.2. Hydraulic Conductivity Sensitivity Analyses

[19] Using a stage equilibrium value of 2.74 m, K was varied for both piezometers to determine the best range of values for K. Values of K between 8.1e-6 m s^{-1} and 2.1e-

Table 2. Head Difference (hbot-htop) Measured at Low Stage

Date	Head Difference (m)		Stage (m)
	Right Channel	Left Channel	
28 June 2005	0.57	0.63	2.47
15 September 2005	0.69	0.84	2.01
11 October 2005	0.71	0.87	2.07
1 November 2005	0.68	0.81	2.01
13 December 2005	0.64	0.71	2.06

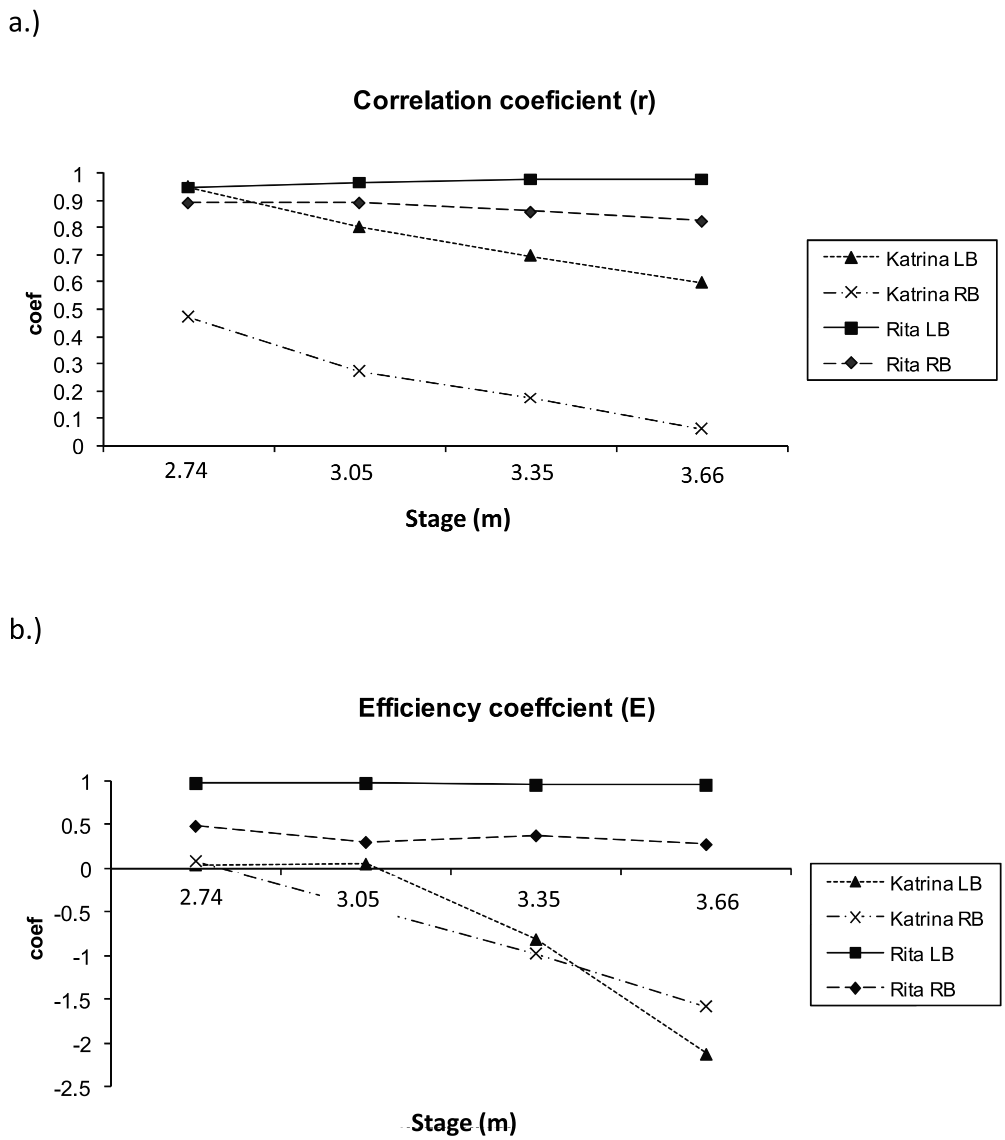

Figure 6. (a) Correlation coefficient versus stage. (b) Nash-Sutcliffe efficiency coefficient versus stage.

5 m s^{-1} were simulated. The initial value of 8.1e-6 m s^{-1} was chosen on the basis of a default value for sandy loam in the VS2DHI software package. *K* was varied by small increments up to 2.1e-5 m s^{-1}, which is close to the VS2DHI default value for fine sand. Table 3 shows the values of *K* used and the statistical results from each simulation for both the right and left channel; the best values for both coefficients have been highlighted. The final range of *K* values for both piezometers, which gives the best fit between the simulated and observed values, is described by the following intervals:

$$K_{\text{right channel}}: \ 1.1e-5 \text{ to } 2e-5 \text{ m s}^{-1}$$
$$K_{\text{left channel}}: \ 8.1e-6 \text{ to } 9.1e-6 \text{ m s}^{-1}$$

Figure 7 shows simulated versus observed values for each simulation within the range of *K* values described above. Both sets of results from the left and right channel overestimate the measured temperature values at the peak of each storm, possibly due to a horizontal flow component. This movement would cause the amount of heat moving with the surface water to decrease with depth as horizontal flow increases, and therefore, the measured temperature values at the peak of each storm should be less than the simulated 1-D values, which only account for the movement of water in the vertical direction. The values for *K* are within the range of values associated with silty sands containing some loess coinciding with the streambed sediments found at the site [*Freeze and Cherry*, 1979].

5. Discussion

[20] Instantaneous flux (q) for each simulation was calculated for each time step (15 minutes) using the following equation

$$q = -K^* dh/dl \qquad (1)$$

where dh equals the difference between h_{bot} and h_{top} and dl equals the distance between the h_{bot} and h_{top} boundaries.

Table 3. Correlation Coefficient and Nash-Sutcliffe Efficiency Coefficient Each Value of Hydraulic Conductivity Used in the Sensitivity Analysis[a]

	Katrina		Rita			
K (m s^{-1})	Right Channel	Left Channel	Right Channel	Left Channel	Average Right Channel$_1$	Average Left Channel$_1$
			Correlation Coefficient (r)			
2.1E − 05	0.78	0.84	0.90	0.91	**0.840**	0.870
1.6E − 05	0.72	0.91	0.90	0.91	0.810	0.910
1.2E − 05	0.64	0.95	0.90	0.93	0.770	0.940
1.1E − 05	0.57	0.96	0.89	0.94	0.730	0.948
9.1E − 06	0.52	0.96	0.89	0.94	0.710	**0.950**
8.1E − 06	0.47	0.95	0.89	0.95	0.680	0.949
			Nash-Sutcliffe Efficiency Coefficient (E)			
2.1E − 05	0.30	−2.35	0.24	0.79	0.270	−0.780
1.6E − 05	0.33	−1.20	0.28	0.85	0.304	−0.180
1.2E − 05	0.26	−0.44	0.36	0.91	**0.310**	0.240
1.1E − 05	0.18	−0.15	0.41	0.94	0.298	0.400
9.1E − 06	0.13	−0.04	0.45	0.96	0.290	0.460
8.1E − 06	0.08	0.04	0.48	0.97	0.280	**0.500**

[a]For the correlation coefficient (r), the coefficients of determination (r^2) were averaged.

The abrupt rise in stage coincident with Hurricanes Katrina and Rita, are immediately followed by abrupt changes in flux (Figure 8). Positive values for q indicate the upward movement of water through streambed sediments, which typically occurs during normal stage, whereas negative values indicate the downward movement of water (Figure 8) at high stage. The difference between fluxes calculated for the maximum and minimum left channel K values (max difference = 0.2 m/d) is much less than the difference between fluxes calculated for the maximum and minimum right channel K values (max difference = 1.5 m/d).

[21] In order to put these values into perspective, the cumulative volume of downward moving water was also calculated for each event and compared to the total stream discharge for each event recorded by the downstream gage. Cumulative volume was calculated by first assuming a 1-m-

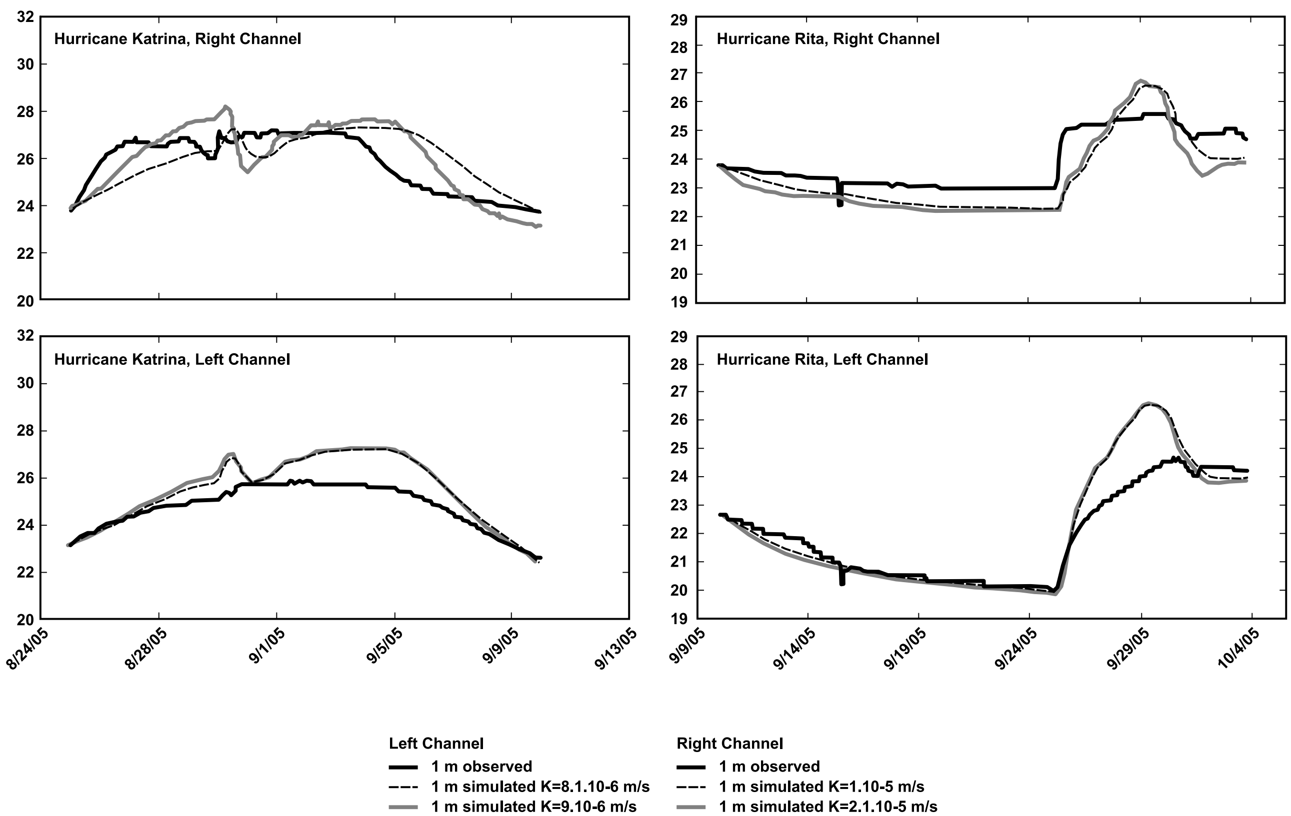

Figure 7. Comparison between the measured and simulated temperature for the selected ranges of K values.

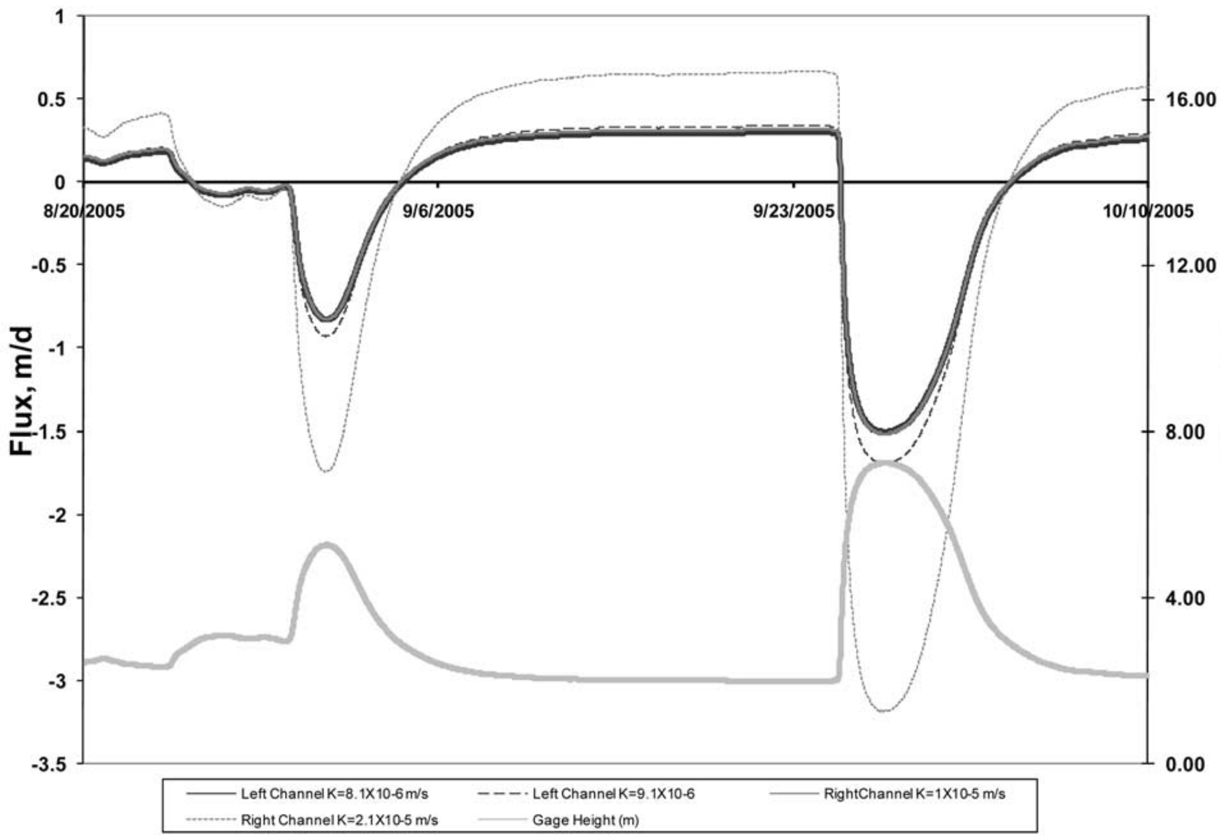

Figure 8. Comparison of flux in meters per day calculated using the predetermined values for hydraulic conductivity.

by 1-m-square area for each piezometer, thereby forcing q to equal the discharge of water into or out of the streambed sediments (Q) at each piezometer. The volume of water for each time step (V_i) was then calculated using the following equation

$$V_i = Q^*dT \quad (2)$$

where dT equals the amount of time passed between each time step (15 minutes). Cumulative volume (V_c) was obtained by summing all the V_i values calculated for downward flow during each event. Table 4 summarizes the values for V_c calculated for each event at both piezometers and the Bogue Phalia, as well as the maximum discharge and percentage of total flow.

[22] The total cumulative volume of downward moving water for each event was estimated for a 25-m reach of the Bogue Phalia using the lowest cumulative volume calculated from each 1D scenario as shown in Table 4. The right channel with a K = 1.1E-5 m s^{-1} had the lowest cumulative volume for both Hurricanes Katrina and Rita. The lowest value was chosen to compensate for a clay feature in the center of the stream channel. The estimated cumulative volume for the 25-m reach was calculated by multiplying the right channel, K = 1.1E-5 m s^{-1} cumulative volume for each event by the reach area equal to 1000 m^2, assuming a constant width equal to the width of BPTR1 (40 m) along the 25-m reach. Table 5 shows the estimated values for each event based on these assumptions. Taking into account the assumptions necessary for this analysis, the results indicate

Table 4. Maximum Discharge and Cumulative Volume Moving Through Each 1 m^2 Monitoring Point and Bogue Phalia Gaging Station for Hurricanes Katrina and Rita

	Katrina: 29 August 2005 to 7 September 2005			Rita: 24 September 2005 to 10 October 2005		
Station	Max Discharge (m^3/d)	Cumulative Volume (m^3)	Percent of Total Flow	Max Discharge (m^3/d)	Cumulative Volume (m^3)	Percent of Total Flow
Bogue Phalia near Leland	66,890,188.8	207,491,259	100	180,392,832	859,064,901	100
Left Channel K = 8.1e − 6 m/s	−0.83	1938	0.0009	−1.51	9787	0.0011
Left Channel K = 9.1e − 6 m/s	−0.93	2177	0.0010	−1.69	10,996	0.0013
Right Channel K = 1.1e − 5 m/s	−0.83	1881	0.0009	−1.52	9641	0.0011
Right Channel K = 2.1e − 5 m/s	−1.74	3949	0.0019	−3.18	20,245	0.0024

Table 5. Estimates of Cumulative Volume Moving Through 25 m by 40 m Reach and Bogue Phalia Gaging Station for Hurricanes Katrina and Rita

Station	Katrina: 29 August 2005 to 7 September 2005		Rita: 24 September 2005 to 10 October 2005	
	Cumulative Volume (m^3)	Percent of Total Flow	Cumulative Volume (m^3)	Percent of Total Flow
Bogue Phalia near Leland	207,491,259	100	859,064,901	100
BPTR1 25 m reach	1,881,000	0.91	9,641,000	1.12

that once downward flow begins, approximately 1 percent of surface-water flow per 25-m reach is flowing downward into the streambed sediments.

6. Conclusions

[23] Precipitation associated with Hurricanes Katrina and Rita created an almost instantaneous rise in stage in the Bogue Phalia. Dynamic changes in sediment-temperature profiles indicate that the Bogue Phalia changed from a gaining to a losing stream in a short period of time, and returned to a gaining stream once the stage returned to a normal level. Sensitivity analyses were used to determine that a reversal from a gaining to a losing stream is most likely to occur when the river stage is greater than or equal to 2.74 m, for groundwater levels during August and September 2005. Heat-based estimates of fluxes increase as the stage increases and are higher when the stream is losing rather than gaining, indicating that surface water recharges the streambed faster than ground water discharges to the stream. Using heat-based estimates of flux, cumulative volume of surface water moving downward through the streambed at a 25-m reach of the Bogue Phalia was estimated to be on the order of 1 percent of the total discharge recorded at the gage, for Hurricanes Katrina and Rita. Using heat as a tracer, these extreme hydrologic events permitted rapid estimates of hydraulic parameters, and demonstrated that rapid recharge of surface water may have occurred during the hurricanes.

[24] Future projects taking advantage of extreme events may benefit from additional piezometers in the stream cross-section to afford the opportunity to extend inverse modeling results to a 2-D analysis of flow paths. The reliance on extreme events to glean hydraulic parameters in low flux environments may be reasonably extended to an array of abrupt water-related events that create a sharp increase of the total heads due to peak stages, including both natural and anthropogenic-induced events, such as spring flood water and dam releases [*Constantz*, 1998], as well as abrupt events that draw down the water table, such as severe drought conditions, surface-water diversions, and local groundwater pumping. Future work warrants evaluation of the utility of heat as a groundwater tracer in a range of these extreme hydrologic events.

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J. R. B. Barlow and R. H. Coupe, Water Resources Division U.S. Geological Survey, 308 South Airport Road, Jackson, MS 39028, USA. (jbarlow@usgs.gov)