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Estimation of vertical groundwater fluxes into a streambed through continuous temperature profile monitoring and the relationship of groundwater fluxes to coaster brook trout spawning habitat

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Estimation of Vertical Groundwater Fluxes into a Streambed through Continuous Temperature Profile Monitoring and the Relationship of Groundwater Fluxes to Coaster Brook Trout Spawning Habitat

By

Matthew Van Grinsven

A Thesis

Submitted in partial fulfillment of the requirements for the degree of

Master of Science

Geology

Michigan Technological University

This thesis, “Estimation of Vertical Groundwater Fluxes into a Streambed through Continuous Temperature Profile Monitoring and the Relationship of Groundwater Fluxes to Coaster Brook Trout Spawning Habitat,” is hereby approved in partial fulfillment of the requirements for the Degree of Master of Science in Geology

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Abstract

We hypothesized that the spatial distribution of groundwater inflows through river bottom sediments is a critical factor associated with the selection of coaster brook trout (a life history variant of *Salvelinus fontinalis*,) spawning sites. An 80-m reach of the Salmon Trout River, in the Huron Mountains of the upper peninsula of Michigan, was selected to test the hypothesis based on long-term documentation of coaster brook trout spawning at this site. Throughout this site, the river is relatively similar along its length with regard to stream channel and substrate features. A monitoring well system consisting of an array of 27 wells was installed to measure subsurface temperatures underneath the riverbed over a 13-month period. The monitoring well locations were separated into areas where spawning has and has not been observed.

Over 200,000 total temperature measurements were collected from 5 depths within each of the 27 monitoring wells. Temperatures within the substrate at the spawning area were generally cooler and less variable than river temperatures. Substrate temperatures in the non-spawning area were generally warmer, more variable, and closely tracked temporal variations in river temperatures. Temperature data were inverted to obtain subsurface groundwater velocities using a numerical approximation of the heat transfer equation. Approximately 45,000 estimates of groundwater velocities were obtained. Estimated velocities in the spawning and non-spawning areas confirmed that groundwater velocities in the spawning area were primarily in the upward direction, and were generally greater in magnitude than velocities in the non-spawning area. In the non-spawning area there was a greater occurrence of velocities in the downward direction, and velocity estimates were generally lesser in magnitude than in the spawning area. Both

the temperature and velocity results confirm the hypothesis that spawning sites correspond to areas of significant groundwater influx to the river bed.

1. INTRODUCTION

Coaster brook trout are a unique life history variant of the brook trout species, *Salvelinus fontinalis*, which have been documented in Lake Superior for hundreds of years (Newman and Dubois 1996, Huckins *et al.* 2008). Currently, only a few populations of coaster brook trout remain in the Lake Superior basin and the Salmon Trout River is the only river on the southern shore of Lake Superior (Figure 1) that has a verified naturally reproducing population of adfluvial coasters (Huckins *et al.* 2008). A long term ecological study of coaster brook trout in the Salmon Trout River has investigated their adfluvial patterns, spawning density and distribution, behavioral characteristics, and genetic linkages (Huckins *et al.*, 2008, Huckins and Baker, 2008). Coaster brook trout have been observed to reach their larges spawning densities during late October through mid November in the Salmon Trout River. To support conservation efforts within the Salmon Trout River, and rehabilitation efforts along the southern shore of Lake Superior, habitat conditions associated with a naturally reproducing coaster brook trout populations need to be characterized.

Several studies have shown a relationship between groundwater seepage and brook trout spawning habitat (Fraser 1982, Curry and Noakes 1995, Ridgeway and Blanchfield, 1998). Groundwater seepage in permeable substrates functionally stabilizes critical biological water quality parameters such as temperature and oxygen availability in near-subsurface riverine environments (Curry et al. 1995, Fraser 1985). Consistency of thermal and chemical properties is critical for the survival of developing embryos in climates which undergo drastic seasonal changes (Curry et al. 1995); exemplified in cold northern regions where formation of benthic ice layers are common during the winter months. Given that groundwater seepage in riverine environments may be associated with the spatial distribution of brook trout spawning habitat, this study focuses on estimating groundwater fluxes in areas where coaster brook trout have been observed to spawn and in environmentally similar areas where no prior spawning activity has been observed.

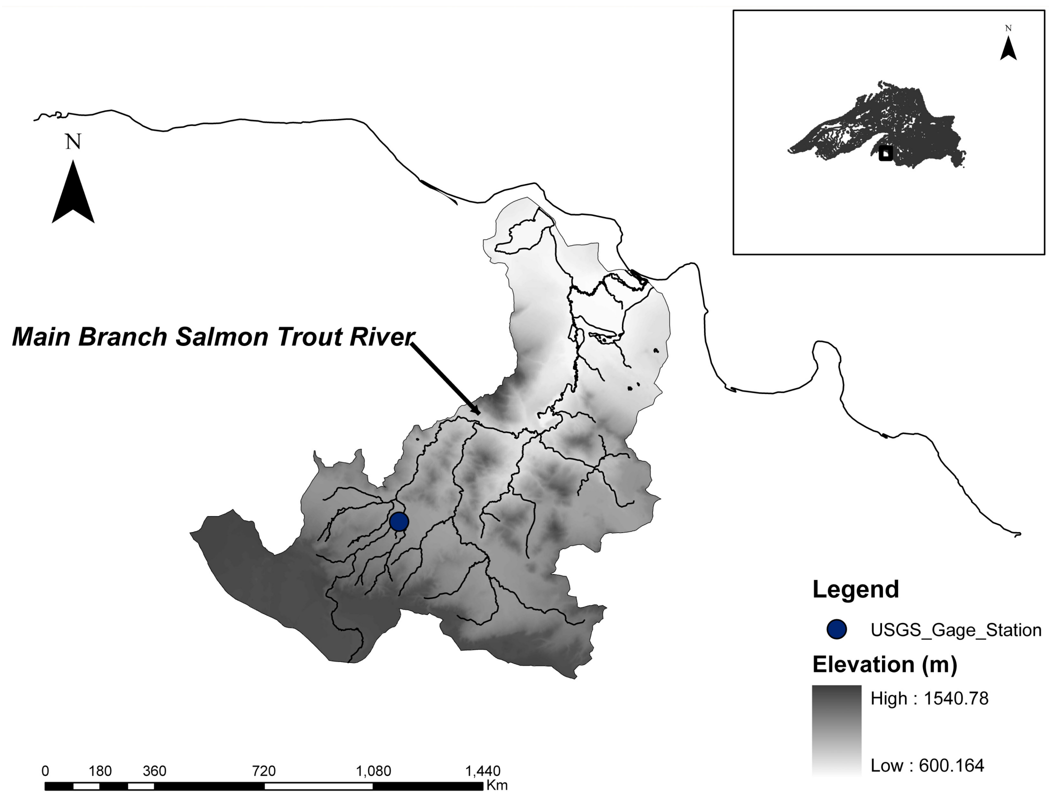

Figure 1. Salmon Trout River watershed map, Marquette County, MI**.**

Various techniques have been implemented in order to determine sub-surface fluxes in stream beds, including estimates of differences between upstream and downstream discharge over lengths of stream bed using current meters (Becker et al., 2004), pressure-head measurements acquired from in-stream monitoring wells (Curry *et* *al.* 1994), chemical tracer injection experiments (Constantz *et al.* 2003), seepage meters (Blanchfield and Ridgeway 1996, Alexander and Caissie, 2003), and acquisition of vertical temperature profiles beneath streams (Stonestrom and Constantz, 2003, Silliman *et al.* 1995, Lapham 1989, Stallman 1965).

The spatial distribution of groundwater discharges can have a significant impact on the distribution of benthic and hyporheic fauna (Brunke and Gonser, 1997; Storey et al., 2003) and the selection of spawning locations by fish (Curry et al. 1995). Temporal changes in water table and steam levels can alter the rate and direction of subsurface fluxes under stream beds (Wroblicky et al., 1998). Spatial patterns and magnitude of groundwater discharge can be critical when aquifer-stream transport and fate of contaminants is an issue (Conant, 2004). However, to our knowledge, no studies have involved measurement of groundwater fluxes under streambeds at small time and space scales and over long time periods (several months or greater), to evaluate ecological hypotheses.

In this study, high resolution temperature data collection methods were implemented to quantify the interaction between groundwater and surface water in order to verify the presence or absence of groundwater discharge in the river at sites that support a reproducing population of coaster brook trout. Networks of monitoring wells equipped with vertically stratified temperature sensors were installed into sections of river that both support and do not appear to support coaster brook trout spawning. We hypothesize that the spatial distribution of groundwater inflows through river bottom sediments is a critical factor associated with the distribution of coaster brook trout spawning redds and activities.

2. METHODS

Temperature measurements were collected to estimate sub-surface water velocities and gradients over a 13-month period (2007-2008) in a section of the Salmon Trout River where coaster brook trout spawning activity has been observed to recur and in adjacent upstream and downstream sections of the river where no spawning activity has been observed to occur. A numerical solution to the one-dimensional convective-diffusive heat transport equation was inverted to obtain best fit estimates of vertical sub-surface water fluxes throughout the study period.

2.1 Study Site

The Salmon Trout River watershed drains approximately 12,690 ha of sub-boreal forestland, and descends approximately 245 meters in elevation between the headwaters and outlet (Bullen, 1986). Average annual precipitation in the area is 762 mm (NCDC, 2009). Average annual snowfall is 2,900 mm, contributing to large spring snowmelt discharge events, while relatively dry summers produce low discharge, baseflow-dominated periods (NCDC, 2009). An average annual discharge of 0.16 m^3/s was recorded over the period 2004-2008 (USGS, 2009). The gaging station is located approximately 15 kilometers upstream from the study site, and is upstream from major tributaries including the East Branch Salmon Trout River (see Figure 1). Temperatures in the Salmon Trout River vary between 0 °C in the winter and 18 to 24 °C in the summer (see Figure 2, Huckins, unpublished data). Several documented coaster brook trout spawning sites in the Salmon Trout River (Marquette County, Michigan) occur within approximately 12 river kilometers upstream from the river's Lake Superior outlet

(Huckins and Baker, 2008). This section of the river is characterized by a relatively shallow gradient, unconsolidated bed material, wide riffles, and deep cut bank pools.

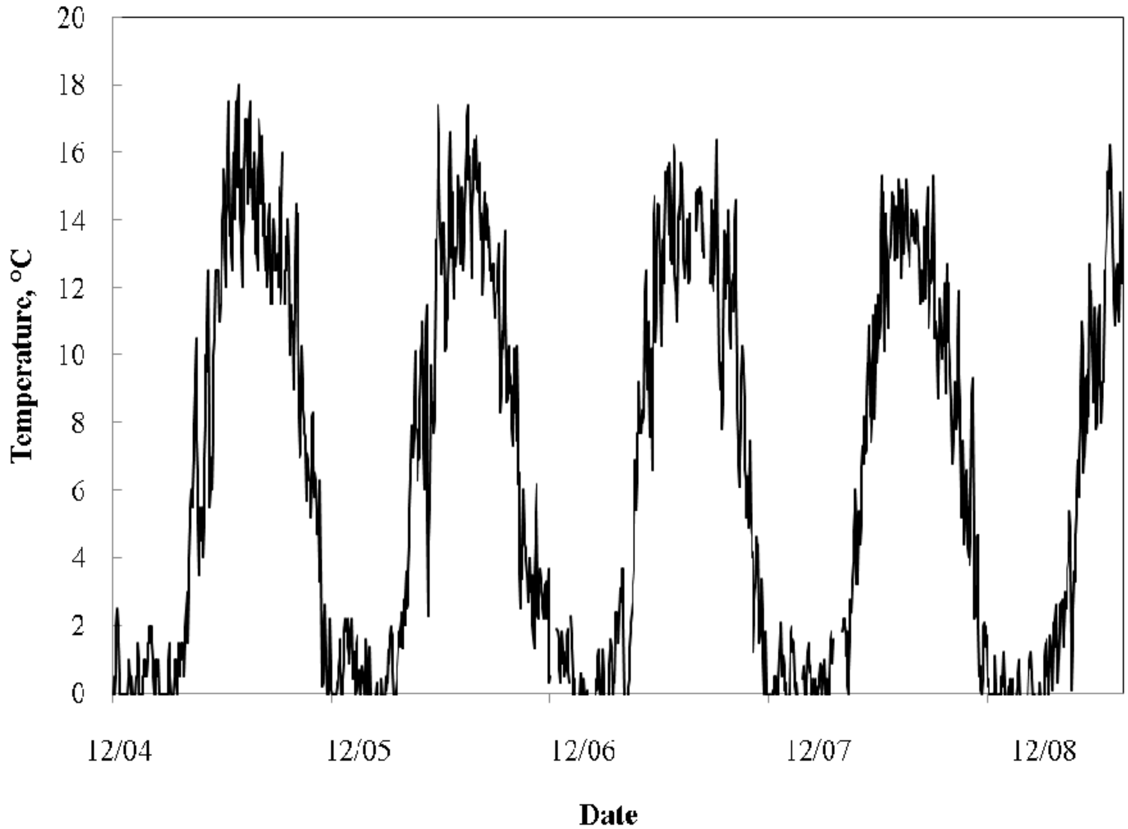

Figure 2. Temperature as a function of time in the Salmon Trout River, Marquette County, MI.

The study site is located along a gradual meander in the river several river kilometers upstream from the mouth. The bed contains poorly sorted materials consisting of cobbles, gravel, and sand. The site is characterized by environmental habitat features that have been previously correlated to suitable salmonid spawning habitat, including the occurrence of in-stream coarse woody debris, dense riparian vegetation, cutbanks, and coarse bed materials (e.g. Curry, 1993, Bernier-Bourgault and Magnan, 2000, Kondolf *et al.,* 2008). After thorough observation, it was determined that environmental habitat conditions within the study site were sufficiently similar to permit isolation of sub-surface water flux as an independent variable associated with the location of naturally re-occurring spawning habitat by the coaster brook trout.

2.2 Network Design and Instrumentation

A contiguous network of nine evenly spaced transects each containing three monitoring wells was installed into an 80-m section of the river. Each transect included one monitoring well located on the in-stream side of each bank, and one at the midpoint between the two river banks. The study site was separated into an active spawning section and a non-spawning section according to the observed locations of active redd building recorded during the 2007 and 2008 spawning seasons (see Figure 3). Location of bank-side monitoring wells permitted the collection of temperature data during active spawning periods. Each monitoring well consisted of a 1.8 m-long section of schedule 40 PVC pipe with an inner diameter of 3.8 cm and a 1.5 m-long screen with 0.25 mm slot openings. The monitoring wells were installed using a rod and casing apparatus to depths of approximately 1 m beneath the bed surface. Each monitoring well was developed using a surge block technique.

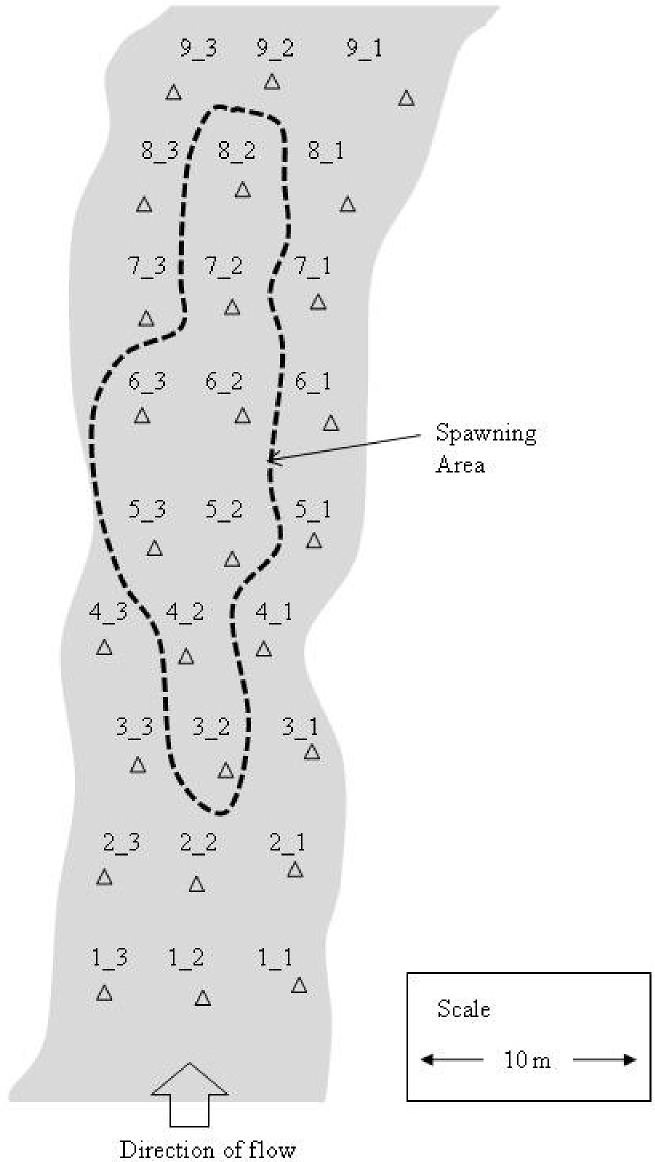

Figure 3. Locations of monitoring wells (triangles), and the region where coaster brook trout consistently have been observed to spawn (dashed line).

Temperatures were measured with Thermochron iButton (Embedded Data Systems: Lawrenceburg, KY) temperature loggers capable of recording temperatures between -5 °C and 26 °C with a resolution of 0.125°C and an accuracy of 1°C. Five loggers, spaced approximately 24 cm apart in the vertical direction, were attached to a

1.25 cm diameter schedule 40 PVC pipe, and installed in each monitoring well (Figure 4). Each temperature assemblage consisted of one logger installed at a height corresponding to approximately 12 cm above the river bed, with the four remaining loggers located beneath the river bed. Depths of the temperature loggers for each monitoring well are reported in Table 1. In order to prevent vertical mixing within monitoring wells, Santoprene™ rubber washer baffles were attached to the PVC pipe at the midpoint between individual loggers. In addition, the uppermost baffle consisted of three staggered rubber washers, to ensure exchange between the surface and sub-surface water did not occur. Data collection began prior to the 2007 spawning season (October), and continued through the duration of the 2008 spawning season (November).

A Water-temp-pro temperature logger (Onset Computer Corporation) was installed prior to this study at a well-mixed location approximately 10 meters downstream of the study site. The temperature sensor was installed on the bed surface in the middle of the river and has a resolution of 0.02°C and an accuracy of 0.2°C.

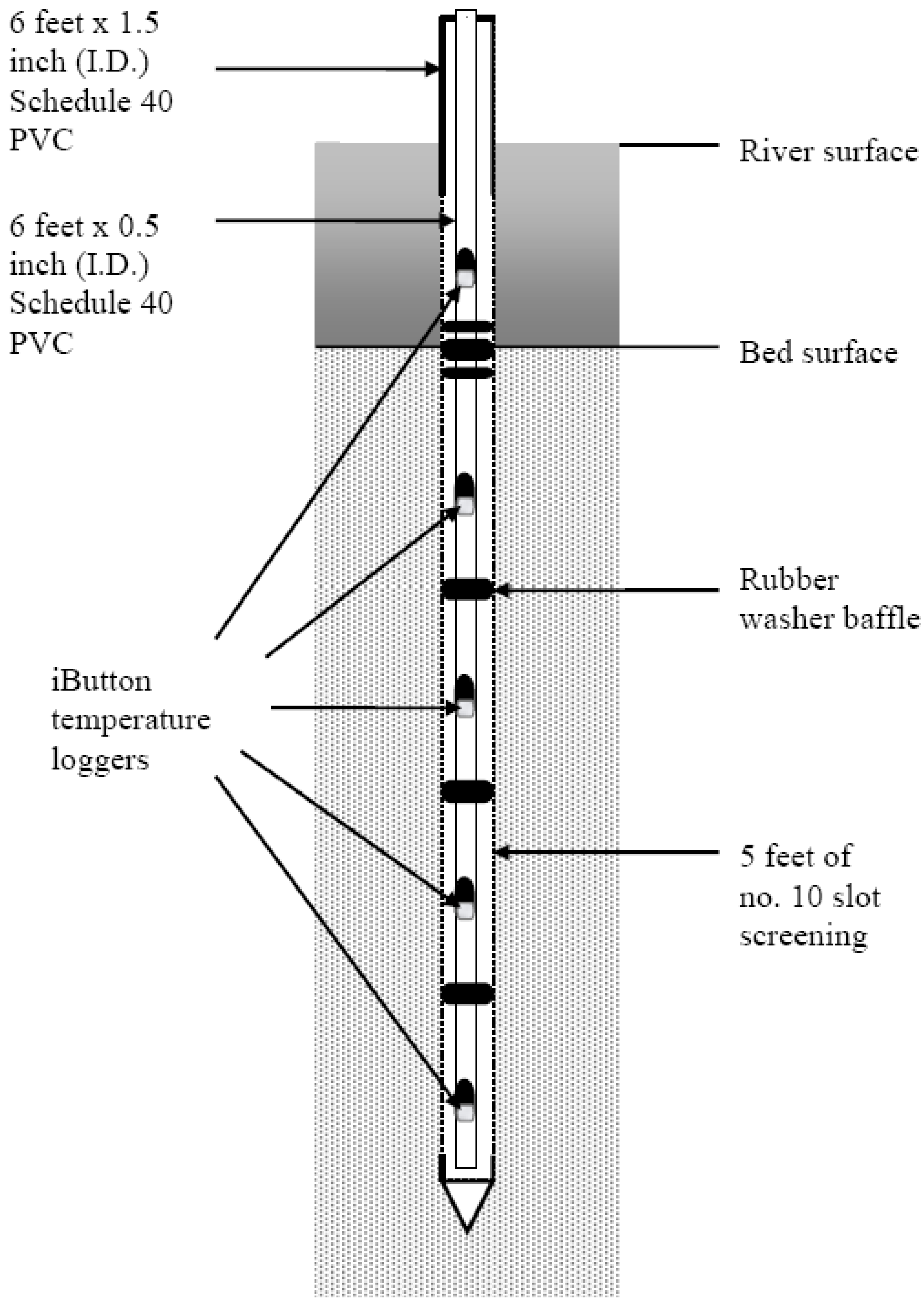

Figure 4. Monitoring well instrument configuration.

Table 1: Installed Depths of Temperature Loggers

Monitoring Well	Temperature Logger Depth (cm below river bed)				
	1	2	3	4	5
1.1	-12	26	52	78	104
1.2	-12	28	56	84	112
1.3	-12	30	60	90	120
2.1	-12	26	50	76	100
2.2	-12	24	48	72	96
2.3	-12	26	50	74	98
3.1	-12	28	56	82	110
3.2	-12	24	48	72	94
3.3	-12	26	50	74	98
4.1	-12	28	56	84	112
4.2	-12	24	48	72	94
4.3	-12	24	48	72	94
5.1	-12	28	54	80	106
5.2	-12	20	38	56	74
5.3	-12	18	36	52	NA
6.1	-12	18	36	54	72
6.2	-12	22	44	66	88
6.3	-12	12	24	36	48
7.1	-12	24	48	72	96
7.2	-12	21	42	62	82
7.3	-12	20	40	60	80
8.1	-12	10	32	54	74
8.2	-12	20	38	56	74
8.3	-12	26	52	76	102
9.1	-12	10	32	54	NA
9.2	-12	18	36	54	72
9.3	-12	28	56	83	110

2.3 Numerical Methods for GroundwaterVelocity Estimation

The one-dimensional, thermal convective-diffusive governing equation, assuming no internal generation or loss of heat and local thermal equilibrium between the solid-fluid matrix, (Domenico and Schwartz, 1990) is

$$k\frac{\partial^2 T}{\partial z^2} - nc_w\rho_w v\frac{\partial T}{\partial z} = c\rho\frac{\partial T}{\partial t} \tag{1}$$

where *k* is thermal conductivity of the rock-fluid matrix (cal/sec-cm-C^o), *T* is temperature (C^o), *z* is vertical distance with a positive downward convention (cm), *n* is sediment porosity (dimensionless), *v* is groundwater velocity (cm/sec), c_w is heat capacity of the fluid (cal/g-C^o), ρ_w is density of the fluid (g/cm^3), *c* is heat capacity of the solid-fluid matrix (cal/g-C^o), and ρ = wet bulk density of solid-fluid matrix (g/cm^3).

First-order, centered-difference in space and first-order implicit in time finite difference approximations were used to solve equation (1) using the computer software MATLAB. Dirichlet boundary conditions were applied to the upper ($z = z_u$) and bottom ($z = z_b$) boundaries, as in

$$\begin{aligned} T(z_u,t) &= T_1^\ell \\ T(z_b,t) &= T_5^\ell \end{aligned} \tag{2}$$

using the upper-most and bottom-most temperature measurements at a particular observation time-step (T_1^ℓ and T_5^ℓ, respectively). A Levenberg-Marquardt algorithm was used to attain best fit estimates of groundwater velocity by minimizing the sum the squares of the residuals (SSR) between simulated vertical temperature profiles and the remaining temperature observations (T_2 , T_3 and T_4), as in

$$\text{find } v \text{ such that } \min \sum_{i=2,3,4} \left(T_i^{\ell,obs} - T_i^{\ell,sim} \right)^2 \tag{3}$$

for each observation time step, where the superscripts *obs* and *sim* refer to observed and simulated temperatures, respectively. The average error (°C) for each observation time step at each well is defined as

$$e_{t,w} = \frac{1}{n_{obs}} \sqrt{\sum_{i=2,3,4} \left(T_i^{\ell,obs} - T_i^{\ell,sim} \right)^2} \tag{4}$$

where $e_{t,w}$ is the average error at a well and time step and $n_{obs} = 3$ is the number of observations at a well.

Equation (1) was solved at each time step $\Delta t = \Delta t_{obs} / m$, where Δt_{obs} is the interval between temperature measurements (3 hours) and $m > 1$ is the internal time step divider, in order to improve the performance of the numerical solution as the Dirichlet conditions (equation (2)) changed and were imposed. Dirichlet boundary conditions were also applied to internal time steps and were estimated by linearly interpolating the boundary temperatures between the corresponding observation time steps, Δt_{obs} .The linear interpolation of boundary conditions enhanced the performance of the numerical solution during periods of large diurnal surface-water temperature fluctuations. Validation of the numerical solution was performed by comparison to the analytical solution from Bear (1972) for the conservative form of the advective-dispersive transport equation with a Dirichlet upstream boundary condition and an no-flux downstream boundary condition.

A spin-up approach was implemented for the purpose of simulating prior temperature conditions, and used as the initial condition for model simulations. Spatial discretizations (Δz) and time steps were set to achieve values within the acceptable range of stability constraints defined by the Peclet ($\mathrm{Pe} = v\Delta z/k$) and Courant numbers ($\mathrm{Cr} = v\Delta t/\Delta z$), i.e. $\mathrm{Pe} \le 2$ and $\mathrm{Cr} \le 1$. A spatial discretization of Δz =1 cm and internal time step divider of m = 2700 were used for each simulation. The Peclet and Courant number constraints constrained the velocity estimates to $0.023 \text{ cm/s} \le v \le -0.023 \text{ cm/s}$. All temperature measurements that produced velocities outside this range were rejected.

Average dry bulk density (1.34 g/cm^3) and porosity (0.314) of the bed sediments were determined using a graduated cylinder technique based on 8 replicate samples from three locations within the study site (Tan, 1995). Thermal conductivity (k) and volumetric heat capacity ($c\rho$, the effective heat capacity of the solid-fluid matrix per unit bulk volume (cal/cm^3-C^o) were estimated from empirical relationships found in literature (Lapham *et al.*, 1989), and resulting in the following parameter values: k = 0.0036 (cal/sec-cm-C^o), and $c\rho$ = 0.68 (cal/cm^3-C^o). Fluid density ρ_w = 0.999 (g/cm^3) and heat capacity c_w = 1.00 (g/cm^3) values were determined from temperature based formulations found in the literature (Snoeyink and Jenkins, 1980). We assume that these parameters are constant in space and time

3. RESULTS AND DISCUSSION

Unanticipated hydrologic events, instrumentation errors, and the inability to retrieve data during fall spawning periods resulted in the loss or fragmentation of temperature data from particular monitoring wells during specific portions of the study period. An average of approximately 12,000 temperature measurements, taken at threehour intervals, was recorded in each monitoring well over the course of the study period. Approximately 45,000 groundwater velocities were fitted over the study period from each of the remaining 22 monitoring wells, with 1.1% of the velocity estimates being eliminated as a result of Peclet or Courant number constraints.

3.1 Temperatures

Figure 5 summarizes the temperature data with the coefficient of variation of temperatures for the deepest temperature logger in each of the 22 monitoring wells and in the downstream river temperature measurement location. Temperature observations were recorded between 10/1/2007 and 11/18/2008. The results in Figure 5 show that temperatures measured in the deepest position in the wells in the spawning area are substantially less variable than wells in the non-spawning area and in the river, as measured by the coefficient of variation. For the most part, wells in the non-spawning area exhibit greater variation than in the spawning area and the temperature variation, as measured by the coefficient of variation, and approach the variation in temperatures exhibited in the river. These results indicate that subsurface temperatures in the spawning area are influenced significantly less by temperatures in the river, implying that upward groundwater fluxes in the spawning area are greater than those in the non-spawning area. The coefficient of variation in monitoring wells 7.3 and 9.3 in the non-spawning area is small, implying an exception to the general result of high temperature variability in the non-spawning area. However, poor spawning habitat features such the presence of fine sediments and detritus layers were observed adjacent to these well locations.

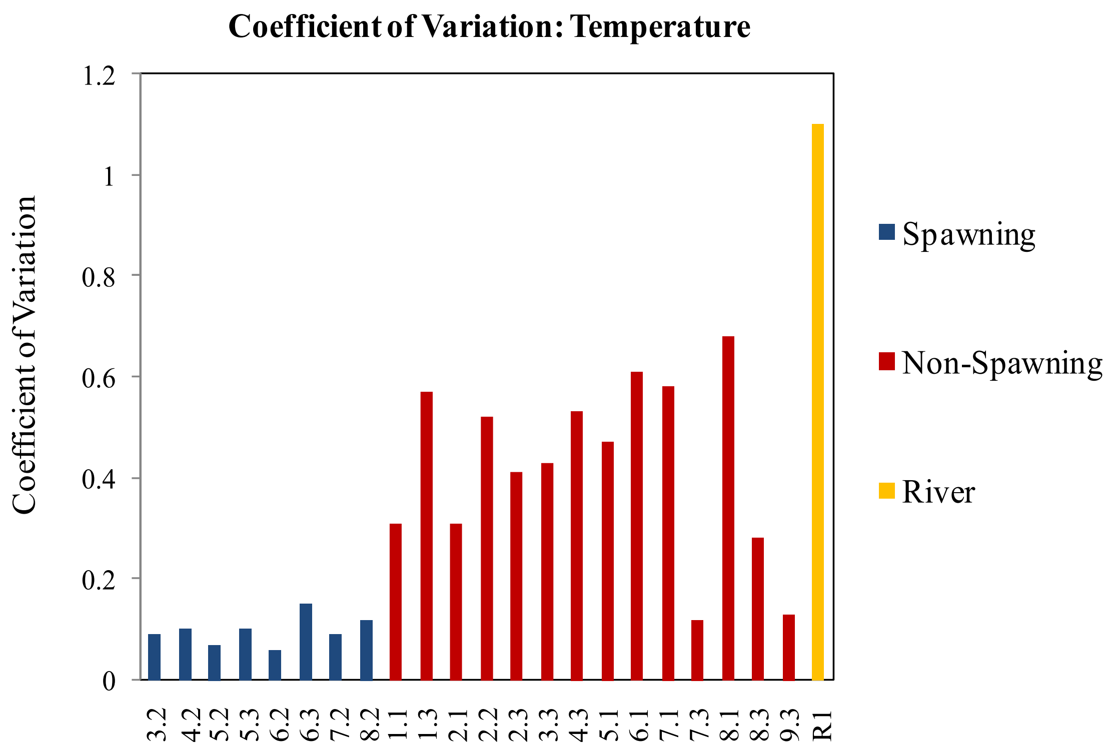

Figure 5. Coefficient of variation of temperature from the deepest sub-surface temperature loggers and from the river temperature location

One representative well from the spawning area (MW 6.3) and one representative well from the non-spawning area (MW 8.1) were selected to demonstrate temperature variation with time over the period 6/14/08 to 10/1/08. Figures 6 and 7 show temperature as a function of depth below the river bed and time at these monitoring wells, along with the river temperature measured in the upstream temperature logger. Observation data from June 2008 to November 2008 at five vertical locations in each monitoring well were contoured using the Kriging method to display results in figures 6 and 7.

The river temperatures shown in Figures 6 and 7 show pronounced diurnal and seasonal fluctuations. Figure 6 indicates that sub-surface temperatures were only minimally impacted by river temperatures in the representative spawning area well. This result confirms the results in Figure 5, in that groundwater fluxes are relatively high in the upward direction in the spawning area. Figure 7 on the other hand, indicates that for the representative non-spawning area well, fluctuations in groundwater temperatures below the riverbed closely correlate to fluctuations in river temperatures, confirming the assessment of the data in Figure 5. This correlation implies that river water was seeping downward into the river bed or that upward groundwater fluxes were low enough such that heat transfer was dominated by conduction from the river.

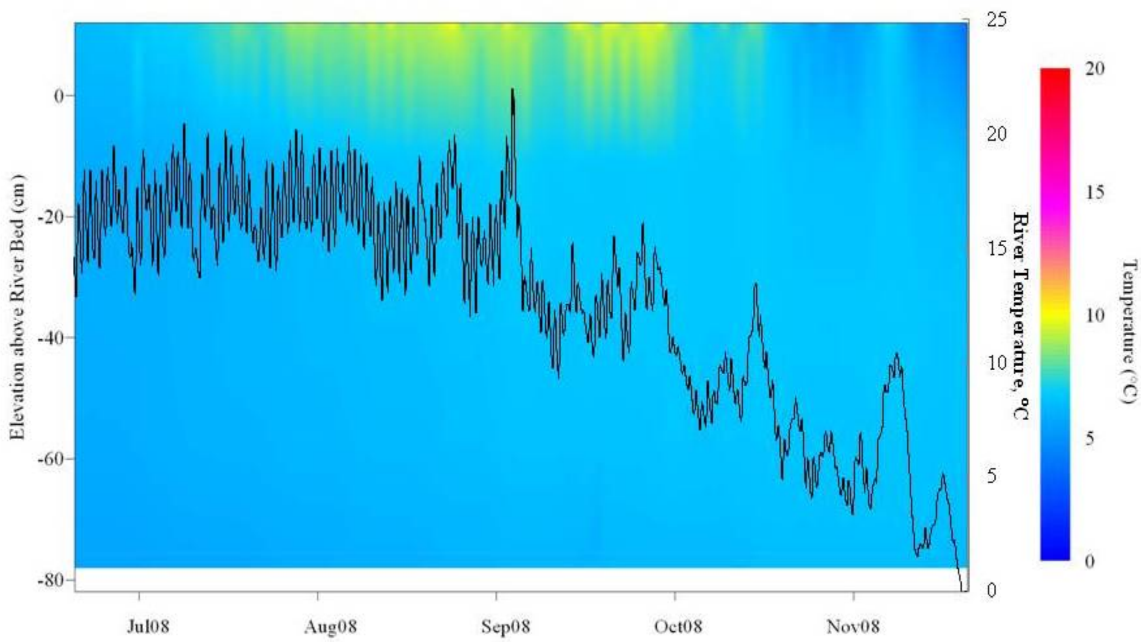

Figure 6. Temperature as a function of time and depth below river bed (color plot) and temperature in the river as a function of time (line plot) for monitoring well 6.3

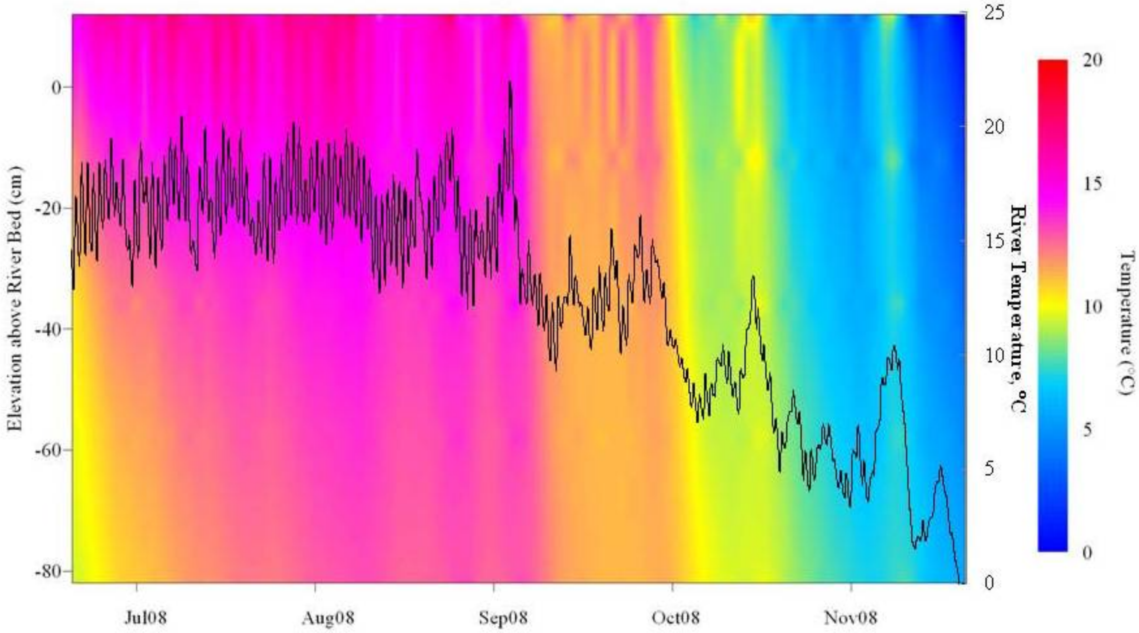

Figure 7. Temperature as a function of time and depth below river bed (color plot) and temperature in the river as a function of time (line plot) for monitoring well 8.1.

3.2 Estimated Velocities

The error associated with model fits (see Equation 4) averaged over the study period ranged between 0.05 and 0.2 degrees °C. Comparison of observed temperatures and the simulated vertical temperature profiles as a function of depth at various times from representative monitoring wells from the spawning area (MW 6.3) and the non-spawning area (MW 8.1) are presented in Figures 8 and 9. Observed and simulated temperatures displayed in Figure 8 and 9 represent mid-afternoon temperatures present on the 15th of each month, from June through November 2008. Velocity estimates from all wells are summarized in Figure 10 as frequency distributions and arithmetic means. Note that groundwater velocities are reported as positive downward.

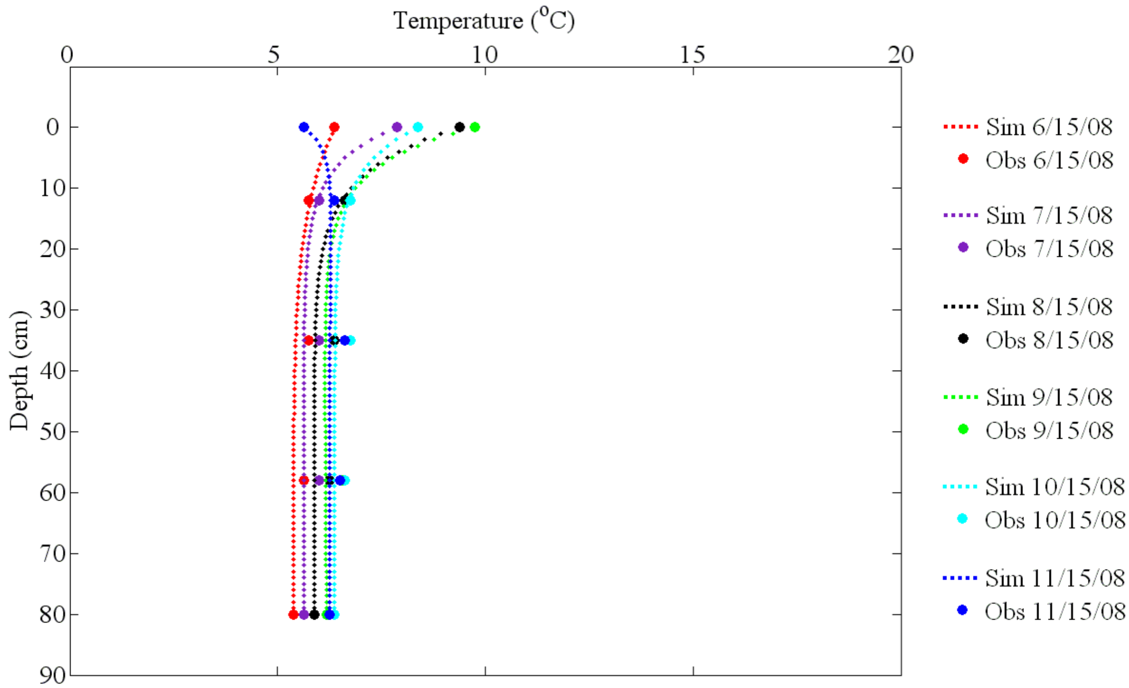

Figure 8. Observed and simulated vertical temperature profiles as a function of time at monitoring well 6.3.

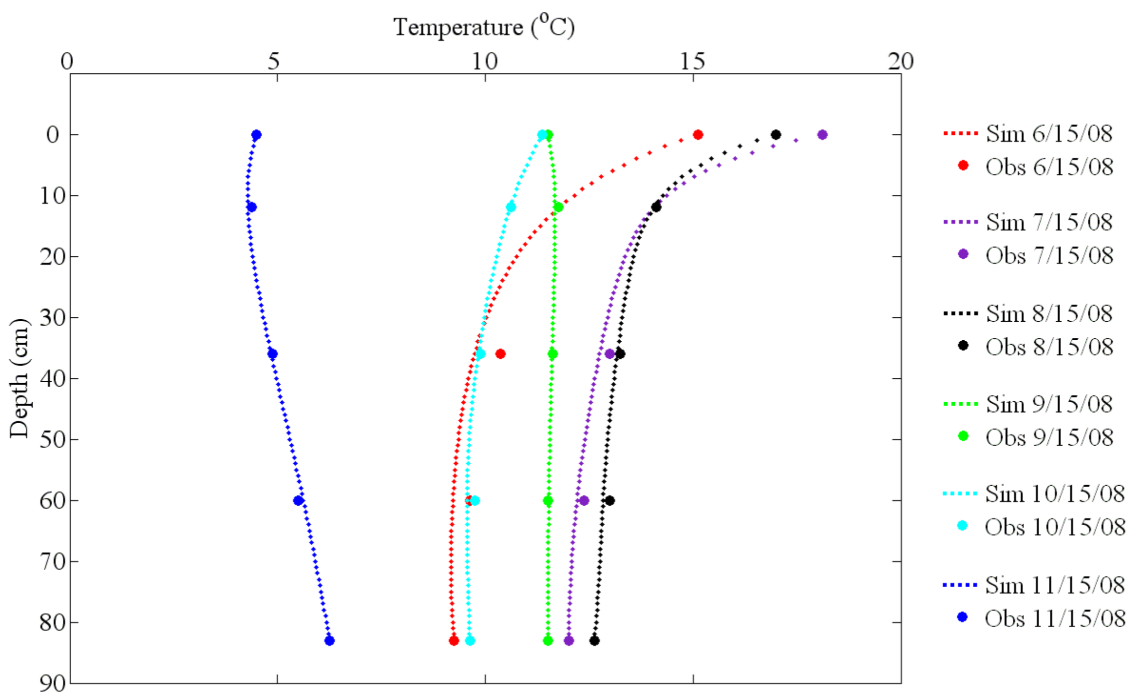

Figure 9. Observed and simulated vertical temperature profiles as a function of time at monitoring well 8.1.

The estimated velocities in Figure 10 indicate that most locations of wells in the spawning area (MW 3.2, MW 4.2, MW 5.2, MW 5.3, MW 6.2, MW 6.3, MW 7.2, and MW 8.2) exhibit primarily upward (negative) velocities as indicated by the velocity frequency distribution and average velocities, with the exception of well MW 6.2 and MW 8.2 However, temperatures in the deepest measurement point in well MW 6.2 and MW 8.2 were relatively consistent (see Figure 5), which implies that groundwater velocities at these location were high enough, in the upward direction, to counter temperature influences from the river.

With the exception of MW 1.1, wells in the non-spawning areas (MW 1.1, MW 1.2, MW 1.3, MW 2.1, MW 2.2, MW 2.3, MW 3.1, MW 3.3, MW 4.1, MW 4.3, MW 5.1, MW 6.1, MW 7.1, MW 7.2, MW 8.1, MW 8.3, MW 9.1, MW 9.2, and MW 9.3) exhibit primarily low upward or downward velocities. It was observed that the areas surrounding MW 1.1 exhibited less than ideal spawning habitat features, such as the presence of fine sediments.

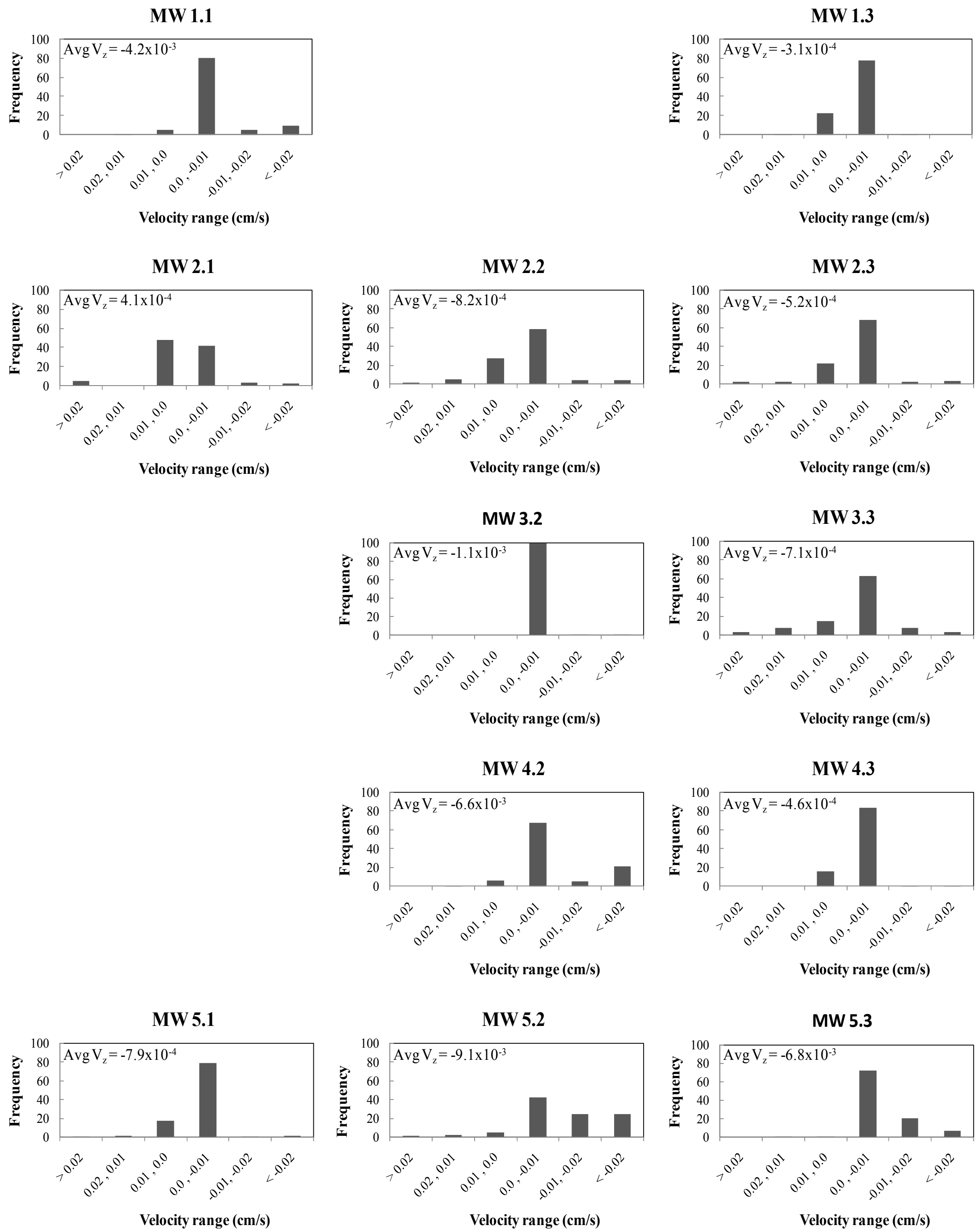

Figure 10. Distribution of estimated groundwater velocities in monitoring wells. Average velocities are reported in upper portion of charts.

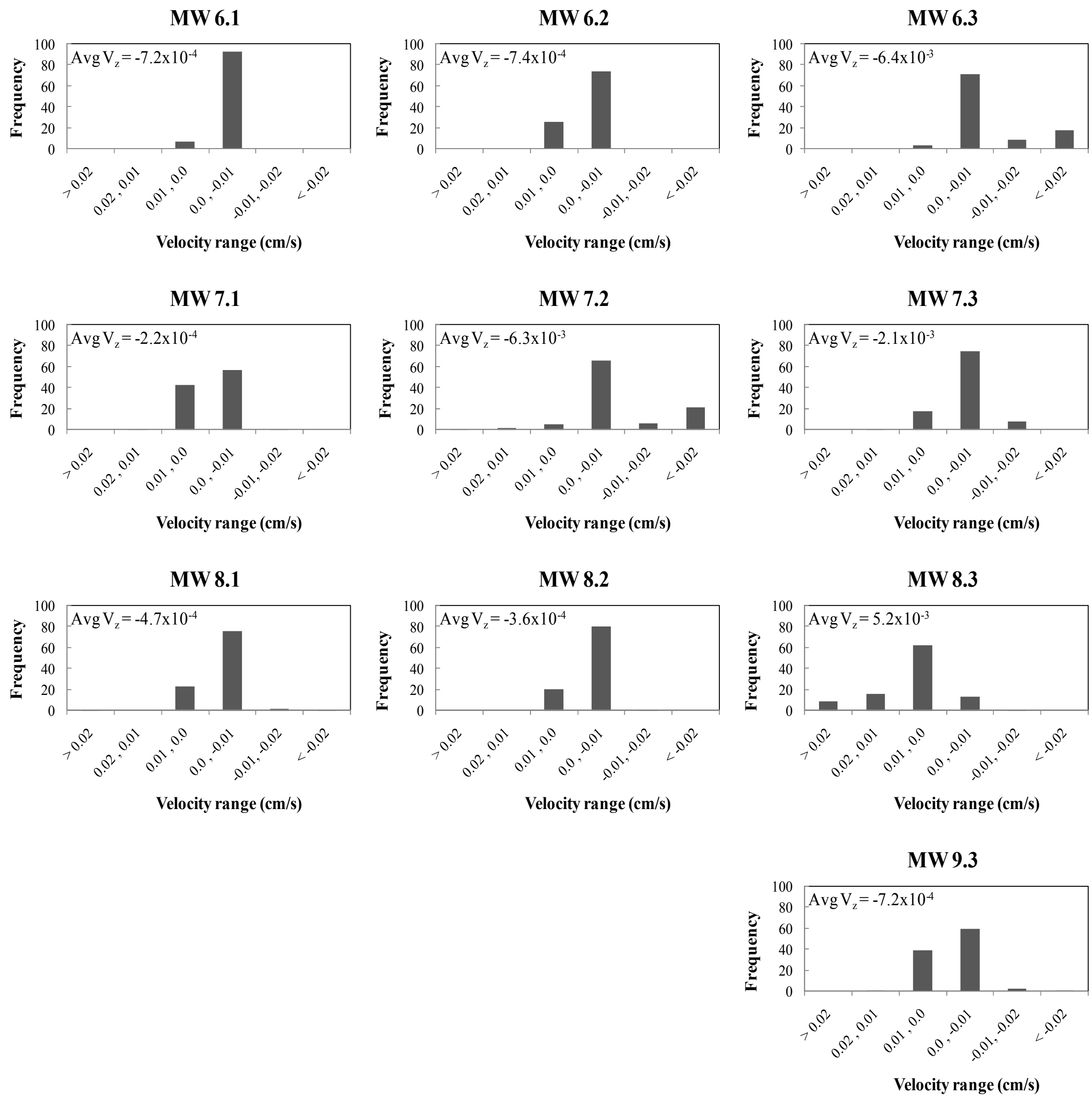

Figure 10. Distribution of estimated groundwater velocities in monitoring wells. Average velocities are reported in upper-left portion of charts.

Estimates of groundwater velocities as a function of time from representative monitoring wells from the spawning area (MW 6.3) and the non-spawning area (MW 8.1) are presented in Figures 11 and 12. All figures contain groundwater velocity estimates for the entire study period except for the spring of 2008. Freeze-thaw cycles in the river removed MW 6.3 from the sub-surface in February 2008 and MW 8.1 in March 2008. All temperature loggers were removed from the study site in May 2008, and re-installed in June 2008.

Figures 11 and 12 show that the velocities estimated from the spawning area (MW 6.3) are more consistently upward and greater in magnitude than the velocities estimated from temperature data in the non-spawning area (MW 8.1).

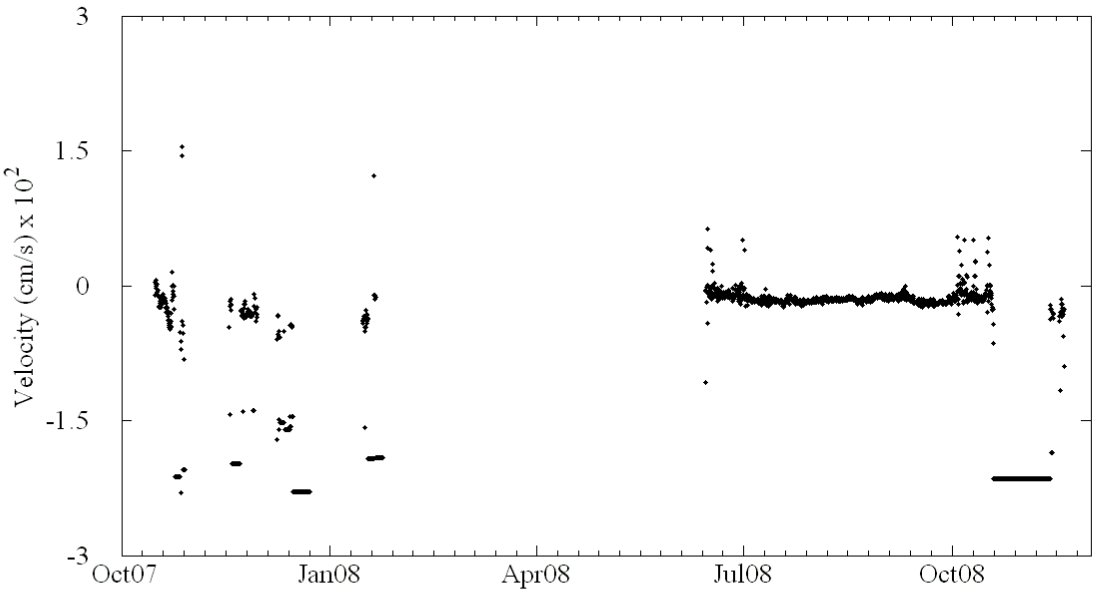

Figure 11. Estimated velocities at monitoring well 6.3 as a function of time.

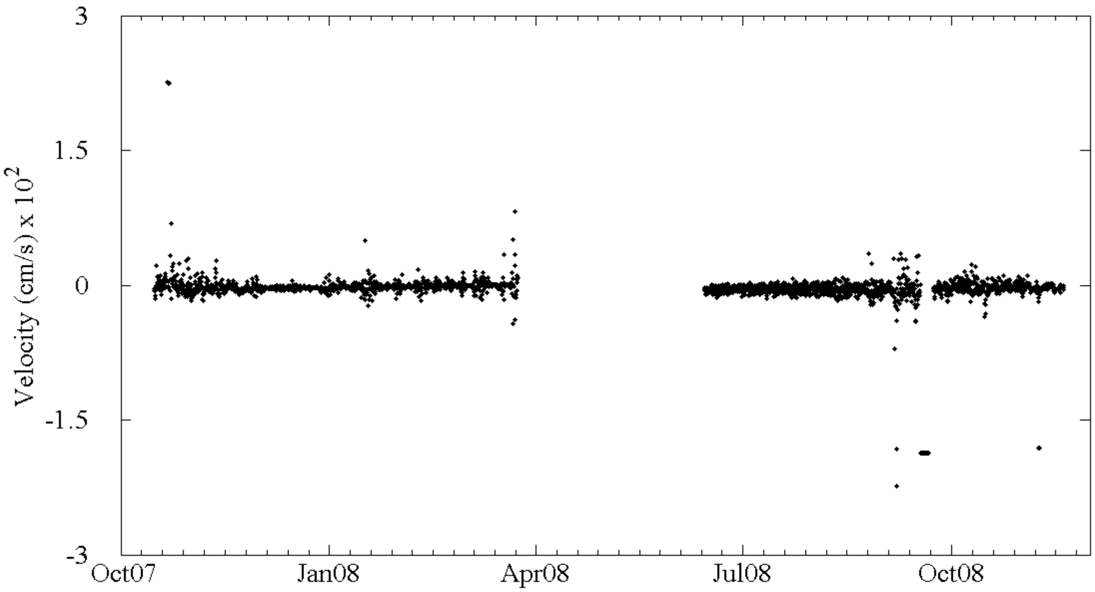

Figure 12. Estimated velocities at monitoring well 8.1 as a function of time.

4. CONCLUSIONS

A monitoring well system was installed to measure subsurface temperatures underneath a riverbed over a 13-month period. In total, over 200,000 temperature measurements were recorded at five vertical locations in 22 monitoring wells distributed aerially over approximately 80-m of river channel. The temperature data were inverted to obtain subsurface groundwater velocities using a numerical approximation of the heat transfer equation applicable to fluids in porous media. Approximately 45,000 values of groundwater velocities were estimated.

Although, the study area was relatively homogenous with respect to substrate and habitat characteristics, coaster brook trout were consistently observed to return to spawn in specific areas within the 80-m river length study area. The monitoring well locations were defined as being either inside or outside the areas where spawning behavior occurred. Temperatures within the stream substrate in the spawning area were generally less variable than river temperatures, indicating that groundwater velocities in this area were high enough to minimize within substrate mixing of river and groundwater. Substrate temperatures in the non-spawning area were generally more variable, and closely tracked river temperatures as they varied temporally.

Estimated velocities in the spawning and non-spawning areas confirmed that groundwater velocities in the spawning area were primarily in the upward direction. In the non-spawning area, groundwater velocities were mostly either in the downward direction or, if they were in the upward direction, the magnitude of the average velocity was generally lower. To our knowledge, no other study has implemented a high temporal and spatial resolution temperature network to quantify sub-surface water velocities over long time periods to evaluate an ecological hypothesis. The overall result of this work is to point out the significance of groundwater seepage in the selection of spawning area by coaster brook trout. This result is critical to recognize for the successful implementation of coaster brook trout rehabilitation.

5. REFERENCES

Alexander, M.D. and Caissie, D., Variability and comparison of hyporheic water temperatures and seepage fluxes in a small Atlantic salmon stream, *Ground Water*, 41:72-82, 2003.

Anderson, M.P., Heat as a ground water tracer, *Ground Water*, 43:951-968, 2005.

Becker, M.W., Georgian, T., Ambrose, H. , Siniscalchi, J., and Fredrick, K., Estimating flow and flux of ground water discharge using water temperature and velocity, *Journal of Hydrology*, 296:221-233, 2004.

Bernier-Bourgault, I. and P Magnan, P., Factors affecting redd site selection, hatching, and emergence of brook charr, *Salvelinus fontinalis*, in an artificially enhanced site, *Environmental Biology of Fishes*, 64: 333–341, 2002.

Blanchfield, P. J. and Ridgway, M. S., Use of seepage meters to measure groundwater flow at Brook Trout redds, *Transactions of the American Fisheries Society*, 125:813-818, 1996.

Brunke, M. and Gonser, T., The ecological significance of exchange processes between rivers and groundwater, *Freshwater Biology*, 37:1-33, 1997.

Bullen, B., *Fisheries management plan for the Salmon Trout River*, Marquette County, Michigan. Michigan Department of Natural Resources. Gladstone, 1986.

Conant, B.: Delineating and quantifying ground water discharge zones using streambed temperatures, *Ground Water*, 42:243-257, 2004.

Constantz, J., Cox, H., and Su, G.W., Comparison of heat and bromide as ground water tracers near streams, *Ground Water*, 41:647-656, 2003.

Curry, R.A. 1993. Hydrogeology of brook charr (*Salvelinus fontinalis*) spawning and incubation habitats: linking aquatic and terrestrial habitats. Ph.D. thesis, University of Guelph, Guelph, Ont.

Curry, R.A., J. Gehrels, D.L.G. Noakes, and Swainson, R., Effects of river flow fluctuations on groundwater discharge through brook trout, *Salvelinus fontinalis*, spawning and incubation habitats. *Hydrobiologia*, 277:121-134, 1994.

Curry, R.A. and Noakes, D.L.G., Groundwater and the selection of spawning sites by brook trout (*Salvelinus fontinalis*), *Canadian Journal of Fisheries and Aquatic Sciences*, 52:1733-1740, 1995.

Curry, R.A. and Noakes, D.L.G., and Morgan, G.E., Groundwater and the incubation and emergence of brook trout (*Salvelinus lonfinalis*), Canadian Journal of Fisheries and Aquatic Sciences, 52: 1741-1749, 1995.

Domenico, P.A., and F.W. Schwartz. 1998. Physical and Chemical Hydrogeology, 2nd ed. New York: John Wiley & Sons Inc.

Fraser, J.M., An atypical brook charr (*Salvelinus fontinalis*) spawning area, *Environmental Biology of Fishes*, 7:385-388, 1982.

Fraser, J.M., Shoal spawning of brook trout, *Salvelinus fontinalis*, in a Precambrian shield lake., *Naturaliste Canadien*, 112:163-174, 1985.

Huckins, C. J, and Baker, E.A., Migrations and biological characteristics of adfluvial Coaster Brook Trout in a south shore Lake Superior tributary, *Transactions of the American Fisheries Society*, 137, 1129–1143, 2008.

Huckins, C. J, .E. A. Baker, K. D. Fausch and J. B. K. Leonard. ecology and life history of ecology and life history of Coaster Brook Trout *Salvelinus fontinalis* and potential bottlenecks in their rehabilitation. *North American Journal of Fish Managementy*, 28, 1321–1342, 2008.

Kondolf, G.M., Williams, J.G., Horner, T.C., and Milan, D., Assessing physical quality of spawning habitat, in D. Sear, P. DeVries, and S. Greig (eds.) Salmon spawning habitat in rivers: Physical controls, biological responses, and approaches to remediation. American Fisheries Society, Bethesda, MD., 2008

Lapham, W.W., Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity, *US Geological Survey Water-Supply Paper 2337*, 1989.

NCDC, 2009. Daily surface data, COOP ID 205178 Marquette, MI, 01/1948 to 01/1979 and 02/1979 to 03/2009, http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwDI~StnSrch~StnID~10500080#DAF, accessed 7/8/09.

Newman, L. E., and R. B. Dubois. 1996. Status of brook trout in Lake Superior. http://midwest.fws.gov/ashland/brook/, Lake Superior Technical Committee, accessed 3/9/04.

Ridgeway, M.S. and Blanchfield, P.J., Brook trout spawning areas in lakes, *Ecology of Freshwater Fish*, 7:140-145, 1998.

Silliman, S.E., Ramirez, J., and McCabe, R.L., Quantifying downflow through creek sediment using temperature time series: One-dimensional solutions incorporating measured surface temperature, *Journal of Hydrology*, 167: 99-119, 1995.

Snoeyink, V.L., and Jenkins, D. 1980. Water Chemistry. New York: John Wiley & Sons Inc.

Stallman, R.W. Steady one-dimensional fluid flow in a semi-infinite porous medium with sinusoidal surface temperature, *Journal of Geophysical Research*, 70:2821–2827, 1965.

Stonestrom, D. A., and Constantz, J., Heat as a tool for studying the movement of ground water near streams, *U.S. Geological Survey Circular 1260*, Denver, CO, 2003.

Storey, R. G., Howard, K.W. F., and Williams, D. D.: Factors controlling riffle-scale hyporheic exchange flows and their seasonal changes in a gaining stream: A three-dimensional groundwater flow model, *Water Resource Research*, 39(2), doi:10.1029/2002WR001367, 2003.

Tan, K.H. 1996. Soil Sampling, Preparation, and Analysis. New York: Marcel Dekker, Inc.

USGS, 2009. Gauging station 04043238 Salmon Trout River near Big Bay, MI, http://waterdata.usgs.gov/nwis/nwisman/?site_no=04043238, accessed 7/9/09.

Wroblicky, G. J., Campana, M. E., Valett, H. M., and Dahm, C. N., Seasonal variation in surface-subsurface water exchange and lateral hyporheic area of two stream-aquifer systems, *Water Resource Research*, 34:317-328, 1998.