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Monitoring**

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Integration of Remote Sensing



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New approaches for monitoring stream temperature:

Airborne thermal infrared remote sensing

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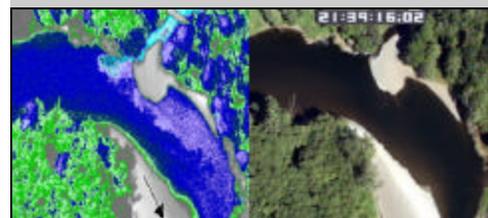
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Abstract

Thermal infrared (TIR) images acquired from airborne platforms have recently become a significant data source in stream temperature monitoring and analysis programs. Thermal imagery is useful for detecting and quantifying warm and cool water sources, calibrating stream temperature models, and identifying thermal processes. TIR imagery has also found application in the mapping of groundwater inflows and the analysis of floodplain hydrology. These remotely sensed data provide a spatially continuous map of temperatures within a watershed and complement temporally continuous, but spatially limited, point monitors traditionally employed to assess stream temperatures. This paper provides an overview of the characteristics, applications, costs, and implementation of TIR remote sensing for monitoring water temperature in rivers and streams.

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Introduction

Stream temperature is influenced by the surrounding landscape and reflects the characteristics and condition of the stream and its valley (Beschta 1997). The physical dimensions and structure of the floodplain and riparian corridor directly influence thermal patterns, making stream temperature an indicator of human disturbance throughout the watershed (Holtby 1988, Johnson and Jones 2000). Alteration of the stream environment generally causes an increase in water temperature with consequences for coldwater-adapted aquatic organisms (Beschta et al. 1987). The biological influence of temperature in stream ecosystems as both a regulating and a limiting factor is well documented for aquatic insects (Vannote and Sweeney 1980, Ward and Stanford 1982) and stream fishes (Li et al. 1994, Peterson and Rabeni 1996). Recently, much of the work on stream temperature and fish–habitat relationships has been conducted in the Pacific Northwest (USA) where elevated stream temperatures threaten cold-water fishes such as salmon and trout (Berman and Quinn 1991, Coutant 1999, Ebersole et al. 2001) (Figure 1.)

Remote Sensing and Stream Temperature

Remote sensing offers a practical way of obtaining the temperature measurements needed for large-scale biological studies (Belknap and Naiman 1998, Torgersen et al. 1999) and modeling programs (Chen et al. 1998a, Chen et al. 1998b). Often temperature problems extend for hundreds of river kilometers that traverse multiple land uses; therefore, identification of human-caused thermal degradation and source areas of heating and cooling requires spatially continuous data (Poole and Berman 2001). The value of spatially continuous data for mapping sea surface temperature has long been recognized in atmospheric sciences and oceanography (Ikeda and Dobson 1995, Robinson 1997), but only recently has advanced technology been available to resource managers for measuring fine-scale thermal patterns in rivers and streams (Torgersen et al. 2001)



Figure 1. Area along Applegate River, Oregon where stream restoration is taking place to mitigate the effects of elevated stream temperatures.

Applications of satellite and high-altitude TIR remote sensing may be beyond the scope of watershed monitoring at local scales, but natural resource managers can benefit from TIR technology developed for airborne high-resolution commercial applications. Thermal scanners originally designed to measure thermal contrast have now been perfected into lightweight, highly accurate thermal radiometers that map surface temperatures directly to a digital image for immediate querying and analysis (Miller 1994).

These airborne tools are effective at mapping spatial and temporal patterns in stream temperature, riparian vegetation, and river channel morphology and can help resource managers detect trends and make decisions that will promote long-term aquatic ecosystem function. With the increased availability and accessibility of new remote sensing technologies, resource managers now have the opportunity to include spatially continuous analysis as a standard tool in stream temperature monitoring programs.

The objectives of this paper are to (1) introduce TIR imagery and derived data products, (2) discuss the application of TIR remote sensing as a complement to in-stream measurement of thermal variability, and (3) provide an overview of systems and techniques for TIR image acquisition using state of the art digital imaging and geospatial technology.

TIR Imagery and Spatial Temperature Patterns

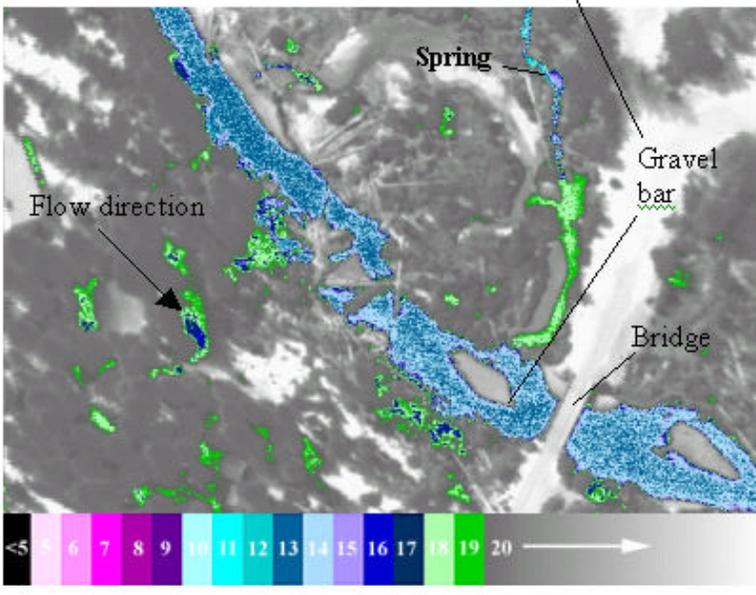
Temperatures measured through remote sensing are often referred to as radiant temperatures. Kinetic energy, on the other hand, is the contact temperature of an object as measured with a standard thermometer. A TIR sensor measures radiant energy (8–14 μm wave band) emitted from the water surface and stores these values as pixels in a digital image. During processing, raw thermal images are calibrated so they represent accurate water surface temperatures. Studies that have compared radiant temperatures from TIR images to kinetic temperatures collected with in-stream data loggers consistently report agreement within $\pm 0.5^\circ\text{C}$ (Torgersen et al. 2001).

Land and water features are distinguishable in a thermal image due to differences in radiant temperature. The TIR image normally shows a distinct contrast between the water and the surrounding terrain with a precision of $0.1\text{--}0.2^\circ\text{C}$ depending on the sensor. At this level of sensitivity, temperature differences within the stream are easily discernable in the image (Figure 2).

TIR images collected for stream temperature applications cover a relatively small ground area when compared to standard aerial photography (Figure 3). The image footprint (150–600 m) is generally based on the channel width and the floodplain characteristics of the survey stream. Flight parameters are selected such that the image includes both the stream and the immediate riparian zone. The objective is to collect high-resolution imagery to



*Tumalo Creek,
Deschutes National Forest,
Oregon*



*Image Footprint:
150m x 100 m*

*Pixel Size:
0.25m*

*Median Stream
Temperature:
13.9 deg C*

Figure 2. Color photograph (top) and pseudo-color TIR image (bottom) of the same area. The color photograph was taken looking upstream from the bridge. The color temperature map at the bottom of the TIR image is in degrees Centigrade.

measure accurate in-stream temperatures while still having a large enough image footprint to include significant thermal features within the floodplain and riparian buffer zone. Visible band color video or digital imagery is often collected with the TIR images to facilitate interpretation.

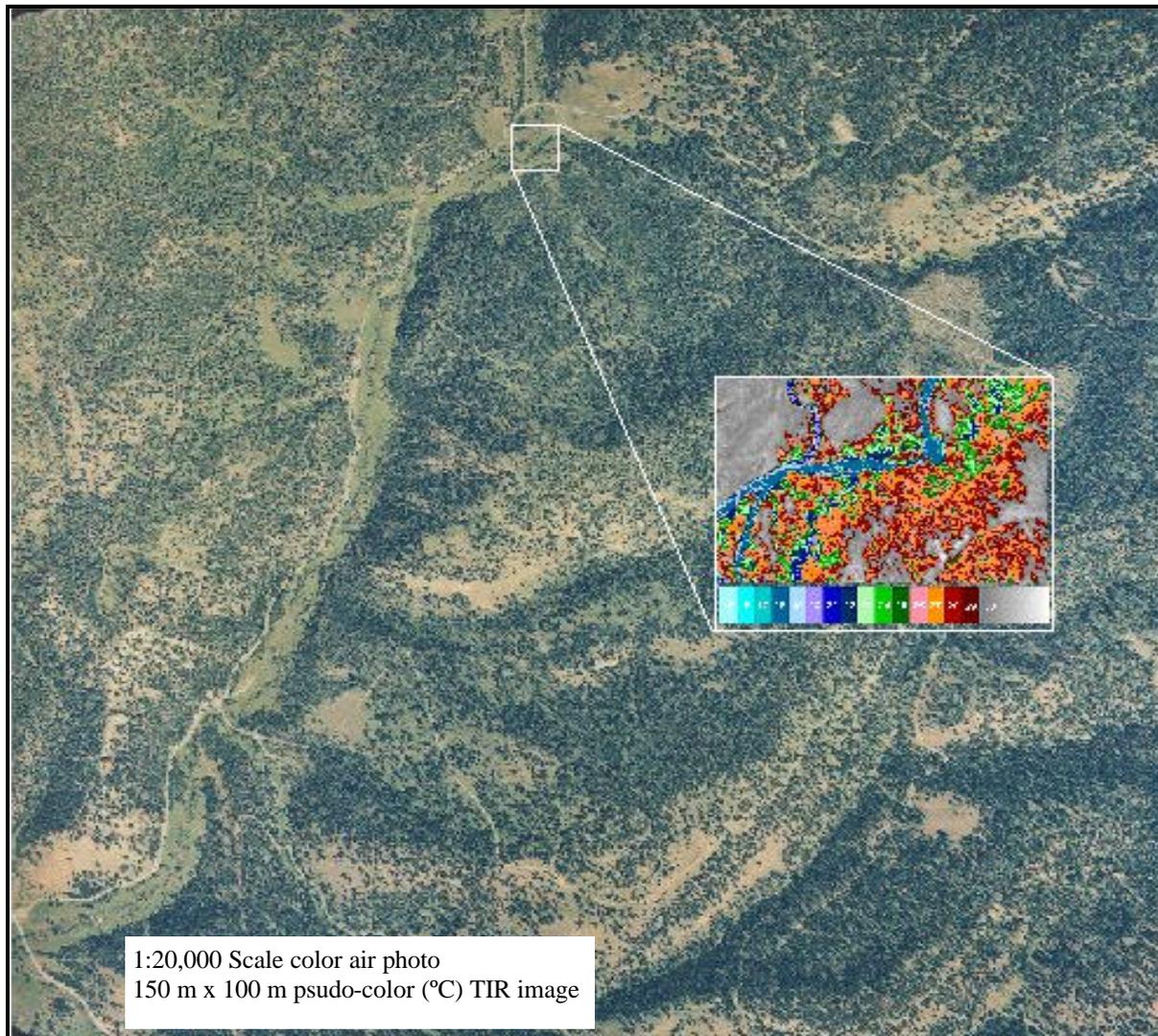


Figure 3. Comparison of image footprints between 1:20,000 scale color aerial photograph and TIR image (inset).

TIR images are analyzed either as a sequence of separate frames or as a mosaic of image frames. A collection of overlapping TIR images composes a mosaic, or continuous map, of surface temperatures over a survey area. A mosaic shows channel features and hydrologic connectivity within the floodplain. In cases where there are sinuous or multiple channels, image mosaics are often developed to facilitate the analysis.

Surface water temperatures can be sampled directly from individual TIR images or mosaicked images to create a longitudinal temperature profile for the surveyed reaches. Longitudinal profiles are straightforward to develop and one of the more useful ways of displaying stream temperature information over a long distances. The longitudinal temperature profile can be presented graphically (Figure 4) or spatially (Figure 5). While these data represent temperatures at the time and date of the survey, the authors have compared stream temperature patterns collected in different years over the same stream

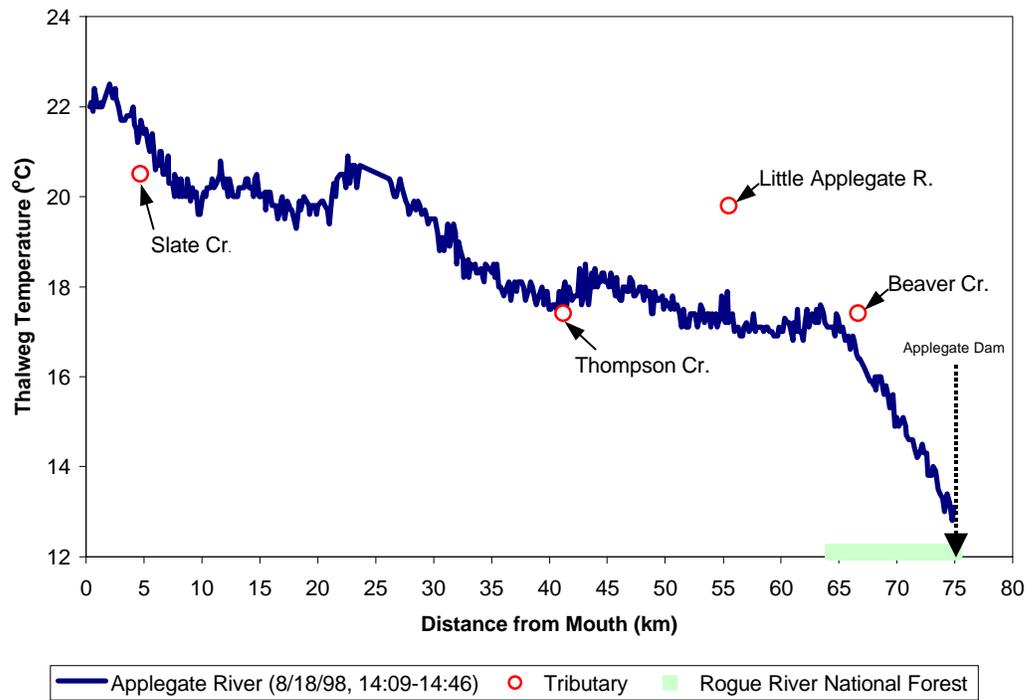


Figure 4. Graphical example of a TIR derived longitudinal temperature profile. Tributaries flowing into the Applegate River are shown as are administrative boundaries.

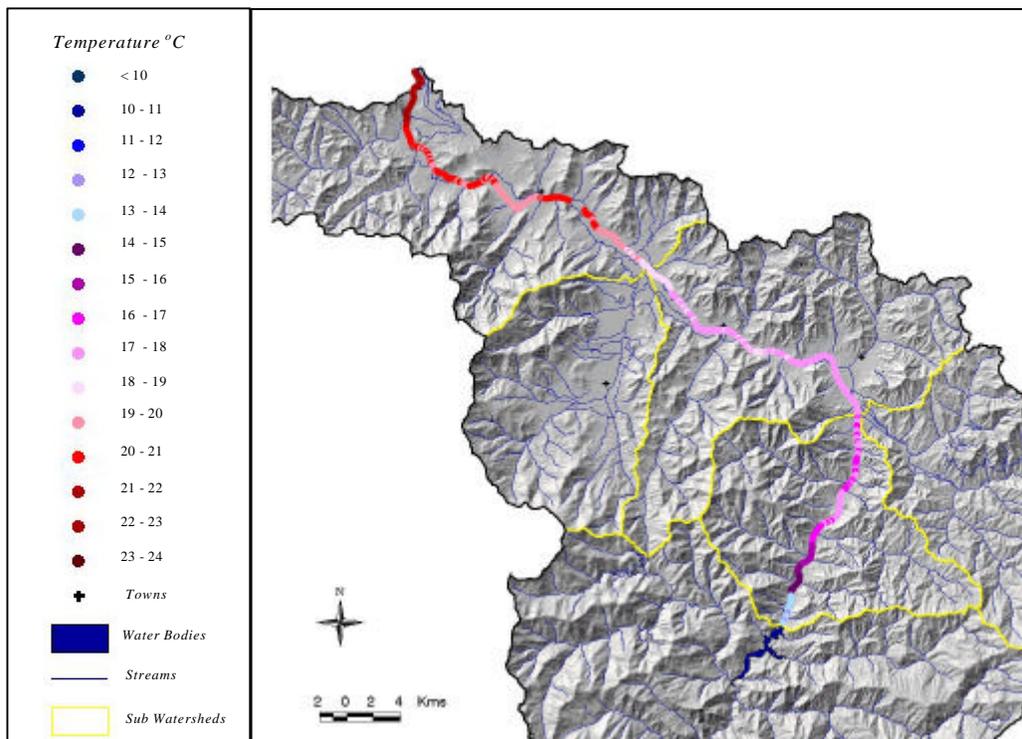


Figure 5. Point pattern map illustrating the spatial distribution of temperatures within the basin based on the profile shown in Figure 4.

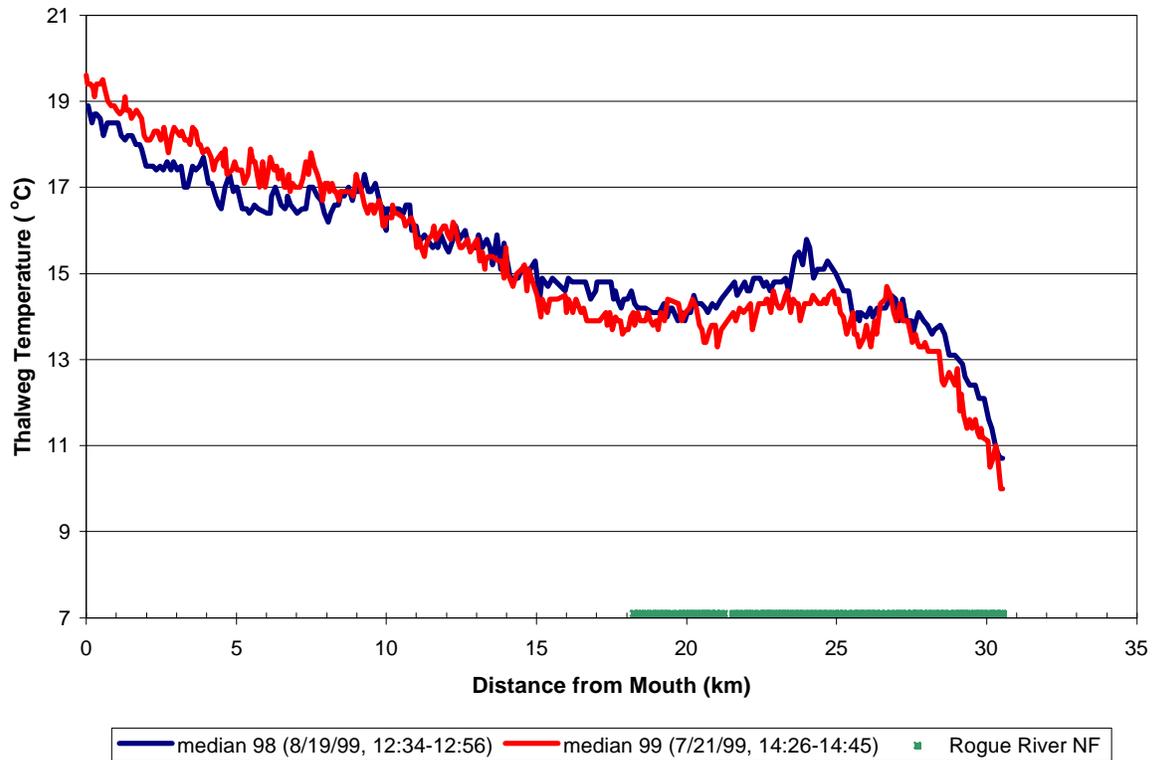


Figure 6. Example of longitudinal profiles collected in consecutive years on the Little Applegate River. While absolute temperatures differ, the patterns of change remain similar.

reach on numerous Oregon rivers. The results of these comparisons show that, though absolute temperatures changed, longitudinal temperature patterns were consistent between years (Figure 6). Cool water sources and locations remained spatially fixed from year to year, as did sources of thermal loading. Consequently, a longitudinal temperature profile developed from a single survey can be a template for understanding a stream's thermal structure.

Stream Temperature Assessment and Monitoring

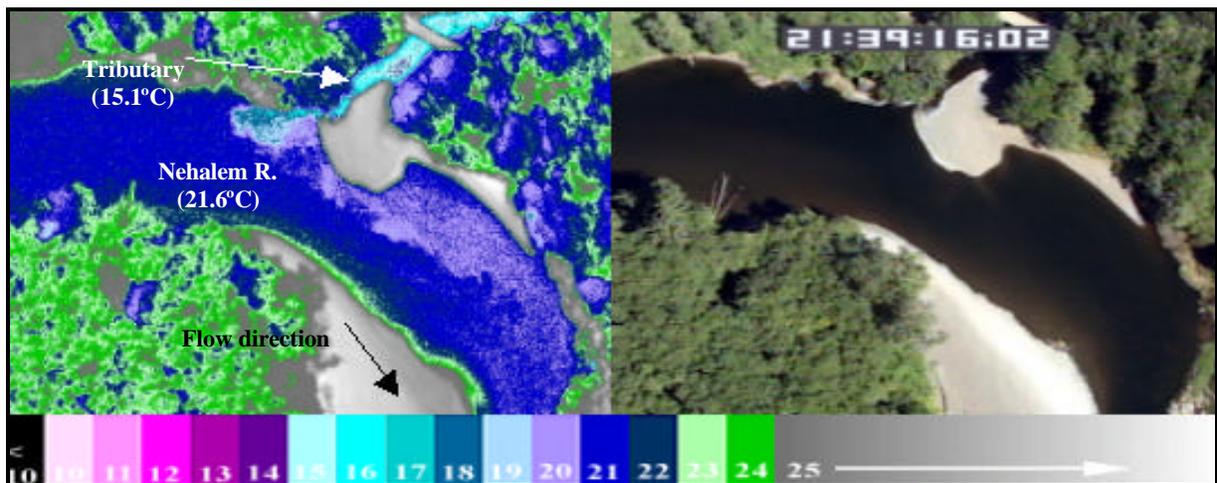
Spatial temperature patterns are governed by the interaction of natural environmental factors and human activities. Natural environmental factors include solar radiation, channel characteristics, air temperature, groundwater exchanges, surface inflows, and ground temperature (Brown 1969, Beschta 1987). Any significant human-caused alterations of these factors will directly or indirectly modify local thermal conditions, and may create thermal discontinuities along the longitudinal stream profile (Ward, 1985). The energy transfer relationship between the different variables, natural or human-caused, determines the magnitude and spatial extent of thermal variability.

TIR remote sensing provides a new approach to assessing and monitoring spatial thermal variability in rivers and streams. As such, the methods for applying these data to watershed

issues are currently evolving. To date, TIR remote sensing has been used to understand stream temperature dynamics, calibrate and validate stream temperature models, map physical habitat variables, and direct future monitoring efforts. The following sections provide a general overview of how TIR remote sensing has been applied in water quality monitoring programs.

Stream Temperature Assessments

TIR imagery provides a means for detecting and measuring tributary and other point source inflows along an entire stream course. In-stream monitoring programs typically monitor major tributaries, but lack the resources to monitor low order streams. As a result, the individual and collective contribution of low-order streams is often poorly understood. In some cases, unmapped (or poorly mapped) spring inflows contribute significantly to mainstream water temperatures. Tributary inflows can be sources of thermal cooling (Figure 7) or of thermal loading. Spring inflows are most often observed as sources of thermal cooling (Figure 8), though hot springs are present on some river systems (Figure 9).



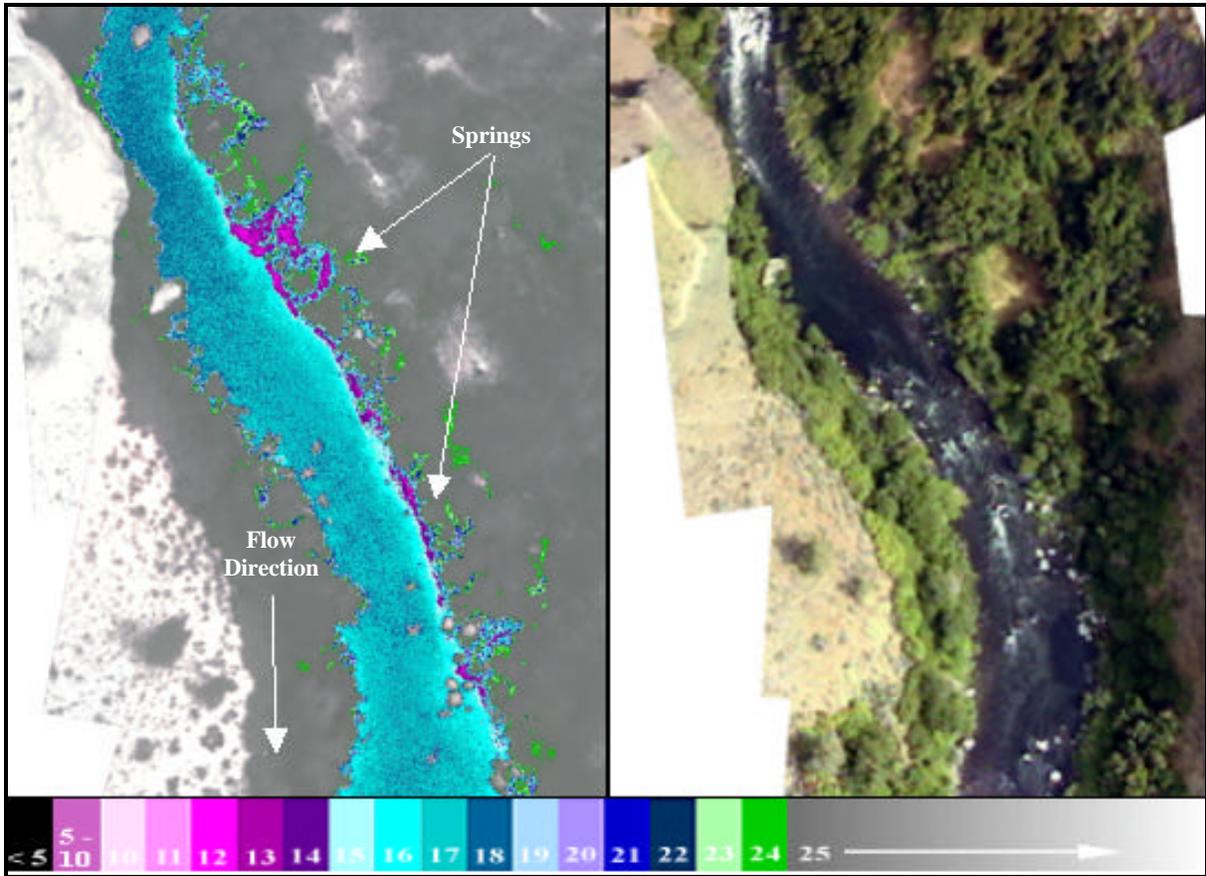
TIR Image/visible band image

Nehalem River, OR 2000

Figure 7. Example of tributary cooling. The river flows from left to right in the image while the tributary flows in from the top of the image.

Thermally significant areas can be identified in a longitudinal stream temperature profile and related to specific causes (i.e. water withdrawal, tributary confluence, landscape vegetation patterns, etc.). Areas where stream-water mixes with subsurface flows (i.e. hyporheic and inflows) are also often apparent in TIR imagery. Thermal changes detected with TIR remote sensing can be quantified as a change in stream temperature over a specific distance. These thermal responses are marked by a change in slope in the longitudinal stream temperature profile and often signify a change in the physical parameters that govern stream heating.

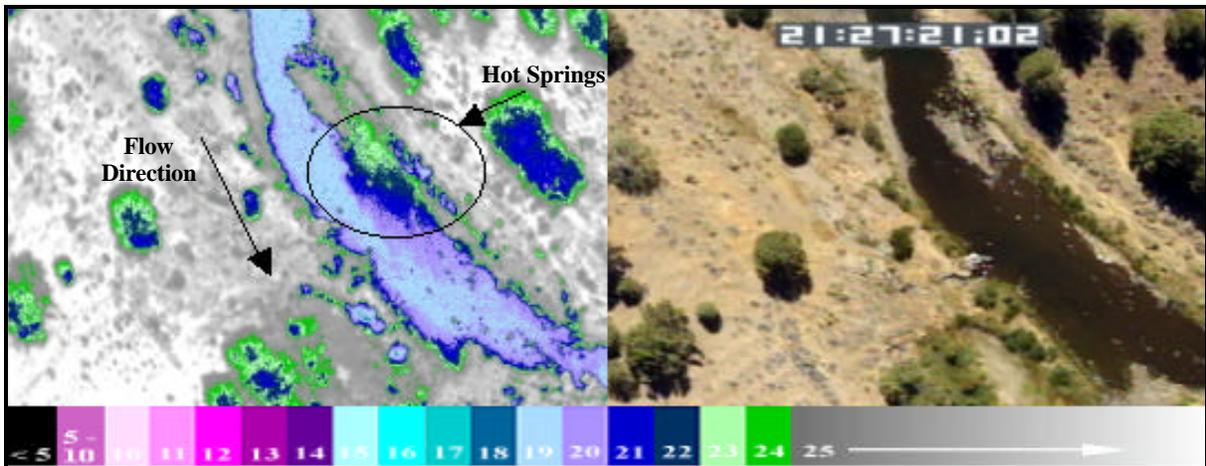
To assess factors contributing to thermal response, the stream temperature profile can be combined with other spatially explicit data layers in a geographic information system (GIS).



TIR/visible band image

Deschutes River, 2000

Figure 8. Example of Spring/Groundwater Inflow. The TIR image on the left is color coded in 1°C increments.



TIR/Visible band image

Warner Basic, CA/OR 2000

Figure 9. Example image showing a hot spring along the right bank (looking upstream). Hot springs are not common and often hard to detect.

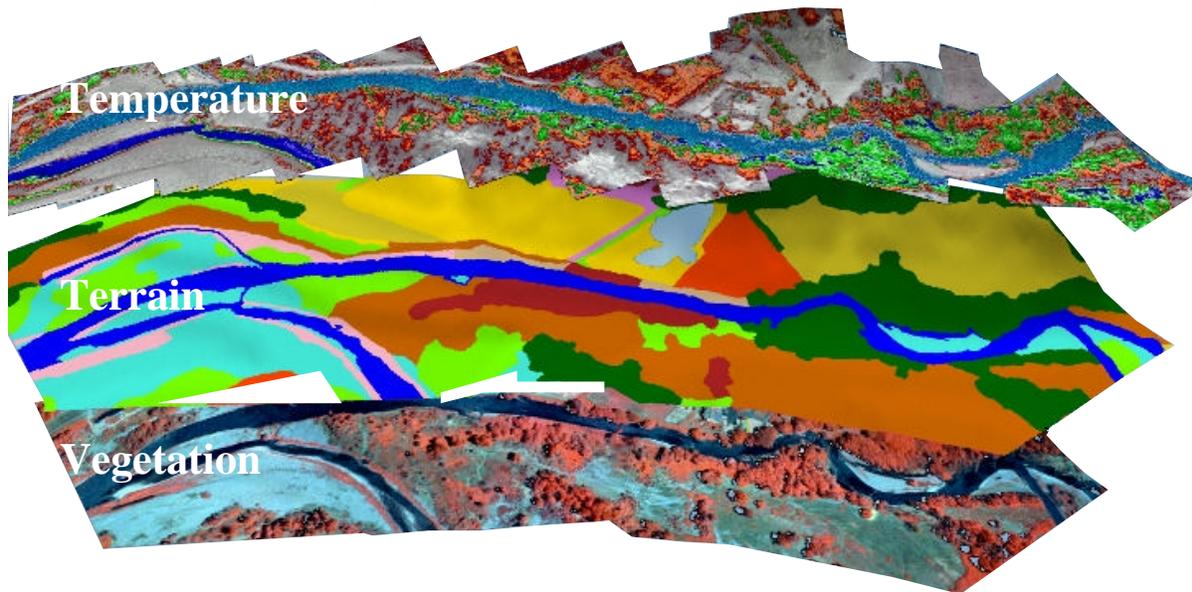


Figure 10. Spatially explicit data layers in a GIS, including topography, vegetation, land-use, hydrology, and ownership, can be integrated with temperature information from FLIR. Using this analysis tool, temperature gradients can be viewed with respect to stream aspect, slope, elevation, channel width, valley form, and riparian vegetation.

The data layers typically include topography, vegetation, land-use, hydrology, and ownership (Figure 10). From these layers, temperature gradients can be viewed with respect to stream aspect, slope and elevation, channel width, valley form, and riparian vegetation. Based on the streams thermal response with respect to these parameters, hypotheses can be developed about the interaction of factors governing stream temperatures at the landscape scale. From these data, the resource manager can identify key areas in the watershed that require further monitoring, restoration, or protection.

Reach scale analysis represents a progression from general temperatures at the basin scale to more specific thermal features at reach and unit scales. Thermal features of interest may differ based on the characteristics of the reach and the underlying objectives of the survey. For example, the analyst may seek to identify locally cool areas in an otherwise warm water reach that represent a thermal refuge for cold-water fish species. The analysis may further seek to determine the factors within the reach that contribute to stream heating. These factors may include the structure and composition of streamside vegetation and channel characteristics. The reach and unit scale analysis generally involves interpretation of the TIR images.

Direct analysis of spatial temperature patterns can identify sources of thermal loading and cooling. However, the temperature effects on aquatic communities depend both on the rate of temperature change and on the length of exposure to sub-lethal and lethal water

temperatures (Armour 1991). A temporal context is therefore required before drawing conclusions about absolute temperatures observed in the longitudinal temperature profile. The timing of the TIR survey should be compared to both the diurnal and the seasonal progression of stream temperatures. A comparison with daily temperatures shows how well the profile compares to daily stream temperature maximums at in-stream monitoring sites.

Stream Temperature Modeling

Watershed-scale simulation is often needed to generate a complete picture of the whole basin for targeting critical reach locations for riparian restoration and for designing and assessing best management practices (Chen et. al. 1998). For example, the Oregon Department of Environmental Quality (ORDEQ, 2000) in cooperation with the US Forest Service, Bureau of Reclamation, and Indian Tribes have collected TIR data to support watershed-scale simulation efforts and subsequent development of temperature Total Maximum Daily Loads (TMDL'-s). In the simulation effort, TIR data were used to develop a mass balance for stream flow using minimal ground level data collection points. A mass transfer represents water volume input (i. e. tributary confluence, point source discharge, groundwater inflow, etc.) or water volume withdrawals (i.e. irrigation diversion) from the stream.

All stream temperature changes resulting from mass transfer processes can be described mathematically using the following relationship:

$$T_{mix} = \frac{(Q_{up} \cdot T_{up}) + (Q_{in} \cdot T_{in})}{(Q_{mix})} = \frac{(Q_{up} \cdot T_{up}) + (Q_{in} \cdot T_{in})}{(Q_{up} + Q_{in})}$$

where,

Q_{up} : Stream flow rate upstream from mass transfer process

Q_{in} : Inflow volume or flow rate

Q_{mix} : Resulting volume or flow rate from mass transfer process ($Q_{up} + Q_{in}$)

T_{up} : Stream temperature directly upstream from mass transfer process

T_{in} : Temperature of inflow

T_{mix} : Resulting stream temperature from mass transfer process assuming complete mix

All water temperatures (i.e. T_{up} , T_{in} and T_{mix}) are apparent in the TIR sampled stream temperature data. Provided that at least one flow rate is known (i.e. instream or inflow) the other flow rates can be calculated.

Identifying mass transfer areas is an important step in quantifying heat transfer within a stream network. For example, using TIR temperature data, thirty-one mass transfer areas were identified in the North Fork Sprague River including ten tributary inflows, six agricultural related return flows, nine subsurface inflows, and six water withdrawals (ORDEQ, 2001).] Prior to TIR surveys, several of the subsurface mass transfer areas were previously unmapped and the relative thermal and hydrologic impact to the stream system was unknown. Furthermore, surface returns from agriculture irrigation were not quantified in terms of flow rates or temperatures prior to the TIR survey.

Stream temperatures derived from TIR data offer a robust validation data set for spatial stream temperature simulation tools. Since the TIR temperature data is continuous, the number of simulated temperatures available for model validation is limited only by model resolution. This represents a significant improvement over previous data sources. As an example, Oregon DEQ simulated stream temperatures for the North Fork Sprague River along 57.6 km. The selected model spatial resolution was 100 meters, allowing 576 discrete model output samples for calculation of validation statistics (Figure 11). A similar effort that relied simply on available in-stream continuous monitors would have allowed only four validation samples.

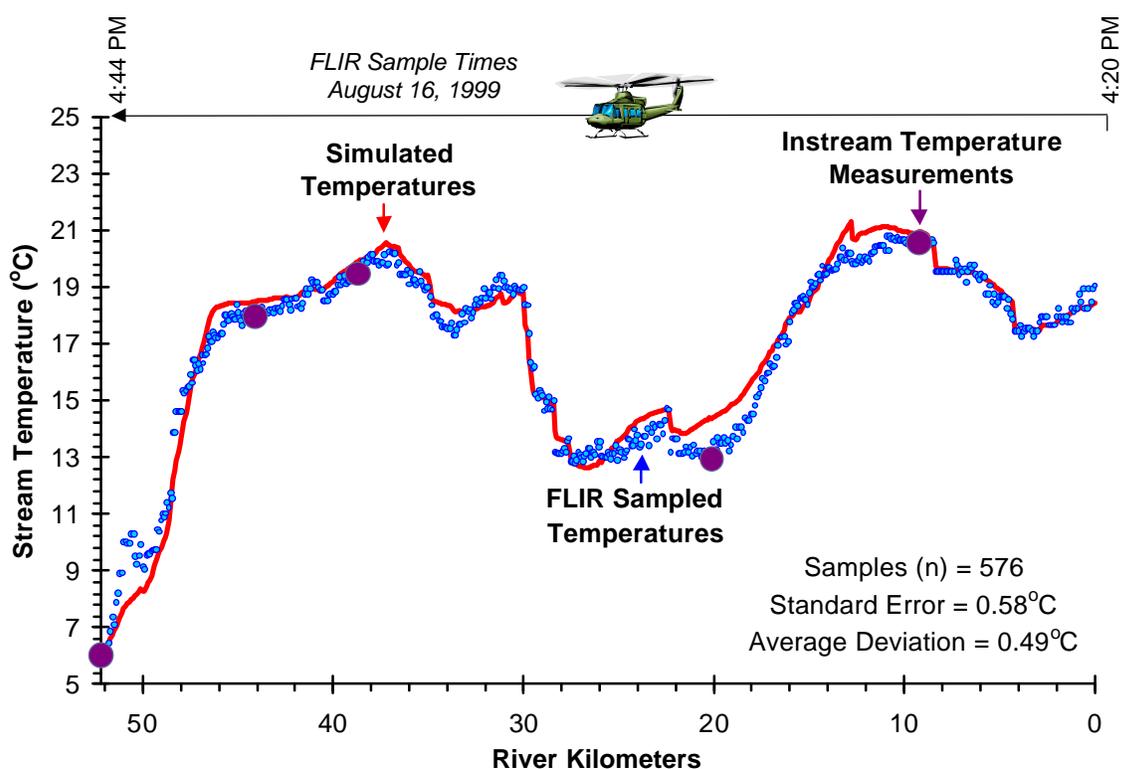


Figure 11. Stream temperature simulation for the North Fork Sprague River (ODEQ, 2001).

Fish Distributions and Thermal Variability

Recent studies of fish distributions in rivers and streams have used TIR surveys to identify local spatial temperature variations that may influence fish habitat selection (Torgersen 2001, USFS 1998). Unlike assessments that seek to identify the causal factors associated with stream heating, this biological application has used the TIR data to provide a spatially continuous description of temperature as a habitat variable.

A Balanced Monitoring Plan

TIR remote sensing provides a spatially continuous complement to traditional, temporally continuous in-stream data loggers. Stream temperatures vary both longitudinally and laterally along the stream course. Traditional point sample monitoring techniques provide little information on spatial variability in stream temperature and may subsequently underestimate the amount of cold water habitat available in a thermally impaired stream. Likewise, inadvertent placement of point monitors in a locally warm (backwater or tributary influence) or cool (groundwater seep) area may result in false interpretation of general thermal conditions. Practical considerations such as road access to the stream, landowner permission, and basin size are often a limiting factor influencing the number and distribution of point sample monitoring sites within a basin. TIR remote sensing combined with in-stream monitoring represents a balanced monitoring approach and can alleviate physical access constraints.

TIR data cannot replace in-stream temperature monitoring. TIR data, however, facilitate the interpretation of in-stream sensors by describing temperature trends between monitoring sites. Resource managers are potentially able to monitor streams with fewer in-stream data loggers because the spatial temperature patterns between sites are understood. With spatially explicit data, future monitoring can redistribute in-stream monitors to locations that best describe basin scale patterns. In general, recommended locations for in-stream data loggers are at transition points in the thermal profile (Figure 12).

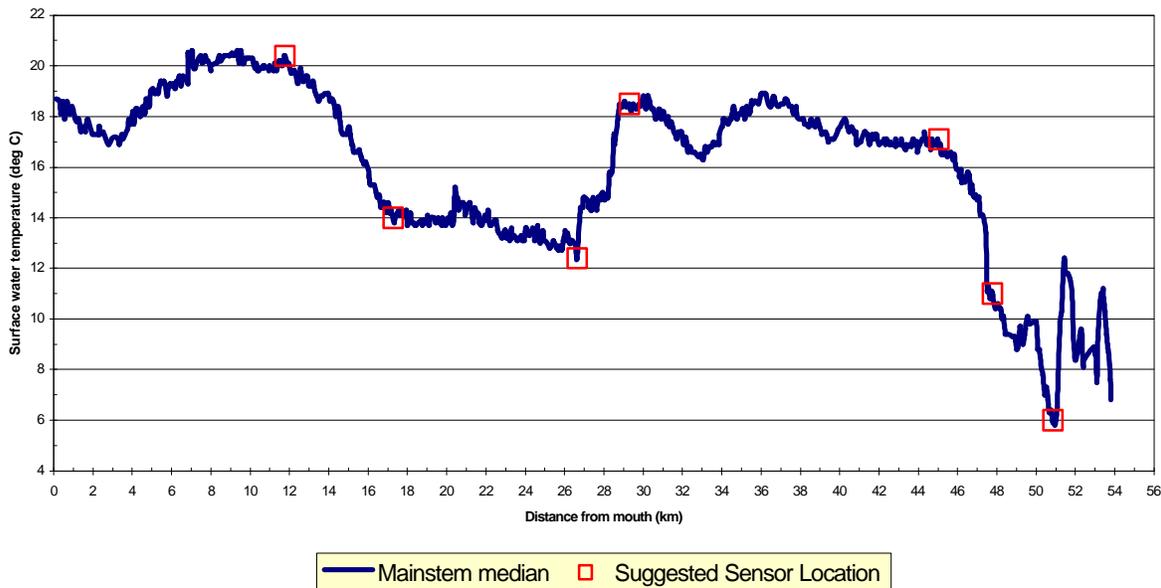


Figure 12. Longitudinal temperature profile of the N.F. Sprague River, Oregon showing the recommended placement of in-stream sensors for monitoring temperatures

Moreover, the TIR data and any associated visible band imagery (i.e. color video) provide information similar to aerial photographs. The imagery provides a photographic record of the stream and riparian conditions at the time of the survey. The visible band imagery can be used directly to select field-monitoring sites for the following season. Finally, the TIR data provide a record of baseline thermal conditions in the basin and can be used to evaluate the effectiveness of reach- and basin- scale restoration efforts.

Riparian Vegetation and Mapping

Thermal imagery has not been used as a primary source for riparian vegetation mapping. TIR imagery is not normally georeferenced and rectified as part of the image acquisition. Consequently, the imagery would have to be georeferenced prior to vegetation mapping. Georeferencing is difficult due to the small footprint and the large number of image frames. In addition, TIR surveys concentrate on the stream channel and immediate riparian zone. As the stream becomes more sinuous, the imagery covers less of the riparian zone. As a result, the extent of riparian zone covered in the TIR imagery is often inconsistent throughout the course of the survey. Projects focusing on mapping riparian vegetation should look to alternate sources of remote sensing such as digital infrared photography and standard aerial photography (Figure 13). TIR imagery is often more useful as a secondary source for validating existing vegetation layers.

The combination of TIR and visible band imagery has been used to illustrate and qualitatively assess riparian conditions including vegetation. These features include physical habitat variables and changes in riparian vegetation that can influence stream heating. Since water has a high thermal inertia, it shows a thermal response to changes in physical factors (i.e. increased solar radiation) over a spatial scale consistent with flow volumes and channel characteristics (i.e. width/depth ratio). Consequently, the TIR images may provide information on riparian vegetation and the associated thermal microclimate.

Restoration Monitoring

TIR data can provide a means to monitor the restoration efforts by comparing spatial temperature patterns collected before and after restoration. A water quality management plan may prescribe solutions affecting multiple land uses at the spatial scale of the watershed. In this case, repeat TIR surveys may be conducted over the entire basin. Likewise, the return period for a TIR survey depends on the projected temporal-scale of restoration efforts. For example, modifications to flow management procedures such as reducing water withdrawals may have an immediate influence on stream temperatures. In this case, TIR surveys may be conducted in consecutive years. Conversely, recovery of riparian vegetation may take several years to begin to show an effect on in-stream temperatures.

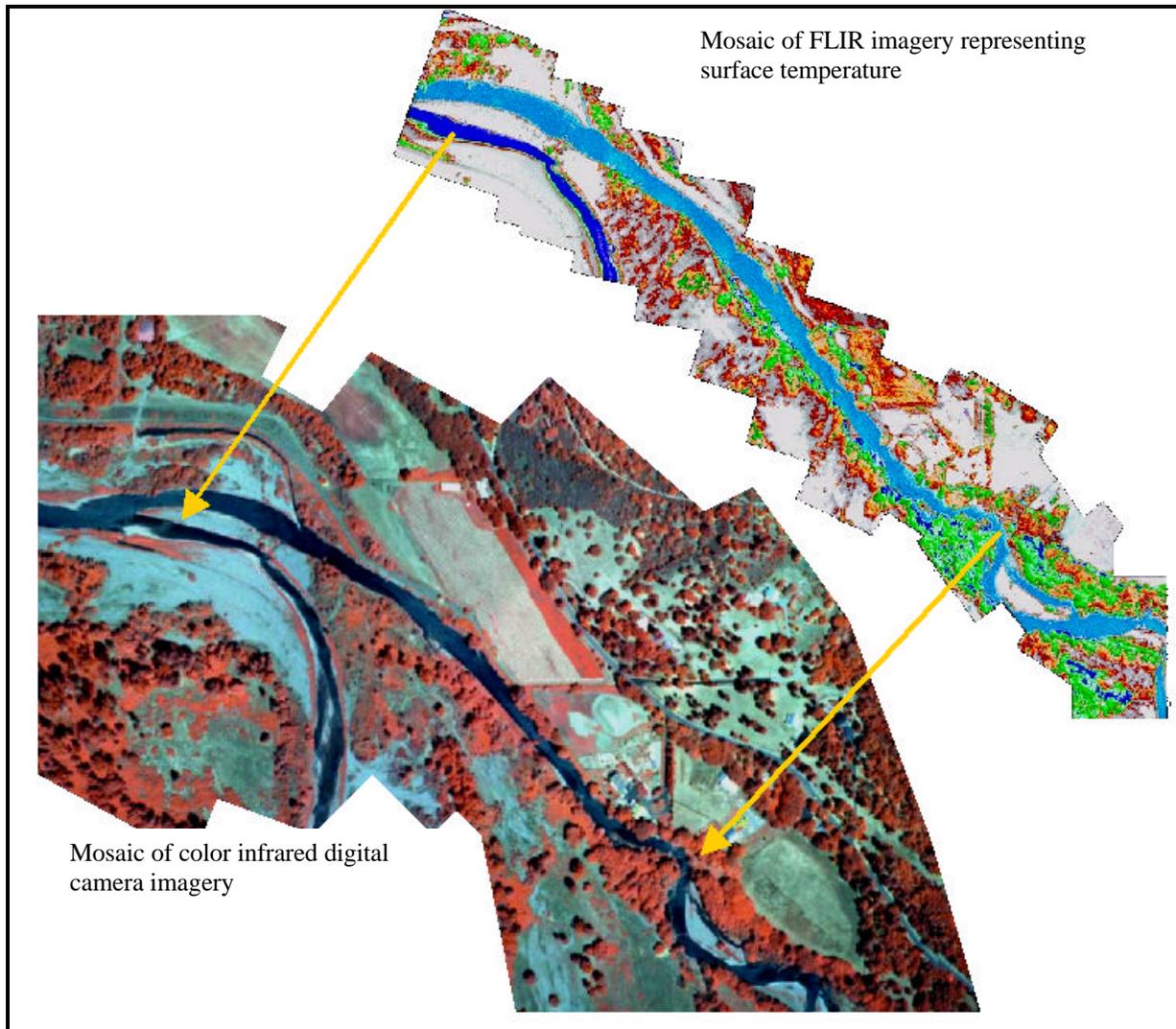


Figure 13. Other remote sensing sources, such as digital imagery acquired from the Kodak DCS 420 Color Infrared camera, can compliment FLIR studies and be used to map riparian vegetation. The digital camera imagery has a larger footprint and is better suited for differentiating land cover and vegetation.

Other Applications

While the objective of this paper is primarily to examine the use of TIR remote sensing for stream temperature monitoring, TIR remote sensing has application in other watershed scale studies. Because TIR images show thermal contrast, they provide a means for detecting and mapping features in the channel and active floodplain having different surface temperatures. Belknap and Naiman (1998) used TIR remote sensing to detect and map wall-based channels in two Western Washington streams. In addition, OR DEQ (2000) data collection efforts have shown several examples of hyporheic discharges to the stream channel and Torgersen et. al. (2001) provides an example of the detection of a floodplain spring brook in Wenaha River.

TIR remote sensing also has applications in the detection of ground water discharges (Avery and Berlin 1992). As previously illustrated, TIR remote sensing during the summer months can directly detect cold groundwater discharges into the stream. Longitudinal temperature profiles have further illustrated relatively cool reaches influenced by diffuse sub-surface inflows. During the summer months, however, spring inflows are colder than in-stream temperatures. As the colder, denser water enters the channel it sinks and this ability to detect low volume or sub-surface discharges is somewhat limited. As a result, TIR surveys with the objective of locating groundwater inputs are best conducted in the winter when stream and terrestrial temperatures are low compared to groundwater temperature. During the winter, groundwater is warmer relative to the stream and terrain and is therefore more easily detected.

TIR Image Acquisition

System Description

A system appropriate for airborne TIR remote sensing of rivers and streams can vary in sensor characteristics, aircraft mounting, associated sub-systems, and overall level of integration. The combination of these factors can ultimately influence operational parameters (survey duration, flight altitudes, etc.), thermal accuracy, supplementary information (i.e. referencing, visible band imagery), and processing requirements. This section describes the baseline system used for TIR remote sensing systems and sample operational parameters.

TIR remote sensing requires the use of a calibrated thermal infrared radiometer mounted on an airborne platform. TIR sensors operate in either the 3-5 μ m (micron) or 8-14 μ m portion of the electromagnetic spectrum. The 8-14 μ m range is most common for natural resource applications such as stream temperature mapping because solar reflections are minimized in this band. In addition, natural objects such as water have temperatures with peak radiated energy in the 8-14 μ m band (Wolfe and Zissis 1985). A radiometer provides a means to convert a recorded signal (analog voltage or digital number) to radiance. Radiance values are stored in the form of a digital image. During the processing phase, the image is corrected for atmospheric, background, and target emissivity effects.

The radiometer (or TIR sensor) is typically housed in a gyro-stabilized mount in order to minimize degradation of the image due to aircraft motion and vibrations (Figure 14). The TIR



Figure 14. TIR Data collection system mounted on a Bell JetRanger Helicopter. A gyro-stabilized mount containing the FLIR and the visible band color video camera is attached to the underside of the helicopter (location 1). A computer, GPS, and digital video recorder are mounted on an equipment rack in the back seat (location 2).

images are recorded digitally to an on-board storage device. In all cases, the data collection system must have the capability to record images at the rate and duration required by the survey. A global positioning system (GPS) is necessary to geo-locate the imagery. GPS positions can be logged separately or encoded directly to the imagery. Visible band color video is often recorded in conjunction with the TIR images.

Flight Parameters

Torgersen et al. (2001) present a detailed discussion of the image acquisition procedures appropriate for water temperature assessments in streams and rivers. The methods focus on capturing heat of the summer, heat of the day conditions. In the Pacific Northwest, seasonal maximum water temperatures typically occur from mid-July to early September and between 1400-1800 in the afternoon. This time frame also facilitates image interpretation since it corresponds to the time of maximum thermal contrast between the water and terrestrial features.

A series of overlapping (30%-50%) images are acquired from a helicopter flown longitudinally over the center of the stream with the sensors in a vertical (nadir) position. Helicopters are used to meet the maneuverability and relatively low altitude requirements of the application. The flight altitude depends on stream width, sinuosity, and valley configuration. The survey is normally conducted in an upstream direction to insure that stream reaches with the highest rate of temperature change (normally headwater reaches) are surveyed last. This minimizes the magnitude of water temperature change that occurs at any single point during the duration of the survey.

The “footprint” or ground area covered by each image frame depends on the size of the stream, the characteristics of the sensor, and the underlying objectives of the analysis. There is a direct trade-off between image footprint and pixel resolution. Since this is an airborne application, flight altitude can be selected to optimize image resolution for the survey reach. Torgersen et. al. (2001) noted decreased temperature accuracy when there were fewer than 10 pixels across the stream (i.e. in the water). For narrow headwater streams, a small image footprint is required. Conversely, larger streams with wide, complex flood plains require a larger image footprint to capture the full channel width. Table 1 lists the image size and pixel resolution relationship for an THV1000 (FLIR Systems, Inc.) thermal infrared radiometer.

Table 1 – Image size versus pixel size for the TIR Systems Inc. THV1000 thermal infrared radiometer in the wide field of view (20°H and 13°V).

<i>Altitude (AGL)</i>	<i>Image Width</i>	<i>Pixel Size</i>
305 m (1000 ft)	107 m	0.18 m
457 m (1500ft)	161 m	0.27 m
607 m (2000ft)	215 m	0.36 m
914 m (3000ft)	322 m	0.54 m

Because each watershed has unique characteristics, image acquisition must be tailored to meet the challenges and restrictions within the basin. For example, wilderness areas and regions with nesting birds, such as marbled murrelets and bald eagles, generally have altitude (above ground level) restrictions that must be considered. Likewise, urban streams are often difficult to track due to a lack of visual cues available to the pilot combined with an increased workload due to air traffic. In designing surveys, the watershed manager and the data collection contractor should review the physical characteristics of the intended stream reach and any possible flight restrictions. Table 2 outlines some of the potential factors that should be considered when designing a flight plan.

Table 2 – Operational considerations in designing and implementing a TIR survey.

Consideration	Questions
Stream	How sinuous is the stream? What is the valley form? Mean summer temperatures? Thermally stratified reaches?
Basin	Designated wilderness – altitude restrictions?
	Proximity to restricted airspace – time and altitude?
	Sensitive species – altitude restrictions/other issues?
Procedural	USFS Dispatch - Project Safety Aviation Plan.
	Coordination with field crews.

Ground-based Measurements

In-stream temperatures are customarily measured as part of a TIR survey. The in-stream data loggers are used both to verify the accuracy (ground truth) of the radiant temperatures derived from the TIR images and to provide a temporal context for assessing the TIR survey in relation to the diurnal temperature cycle. The number and location of in-stream monitoring sites depend on the extent of the survey and accessibility to the stream. Ideally, in-stream sites are located at the beginning, middle, and end of the survey. The data loggers should be deployed in accordance with state water quality monitoring guidelines.

Meteorological parameters are measured in the basin at the time of the survey. These parameters include air temperature, relative humidity, wind speed, and sky condition. In addition to a record of conditions on the date of the survey, the TIR contractor uses these meteorological data to compute atmospheric transmission and ambient background conditions for calibration of the TIR imagery.

Additional ground based measurements depend on the specific objectives of the study. For example, for stream temperature modeling efforts, in-stream flow measurements are recommended. Generally these measurements should occur at the time of the TIR survey. For example if the stream has flow regulation (e.g., inputs and withdrawals), in-stream flow measurements should occur on the same day of the survey. On these streams, continued flow monitoring should determine whether the TIR survey represents characteristic flow conditions. On streams without flow regulation, the in-stream flows should be measured within a week of the TIR survey and inside of any major rainfall events.

Image Processing

The objective of image processing is to produce the base products used for stream temperature analysis. In this regard, the procedures and level of processing depend on the specifics of the instrumentation and the intended applications. At a minimum, image acquisition produces a series of TIR images in a format that is readable by common image processing software. Image processing generally consists of image calibration, image georeferencing, image interpretation, and temperature sampling. Each of these is explored in turn.

Calibration

Image calibration refers to the conversion of measured energy to accurate surface water temperatures. The specific methodology depends on the format of the raw images and the method used to apply sensor calibration coefficients to the imagery. As a result, image calibration is often performed by the image acquisition contractor and independently verified by the end user. In general, conversion of the measured radiance values to temperatures is a direct application of Planck's Blackbody law with corrections for the emissivity of natural water, ambient background reflections, and atmospheric transmittance (Torgersen et. al. 2001). Since TIR stream surveys typically cover large spatial areas and changing aspects, ground truthing is often a preferred method for fine-tuning the calculation of atmospheric transmittance and ambient reflection.

Georeferencing

Automated georeferencing of image frames requires accurate recording of aircraft/sensor attitude (pitch, roll, yaw), aircraft elevation above ground level (AGL), and aircraft position. While aircraft altitude and position are commonly recorded, the attitude of the sensor is not normally known with enough precision to provide accurate control points in the images. In order to record these values, the sensor suite would have to include an inertial measurement unit. These units are quite expensive and not typically integrated into commercially available TIR sensor mounts. Consequently, geographic position information is often presented in the form of a flight index that contains the image name, acquisition time, and geographic location of the aircraft at the time of acquisition.

Because TIR imagery is typically acquired without specific information about the attitude of the aircraft, (tip, tilt, and roll) imagery must be manually mosaicked and georeferenced. There is no technical difference between referencing TIR imagery and referencing other types of digital imagery. One characteristic, however, that may make it difficult to georeference is that digital TIR images are small in size. As Table 1 illustrated, images typically range in size from 100 to 300 meters across. Small size footprints are difficult to georeference not only because of the large number of images needed to obtain information over a large area of land, but also because each image has fewer features by which to locate it on the reference base. In addition, the small size requires the user to mosaic several frames in order to obtain a large area on the ground.

For many applications, TIR images do not need to be georeferenced to provide useful information. Due to the relatively low operating altitude, the position of the aircraft at the time of image acquisition is on average within 100 meters of the image center point (sensor at nadir) (Figure 15). In specific cases, where temperature variation within a small area needs to be addressed, it may be necessary to mosaic and georeference portions of stream segments. However, because of the overwhelming amount of information that TIR provides over small areas, georeferencing should only be done for project-level analysis (as opposed to watershed level analysis) where a georeferenced image mosaic enhances the overall interpretability of the frames (Figure 16).

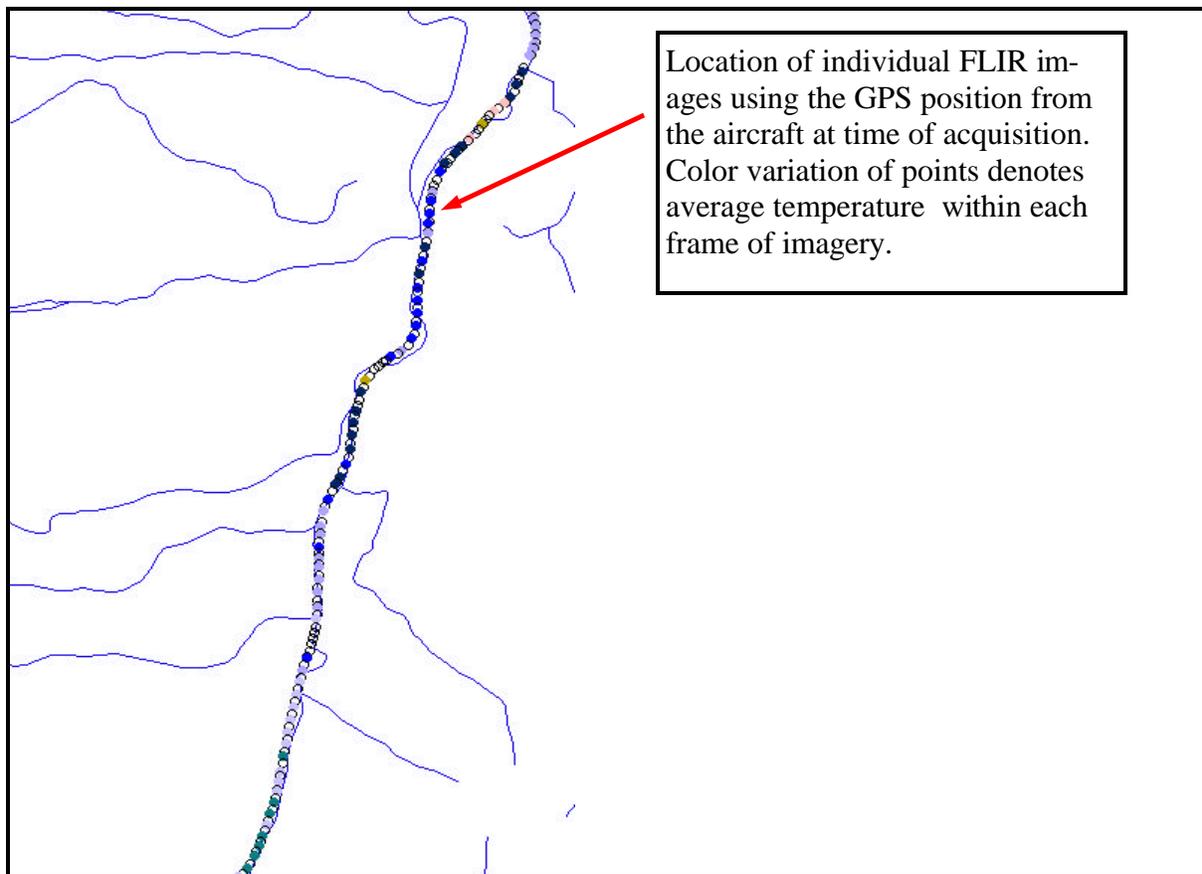


Figure 15. For most applications, georeferencing and mosaicking FLIR images is not necessary. As shown here, the GPS location for each image is associated with the corresponding average temperature and plotted on a base map.

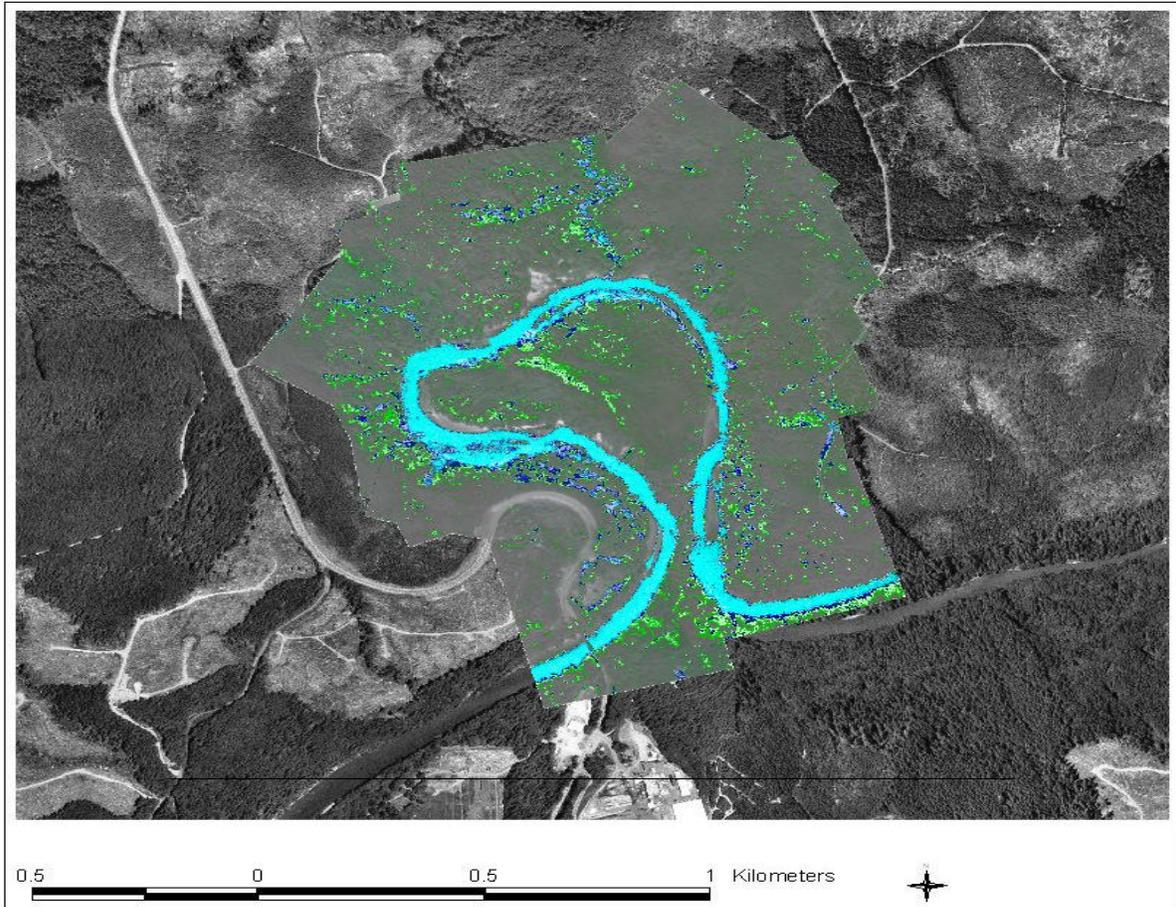


Figure 16. Example of a TIR image mosaic registered and warped to a digital orthophoto. Note that the downstream features match relatively close to the reference image, but the stream channel upstream of the Oxbow is off by approximately 70 meters.

Temperature Sampling

Calibrated TIR images are viewed within an image processing or GIS environment. The images are typically assigned a color map emphasizing differences in stream temperatures. Stream temperatures are sampled directly from the images. There are several options for sampling the imagery. One of the most straightforward is for an analyst to sample image pixel (temperature) values longitudinally along the center of the stream channel. Ten or more samples are taken in the center of the stream channel and the median value of the sample set is entered directly into the point coverage. The point coverage, recall, is the file derived from the GPS flight locations for each of the FLIR images. Likewise, the temperature of tributaries and other detectable surface inflows is also sampled from the images. These inflows are sampled at their mouth using the same techniques described for sampling the main channel. If possible, the surface inflows are identified on the base maps. Once all images are sampled, the median temperature for each image is plotted versus the stream measure (i.e. river mile). Examples illustrating this technique were shown previously in Figures 4 and 6.

Image Interpretation

During sampling, the analyst interprets the imagery to identify thermal features and make observations about channel characteristics. Thermal features include locally cool areas, such as sources of hyporeic flow that may represent thermal refugia. Man made features such as impoundments and diversions are also noted. Detection of the main channel and major tributaries is straightforward due to the normally high thermal contrast between the stream and the surrounding terrain. However, interpretation of off-channel features normally requires knowledge of the inherent characteristics and limitations of TIR images. As with all forms of image interpretation, the analyst should have experience with the object under study (i.e. stream hydrology).

Water has a high thermal inertia and therefore changes slowly in response to shadows from terrain and/or clouds. By contrast, terrestrial features often change temperature rapidly in response to shading or wind. As a result, shadows within the riparian zone often create signals on TIR imagery that are difficult to interpret (Figure 17). The analyst should consider whether the feature corresponds to visible shadows or if the shape and location of the feature is consistent with natural hydrologic features. In some cases, a thermal feature is left unclassified and may require field verification depending on its significance.

Ambient reflections in the TIR band can result in thermal patterns on the water surface. These reflections are typically low in magnitude ($\leq 0.5^{\circ}\text{C}$), but can confound image interpretation. Torgersen et. al. (2001) documented a 0.4°C difference in apparent temperature of pools and associated riffles. The dissimilarity was associated with differences in the reflective characteristics of pool and riffle surfaces. In addition, reflections from clouds and surrounding terrestrial objects are often visible in the thermal imagery of stream surfaces. Maintaining vertical view angles during the survey minimizes the coincidence of TIR reflections, however, the image interpreter should be aware of the possible presence of reflections.

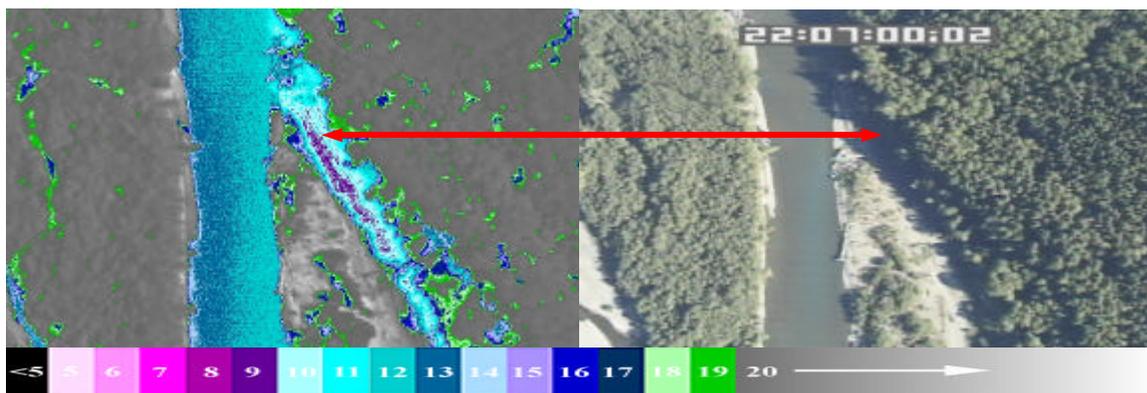


Figure 17 - TIR/visible band image illustrating how visible shadows can create features within the riparian zone that appears cooler than the stream. As shown, the features are often linear and make manual interpretation difficult. These features also add complexity to automated sampling procedures.

An important property of water is that it is essentially opaque to thermal infrared wavelengths. The water surface, which is 0.01 cm thick, determines the thermal radiance of water (Wolfe and Zisisse 1985). This fact drives two important considerations in the interpretation of TIR images. First, heat energy that is transferred from the streambed through conduction is not transmitted through the water column even at shallow depths. Consequently, the TIR remote sensing can provide accurate surface water temperature without needing to consider stream depth. This is important since water depth varies both horizontally and laterally along the natural stream course. Second, because TIR remote sensing is only measuring the water surface, it may not accurately describe temperatures vertically in the water column. This occurs where the water column is not completely mixed and a thermally stratified condition develops. While natural stream systems are often characterized by turbulent flow, thermal stratification may occur in deep slow moving channels or behind in-stream impoundments. The occurrence of a thermally stratified condition is largely a matter of spatial scale and does not generally impact the utility of the TIR data.

A number of techniques can be collectively used to identify thermally stratified areas. One method is the calculation of Reynolds Number (Fetter, 1994) to determine whether flow within a reach is turbulent or laminar. In addition, because thermal stratification in moving water is inherently unstable, TIR imagery itself is a good source for identifying thermally stratified areas (Figure 18). If present, thermal stratification generally occurs in locations that are sub-sets of the overall survey.

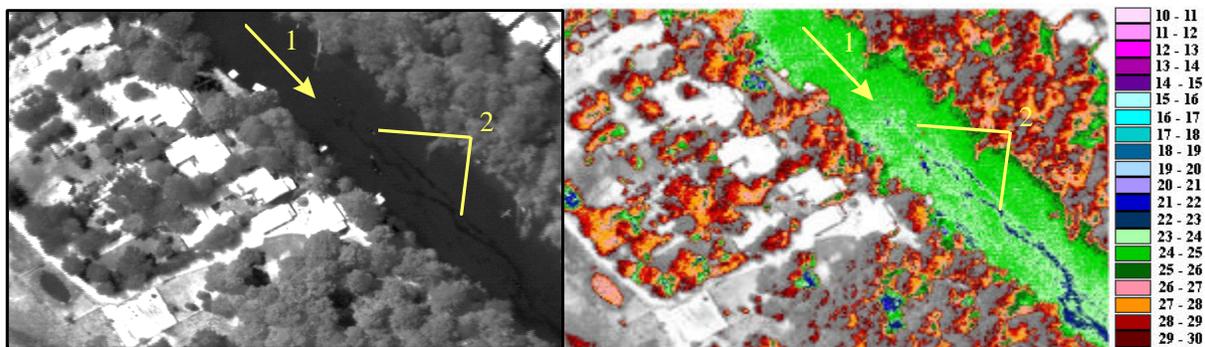


Figure 18 – The same TIR image (gray scale/pseudo-color) of the Tualatin River showing an area of probable stratification as evidenced by the cool water streaks behind in-stream objects (ORDEQ, 1999).

While the detection of a thermally stratified condition can be straightforward, the ability to directly detect cool sub-surface seeps depends on the volumetric relationship between the discharge and the in-channel flow. If the discharge is large enough relative to the stream, colder water will quickly mix to the surface and be detected as a change in bulk water temperature. If the discharge is small, however, it may not create a signal in the vertical water column. Diffuse sub-surface discharge over a reach length will be reflected in longitudinal heating profile for that reach, but may not be directly detected as such in the imagery.

An additional consideration in the interpretation of TIR remote sensing is that riparian vegetation can mask the stream and/or riparian features from the sensor. This is particularly true on small, forested streams. While most streams are at least intermittently visible through the canopy, riparian vegetation can limit the utility of the TIR sensor for identifying off-channel features and measuring the temperature of tributaries (Figure 19).

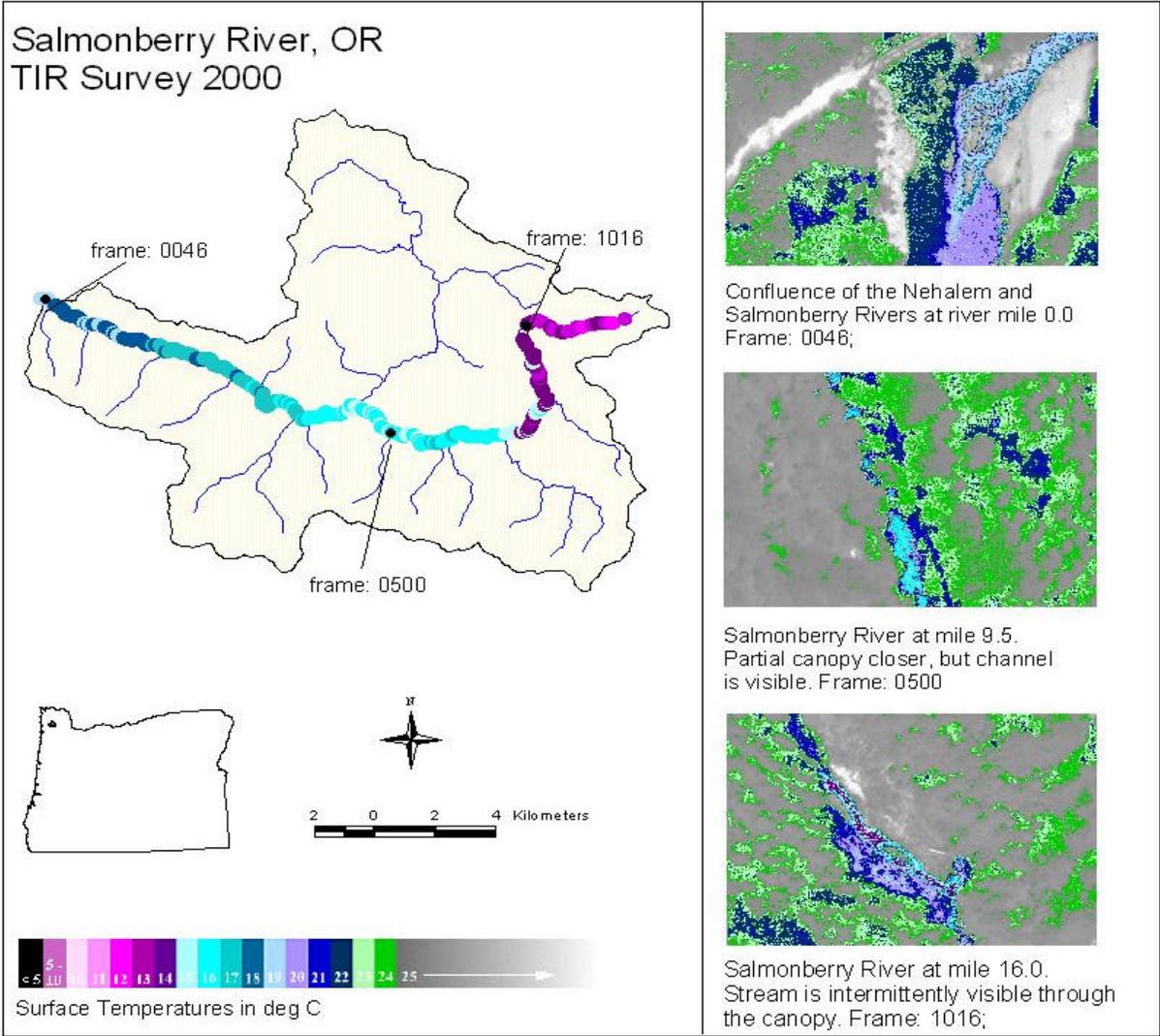


Figure 19 - Point pattern map of a TIR survey conducted on a heavily canopied 6th field watershed in Western Oregon. The pseudo-color TIR images on the right provide examples of canopy closure at different locations along the stream length.

Including TIR Remote Sensing in a Monitoring Program

As with many remote sensing applications, the purchase of a TIR sensor suite represents a significant capital investment. The direct cost of the sensor suite (TIR radiometer, color video camera, GPS, recorders, etc.) and aircraft mounts typically exceeds \$250,000. The indirect cost of training personnel to operate and maintain the equipment is similarly high. As a result, experienced commercial contractors are typically hired to acquire and process the TIR images. Table 3 outlines a characteristic set of deliverables for recent TIR surveys in the Pacific Northwest. The cost for this level of data collection and analysis averages about \$250/mile plus mobilization. Since temperature issues traverse multiple land-uses and interests, the costs for basin scale surveys are often shared through cooperative agreements between federal, state, tribal, and private entities.

Table 3 - Standard Deliverables for TIR Surveys.

Standard Deliverables	<ul style="list-style-type: none">• A sequence of calibrated overlapping digital TIR images of selected stream reaches in a generic format.• Verification of TIR image accuracy for measuring surface water temperatures (0.5°C).• Flight log containing the name and geographic coordinates (i.e. latitude, longitude) for each image frame.• Longitudinal temperature profile showing the median stream temperature and temperature of point source inflows plotted versus stream mile.• Observations of thermal features along the survey reach.• Visible band color video showing the same ground area that can be used to facilitate interpretation of the TIR images.
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Conclusions

TIR imagery provides a spatially continuous map of surface water temperatures that complements traditional in-stream point monitors. These data present a synoptic view of thermal conditions in a river basin and ultimately provide a better understanding of the physical factors influencing stream temperatures at different spatial scales. A standard product of a TIR project is a longitudinal temperature profile that shows the patterns of warming and cooling in relation to distance from the stream mouth (or watershed divide). The TIR survey also documents the location and temperature of surface water inflows and the location of thermal features such as springs.

TIR surveys conducted on the same stream reach in multiple years have shown that the patterns of warming and cooling remain spatially fixed between years. Simply stated, an area of cool thermal refugia will likely persist year after year (barring significant landscape or channel changes). Similarly, heat source areas remain at fixed locations year after year. As a result, spatial temperature patterns measured during one summer can help direct future monitoring and restoration efforts by providing a basis for placement and interpretation of in-stream sensors. Spatial temperature patterns at the unit and sub-unit scale can identify potentially critical habitat within the watershed. These data can direct future field monitoring or designate areas for protection. Further, TIR surveys provide baseline measures for recovery tracking

As with other non-visible data, interpretation of TIR necessitates an understanding of the inherent nature of the imagery. The analyst should understand how thermal, not visible, contrast allows detection of features within the scene. To date, the interpretation and analysis of the imagery has been a manual process with the primary automation in the organization and display of imagery. A manual review of the images allows the analyst to make knowledge-based judgments regarding the biologic and/or hydrologic importance of the observed features. In addition, manual review allows the analyst to draw conclusions about riparian conditions and the near stream microclimate. These types of knowledge-based assessments are especially difficult to automate in non-georeferenced imagery where the computer cannot draw supporting information from other images or data sets.

The ability to remotely measure accurate water temperatures requires an understanding of the nuances of sensor calibration and of the relative contributions of atmospheric and ambient factors to the measured radiant energy value. In addition, ground truthing is often necessary to fine-tune the temperature conversion and to verify the overall accuracy of the results. As a result, the acquisition of TIR imagery generally involves hiring a qualified contractor to provide flight services and accurate calibration of the imagery.

Resource managers should consider how TIR data can contribute to their stream temperature monitoring programs. The contribution of TIR and in-stream sensor data represents a balanced monitoring approach where both the inherent temporal and spatial components of stream temperature are quantified. In this regard, the principal uses of the TIR images to date have been to (1) better understand the dynamics of thermally complex stream systems,

(2) calibrate stream temperature models, (3) map thermal refugia, (4) identify ground water sources, (5) establish a baseline for long term tracking, and (6) facilitate interpretation and placement of in-stream monitors. Secondary uses include qualitative assessments of the riparian corridor including thermal microclimate.

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