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AIRBORNE THERMAL INFRARED REMOTE SENSING OF STREAM AND RIPARIAN TEMPERATURES IN THE NICOLA RIVER WATERSHED, BRITISH COLUMBIA, CANADA

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Airborne thermal remotely sensed images of riparian and water surface temperatures were acquired at 12 sites in the Nicola River watershed of south-central British Columbia, Canada, using a forward-looking infrared (FLIR) camera. Ground-truth observations to correlate radiant (T_r) versus kinetic (T_k) water temperatures were performed at 3 sites and showed an accuracy of ±0.4°C. Landscape and water thermograms obtained at 3 representative sites in the study area were analyzed and revealed apparent thermal landscape-water interactions contributing to the observed spatial heterogeneity in stream temperatures. However, a critical analysis of remotely sensed stream heating patterns revealed that approximated solar energy inputs and conduction from adjacent streambanks and the atmosphere could only account for ca. 0.5% of the apparent required heat influx in some locations, suggesting imaging interference by emissive radiation from the exposed land surfaces. Pixel mixing of land and water surface temperatures was also found to be a potential interferant in narrow braided channels with widths near the resolution of the camera (0.15-0.5 m). The utility of the method for assessing mixing in and between riverine systems was also shown. Overall, aerial remote sensing of stream and riparian surface temperatures appears to be a promising technology for assessing spatial heterogeneity, and may be useful in conjunction with conventional in-stream methods as part of a hybrid spatial-temporal observing system for aquatic management, provided further work is performed to validate observed temperatures near exposed streambanks, in vegetation shadows, and other areas where emissive interference may be problematic.

INTRODUCTION

Stream temperature is an important parameter in aquatic management (Poole and Berman, 2001). High water temperatures impact in-stream habitat by surpassing temperature thresholds for biota. Natural and anthropogenic factors can influence stream temperature, including relative contributions from groundwater, lentic and lotic headwaters, shading by riparian vegetation, tributary inflows, and air temperature, among others (Allen, 1995). Thus, obtaining high quality stream temperature data is important, yet it is difficult to design and install in-stream measurement methods that capture spatial and temporal temperature patterns at a desired scale. As well, obtaining large numbers of in-stream data points over a length of the stream system becomes both expensive and time-consuming. Furthermore, understanding thermal linkages between stream and riparian landscapes is difficult using on-the-ground methods of temperature measurement because the inherent wide variation in landscape temperature prohibits acquiring sufficient data points for a meaningful assessment where the contributing riparian area in the watershed may exceed hundreds of square kilometers. To help address these limitations, remote sensing methods were developed, and in addition to temperature, several other water properties of riverine environments have been remotely sensed, including water surface elevation, discharge, inundation boundaries, ice properties, and water quality (Mertes, 2002). Remote thermal imaging offers the potential to record spatial patterns of stream temperature at different scales over a complete watershed or a short stream reach. As such, it is a valuable tool to help augment the design and interpretation of on-the-ground methods. And yet, while remote thermal imaging of marine and lacustrine environments has been in use for some time (Lillesand, 2004), relatively few published studies have used remote sensing to investigate stream temperature regimes (Belknap and Naiman, 1998; Torgersen et al., 2001; Torgersen et al., 1999).

A distinct feature of aerial thermal remote sensing is the ability to simultaneously map both stream and riparian landscape temperatures. The expense to do this using on-the-ground methods at a resolution necessary for a comprehensive understanding of thermal regimes is prohibitive. Hence, when attempting to model stream temperatures as a function of other landscape and site specific factors, single data points in a stream reach are often used with the assumption that temperatures are relatively uniform with depth and width. When there is variation in stream temperature at small scales, however, single data points are often not representative of the local region. This may help to explain the current difficulties in generating rigorous site-specific models of stream temperatures without excessive scatter compromising the predictive abilities. In contrast, aerial thermal remote sensing offers the opportunity to measure surface temperatures at scales sufficient to provide significant advances in our understanding of thermal processes within watersheds, and to subsequently apply the knowledge to further aquatic management. To help demonstrate the utility and drawbacks of aerial remote sensing for stream and riparian landscape temperatures, we present a critical analysis of some exploratory thermal imaging results in the Nicola River watershed of British Columbia, Canada (Figure 1).

METHODS

Thermal imaging of the Nicola and Coldwater Rivers in the mountainous southern interior of British Columbia, Canada, was carried out by helicopter on July 3, 2001 from approximately 2:30 pm to 3:45 pm (including shuttle time) as part of a larger study into the natural and management factors influencing stream temperature regimes in the Nicola River watershed between 1999 and 2002 (Henderson, 2001b, 2003; Henderson et al., 2004). The timing of the airborne survey was designed to capture maximum daily stream temperatures. At the time of the flight, the sky was clear

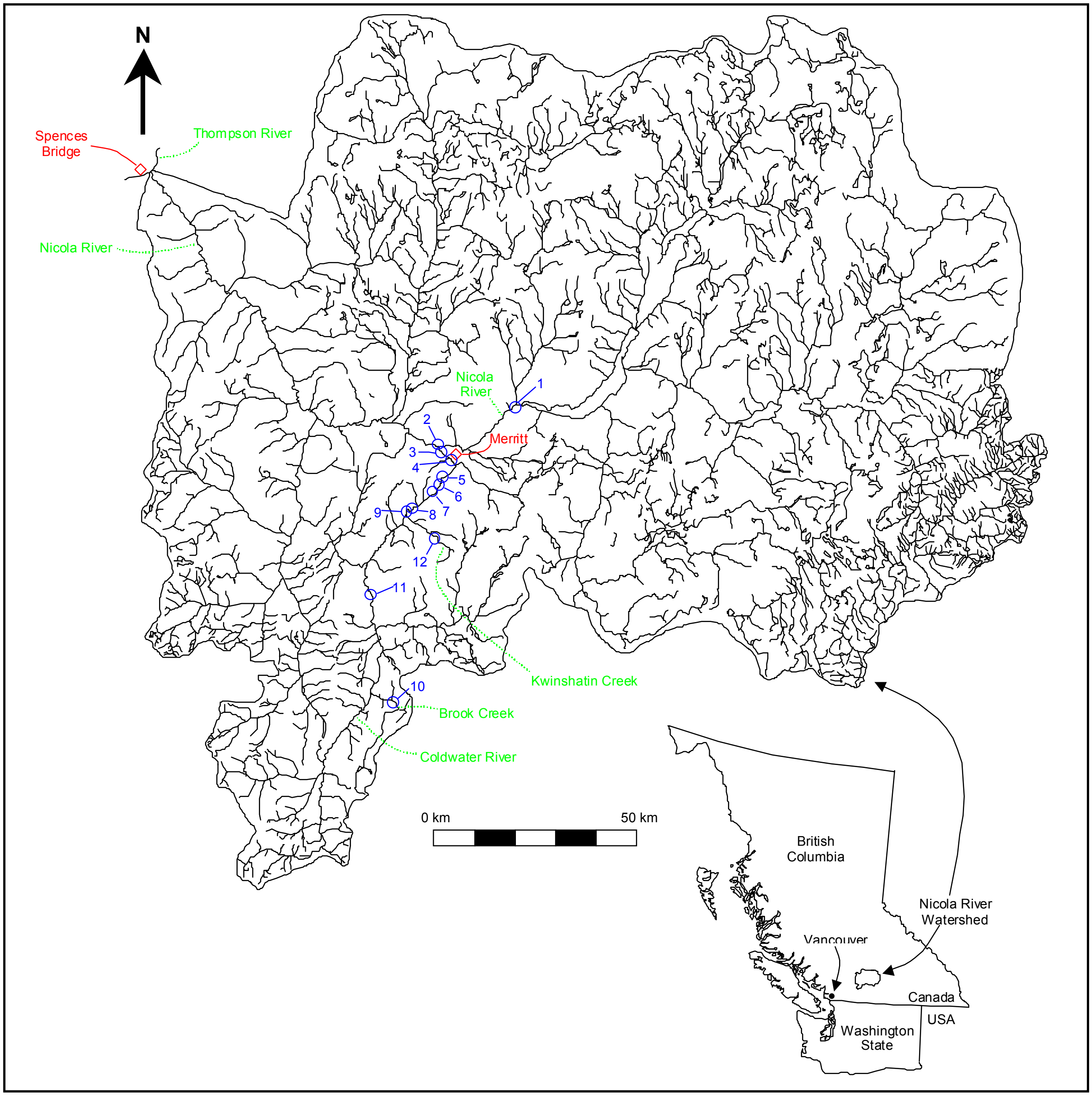

Figure 1. Map of the study area showing locations of aerial remote sensing sites.

and the regional air temperature was 32.0ºC. The Bell Jet Ranger helicopter was equipped with an on-board GPS system and below-mounted camera that recorded continuous color video and audio along with latitude and longitude. Radiant temperatures (T_r) from stream and riparian landscape surfaces were recorded using a ThermaCAM PM 695 camera (FLIR Systems, Inc.; Portland, OR, USA). High definition 14-bit thermal images were simultaneously recorded with visual images captured by the PM 695 visual camera. The PM 695 has a spatial resolution of 1.3 mrad with a focal plane array uncooled microbolometer 320x240 pixel detector, a spectral range of 7.5-13 µm, a thermal sensitivity of 0.08°C, and real-time 60 Hz imaging. Atmospheric transmission correction on the PM 695 is automatic and based on inputs for distance, atmospheric temperature, and relative humidity. Optics transmission correction is also automatic, based on signals from internal sensors. Automatic emissivity correction is variable from 0.1 to 1.0 or can be selected from listings in a pre-defined materials list. Instrumental accuracy is reported by the manufacturer to be ±2°C.

Thermal images were taken at 12 sites along the Nicola River starting at the confluence with the Coldwater River and moving upstream the Coldwater River to Brook Creek (Figure 1). Images were stored on a PC card and later removed to download information for viewing and processing. During image acquisition, the camera was hand-held, positioned downward ca. 30º above the nadir at the forward passenger side of the helicopter with the door removed to facilitate filming. Helicopter speed ranged from 40 to 80 km·h^{-1} at an altitude of 100 m to 300 m above ground level (AGL) depending on the wetted width of the channel, topography, wind, and flying restrictions. At this elevation range, the thermal and visible cameras captured a 24°x18° field of view with dimensions ranging from ca. 50x40 m to ca. 150x120 m, giving ground resolutions (pixel sizes) of ca. 0.15-0.50 m.

The ThermaCAM PM 695 camera created a series of near-simultaneous still thermal and visible-band digital images at each site. Imaging attempted to capture both the width of the Nicola or Coldwater Rivers as well as a significant portion of the riparian areas on either side of the channels. Thermal and digital images were offset by approximately 5 seconds of time (required to switch image type) and by several lineal meters of distance depending on wind and helicopter hovering factors. The still images were referenced to the ground using a combination of GPS coordinates and easily identifiable reference points such as bridges, roads and confluences of streams. GPS coordinates were approximate because the camera was aimed ca. 30º above the nadir of the helicopter. Using 100 m to 300 m hovering elevations above ground surface, the forward camera angle resulted in a ground location approximately 60 m to 180 m ahead of the helicopter. GPS data were not adjusted to an actual ground location in this exploratory flight. Thermal images were transformed into Adobe Acrobat (PDF extension) files for examination and subsequent analysis.

Two sets of landscape and water thermogram images were created for each of the 12 sites plus a visible-band digital image. Thermal imagery was color-coded to visually enhance temperature differences and facilitate interpretation of thermal patterns. For the landscape thermograms, the apparent temperature ranges were from 10ºC to >50ºC depending on site characteristics. The color scale of the water thermogram images were adjusted to lower temperature ranges to emphasize variation across the water surface. Additional details on image collection and processing methods, as well as paired landscape and water thermograms for each of the 12 sites, are available in a report published elsewhere (Henderson, 2001a), or by contacting the report's author (ghenderson@telus.net). Ground-truth measurements were collected simultaneously with thermal overflights at the following three sites to compare the kinetic water temperatures measured in-stream (T_k) to the radiant temperatures (T_r) recorded in the remotely sensed imagery: (1) near the mouth of the Coldwater River (site 3) where T_k=21.1°C and T_r=20.7°C; (2) at Brook Creek (site 10) where T_k=13.0°C and T_r=12.7°C; and (3) at Kwinshatin Creek (site 12) where T_k=10.1°C and T_r=10.1°C.

RESULTS AND DISCUSSION

Airborne thermal infrared remotely sensed images of riparian and water surface temperatures were acquired at 12 sites in the Nicola River watershed of south-central British Columbia, Canada. Ground-truth observations to correlate radiant (T_r) versus kinetic (T_k) water temperatures were performed at the thalweg of 3 sites and showed an accuracy of ≤0.4°C, within the range of similar accuracies (±0.5°C) for this type of method reported elsewhere (Torgersen et al., 2001; Watershed Sciences LLC, 2002). Landscape and water thermograms measuring T_r at 3 representative sites in the study area are discussed below to critically examine both the utility and drawbacks of airborne thermal infrared remote sensing.

The utility of airborne thermal infrared remote sensing of stream and riparian temperatures resides in its contribution to regional-scale assessments of aquatic thermal regimes. Both spatial and temporal stream temperatures must be characterized for a more complete understanding, and a hybrid approach can be undertaken whereby remotely sensed temperatures are used to document spatial patterns, while continuously recording thermometers document temporal patterns . However, there are several major technical issues that must be addressed or considered when using remotely sensed stream and riparian landscape temperatures. The relationship (ideally, the equality) between T_r and T_k should be known (see below), and what hydraulic and/or meteorological conditions influence this relationship and in the manner they do so. Additionally, images are obtained with finite pixel sizes, and methods for determining how much of each pixel is land or water, and how to “unmix” the thermal radiance of these pixels, should be developed (Burges et al., 2004; Naveh et al., 2004).

At the Nicola River site between Nicola Lake and the confluence with the Coldwater River (site 1), landscape-stream thermal interactions arising from a lack of riparian overstory and a subsequently exposed point bar in the upper right appear to be evident (Figure 2). Stream flow at this site is from upper right to lower left. In the landscape thermogram, surficial temperatures on the point bar range from ca. 40ºC to >50ºC, with a maximum surface temperature of 56.7ºC that is ca. 25ºC higher than the ambient air temperature of 32.0ºC. The water thermogram (Figure 2(b)) suggests the accumulated thermal energy of the point bar (and the exposed opposite bank) being efficiently transferred to the

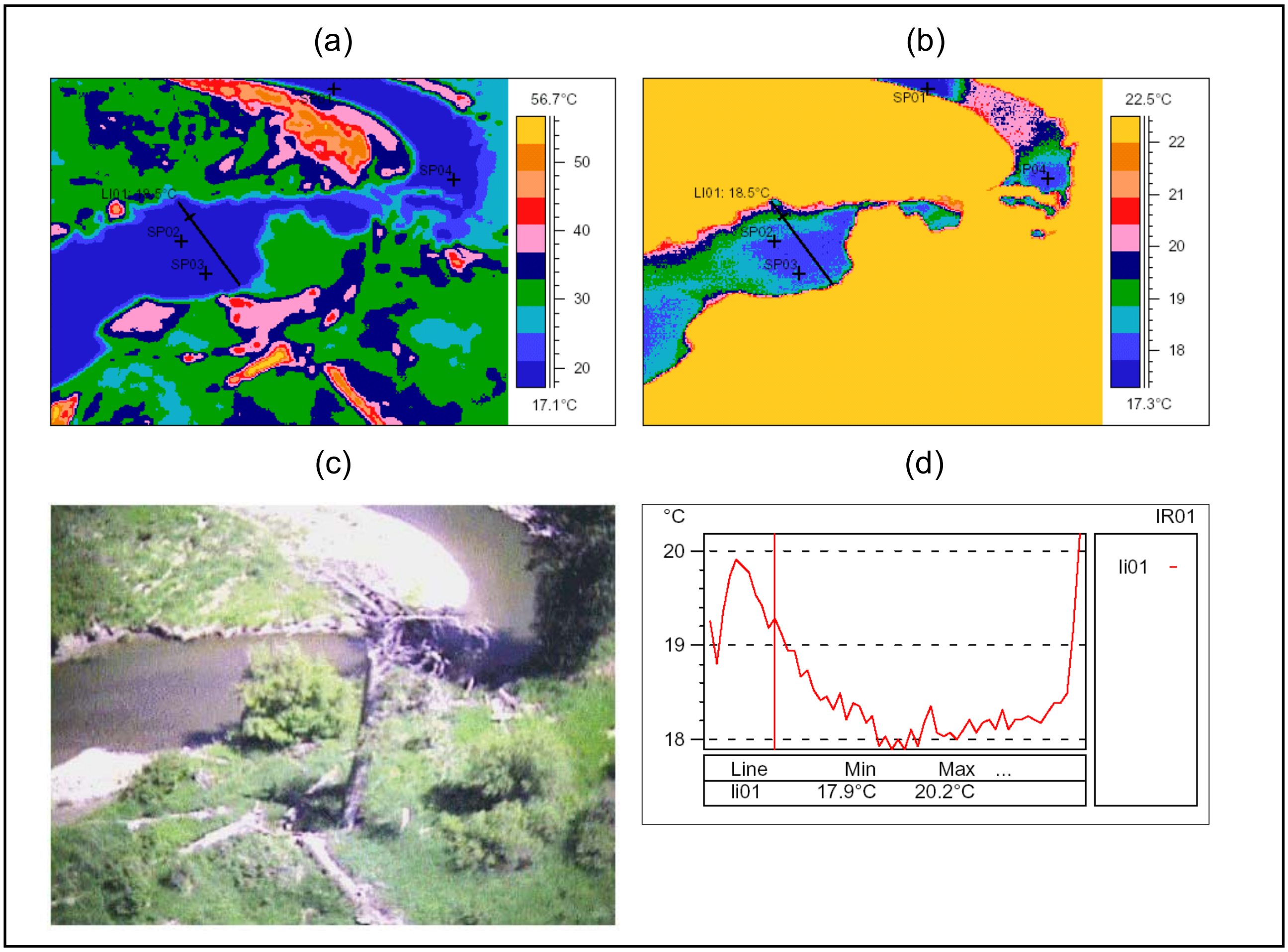

Figure 2. (a) Landscape thermogram, (b) water thermogram, (c) location photograph, and (d) a stream temperature cross-section (along line “li01” in Figures 2(a) and (b)) of the Nicola River between Nicola Lake and the confluence with the Coldwater River (site 1).

water edge and across the stream width, as shown by the relative uniformity of remotely sensed cross-sectional stream temperature (ca. 20°C) at this location. The efficiency of heat transfer perpendicular to stream flow would be increased because stream velocities are generally lowest immediately next to the stream banks and thus facilitate increased heat transport from the land surface to the stream. Because stream velocities are even more reduced on the inside curve of a meander, heat transfer is further enhanced. That transverse heat conduction from the exposed point bar may explain the localized heating is suggested by the parabolic temperature contours immediately downstream of point SP01. A finite time is required for heat to be conducted across the stream, and thus there is a "lag distance" between downstream heating nearshore and at the thalweg. Similarly, stream temperatures appear to cool less rapidly adjacent to the exposed banks downstream of this reach versus the cooling observed at the thalweg, as is evident from the parabolic temperatures near the downstream limit of the exposed point bar.

Of note is the minimum stream temperature of 17.1ºC located at point SP01, ca. 5-15 m (and ca. 10-30 s of flow time assuming an average stream velocity of 0.5 $m \cdot s^{-1}$) upstream of the ca. 20°C stream temperature opposite the point bar. Heating of the water column by ca. 0.2-0.6$^{\circ}C \cdot m^{-1}$ and ca. 0.1-0.3$^{\circ}C \cdot s^{-1}$ lineal travel distance appears to be occurring within the stream. This apparent temperature increase due to the point bar is detectable using the combined visuals of the two thermograms but would likely be overlooked using in-stream monitoring methods because dataloggers are generally not situated in such shallow regions. Such thermal landscape-stream connections and resultant stream heating profiles are important as they may negatively impact resident and migrating fish populations and provide a thermal barrier to upstream movement. One must also note that the elevated stream temperature next to the point bar appears to be transient and does not have a lasting downstream influence, analogous to a similar apparent water-landscape thermal connection at a downstream exposed point bar in the middle left of the image.

Torgersen et al. (2001) have discussed the relationship between radiant water temperatures emitted from the upper 0.1 mm of the water surface (T_r) and kinetic water temperatures measured 10 cm below the water surface with a thermometer (T_k). Where the water column is sufficiently mixed such that thermal gradients at this scale are absent, T_r is a suitable surrogate for T_k. Our ground truthings demonstrated a ≤0.4°C error between T_r and T_k at the thalwegs of three sites; however, the relatively wide spatial heterogeneity in stream temperature observed at site 1 requires a more critical examination of this accuracy and whether it holds at a finer scale and in shallow regions adjacent to exposed streambanks. As noted elsewhere, one of the potential errors in processing remotely sensed infrared images is the failure to account for all sources of infrared radiation, including (1) emitted radiation from the water, (2) reflected radiation from the water, and (3) ambient sources of filtered radiation in the atmosphere and surrounding landscape scattering into the camera (Larson et al., 2002). Previous work has also suggested that remotely sensed cooling rates of ca. 0.1-1$^{\circ}C \cdot m^{-1}$ must reflect an error in data collection because of the inability to account for such heat transfer using simple thermodynamic models (Larson et al., 2002, 2003), although other researchers have noted that a more complex thermal balance is necessary before such data should be discarded (Beschta et al., 2003).

Taking a unit control mass of the water column (1 kg), heating this sample by 3°C would require 12 570 J of net energy input. Neglecting energy losses (e.g. reflection, evaporation, etc.) over the short (5-15 m) reach in Figure 2 immediately downstream of SP01, solar inputs and conduction from the substrate and atmosphere were considered in a rudimentary thermal accounting. The relevant equations and values for physical constants used in these calculations are given elsewhere (Beschta et al., 2003; Larson et al., 2002). Assuming the entire net solar radiation of ca. 1 000 $J \cdot s^{-1} \cdot m^{-2}$ is absorbed within the ca. 0.5 m deep control mass flowing at a velocity of ca. 0.5 $m \cdot s^{-1}$ with a surface area of $2x10^{-3}$ m^2 immediately downstream of point SP01 in Figure 2(b), only 60 J of heat would enter the control mass within 30 s. Heat conduction from the atmosphere (at 32°C) would contribute ca. 0.02 J, while heat conduction from the substrate (assumed to be at 58°C, the maximum point bar temperature, to give an upper limit to the transfer) adds only 1.2 J. As Larson et al. (2002) have previously noted, in some cases, remotely sensed temperature changes exceed known net heat inputs or outputs by up to several orders of magnitude, as we observe here where the combination of solar and conductive inputs only provides ca. 0.5% of the heat require to explain the observed thermal patterns. We must note that our observed patterns are not unusual; other groups have reported similar cooling and heating rates that – in retrospect – cannot likely be explained by a simple thermodynamic analysis. Pixel mixing between land and water surfaces cannot also explain the temperature patterns, as the image resolution (0.15-0.5 m) is sufficient to distinguish between the different surfaces in this reach. Given our inability to account for even a minor portion of the heat input required to explain the observed temperature patterns in this stream segment, and the critical work of Larson et al. (2002), a more thorough investigation is required by our group and others into the reliability of remotely sensed stream temperatures in reaches potentially susceptible to other thermal interferences such as reflective emissions from nearby exposed land surfaces.

Similar apparent stream heating effects were observed in an aggraded and braided reach of the Coldwater River at site 6 (Figure 3). Such channel forms may occur in this region both naturally and from anthropogenic influences such as water abstractions for irrigation or a variety of riparian management activities including farming, forestry, and construction. The main flow system (from right to left) at site 6 is dispersed into numerous smaller and shallower channels creating an apparent micro-scape of stream temperatures that range from 20.2°C at SP01 to 24.9°C at SP03. Exposed mid-stream gravel bars heat to ca. 60ºC (the maximum land surface temperature in Figure 3 was 59.4ºC, 27ºC warmer than the ambient air temperature of 32.0ºC). Water temperatures appear to range from ca. 23ºC up to 27.0ºC (e.g. points SP02, SP03, and SP04) in the braided channels compared to stream temperatures of ca. 21ºC in the unbraided mainstem (e.g. points SP01, SP05, SP06, and SP07). These temperatures could have detrimental effects on aquatic biota as stream temperatures above 26°C approach lethal limits for salmonids (Sullivan et al., 2000). However, the width of the braided channels (1-3 m) is near the resolution of the imaging method (0.15-0.5 m), and thus, pixel mixing between land and water surfaces may help to explain the observed heating patterns. As discussed above with regard to site 1, stream heating of this magnitude can generally not be explained by simple heat transfer models, and both radiative interference from adjacent exposed land surfaces and pixel mixing may disguise the true temperature patterns within these channels. The cooling effects of riparian vegetation are also readily observed at site 6 by the vegetated green and light blue regions lying perpendicular to the stream axis in the lower left of the landscape thermogram. Even when sparsely vegetated, these vegetated regions are as much as ca. 30ºC cooler than the otherwise exposed gravel banks. While similar emissive interferences may exist for remotely sensing land surface temperatures, it is unlikely these could result in errors of >20ºC. Hence, relatively small emissive interferences (i.e. ca. 2-3ºC) can be tolerated when mapping the wide temperature heterogeneity of land surfaces, but not for mapping the thermal fine structure of riverine systems. Overall, provided future validation of the thermal remote sensing method verifies such spatial temperature heterogeneity, aerial remote thermal sensing may offer a readily available tool to rapidly evaluate the effects of stream aggradation on water temperatures in difficult to access stream environments such as remote headwater regions and near private land.

A potential additional utility of remote sensing of stream temperatures is for assessing mixing in aquatic systems. Where the Nicola River enters the Coldwater River (site 2 and Figure 4), the cooler waters of the Nicola River at left do not fully mix with the warmer waters of the Coldwater River at right immediately after confluence. Rather, the two fluxes remain horizontally stratified for a significant distance downstream prior to fully mixing in a relatively uniform stream temperature. This horizontal stratification is common when two fluvial systems of differing physical and chemical properties combine, and can often be measured by optical properties (e.g. turbidity, albedo, etc.), pH, concentrations of major inorganic ions (e.g. Na^+, Cl^-), and other physico-chemical characteristics. As shown in Figure 4(c), the warmer waters of the Coldwater River are also more turbid with a brownish hue than the cooler waters of the Nicola River which are less turbid and have a greenish hue. In the mixing zone, the waters combine for a grayish hue of intermediate temperature. While in this confluence, the approximate degree of stratification between these two water bodies can be assessed in the visible spectrum under suitable lighting conditions, such is not always the case. In this regard, aerial thermal imaging of stream temperatures offers distinct advantages over other sensing methods for assessing the mixing of water bodies in that it does not require on-the-ground surveying (as is required for turbidity and chemical parameters which are not readily remote sensed) and can thus be

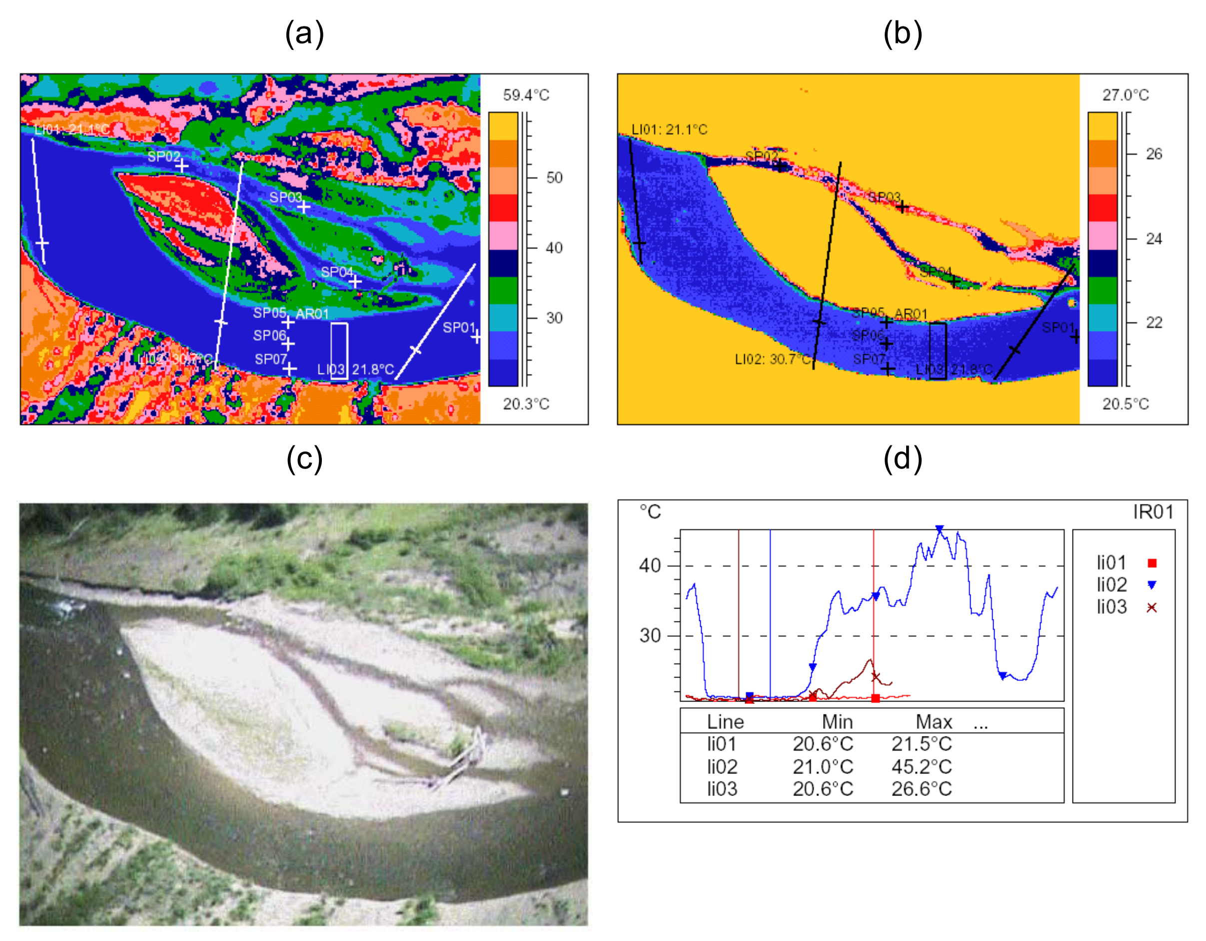

Figure 3. (a) Landscape thermogram, (b) water thermogram, (c) location photograph, and (d) a stream temperature cross-sections (along lines “li01”, “li02”, and “li03” in Figures 3(a) and (b)) of the Coldwater River approximately 500 m upstream of site 5 (site 6).

performed more rapidly and efficiently, the data points are automatically created in a digital database for subsequent analysis, the method is non-invasive (i.e. no need for site disruption by on-the-ground activities in sensitive areas or addition of any compounds [e.g. dyes, tracers] to the water column), and the sensing may still take place where visual optical properties do not differ between the interacting water bodies or under poor lighting conditions, even at night. The technique may also be applied to assess and monitor downstream mixing of effluents where dilutional processes are of interest (i.e. contaminants must be diluted below impact thresholds) and the effluent has differing thermal properties from the receiving water. Furthermore, for larger river systems where in-stream measurements are difficult, aerial remote sensing methods may be more cost effective due to the short time required for complete imaging, even if the per hour costs for remote sensing are generally greater.

As presented at the 3 sites discussed above, aerial thermal imagery appears to offer rapid insights into stream temperature regimes and processes occurring along and across a stream. However, one must remember that aerial thermal imagery is a snapshot of stream temperature in time and space and may not capture temperature extremes that most affect biota. As well, precipitation can affect the accuracies of radiant temperatures. A view of the channel is also needed to measure stream temperature, and thus, this technique is limited to streams not obscured by canopy cover. Further care is needed in interpretation of average stream temperature where thermal emission from rocks, bars,

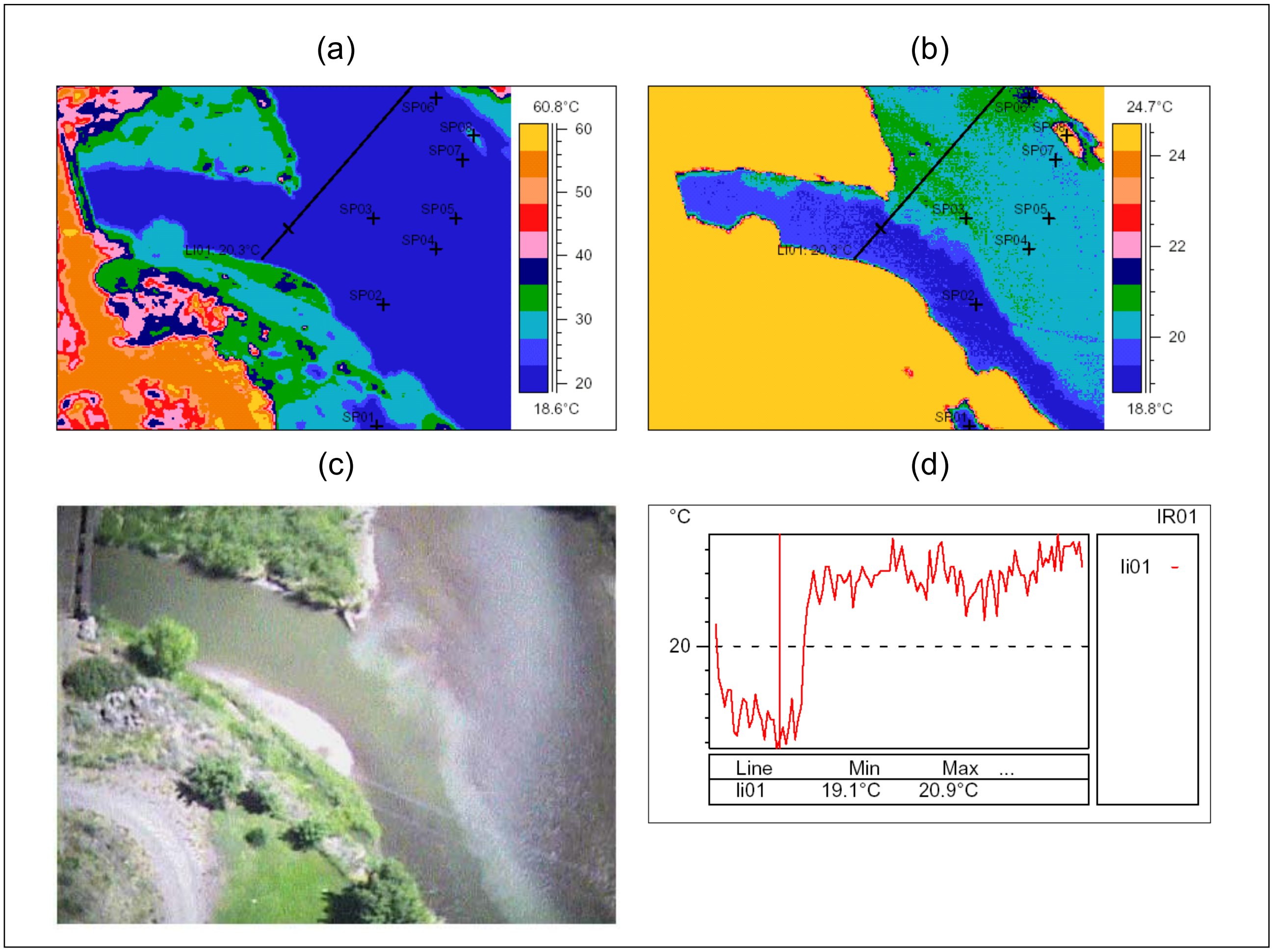

Figure 4. (a) Landscape thermogram, (b) water thermogram, (c) location photograph, and (d) a stream temperature cross-section (along line "li01") of the Nicola River confluence with the Coldwater River (site 2).

or near shore features may skew recorded values. As discussed above, camera calibration to a correct emissivity is required to compensate for ground reflection, and the built-in compensatory features of commercial cameras may not adequately account for such thermal interferences, potentially leading to spurious conclusions regarding stream heating or cooling. A critical eye, and likely a physical model, is necessary to confirm whether observed patterns are consistent with known heat inputs/outputs. Often, such determinations cannot be made while airborne in the field and it is more difficult to assess the accuracy of the data during subsequent processing efforts where the opportunity to ground-truth “controversial” sites (such as in Figure 2(b)) is not readily available.

Nevertheless, when complemented with in-stream sensors, the temperature variation from headwater areas downstream to higher order regions of a stream can be mapped in a rapid fashion and archived in a permanent record. Multiple flights can document seasonal stream temperature change in the mainstem and the dynamic effects of tributaries. Multi-scale assessment of temperature patterns using landscape and water thermograms may help identify both natural drivers and anthropogenic activities that influence stream temperature. Mapping can be also carried out in most weather types and during the day or night. In practical terms, helicopter rental costs in Canada are ca. CDN\$1,000 hr^{-1}, and at a flight speed of 40 $km{\cdot}h^{-1}$, the entire mainstem of the Coldwater River can be mapped in point form approximately every 0.5 km in 2 h (some hovering time may be needed at key sites). While camera personnel and pre- and post-flight time are additional and highly dependent on project objectives, these numbers provide a base for budget calculations.

CONCLUSIONS

Aerial thermal imaging using a forward-looking infrared (FLIR) camera of stream and riparian landscape temperatures in the Nicola River watershed in south-central British Columbia demonstrated the utility and potential limitations of this emerging technology. The complex spatial patterns of water and land surface temperature are readily obtained in rapid fashion, and may be used to compliment in-stream temperature acquisition methods for hybrid spatial-temporal stream temperature analyses and also to assess mixing within and between riverine systems. Regions of stream heating and cooling that would otherwise be overlooked by in-stream methods may be revealed using remote sensing methods, although the current study and results reported elsewhere demonstrate that more rigorous data quality investigations combined with physical models of expected spatial patterns are required to avoid making spurious claims regarding water temperature heterogeneity.

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