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Key Points:

- Independent Component Analysis (ICA) to assess sediment-water interface temperature variability
- Combine ICA and cross correlation to identify streambed temperature components
- Streambed temperatures influenced by temporally variable groundwater inflows

Supporting Information:

- Suppporting Information S1
- Figure S1
- Figure S2
- Figure S3

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Independent component analysis of local-scale temporal variability in sediment-water interface temperature

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Abstract Temperature recorded at the sediment-water interface has been identified as a valuable tracer for understanding groundwater-surface water interactions. However, factors contributing to the variability in temperatures can be difficult to distinguish. In this study, the temporal variability in daily temperatures at the sediment-water interface is evaluated for a 40 m reach of a coastal stream using Independent Component Analysis (ICA). ICA separation is used to identify three independent temperature components within the reach for each of four summer periods (2008–2011). Extracted temperature signals correlate with stream discharge, estimated streambed temperature, and groundwater level, but the strength of the correlations varies from summer to summer. Overall, variations in the temperature signals have clearer separation in summers with lower stream discharge and greater stream temperature ranges. Surface heating from solar radiation is the dominant factor influencing the sediment-water interface temperature in most years, but there is evidence that thermal exchanges are taking place other than at the air-water interface. These exchanges take place at the sediment-water interface, and the correlation with groundwater levels indicates that these heat exchanges are associated with groundwater inflow. This study demonstrates that ICA can be used effectively to aid in identifying component signals in environmental applications of small spatial scale.

1. Introduction

Stream temperature is a key parameter for assessing water quality and the overall health of aquatic ecosystems [*Caissie*, 1991; *Winter et al*., 1998; *Poole and Berman*, 2001; *Hatch et al*., 2006; *Hannah et al*., 2008; *Cunjak et al*., 2013; *Rau et al*., 2014]. The temperature of a stream influences biological and chemical processes, the life histories of aquatic species, and community processes and structure [*Power et al*., 1999; *Alexander and Caissie*, 2003; *Benyahya et al*., 2007; *Velasco-Cruz et al*., 2012]. Stream temperature, however, has a complex response to a variety of processes, particularly interactions between the water and the environment through exchanges across the water surface and the sediment-water interface [*Johnson and Jones*, 2000; *Hannah et al*., 2004; *Moore et al*., 2005; *Caissie*, 2006].

Most variations in stream water temperature (e.g., diel, daily, and seasonal) occur as the result of heating and cooling of the river by outside sources, which are strongly influenced by meteorological and geophysical conditions [e.g., *Webb and Zhang*, 1997; *Evans et al*., 1998; *Bogan et al*., 2003; *Moore et al*., 2005]. As such, regression and stochastic models have been used to predict the thermal regime of a surface water body using air temperature as a predictor [*Mohseni et al*., 1998; *Stefan and Preud'homme*, 1993; *Benyahya et al*., 2007]. Deterministic models have also been used to quantify heat fluxes across the sediment-water interface [e.g., *Caissie et al*., 2014].

Water exchanges between the stream and the groundwater system are of particular importance. From a thermal perspective, groundwater flux can be considered to have both diffuse and localized effects. Groundwater temperatures are relatively constant throughout the year, and groundwater influxes (whether diffuse or localized) buffer the temperature fluctuations in the stream [*Alexander and Caissie*, 2003; *Constantz*, 2008; *Brewer*, 2013]. Localized groundwater influxes (e.g., seeps, springs, alcoves, and hyporheic discharge) create thermal anomalies that can provide microhabitats (thermal refugia) for cold-water fish and other aquatic species [*Brunke and Gonser*, 1997; *Alexander and Caissie*, 2003; *Brewer*, 2013; *Briggs et al*., 2013;

Kurylyk et al., 2014]. These anomalies can have a temperature difference of only 1–2°C and still be biologically important [*Caissie*, 2006; *Velasco-Cruz et al*., 2012]. Summer low-flow periods are particularly critical for aquatic health because streamflow is at a minimum and the stream temperatures typically reach the annual maximum [*Fleming et al*., 2007; *Brewer*, 2013; *Moore et al*., 2013]. Therefore, during summer in the Pacific Northwest, when precipitation inputs are minimal, the contributions of groundwater become increasingly important to maintain suitable flow and thermal conditions for aquatic life [*Smakhtin*, 2001; *Hatch et al*., 2006; *Mayer*, 2012; *Briggs et al*., 2013; *Kurylyk et al*., 2014].

Temperatures measured within the stream water column, the streambed, and at the sediment-water interface have been identified as valuable tracers for understanding groundwater-surface water interactions, which often vary both spatially and temporally [*Evans and Petts*, 1997; *Evans et al*., 1998; *Conant*, 2004; *Anderson*, 2005; *Hatch et al*., 2006; *Constantz*, 2008; *Rau et al*., 2014]. Variations in the sediment-water interface temperature, in particular, can be attributed to differences in exchanges between the stream water and groundwater [*Krause et al*., 2012]. For example, streams with a connection to groundwater can seasonally become gaining streams during the low-flow period [*Silliman and Booth*, 1993; *Winter et al*., 1998; *Sophocleous*, 2007; *Constantz*, 2008]. Understanding of the spatial variability in groundwater contributions to streamflow may be gained by mapping streambed temperatures [e.g., *Conant*, 2004], while time series analysis can be used to determine fluxes between streams and groundwater [e.g., *Hatch et al*., 2006; *Rau et al*., 2010; *Irvine et al*., 2015]. The influence of multidimensional flows (e.g., hyporheic, diffuse groundwater discharge, etc.) and the high degree of spatial heterogeneity in streambed and aquifer hydraulic properties strongly influences the temperatures (and fluxes), making analysis and interpretation challenging [*Irvine et al*., 2015]. Thus, there is value in examining temperature information from multiple time series.

This paper examines temporal variability in sediment-water interface temperature recorded at the reach scale over four summer periods (July through September) in a coastal stream. Independent Component Analysis (ICA) is employed as a statistical method to separate the observed signals into the independent components in order to compare how the signals differed between the 4 years. Independent Component Analysis (ICA) has many applications for signal separation. Classic applications of ICA include audio signal processing, separation of biomedical signals such as electrocardiogram components, and image processing [*Funaro et al*., 2003; *Mitiandoudis and Davies*, 2003; *Ungureanu et al*., 2004]. More recent applications of ICA have extended the method into climate analysis, modeling, forecasting, and hydrologic time series analysis [*Aires et al*., 2000; *Westra et al*., 2007; *Moradkhani and Meier*, 2010]. Much of the ICA literature related to climate and environment research has focused on problems at spatial scales ranging from global (e.g., global climate models) to basin and watershed scales. The temporal scales considered in these studies employ periods of record that are appropriate for the spatial scale; for example, decadal oscillations, and monthly or seasonal variations. Here ICA is used to examine time series of daily sediment-water interface temperatures observed at a spatial scale of meters.

2. Study Area

The study site is a reach of Fishtrap Creek, located in the Lower Fraser Valley of southwestern British Columbia (BC) (Figure 1). Fishtrap Creek watershed is situated within the regional Abbotsford-Sumas aquifer. This particular reach was selected because it is a gaining reach during the summer [*Johanson*, 1988; *Berg and Allen*, 2007]. There is no forest canopy or overhanging vegetation, only seasonal grasses present as in-stream vegetation, so the direct and indirect effects of shading on stream temperature are avoided [*Middleton et al*., 2015]. The reach is well suited for making comparisons of temperature patterns between years because the channel characteristics, such as summer water depth, bed material, and stream vegetation cover, are stable. This location has other data sources, including a Water Survey of Canada gauging station at the downstream end of the site (Fishtrap Creek at International Boundary 08MH153), and a climate station at the nearby Abbotsford International Airport (Climate ID 1100030).

The climate of Fishtrap Creek watershed is Maritime and dominated by moderate temperatures with high annual precipitation rates. The temperatures throughout the year are moderated by the close proximity to the Pacific Ocean. The annual average precipitation is 1500 mm/yr, with little snow; less than 100 mm as water. Approximately 70% of precipitation falls in the period between October and May, and only 6% of the

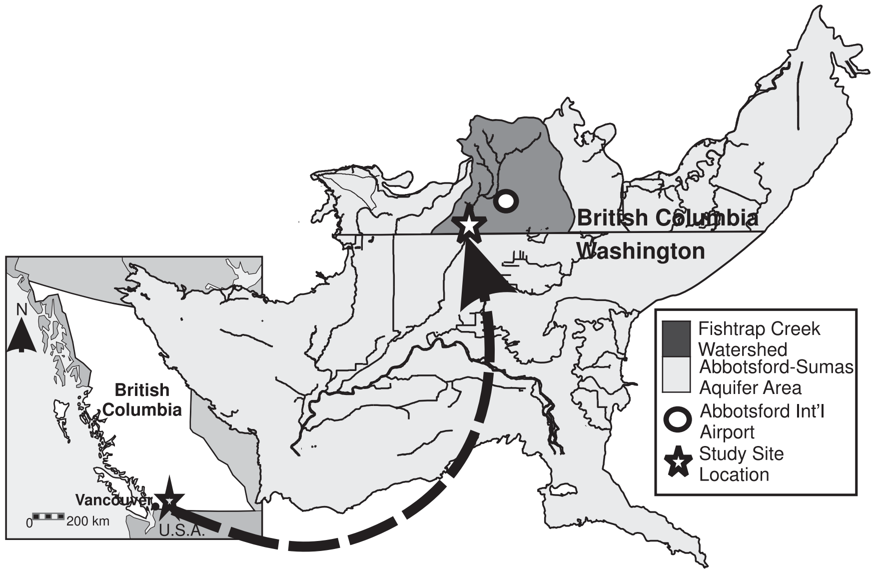

Figure 1. The location of the Fishtrap Creek study site in British Columbia, Canada, within the Abbotsford-Sumas aquifer which spans the international border (Canada-U.S.). Abbotsford International Airport is the location of the Environment Canada climate station.

precipitation falls in July and August [*Wernick et al*., 1998; *Zebarth et al*., 1998; *Berka et al*., 2001; *Environment Canada*, 2002].

Fishtrap Creek watershed is $\sim$47 km^2 and originates at relatively low elevation and relief (slightly above mean sea level). The flow regime is driven by rainfall and interaction with the groundwater [*Johanson*, 1988; *Berg and Allen*, 2007]. The flow regime is pluvial and runoff mimics the timing of the precipitation, with a time lag of only a few days. The lowest streamflows generally occur during August [*Berg and Allen*, 2007]. During this period, groundwater sustains the streamflow, as there are no other major inputs to the streams because precipitation levels are at a minimum [*Johanson*, 1988; *Pearson*, 2004]. Average monthly groundwater levels have an approximately 1.5 month lag relative to stream discharge [*Berg and Allen*, 2007].

3. Methodology

3.1. Data Acquisition and Preprocessing

Fifteen TidbiT® v2 Temp loggers (UTBI-001) were installed over a distance of approximately 40 m in a reach of Fishtrap Creek (Figure 2). The loggers were placed directly on the streambed to observe temperatures at the sediment-water interface and were attached to rebar to prevent movement. The loggers have an accuracy of $\pm$0.2°C and a resolution of 0.02°C. Data were collected hourly; however, all analysis reported here are based upon daily averages. Loggers were first installed in July 2008, and the final data reported here are from October 2011. One data logger (#12; see Figure 2) was lost following October 2008, and another was removed in July 2011 due to a low battery (#14).

The manufacturing specifications for the Tidbit temperature loggers indicate an annual drift of up to 0.1°C/yr. The calibration of the data loggers was verified in a temperature bath prior to deployment and at the end of the sampling period. A logger-specific linear drift correction was applied to the data. The mean drift over the 4 years was 0.04°C/yr, and none of the data loggers exceeded the maximum 0.5°C suggested by the specifications.

Data loggers at the downstream end of the site (Figure 2) were distributed in two transects perpendicular to the channel to monitor a cross section of the streambed. The remaining data loggers were installed up the channel at approximately evenly distributed distances to capture differences along the direction of flow. This design was intended to capture the range of spatial variability of temperature that might exist by employing a spot measurement strategy commonly used by fisheries biologists. Figure 2 also shows the location of the 19 m deep BC Ministry of Environment Observation Well #2, which records daily groundwater levels, and the 8 m deep Environment Canada Observation Well ABB01, which records hourly

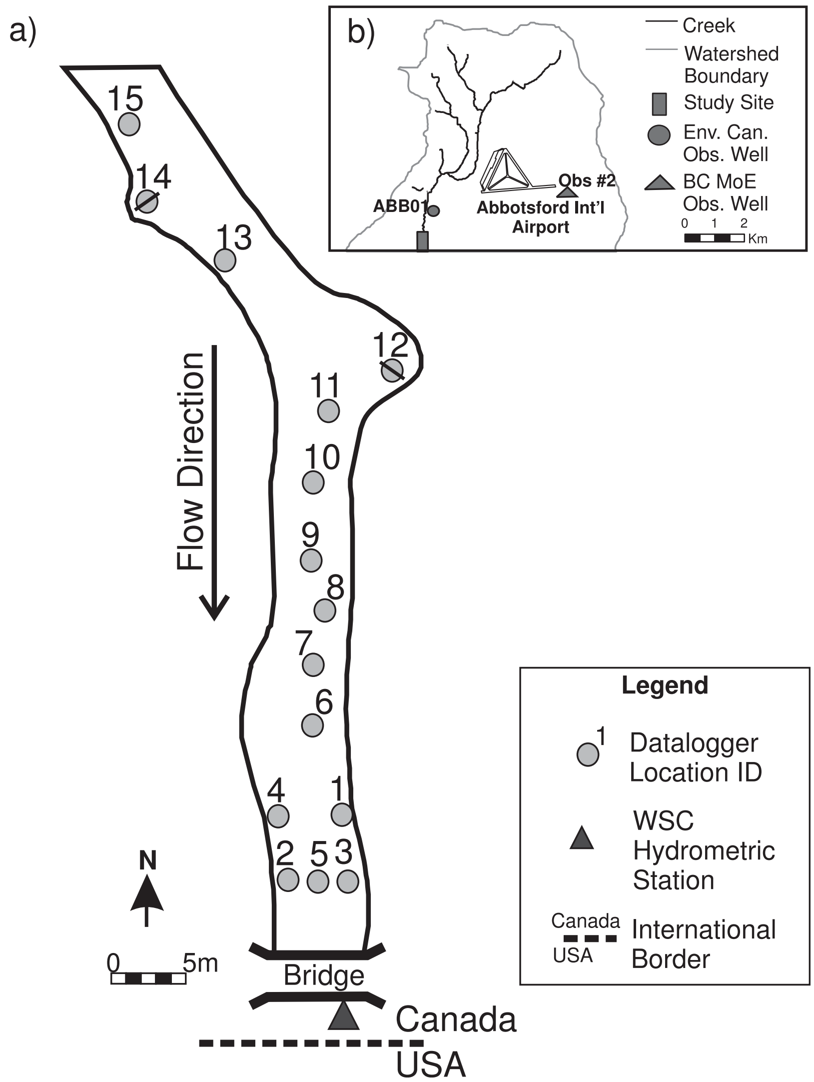

Figure 2. (a) The distribution of temperature data loggers at the study site. At the data logger locations, a "/" stroke indicates a station lost in 2009 and a "\" lost in 2011. (b) Inset map showing the site location in Fishtrap Creek watershed and the locations of the Environment Canada observation well (ABB01) and the BC observation well (Obs.#2).

groundwater temperatures. Unfortunately, no single observation well recorded both groundwater level and groundwater temperature over the period of the study.

The multiple time series files from each data logger within each year were joined, time/date formats standardized, and quality assurance/quality control checks on the data performed using Aquarius v. 3.0.75.1 [*Aquatic Informatics Inc*., 2012]. Data gaps up to several hours occurred during downloading events when data loggers were removed from the stream. These minor gaps were filled using polynomial interpolation which was found to provide the best fit for hourly data gaps. The infilling of these gaps has little effect on the daily temperature series used here.

The analyses were performed in R [*R Development Core Team*, 2011] using the contributed packages *lubridate* [*Grolemund and Wickham*, 2011] for converting data and time from data loggers, *xts* [*Ryan and Ulrich*, 2011] for aggregating data to daily time steps, and *fastICA* [*Marchini et al*., 2010].

3.2. Heat Balance Model

Stream temperature is controlled by fluxes of heat energy that act on the water course, including a combination of radiation, conduction, convection, and advection [*Webb*, 1996; *Webb and Zhang*, 1997; *Evans et al*., 1998; *Hannah et al*., 2004]. The heat balance in the stream is the combination of energy fluxes at the water-air interface and the sediment-water interface. Dividing the system into interfaces can be useful for isolating the factors influencing the stream temperature which act to add or remove heat from the system [*Evans et al*., 1998; *Hannah et al*., 2004]. The daily heat balance was calculated for the water-air interface to isolate climatic factors that may be influencing how the stream temperature changes as water flows from upstream to downstream through the reach. We needed to confirm that solar radiation dominated the heat balance and that other effects (e.g., precipitation events) were negligible.

The simplified heat balance for the site was calculated based on the following equation, following the methods described in *Sinokrot and Stefan* [1993], *Evans et al*. [1998], and *Xin and Kinouchi* [2013] for the exchange of thermal energy across the air-water interface:

$$H_{net} = H_{is}(1-\alpha) - H_l - H_e - H_c \tag{1}$$

where H_{net} is the net heat exchange at the air-water interface, H_{is} is the incident solar radiation, α is the albedo of the stream surface, H_l is the net longwave radiation, H_e is the evaporative heat transfer, and H_c is the convective (sensible) heat transfer. Daily incident solar radiation (H_{is}) was estimated using the solar position and radiation calculator developed by the *State of Washington Department of Ecology* [2014]. The Bird Clear Sky model for direct radiation incident upon a horizontal surface was used, which is based on the latitude and elevation of each site [*Bird and Hulstrom*, 1981]. A value of 0.06 was used for α, following the approach by *Xin and Kinouchi* [2013]. The output is a daily estimate of the solar radiation; note that there is no correction for the conditions in the atmosphere except as exhibited in the air temperatures.

The net longwave radiation (H_l) was calculated using the daily mean stream and air temperatures and emissivities of the water surface and atmosphere [*Xin and Kinouchi*, 2013]. The evaporative heat flux (H_e) was calculated using the air temperature, relative humidity, and wind speed from the climate station following *Xin and Kinouchi* [2013] and *Sinokrot and Stefan* [1993]. The convective heat flux (H_c) was calculated using the air and mean stream temperatures and the air pressure [*Xin and Kinouchi*, 2013; *Sinokrot and Stefan*, 1993]. The equations and methods for calculation of the heat budget are presented in more detail in *Middleton et al*. [2015].

Heat budget plots were examined for variations in the net radiation, and to identify heat budget components that were dominating those variations. Plotting the daily heat balance for short windows of the summer period (Figure 3) allowed for comparison of the components that dominate the heat balance under different precipitation conditions as precipitation was not directly considered in the simplified heat budget. Figure 3a shows a 2 week period with precipitation, while Figure 3b shows a period without rainfall. The absence of variation in the heat budget components during the wet period indicates that precipitation events do not appear to impact the daily heat balance for this site. The period with precipitation was examined specifically to evaluate if there were any lags in the daily heat balance as a result of precipitation events. For both conditions, incoming solar radiation dominates. Net longwave radiation and convective heat fluxes remained relatively unchanged in the daily heat balance, and therefore are not considered to be influencing factors for individual sediment-water interface temperature measurement locations. However, evaporative fluxes were reflected in the net heat flux for the stream, indicating evaporative processes can be important to the overall heat balance at a daily time scale. Figure 3 shows that variations in the evaporative heat flux are reflected inversely in the net radiation, with no time lag. The strong dependence of the heat balance on solar radiation means that, at this site, the air temperature can be used as a predictor of the sediment-water interface temperature to evaluate the influence of solar radiation on the interface temperatures. The use of air temperature as a surrogate for solar radiation in the absence of detailed heat flux data has been demonstrated in the literature as a reasonable approach [e.g., *Smith*, 1981; *Mohseni and Stefan*, 1999].

3.3. Estimated Sediment-Water Interface Temperature

Both air and water temperatures respond to changes in incoming solar radiation; however, water temperature responses are delayed and damped due to the thermal inertia of water. Given that the sediment-water interface temperature was expected to correlate with solar radiation to some degree, a daily time series was needed for cross-correlation analysis with the ICA extracted components (as discussed later).

Water temperature at the sediment-water interface can be estimated from air temperature through an empirical linear relationship [*Stefan and Preud'homme*, 1993]. Comparisons between linear relationships and

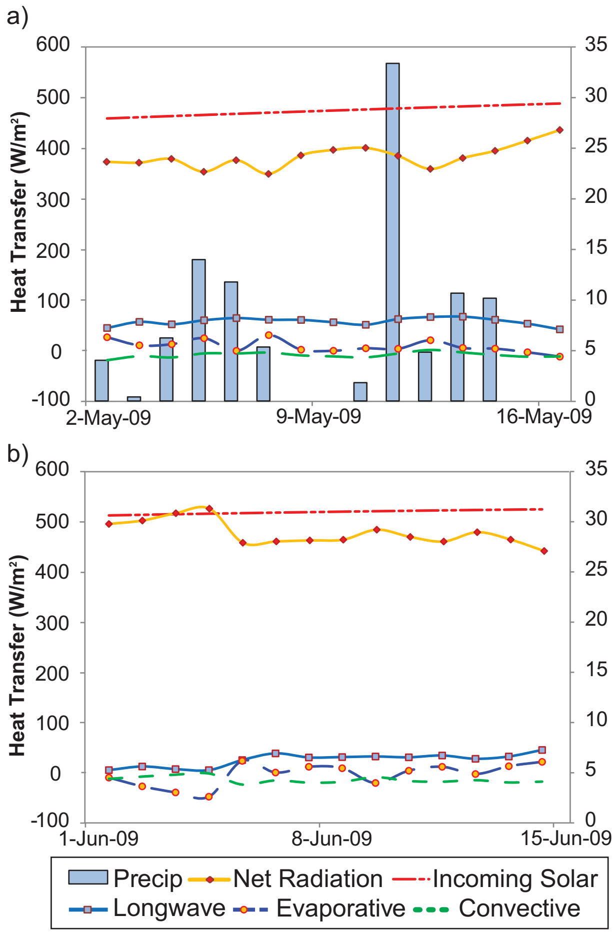

Figure 3. Daily heat balance components showing examples from 2009 of early summer periods with (a) a period of rainfall and (b) a period without rain.

higher-order polynomial relationships have found that a linear relationship is appropriate for estimating moderate (0°C–20°C) water temperatures, which is the range of Fishtrap Creek summer temperatures [*Mohseni et al.*, 1998; *Mohseni and Stefan*, 1999; *Kelleher et al.*, 2012]. To relate the air temperature to sediment-water interface temperature, it is assumed that the stream is well mixed, uniform, and free flowing.

The time lag between the air and sediment-water interface temperatures for the study site was calculated as 30 h. The lag period was found using the net surface heat transfer coefficient for heat transfer between the atmosphere and the water surface, and a mean summer water depth at the study site of 0.78 m [see *Middleton et al.*, 2015]. The value of the heat transfer coefficient of 30 W/m^2/°C is consistent for this stream depth based on the time lag estimate given in *Sinokrot and Stefan* [1993] for summer values. For the calculation of sediment-water interface temperature at a daily time step, a lag of 1 day was used for simplicity. Thus, the lag is slightly lower (24 h) compared to the calculated lag (30 h)—see section 5 for the implications. The mean daily sediment-water interface temperature was calculated from the mean of all the interface loggers across the site. Using daily mean air temperatures with only positive values over the period of record, the linear relationship between daily sediment-water interface temperature (T_s) and daily air temperature (T_a), at a lag of 1 day, was determined empirically for the site as:

$$T_s(t) = 5.15 + 0.49 * T_a(t - 1\ \text{day}) \tag{2}$$

where T is in °C.

3.4. ICA

Independent Component Analysis is a statistically based, signal processing technique that can be used to separate independent source components from an input of mixed signals that are time series [*Comon*, 1994; *Whitfield et al.*, 1999; *Hyvarinen and Oja*, 2000; *Naik and Kumar*, 2011; *Hyvarinen*, 2012]. The classic explanation of ICA is the "cocktail party problem"; sample data from a number of microphones that "observe" people talking simultaneously in a room are separated into individual speech signals. ICA finds the independent components by maximizing the statistical independence of the estimated components. There are different ways to define independence, and this choice governs the form of the ICA algorithm. The two broadest definitions of independence for ICA are minimization of mutual information and maximization of non-Gaussianity. The non-Gaussianity family of ICA algorithms, which include FastICA, are motivated by the central limit theory. Typical algorithms for ICA use centering (subtract the mean to create a zero mean signal), whitening (usually with the eigenvalue decomposition), and dimensionality reduction. These preprocessing steps are used in order to simplify and reduce the complexity of the problem for the actual iterative algorithm. Whitening ensures that all dimensions are treated equally a priori before the algorithm is run. ICA cannot identify the actual number of source signals, a uniquely correct ordering of the source signals, nor the proper scaling (including sign) of the source signals. ICA requires no prior knowledge of the mixing process and thus is one of the most common forms of blind signal separation.

The basis of ICA is that recording devices, such as temperature data loggers, record mixed signals (x). These mixed signals are products of source signals (s) and some mixing matrix (A), where both s and A are unknown:

$$x = As \tag{3}$$

The goal of ICA is to obtain an estimate of the independent source components (s), using the recorded signals (x). The source components (s) can be estimated from the mixed signals (x) and an unmixing matrix (W):

$$s = Wx \tag{4}$$

where $W = A^{-1}$. The only observed variable is the mixed signal, x, and there is no prior input information on the original source signals or the mixing matrix, A. This absence of input information is the aspect of the method that is considered "blind." To simplify the process, the equations do not consider any noise components, or time lag in the recordings.

Several ICA algorithms have been discussed in the literature and one of the most common is the FastICA method [*Hyvarinen*, 1997; *Hyvarinen and Oja*, 1997; *Hyvarinen*, 1999; *Hyvarinen and Oja*, 2000; *Naik and Kumar*, 2011]. Fast ICA is a fixed point algorithm that uses higher-order statistics for estimating the independent source components. The FastICA method [*Marchini et al*., 2010] performs centering and the pre-whitening, in addition to the ICA component extraction. The ICA separation of mixed signals is based on two assumptions and three effects of mixing source signals. The assumptions are (a) the source signals are independent of each other and (b) the values in each source signal have non-Gaussian distributions. The three effects of mixing are:

1. The source signals are independent; however, their signal mixtures are not. This is because the signal mixtures share the same source signals.
2. According to the Central Limit Theorem, the distribution of a sum of independent random variables tends toward a Gaussian distribution. Thus, a sum of two independent random variables usually has a distribution that is closer to Gaussian than any of the two original variables. Here we consider the value of each signal as the random variable.
3. The temporal complexity of any signal mixture is greater than that of its simplest constituent source signal.

If the components extracted from a set of mixtures are independent (like source signals), or have non-Gaussian histograms (like source signals), or have low complexity (like source signals), then they must be source signals. One can drop the independence assumption and separate mutually correlated signals, thus, statistically "dependent" signals. *Whitfield et al*. [1999] demonstrated that ICA separation worked well in the presence of Gaussian noise. Some authors have noted that there is no guarantee that any particular algorithm can capture the individual source signals if its components are a nonlinear mixtures [*Chawla*, 2009]. In such cases, ICA does not ensure separation, and emphasizes very large indeterminacies [*Jutten et al*., 2004]. While the transfer of heat into the groundwater is nonlinear, and at some time scales, the temperature of the groundwater and the surface water could be correlated, the difference in statistical memory of these two sources suggests that the temperature of the sources can be considered locally independent at a daily time step. Surface water temperature is linked to air temperature relatively directly, as explained above, and groundwater temperature is similarly nonlinearly driven at a longer time scale and considerably dampened. The groundwater temperature thus varies only a small amount over a summer. Since the process we are interested in is the flux of water from different sources, that mixing, and hence the signal mixing, is linear which is sufficient to meet our objective of comparing daily signals between years of groundwater heat fluxes. In our study, we take a further step of conducting a cross-correlation analysis with variables that are expected to be related to the various extracted components, in order to limit ambiguities, and to identify the main hydrological processes linked to the components.

Two ambiguities exist in the ICA output components [*Hyvarinen and Oja*, 2000; *Naik and Kumar*, 2011; *Hyvarinen*, 2012]. The first is a magnitude and scaling ambiguity, in which the true variance of the independent components cannot be determined. The second is that the order of the estimated sources cannot be determined. Both ambiguities result because the source signals and the mixing matrix are unknown. Thus, no restrictions or conditions are imposed on the sources during separation, leaving the order indistinguishable, and each permutation equally valid.

In this study, ICA was used to perform a blind separation of the component signals contained in the records for each summer for all available temperature loggers. The number of available recorded signals was 15 in 2008, 14 in 2009 and 2010, and 13 in 2011. ICA was run for each year using all available loggers as input signals. Any number of components may be extracted; however, as the number of extracted components increases, they become nonunique and it becomes difficult to distinguish between them. The strategy, therefore, was to consider what variables likely contribute to the heat budget of the stream reach, as determined by the simplified heat budget. At this site, solar radiation, stream inflow, and groundwater exchange were considered the dominant variables. Therefore, three components were extracted.

3.5. Cross-Correlation Analysis

The extracted temperature components were then compared to three main variables using the cross correlation with the ICA components (estimated streambed temperature, stream discharge, and groundwater level). Unsmoothed and smoothed (2 day moving average) stream discharge were considered. The smoothed stream discharge was used to strengthen the cross-correlation results by removing the short-term influence of precipitation events on stream discharge. The groundwater temperature remained relatively constant over all the summer periods, while the groundwater level fluctuated during and between the summer periods, and for this reason groundwater level is a more appropriate variable to test with cross correlation. These variables are considered most likely to relate directly to three contributing variables described above. Cross correlation provides a value that indicates the strength of the relationship between the variables, and also any lags between the two variables. The sign of the lag indicates which variable leads in the correlation, with a positive lag indicating that the x variable lags the y, and a negative lag the reverse. The estimated sediment-water interface temperature signal is the x variable in all cross correlations. The lag is useful in evaluating the timing in the interface temperature responses.

4. Results

A linear model of daily mean air temperature and the 1 day lagged mean measured sediment-water interface temperature for all nonnegative temperatures in the 4 year period was found to explain more than 86% of the variance in interface temperature (Figure 4a). In the individual years, the relationship was consistent, with the air temperature explaining between 82% and 89% of the variance. The regression slope (0.50) and the positive intercept (5.1°C) are characteristic of streams with groundwater contributions, which moderate seasonal temperature fluctuations [*Smith*, 1981; *Caissie*, 2006]. Over the summer period only, the linear model explains only 31% of the variance over the four summers (Figure 4b), suggesting that other factors dominantly contribute to the remaining variance. In individual summers, the air temperature explained between 18% (2011) and 57% (2009) of the variance in the sediment-water interface temperature. In 2008 and 2010, the variance explained was 25% and 23%, respectively. The lower regression slope (0.25) indicates that the interface temperature increases less relative to the increase in air temperature during summer compared to annually. As this reach is physically uniform, and evaporative fluxes do not dominate the heat budget over the summer period, the observed variability in sediment-water interface temperatures that are not explained by the estimated sediment-water interface temperature can be attributed to variations in the groundwater flux or other local-scale drivers. The extraction method presented next seeks to understand these additional components over each summer.

Two important hydrologic variables in this reach of Fishtrap Creek are stream discharge and groundwater level. The mean daily summer stream discharge was 0.20 m^3/s ($\pm$0.25 m^3/s), but stream discharge generally decreased over the summer period, and had peaks associated with precipitation events throughout the summer. Figure 5a shows mean daily stream discharge over the 2008–2011 period. Groundwater levels in observation well #2 for the period from 2008 to 2011 are shown in Figure 5b. There is a definite seasonal pattern of groundwater levels and some year to year variation; highest groundwater levels were observed

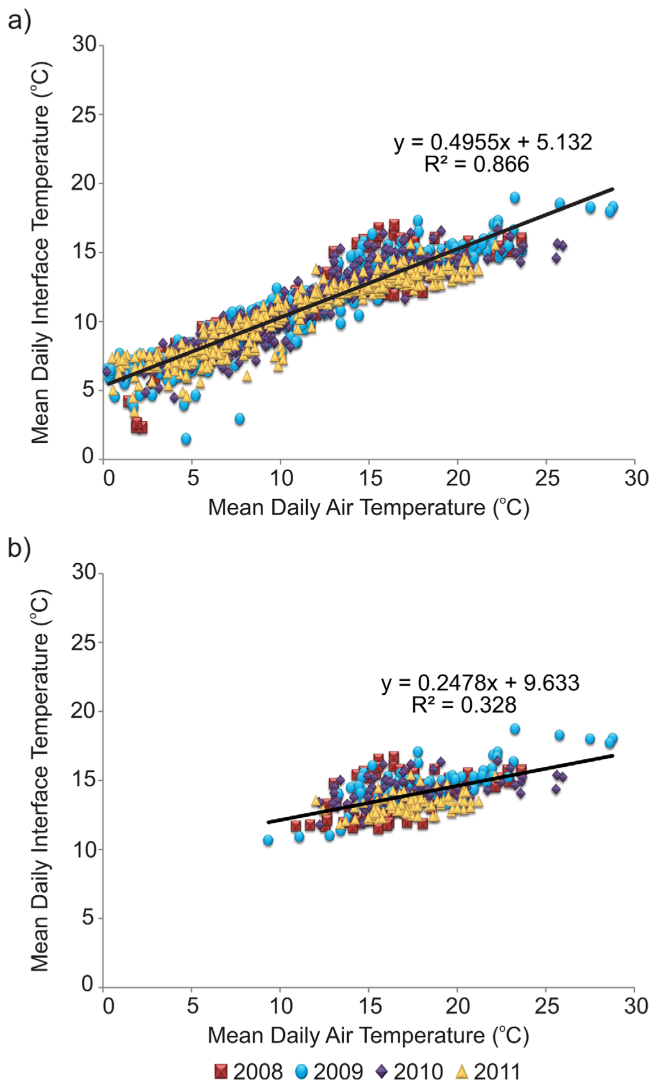

Figure 4. (a) The relationship between daily mean air temperature and mean observed 1 day lagged sediment-water interface temperature for days with all nonnegative air temperatures for the 4 year study period, including all data for the period of July 2008 to October 2011. (b) The relationship between daily mean air temperature and mean observed 1 day lagged sediment-water interface temperature for only the summer periods from 2008 to 2011.

in 2011. The mean daily summer groundwater level was 12.8 m (±0.73 m) belowground surface, with a mean recession of 1.44 m. The summer periods consistently show a decline in groundwater levels. Precipitation amounts were low during the summer periods, with maximum summer rainfall events ranging from 16 mm in 2012 to 45.5 mm in 2010; the mean daily summer precipitation was 1.8 mm (±5.5 mm).

4.1. Sediment-Water Interface Temperatures

Figure 6 shows the mean sediment-water interface temperatures (from all loggers across the site), air temperature, groundwater temperature, stream discharge, groundwater level, and precipitation over the four summer periods (July through September). In all years, the mean sediment-water interface temperature is lower than the air temperature with a pattern that closely follows the fluctuations in air temperature, but with a dampened amplitude in the temperature range as would be expected if incoming solar radiation were the greatest contributor of heat to streams [*Stefan and Preud'homme*, 1993; *Webb and Zhang*, 1997; *Hannah et al.*, 2008]. There are also generally consistent peaks in air and sediment-water interface temperatures over the summers. The air and the sediment-water interface temperatures in 2011 had the smallest standard deviation and range of all of the 4 years. In the summer periods, the mean daily air temperature was 17.3°C (±2.8°C), the mean daily sediment-water interface temperature was 13.6°C (±1.0°C), and the mean daily groundwater temperature remained relatively constant with a mean of 10.6°C (±0.3°C). The lag between precipitation and discharge of up to 1 day is also evident in Figure 6.

To illustrate the ICA methodology, we will focus on the results for the summer of 2008; the other years were approached identically. The observed daily mean sediment-water interface temperatures for each of the 15 data loggers are shown in Figure 7. These constitute the input signals that were used in the analysis. As mentioned, three components were extracted using ICA for each summer period. The complete set of ICA components extracted for summer 2008 is shown in Figure 8, along with the estimated sediment-water interface temperature and stream discharge for comparison. Groundwater level is not plotted in Figure 8; groundwater level declines throughout the summer as shown in Figure 5.

For each of the four summer periods, cross-correlation analysis was conducted to classify the three extracted components. For classification, we considered whether each extracted component (1, 2, and 3) correlated with (a) estimated sediment-water interface temperature, (b) stream discharge, and/or (c) groundwater level.

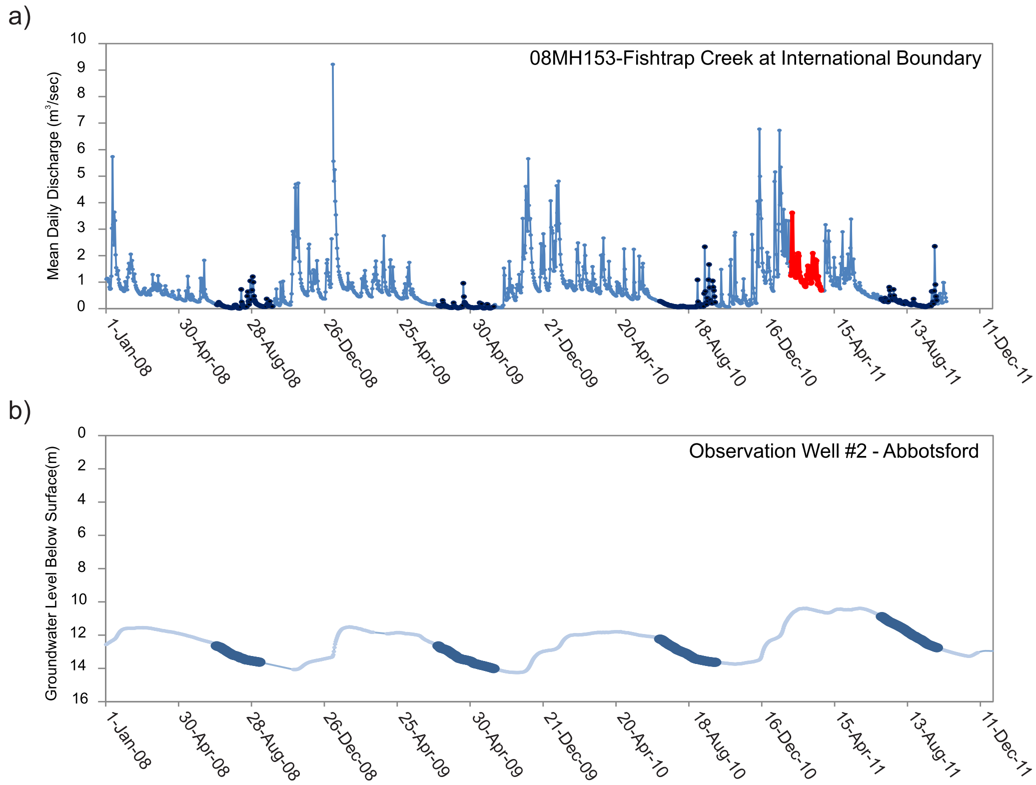

Figure 5. (a) Mean daily stream discharge for Fishtrap Creek and International Boundary for 2008–2011. Data from Water Survey of Canada Station 08MH153. The summer periods are emphasized by darker symbols. Periods of estimated data are indicated in red. (b) Mean daily groundwater levels for the period of January 2008 to December 2011. The heavy line sections indicate the summer periods (data from BC Ministry of Environment Observation Well #2).

Component 1 was most strongly correlated with the estimated sediment-water interface temperature measured over that particular summer. Correlation values were >0.1 (considered significant). The patterns for components 2 and 3 differed between the summers.

As an example, Figure 9 shows the ICA components for 2008, with the various cross-correlation results. The top row is the plot of the time series for each variable, with the cross correlations with each ICA component signal shown below. The mean sediment-water interface temperature and the ICA components are shown in the left column, followed by correlations with the estimated 1 day lagged estimated sediment-water interface temperature in the second column. The third and fourth columns show the cross correlations with discharge (unsmoothed discharge, then smoothed with a 2 day moving average). The final column shows cross correlation with the groundwater level. For completeness, the cross-correlation results are shown for 2009, 2010, and 2011, in supporting information Figures S1–S3.

Because climate conditions varied from summer to summer, there are 12 unique ICA components; 3 in each of the 4 summer periods. Visual comparison of these components in Figure 9 (for 2008) and the additional figures in the supporting information (for 2009–2011), demonstrates the variability between the years (discussed later). Table 1 provides a summary of the results of the cross-correlation tests for each of the summer periods. Correlations were considered significant when they were both greater than 0.1 and exceeded the calculated statistical significance values on the cross-correlation plot. In Table 1, components are listed in order of strongest correlation (e.g., in 2009 groundwater level correlates strongly with component 2 and to a lesser degree with component 1).

5. Discussion

ICA differs from the analytical approaches that are classically used to examine stream temperatures. Those approaches consider the source signals and relevant noise and bias components (air temperature,

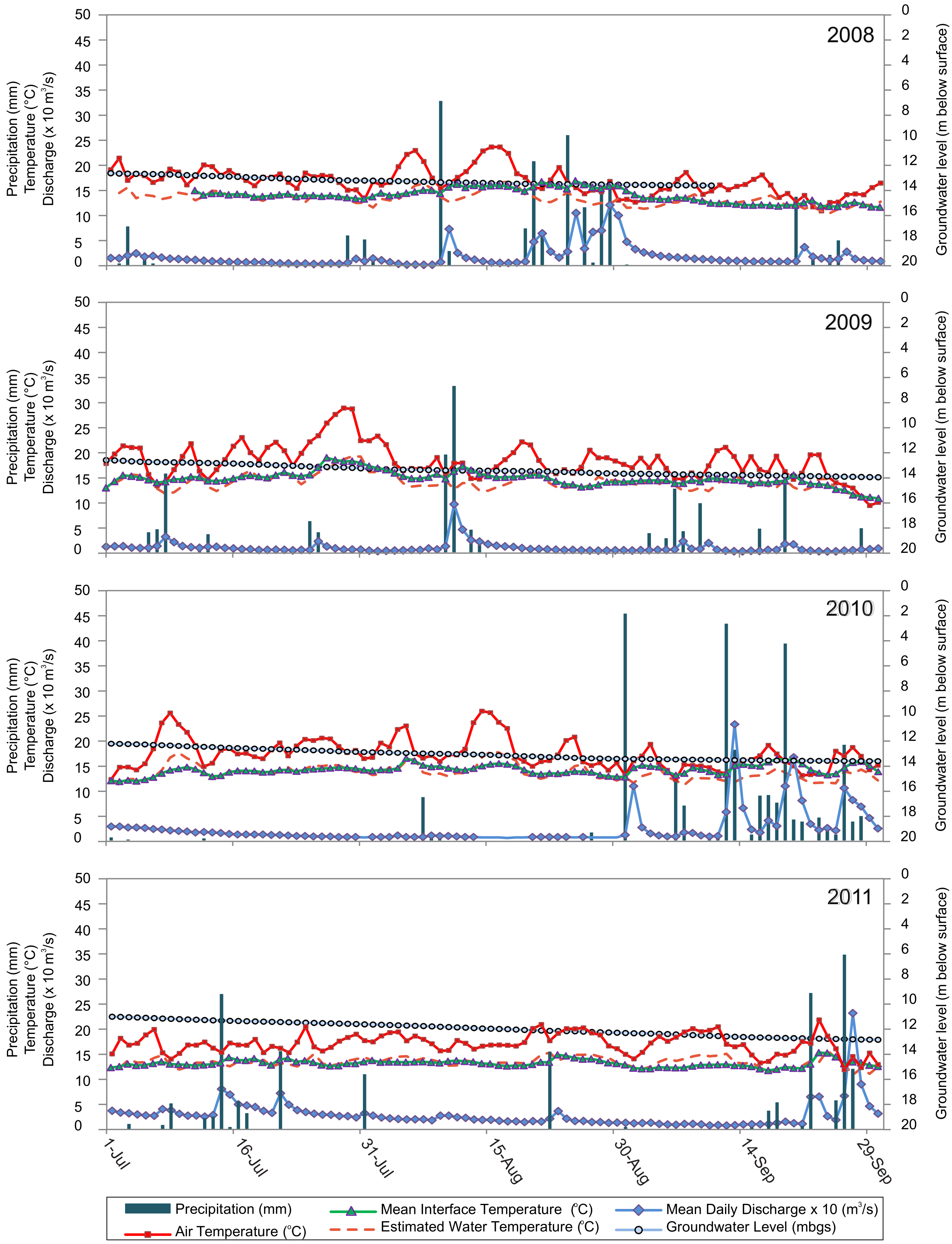

Figure 6. Daily air temperatures, estimated sediment-water interface temperatures, mean daily sediment-water interface temperatures, daily precipitation, stream discharge (all on primary *y* axis), and groundwater levels (secondary *y* axis) for the summer periods of 2008–2011. The estimated sediment-water interface temperatures were calculated using equation (2).

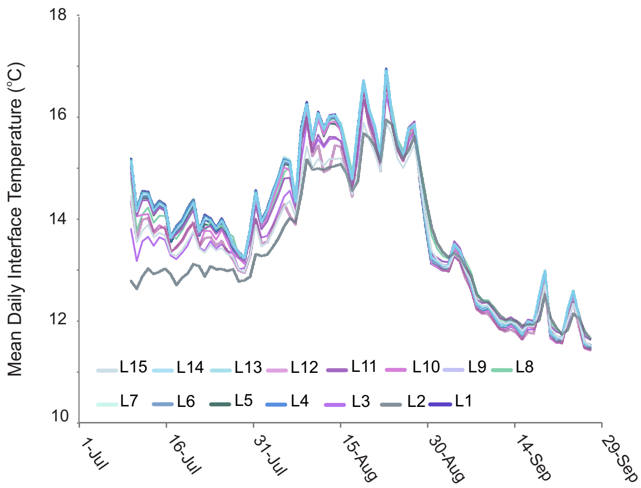

Figure 7. The 15 observed daily mean temperatures at the sediment-water interface for 2008. L.1 to L.15 relate to the site locations shown in Figure 2.

water temperature, groundwater temperature, noise, and sensor drift). We do not consider these components directly. Rather, using ICA, we extracted independent signals from the observed time series and correlated those signals to variables that can influence sediment-water interface temperature through inputs to the heat budget over the distance of the stream reach. These variables include the solar radiation, represented by the estimated sediment-water interface temperature; the heat of the incoming streamflow, changes to which are represented by the stream discharge; heat transfer due to groundwater whereby changes in the groundwater levels reflect the potential of the groundwater to contribute to the streamflow and thus influence the sediment-water interface temperature.

To interpret the ICA and cross-correlation results, Table 2 summarizes the climate and hydrological processes in each summer that are captured across the top row in Figure 9 (supporting information Figures S1–S3). The table ranks each parameter (where [1] is highest and [4] is lowest) and provides generalized comments about responses.

The estimated sediment-water interface temperature varied each summer. In all summers except 2010, component 1 was strongly correlated with estimated interface temperature. This suggests that surface heating from solar radiation is the dominant factor influencing the sediment-water interface temperature in most years. In summer 2008, however, there was a negative lag of 1 day in the correlation between the ICA component and the estimated sediment-water interface temperature (Figure 9). The negative lag in the temperature correlation suggests that in the cool periods, such as in 2008, the 1 day calculated lag for thermal energy transfer from solar radiation may be an over estimation of the lag. In the other summer periods, the correlation with estimated sediment-water interface temperature was at zero lag time, indicating that the 1 day calculated lag was representative of the heat transfer rate.

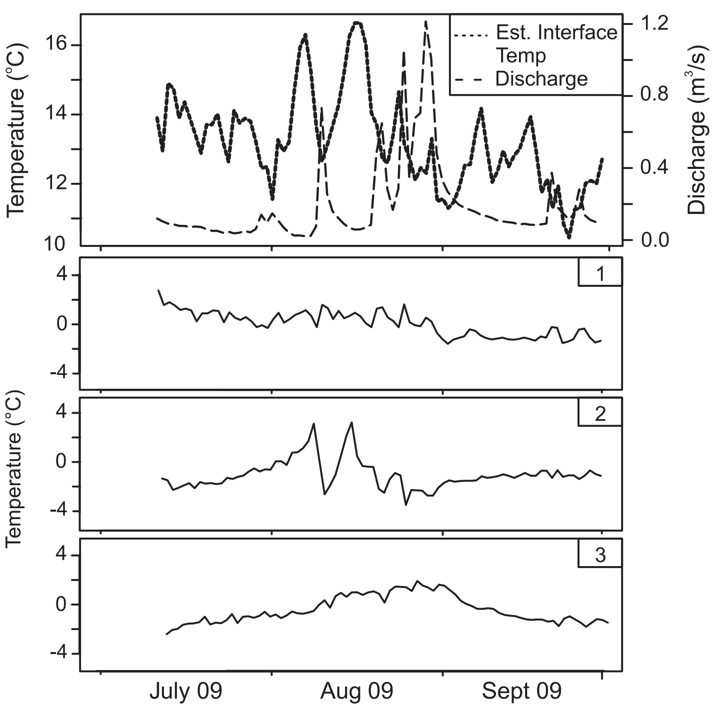

Figure 8. The three ICA components (1–3) extracted for summer 2008. The estimated sediment-water interface temperature and stream discharge are included at the top for comparison. The units for all ICA components are °C.

Stream discharge differed between the four summers, as might be expected due to variations in

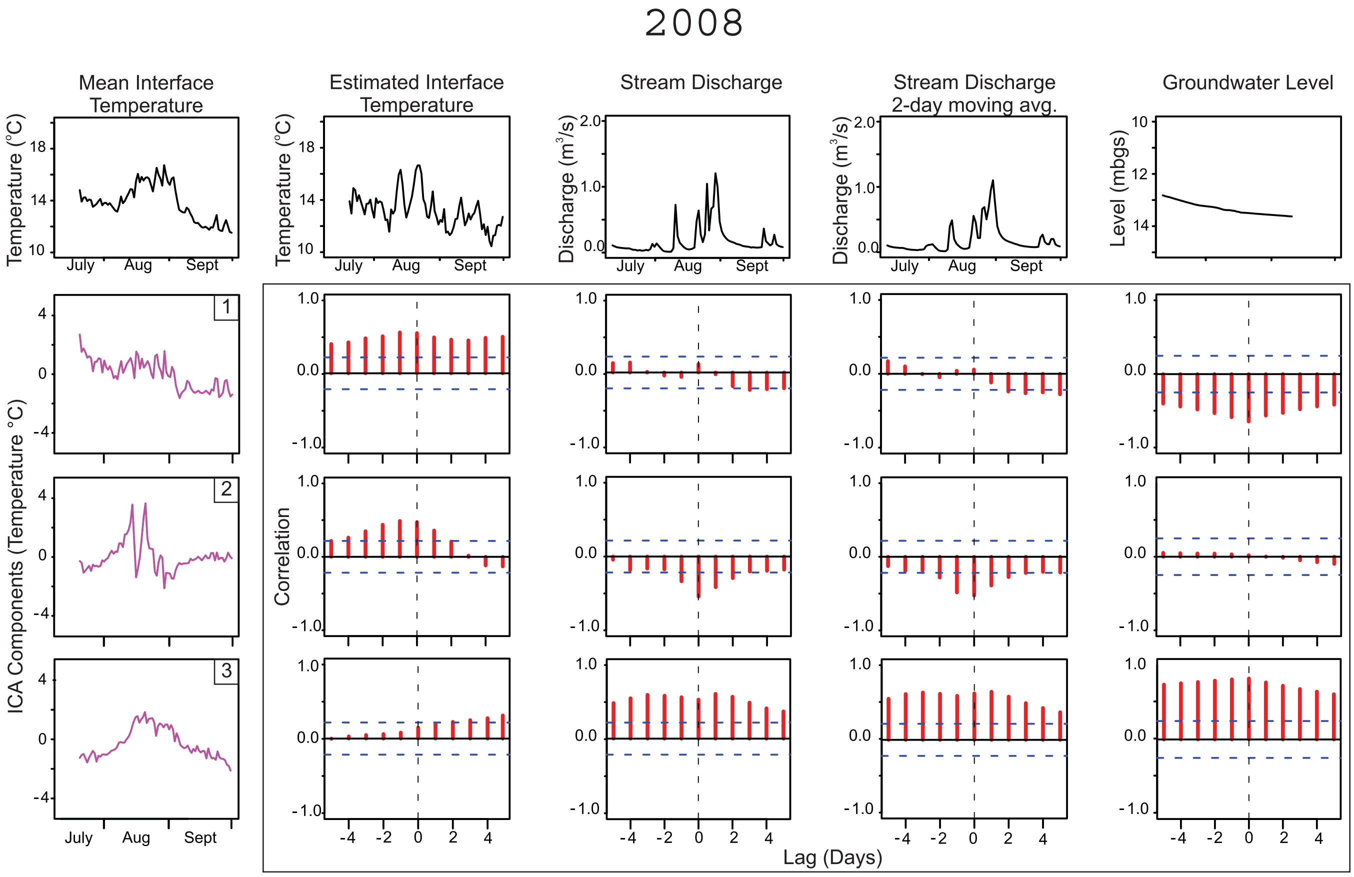

Figure 9. Results for summer 2008 of the ICA components and the cross correlation with the variables contributing to the heat exchanges. The extracted ICA components are shown in the left figure (pink) below the mean stream temperature recorded by the data loggers at the sediment-water interface. The cross correlations for each ICA component are shown in red, with the correlated variable shown in the top row of each column. The horizontal dashed lines in the correlation plots mark the 0.1 correlation value, above which the correlations were considered significant.

precipitation. However, no consistent patterns emerged when comparing the cross-correlation results between summers. In contrast, there is a distinct decline in local groundwater levels each summer, although the amount of decline varied between the summers. This indicates that groundwater is discharging and contributing to the surface flow but that the magnitude of groundwater discharge decreases over the summer and is variable between summers. The groundwater may contribute a diffuse influence on the sediment-water interface temperature distributed along the stream channel, or groundwater influxes may be localized, particularly when hyporheic flows are present due to variations in bed and reach morphology, among other factors. However, because all the loggers were combined in this study (i.e., ICA was run for all available loggers each year), the diffuse or localized nature of the groundwater contribution could not be distinguished. A spatial analysis using the ICA method, comparing signals among data loggers situated at different locations, may provide greater insight into the spatial variability of groundwater influxes.

In each of the four summer periods, the ICA components correlate to at least one of the three heat contributing variables (Table 1). In most years, however, more than one component correlated with a particular heat contributing variable. While independence of the variables is an assumption of ICA, these results suggest that the variables influencing the sediment-water interface temperatures are not entirely independent. The correlation of the components (Table 1) is related to the trends in the variables listed in Table 2. In cool wet years, such as 2008, the stream temperatures are lower, while the discharge and groundwater levels are higher. In summer 2008, three components correlated to multiple variables (Table 1), indicating that when variations in groundwater levels are low, the variations in the temperature signals and groundwater contributions are more difficult to separate. In 2009, the streamflow and groundwater levels were among the lowest of the summer periods, the air and stream temperatures reached their highest values. In 2009, fewer components were correlated

Table 1. A Summary of the ICA Components and the Correlations With Predictor Variables[a]

Summer	Estimated Sediment-Water Interface Temperature	Discharge (Unsmoothed)	Discharge (2 Day Moving Average)	Groundwater Level
2008	**1, 2**	**2, 3**	**3, 2**	**3, 1**
2009	1	3	3	2, 1
2010	3, 2, 1	1	1	1, 2, 3
2011	1	2, 1	2, 1	2, 3

[a]The table lists the ICA component number (1–3). Each component correlates with one or more of the variables listed in the top row. The results for 2008 are given in bold for comparison with Figure 9. Correlations were considered significant when they were both greater than 0.1 and exceeded the calculated statistical significance values on the cross-correlation plot. Components are listed in order of strongest correlation.

to more than one variable (Table 1). Summer 2010 had moderate rankings in all variables, but had the highest precipitation, which occurred mainly in September resulting in the higher streamflows. The mean sediment-water interface temperature in 2010 also had the highest range of values. The components also correlated with a mix of variables in 2010, with only component 1 correlating with discharge, but all components correlating with estimated sediment-water interface temperature and groundwater level. In 2011, the stream discharge and groundwater levels were high, and the air and stream temperatures were low. The lowest range in stream temperature occurred in 2011. One component signal (component 2) in 2011 correlated to both discharge and groundwater levels (Table 1), indicating that variation in temperature contributions from these variables are more difficult to separate when they are both high.

Overall, in all summers, the extracted components were correlated with more than one variable. However, in summers with lower stream discharge and greater stream temperature ranges, the contributing variables were more easily separated. This inability to completely separate the components and relate them to specific variables is no doubt a product of the fact that the variables we considered might be nonlinear combinations (e.g., the interaction between air temperature and streamflow). Cloudy conditions affect air temperature, increase the probability of precipitation, and subsequently discharge and groundwater level. We suspect that the separations in Table 1 reflect this complex interrelationship. Thus, ICA has limitations in natural settings where, for example, climate influences multiple processes and interactions between processes exist.

Table 2. Overview of the Climate and Hydrological Observations Over the Four Year Period[a]

Summer	Mean/Max Air Temperature (°C)	Mean/Range Sediment-Water Interface Temperature (°C)	Total Precipitation (mm)	Median Discharge (m^3/s)	Max/Range Groundwater Level/(m)
2008	16.8 [4]/23.6 [3]	13.8 [3]/5.2 [2]	186 [2] Most in August	0.11 [2] Discharge punctuated with several moderately high discharge events from late July to mid-August that persisted for several days	13.6 [3]/1.0 [4] Declined throughout the summer
2009	18.1 [1]/28.8 [1]	14.6 [4]/8.1 [1]	155 [4]	0.05 [4] In late-July, there was a high discharge period which lasted approximately 4 days with maximum mean daily flow up to 1.0 m^3/s	14.0 [1]/1.4[3] Declined throughout the summer
2010	17.3 [2]/25.9 [2]	14.1 [2]/4.7 [3]	252 [1] Most in September	0.1 [3] Rain events corresponded to the periods of high discharge from mid-August to September	13.6 [2]/1.4 [2] Declined from July to August with little variation in September
2011	17.3 [3]/22.1[4] [1]	13.3 [4]/3.6 [4]	182 [3] Rainfall events were mainly in early July and late September	0.2 [1] Very few high discharge events from mid-July to mid-September. Discharge remained high throughout the summer period relative to the previous summers	12.8 [4]/1.9 [1] Declined throughout the summer

[a]Rank is shown in "[]" with [1] the highest and [4] the lowest.

Nevertheless, some broad observations can be made based on the ICA results, which enhance our understanding of the system. Specifically, thermal exchanges appear to be taking place in addition to the air-water interface. These exchanges also take place at the sediment-water interface, and the correlation with groundwater levels indicates these heat exchanges are associated with groundwater inflow. The results are not surprising given that Fishtrap Creek has been described as a groundwater-fed stream [*Berg and Allen*, 2007]. This study provides stronger evidence that in some years (e.g., 2009) the sediment-water interface temperature is highly influenced by groundwater inflows across the site. Based on the spatial variability of the component signals (results not shown), the locations of groundwater inflow are variably distributed across this site, indicating that this reach is influenced by a combination of focused and diffuse groundwater discharge.

Other studies have similarly reported temporal variability of groundwater inflows [e.g., *Constantz*, 1998; *Wroblicky et al*., 1998; *Keery et al*., 2007]. The inflow of groundwater to streams was reported in these studies to be a complex process, with scale-dependent variability occurring both spatially and temporally. Temporally, variability can range from diurnal to interannual as shown in this study. Here we have demonstrated the use of ICA in blind separation of mixed signals from temperature loggers at the sediment-water interface and assessed how those component signals can be used to identify important heat transfer processes. While there were some ambiguities in the extracted signals, likely due to nonindependence of the temperature signal components, the use of cross correlation helped to reduce these ambiguities. Without cross correlation, it was challenging to associate a particular extracted component with a particular variable, with the exception of the estimated sediment-water interface temperature, which was both visually similar to component 1 and often had a high correlation with it in most years.

The value of ICA is that temperature signals from multiple data loggers can be evaluated against known, or suspected, variables. A priori knowledge of these variables (here estimated sediment-water interface temperature, stream discharge, and groundwater level) helped to determine the number of components for extraction. In previous iterations of this work, we used ICA somewhat blindly, and extracted several components. Through experimentation, we ultimately settled on three to reflect the dominant processes at the site. Other studies may benefit from this approach, but a reasonable conceptual model of the site is warranted in order to focus the analysis.

Finally, as mentioned above, other applications of ICA in the hydrological sciences should be explored. In particular, given the presence of multidimensional flows such as those due to hyporheic flows, and the high degree of spatial heterogeneity in streambed and aquifer hydraulic properties that may influence the temperatures (and fluxes), a spatial analysis using ICA may prove particularly useful at some sites.

6. Conclusions

The study focused on the summer period of July to September, when streamflow in the studied coastal stream is low and the relative contribution of groundwater to streamflow is often the highest for the year. Sediment-water interface temperatures in this small 40 m reach of Fishtrap Creek are controlled by multiple processes. The dominant process is the transfer of thermal energy from the atmosphere to the stream and then to the streambed in each of the four summers. Stream discharge and groundwater contributions influence the observed sediment-water interface temperatures and their importance varied between the four summers reported here. The contributions of these processes are complex, varying between and within the summer periods. It is demonstrated that components of observed sediment-water interface temperatures extracted using ICA can be used to interpret information from multiple sediment-water interface temperature sensors.

The timing and magnitude of discharge in the summer periods as well as annual groundwater levels are important factors in the distribution of the temperature components across the stream reach. Separation of the temperature components is more apparent during summers with lower flows, and greater stream temperature ranges. While solar radiation is the dominant thermal contribution to the reach, observed sediment-water interface temperatures are modified by streamflow variations and groundwater inputs.

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