

Prepared in cooperation with the  
New York State Department of Environmental Conservation and Rochester Institute of Technology

## Identifying Trout Refuges in the Indian and Hudson Rivers in Northern New York Through Airborne Thermal Infrared Remote Sensing



Open-File Report 2015–1078

**Cover.** The Hudson River upstream of its confluence with the Boreas River. Photograph by Barry P. Baldigo, U.S. Geological Survey.

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# Contents

Abstract.....	1
Introduction.....	1
Study Area.....	2
Methods.....	4
In-Stream Temperature and Stage Loggers.....	4
Airborne Thermal Infrared Sensing.....	4
Image Processing.....	5
Image Analysis.....	5
Longitudinal Temperature Profiles.....	5
Refuge Determination.....	5
Split 1-Kilometer River Reaches.....	6
Tributary Confluences.....	6
Results.....	6
Water Stage and Temperature at Data Logger Sites in Relation to Reservoir Releases.....	6
Longitudinal Temperature Profiles.....	7
Refuge Identification in Split 1-Kilometer Sections.....	7
Cold-Water Contributions From Tributaries.....	11
Discussion.....	13
Study Limitations.....	14
Summary.....	15
References Cited.....	15

## Figures

1. Map showing locations at seven stream sites where temperature loggers and crest stage gages were placed for study of thermal refuge areas along a 27-kilometer study reach below the Lake Abanakee Dam on the Indian and Hudson Rivers in northern New York in 2005–6 .....3
2. Graphic representation of refuge number, size, and distance calculations.....6
3. Graphs showing longitudinal thermal infrared temperature profiles along the study reach on August 25, 2005, at *A*, 1012; *B*, 1239; and *C*, 1542 eastern standard time (EST), with box plots showing temperature range and mean at seven sites on release and on nonrelease days from July 21 through September 21, 2005, and locations of five cold-water tributaries.....8
4. False-color thermal infrared images showing cold-water areas at the confluences of Raquette Brook at kilometer 24 and Deer Creek at kilometer 27 with the Hudson River in the Adirondack Mountains, New York, during three overhead flights on August 25, 2005, at *A*, 1012 eastern standard time (EST), *B*, 1239 EST, and *C*, 1542 EST when passage of reservoir release overwhelmed any cooling effect of inflow from tributaries.....12

## Tables

1. Median water temperature for right (R) or left (L) half of each 1-kilometer (km) section of river channel; mean size, standard deviation, and maximum size of refuge areas in which water temperature was 1 to 2 degrees Celsius (°C), and more than (>)2 °C below the median temperature for that section; and mean distance, standard deviation, and median and maximum distances between refuges during three flights over the 27-km study reach of the Indian and Hudson Rivers in northern New York, August 25, 2005 .....9
2. Median water temperature in five river sections containing a cold-water tributary; mean size, standard deviation, and maximum size of refuge areas in which water temperature was 1 to 2 degrees Celsius (°C) and more than (>)2 °C below the median temperature for that section; and mean distance, standard deviation, and median and maximum distances between refuges during three flights over the 27-kilometer (km) study reach of the Indian and Hudson Rivers in northern New York, August 25, 2005 .....11

## Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m <sup>2</sup> )
acre	0.4047	hectare (ha)

International System of Units to Inch/Pound

Multiply	By	To obtain
Length		
kilometer (km)	0.6214	mile (mi)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as  
 $^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$ .

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as  
 $^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$ .



## Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

## Abbreviations

BMT	below median temperature
EST	eastern standard time
FLIR	forward-looking infrared
RIT	Rochester Institute of Technology
TIR	thermal infrared
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator



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By Anne Gallagher Ernst,<sup>1</sup> Barry P. Baldigo,<sup>1</sup> Fred J. Calef,<sup>1</sup> Douglas A. Freehafer,<sup>1</sup> and Robert L. Kremens<sup>2</sup>

## Abstract

The locations and sizes of potential cold-water refuges for trout were examined in 2005 along a 27-kilometer segment of the Indian and Hudson Rivers in northern New York to evaluate the extent of refuges, the effects of routine flow releases from an impoundment, and how these refuges and releases might influence trout survival in reaches that otherwise would be thermally stressed. This river segment supports small populations of brook trout (*Salvelinus fontinalis*), brown trout (*Salmo trutta*), and rainbow trout (*Oncorhynchus mykiss*), and also receives regular releases of reservoir-surface waters to support rafting during the summer, when water temperatures in both the reservoir and the river frequently exceed thermal thresholds for trout survival. Airborne thermal infrared imaging was supplemented with continuous, in-stream temperature loggers to identify potential refuges that may be associated with tributary inflows or groundwater seeps, and to define the extent to which the release flows decrease the size of existing refuges. In general, the release flows overwhelmed the refuge areas and greatly decreased the size and number of the areas. Mean water temperatures were unaffected by the releases, but small-scale heterogeneity was diminished. At a larger scale, water temperatures in the upper and lower segments of the reach were consistently warmer than in the middle segment, even during passage of release waters. The inability of remote thermal infrared images to consistently distinguish land from water (in shaded areas) and to detect groundwater seeps (away from the shallow edges of the stream) limited data analysis and the ability to identify potential thermal refuge areas.

## Introduction

Water temperature is a central component of aquatic ecosystems, and plays a pivotal role in determining the suitability of stream and river habitat to trout, especially

with the threat of climate change (Elliott and others, 1995; Biro, 1998; Wehrly and others, 2003; de la Hoz Franco and Budy, 2005; Caissie, 2006; Flebbe and others, 2006; McMahon and others, 2007; Wehrly and others, 2007). Stream temperatures not only affect the distribution, behavior, and survival of trout (and other species), but also compel these species to move toward areas of preferred temperatures, known as refuges, to maximize growth, survival, and fitness (Peterson and Rabeni, 1996; Torgersen and others, 1999; Ebersole and others, 2001). The longitudinal gradient of temperatures along a stream has been recognized as a factor affecting the distribution of fish (Vannote and others, 1980), but lateral and vertical heterogeneity is increasingly recognized as an important component of stream thermal structure (Torgersen and others, 2001; Ebersole and others, 2003b). This heterogeneity can create a patchwork of water temperatures that includes cold-water refuges in a warm stream. Several studies confirm that salmonids can avoid the sublethal stresses when water temperatures approach critical limits by relocating to cold-water refuges (Bermann and Quinn, 1991; Power, 1997; Torgersen and others, 1999; Baird and Krueger, 2003). For example, mature Chinook salmon (*Oncorhynchus tshawytscha*) in the Yakima River, Washington, maintained body temperatures that were 2.5 degrees Celsius (°C) lower than the surrounding stream temperatures by sheltering in areas of cooler temperature to optimize energy conservation (Bermann and Quinn, 1991). Similarly, Baird and Krueger (2003) determined that brook trout (*Salvelinus fontinalis*) and rainbow trout (*Oncorhynchus mykiss*) in an Adirondack river occupied sites that were 4 °C and 2.3 °C cooler, respectively, than surrounding waters. Cold-water refuges, if available, can therefore allow fish to survive in streams that otherwise might be uninhabitable.

Cold-water refuges in streams are a product of thermal heterogeneity, which can result from the interaction of surface, hyporheic, and groundwater sources along alluvial streambeds or from any patchiness in water temperatures caused by geomorphology, hydrology, or vegetation. Thermal refuge areas may include groundwater seeps, tributaries, emerging streambed flow, and vegetative and topographic shading (Bilbey, 1984). The development and extent of these

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## 2 Identifying Trout Refuges in Northern New York Through Airborne Thermal Infrared Remote Sensing

features may be highly spatially variable and reflect a variety of landscape characteristics. Refuges can provide resilience to fish and other stream organisms under thermal stress, but the effectiveness of the refuges at sustaining populations depends on the spatial arrangement, frequency, and connectivity of the refuge patches, as well as the condition of the refuge itself (Dunning and others, 1992; Townsend and others, 1997). Determining the spatial distribution and characteristics of thermal refuges within stream systems, therefore, is critical to understanding the habitat of cold-water fish and other organisms.

Airborne thermal infrared (TIR) sensing has recently begun to be used in the eastern United States as a remote stream-monitoring tool. Applications of airborne TIR sensing have been important to both marine and lacustrine systems and have more recently been developed for streams in the Pacific Northwest of the United States (Belknap and Naiman, 1998; Torgersen and others, 1999; Torgersen and others, 2001). Several studies have used TIR remote sensing to assess stream temperature patterns in relation to habitat use by salmon. For example, Belknap and Naiman (1998) indicated that TIR remote sensing was effective at detecting wall-base channels, a geomorphic habitat essential for juvenile Coho salmon refuge and rearing, and Torgersen and others (1999) correlated Chinook salmon distribution and cold-water temperature patterns using TIR remote sensing.

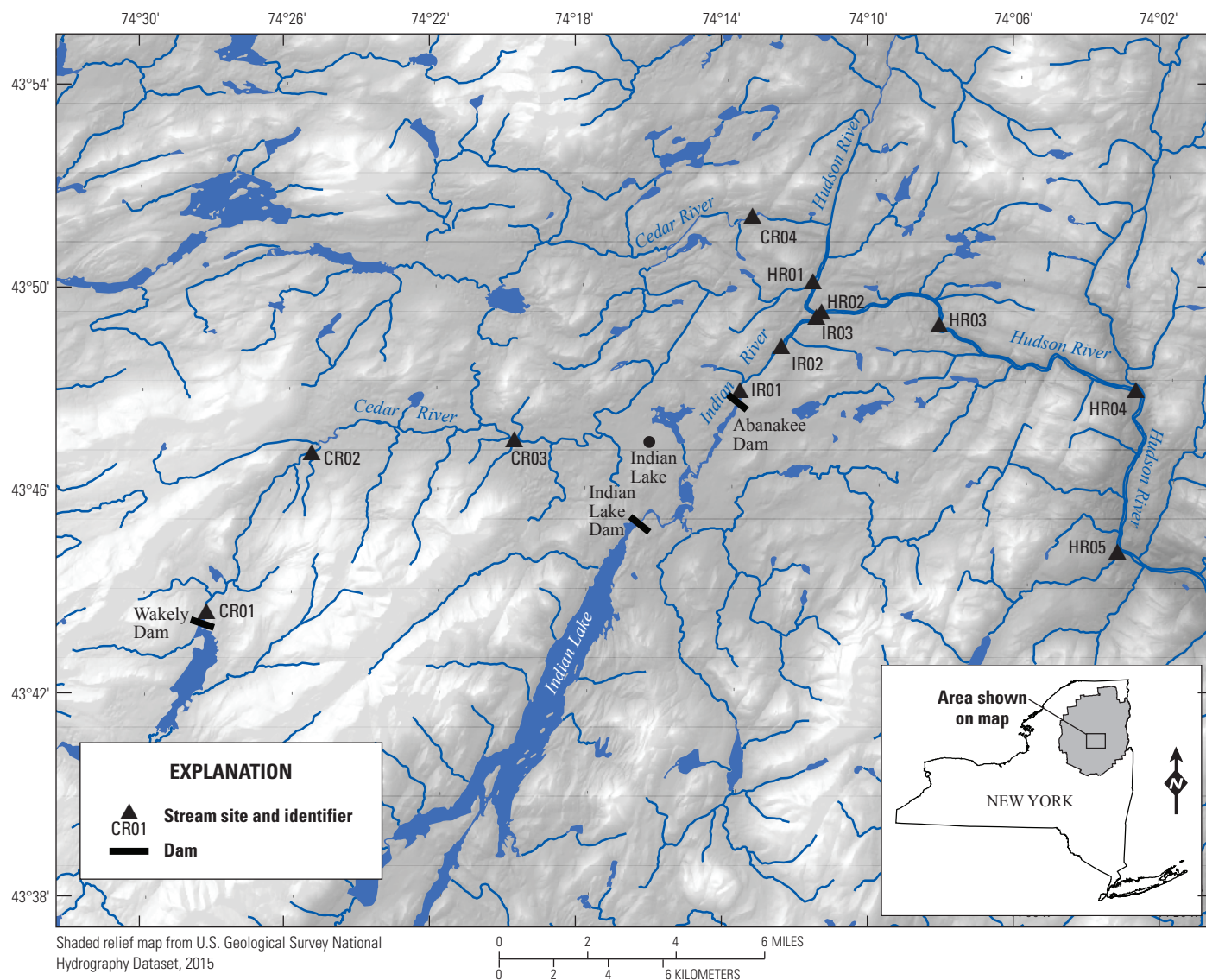
Airborne TIR sensing can be an effective tool for determining the spatial distribution of thermal heterogeneity in a stream system. For a large area, TIR can cover hundreds of river kilometers, whereas for smaller areas it can reveal thermal patterns along short reaches to allow delineation of cold-water refuges. It is especially useful for remote streams or river reaches with only limited access (Faux and others, 2001; Torgersen and others, 2001). This type of imaging can be used to map water temperature patterns along streams or rivers at multiple scales (Torgersen and others, 1999, 2001) and thereby reveal the locations and potential suitability of cold-water areas as fish refuges. Torgersen and others (2001) analyzed temperature patterns in several rivers in Oregon and determined that peaks and troughs in the longitudinal profile over short distances were caused by tributary inputs, whereas large-scale patterns like warming or cooling trends over 5 to 10 kilometers (km) generally reflected watershed-scale processes, such as geomorphic, riparian, and hydrologic processes. Thus, thermal remote sensing of streams provides limited information about the hydrologic processes that influence stream temperature, but it can be an effective tool for evaluating the patterns caused by those processes. The ability of TIR remote sensing to map the spatial distribution (patchiness) and detect changing patterns in cold-water refuges at multiple spatial scales could be used to effectively assess the availability and quality of thermal refuges for resident trout at the reach level.

In 2005, the U.S. Geological Survey (USGS), in cooperation with the New York State Department of Environmental Conservation and Cornell University, began

a multidisciplinary study to assess natural resources in the Indian and Hudson Rivers along a reach that receives regular recreational releases from an upstream reservoir to support whitewater rafting. The main objective of the study was to evaluate the potential effects of these releases on the resident and stocked brown trout (*Salmo trutta*) fishery. A related goal, and the focus of this report, was to identify cold-water areas that could provide refuges possibly critical to the survival of stocked and resident trout during periods of thermal stress (the warm summer months). Stream temperature data from seven continuous loggers and TIR remote sensing data from the 27-km reach affected by release flows were analyzed to (1) assess the effectiveness of thermal remote sensing to detect spatial patterns in stream temperatures at multiple spatial scales, (2) identify potential thermal refuges at base flow and during release flows, (3) define how the release flows affect the size and temperature of the identified refuges, and (4) compare the results of thermal refuge identification made at several spatial scales. Analyses evaluate hypotheses that the size and number of thermal refuges are diminished by recreational flow releases.

### Study Area

The study reach is located in the Adirondack Park of northeastern New York and includes the lower 5 km of the Indian River, from the Lake Abanakee Dam to its confluence with the Hudson River, and 22 km of the Hudson River from that confluence to North Creek, New York (fig. 1). This section of the Hudson River flows through the Hudson Gorge Primitive Area, a 17,000-acre New York State Forest Preserve. This study reach was selected because it is directly affected by the reservoir releases, it covers the entire affected section of river that runs through the Hudson Gorge Primitive Area, and it is of manageable length for field measurements. The drainage area is 505 square kilometers (km<sup>2</sup>) near the top of the reach at station IR01 and increases to 1,626 km<sup>2</sup> after its confluence with the Hudson River (station HR02) and to 1,968 km<sup>2</sup> by the bottom of the reach (station HR05; fig. 1). The reach is mainly accessible by foot along several hiking trails or by boat, and supports populations of native brook trout as well as naturalized and hatchery (stocked) brown trout and rainbow trout. Water temperatures in parts of the study reach typically exceed lethal thresholds for these species (22–24 °C for brook trout, 24–27 °C for brown trout, and 24–25 °C for rainbow trout; Raleigh, 1982; Raleigh and others, 1984, 1986; Wehrly and others, 2007) for several weeks each summer (Baldigo and others, 2010). Extensive whitewater in the study reach also provides the setting for a commercial rafting industry that operates from April through October. The raft-launching site is located on the Indian River just downstream from the Lake Abanakee Dam. The dam is owned and operated by the Town of Indian Lake. The town makes regular top-water releases from the dam daily during



**Figure 1.** Locations at seven stream sites where temperature loggers and crest stage gages were placed for study of thermal refuge areas along a 27-kilometer study reach below the Lake Abanakee Dam on the Indian and Hudson Rivers in northern New York in 2005–6. The upper, middle, and lower study reaches fall between sites IR01 and IR03, HR02 and HR04, and HR04 and HR05, respectively. An eighth, control site (HR01) was upstream from the middle study reach. Modified from Baldigo and others (2010).



## 4 Identifying Trout Refuges in Northern New York Through Airborne Thermal Infrared Remote Sensing

the spring and on 4 days of each week in the summer and fall to augment seasonal low flows. These brief (1.5- to 2-hour) recreational releases are vital to the rafting industry.

## Methods

### In-Stream Temperature and Stage Loggers

Fixed stage and temperature loggers were placed in steel pipe extending well above bankfull to roughly 0.67 meter (m) below the water surface at each of seven sites along the 27-km study reach; three of the sites were on the Indian River, and four were on the Hudson River (fig. 1). An eighth (control) logger was placed on the Hudson River upstream from the confluence with the Indian River and thus was unaffected by releases from the impoundment. Loggers along the Hudson River were placed in areas that were accessible by hiking trails, railroad tracks, and (or) moderate wading. The loggers recorded water temperatures and stage at 15-minute intervals from approximately June 30 through October 27 in 2005 and from approximately April 20 through September 26 in 2006 to provide a record of daily and seasonal in-stream temperature fluctuations (Baldigo and others, 2010). The gages at each site recorded changes in water level (stage), the times of day at which stage increases associated with a dam release occurred, and the times at which stage returned to its original starting level. These data were plotted as a function of distance downstream from the Lake Abanakee Dam to estimate the start and end times of high water along the river at each gage. These times on August 25, 2005, were compared with time-stamped TIR images of the river at high and low flows to verify their accuracy.

### Airborne Thermal Infrared Sensing

Spatially continuous surface water temperatures along the study reach were mapped with TIR photography during three low-altitude flights (beginning at 1012, 1239, and 1542 eastern standard time [EST]) on August 25, 2005, a release day. The release began at 0930 EST and lasted 2 hours. Durations for the three low-altitude flights of the survey airplane were 43 minutes, 37 minutes, and 23 minutes, respectively. Airborne TIR remote sensing detects thermal radiation from the upper 0.1 millimeter (mm) of the water surface (Wick and others, 1996). Because the study reach consists of many rapids and riffles, the water in the reach was generally assumed to be well mixed and surface water temperatures were assumed to be a valid proxy for water temperature profiles along the river. Thermal stratification is uncommon in streams with turbulent flow (Torgersen and others, 2001), although cold seeps and (or) tributaries may alter temperatures locally. The plane was equipped with a forward-looking infrared (FLIR) system,

which detected thermal energy in the 0.7- to 9.2-micrometer ( $\mu\text{m}$ ) waveband (also called thermal infrared). Long-wave infrared typically measures a band of 8 to 14  $\mu\text{m}$ , but the equipment used in this study measured a smaller band (1.4 to 8  $\mu\text{m}$ ). Short bandwidths are more sensitive to reflection than longer bandwidths and thus may have increased the error. A separate camera collected visible spectral band imagery (0.4–0.7  $\mu\text{m}$ ). Thermal and visible cameras covered the same ground area; each image frame represented a ground area of about  $100 \times 150$  m and had a spatial resolution of about 1 m. Each pixel represented 1 square meter ( $\text{m}^2$ ) of water surface. Thermal images were collected digitally and recorded directly from the sensor to an onboard computer and tagged with acquisition time and geographic position data. Visible band imagery and acquisition time were recorded to an onboard digital video recorder.

All flights surveyed the river in a downstream direction. These flights recorded data during low and high flows (before, during, or after the arrival of the slug from the release) at most points along both rivers, although no single flight covered the whole study reach under either low or high flow. The datasets from all three flights are missing from 0.3 to 0.7 km of data near kilometer 16 of the study reach; the first flight also is missing 0.5 km of data from kilometer 23.

Thermal radiation measurements can be affected by emissivity, atmospheric transmission, view angle, and water surface characteristics (Smith and others, 1996; Faux and others, 2001; Torgersen and others, 2001). Emissivity is a measure of the ability of a material to absorb and radiate energy in relation to the energy radiated by a black body at the same temperature. Water is a nearly ideal infrared black body emitter with an emissivity close to 1; therefore, no emissivity corrections were made. Atmospheric transmission effects were small because the flying altitude was low; the data were corrected through an in-scene calibration from the seven temperature-measurement sites and had a resolution of approximately 0.1 °C. View-angle effects were minimized by flying at a low altitude near vertical incidence and by using a narrow field of view (approximately 50-degree full width). Rough water surfaces, such as riffles and rapids, have lower emissivity than smooth water and therefore can seem slightly warmer, although the difference is small (less than [ $<$ ] 0.1 °C; Masuda and others, 1988).

Airborne TIR remote sensing is an effective means of detecting cold-water refuges within a large river system, but it only gives an instantaneous overview of spatial stream temperature patterns, whereas a temperature logger record is continuous but limited to a single location. Thermometers can be physically moved through streams to detect thermal refuges (Ebersole and others, 2003a), but this technique is spatially limited. Combining temporally continuous data from stationary instruments with spatially continuous data obtained through remote sensing provides an integrated database of stream temperatures across scales ranging from geomorphic channel units (riffles and pools) to an entire drainage basin (Torgersen and others, 1999, 2001).

## Image Processing

Airborne TIR remote sensing data were processed through ERDAS Imagine version 8.4 image-processing software and analyzed within the Esri Inc. ArcGIS geographic information system (GIS; ESRI Inc., 1995). The FLIR imagery was converted into GIS-point coverage to provide a basis for integration with other spatial data layers. Each image was geometrically corrected to a Universal Transverse Mercator (UTM) zone 18N projection, the standard for New York State. A linear equation was derived to convert TIR radiance values into temperature values based on corresponding temperatures at the in-stream loggers. Images were stored in a format in which each pixel was assigned a temperature value, rounded to the nearest 0.1 °C. Thermal images were color-coded to facilitate interpretation of thermal patterns.

Individual thermal image frames (119–188 per flight) were aligned with 30 to 40 percent overlap in a downstream direction to form a single mosaic image for each of the three flights. A separate mask for each flight was digitized by hand with the visible-spectrum image data to separate land from water. Each mask was then overlaid on the TIR image to locate and isolate the water. The edge of water was hidden on the visible-spectrum image in places by overhanging riparian vegetation; therefore, the location of the water edge in these areas was estimated. The total length estimated was 6 to 8 km along both banks, or 11 to 15 percent of the water edge. The Imagine data profiler was used to interlock temperature data from adjacent pixels down the middle of the river channel, which served as a substitute for the river thalweg.

## Image Analysis

The location of the high-water slug was determined through visual inspection of the aerial photographs and by the crest stage gages along the study reach. Each of the three flights included data from a different section of the 27-km reach under high flow from the passage of the slug from the reservoir. For this reason, data were interpreted on an entire-reach basis as discussed in the “Longitudinal Temperature Profiles” section, and in smaller (1-km) sections as described thereafter for evaluation of each section at low and high flows. Additionally, a smaller scale analysis was used to assess aggregations of cold-water pixels at potential refuge locations.

## Longitudinal Temperature Profiles

Median temperatures were calculated for each pixel along the thalweg (median of 5 pixels above and 5 pixels below each pixel) and plotted as a function of distance downstream from the top of the reach to obtain a running average of temperatures along the 27-km reach for each flight. Median temperatures were used because they minimize the effect of extreme values. Although longitudinal temperature profiles represent absolute temperatures from only the time and day of

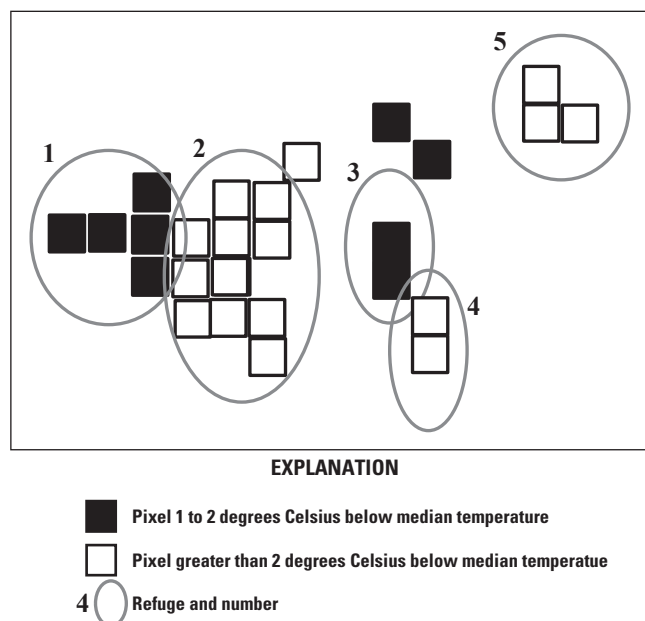
the survey, the spatial temperature patterns are often consistent among years and thus can provide a general interpretation of a river’s thermal structure (Faux and others, 2001). Longitudinal temperature profiles can also reveal thermally unique areas that can be linked to specific causes, such as groundwater seeps and tributary inflows, if a stream is shallow and (or) narrow; however, longitudinal temperature profiles may fail to reveal temperature anomalies along the edges of deep, wide rivers unless the seeps and inflows are large enough to affect the temperature in the center of the channel.

## Refuge Determination

Cold-water refuges were defined as any group of two or more consecutive pixels at least 1, 2, or 3 °C below median temperature (BMT), although no pixels in this study were more than 3 °C BMT. Previous studies have defined “cold-water refuge” as water that is at least 3 °C colder than the surrounding water (Garrett and Bennett, 1995; Ebersole and others, 2003a). Even minor differences between fish body temperature and river temperature denote active thermoregulation, however, and can be important for fish health and survival (Somero and Hoffman, 1997); therefore, the classification of a thermal refuge as being as little as 1 °C colder than surrounding water reflects this importance.

Individual pixels at least 1 °C BMT were identified in ArcGIS. Pixels that shared an edge (but not a corner) were considered connected (fig. 2). Individual, unconnected pixels at least 1 °C BMT were not included in any refuge calculations in case they were false results, and because individual, isolated pixels may not represent a usable refuge area for local fish. For all other pixels at least 1 °C BMT, the number of groups of connected pixels (refuges) and number of pixels in each group were calculated for pixels between 1 and 2 °C BMT and for pixels greater than (>) 2 °C BMT. Figure 2 illustrates how refuges were determined.

Distances between refuges were calculated by counting the minimum number of pixels from a refuge to the next nearest refuge. This calculation included all refuges where the median temperature was at least 1 °C BMT rather than separate calculations for pixels where the median temperature was 1 to 2 °C BMT and for pixels where the median temperature was >2 °C BMT. For example, a refuge with a median temperature 1 to 2 °C BMT that shared an edge with a refuge with a median temperature >2 °C BMT was considered to have a distance of 0 m separating the first from the second refuge. Refuges that were connected by corners (rather than by a shared edge) were also considered to have a distance between them of 0 m. Figure 2 illustrates how distances between refuges were determined. The decision to treat refuges of 1 to 2 °C BMT and >2 °C BMT separately may have underestimated median (and to a lesser extent mean) distances between refuges. Thus, although potentially conservative, mean values may be the best estimate of distances between refuges in most sections.



**Figure 2.** Graphic representation of refuge number, size, and distance calculations. In this example, there are two refuges 1 to 2 degrees Celsius ( $^{\circ}\text{C}$ ) below median temperature (BMT; sizes: 5 and 2 pixels) and three refuges at least 2  $^{\circ}\text{C}$  BMT (sizes: 2, 3, and 1 pixels). The distance between refuges 1 and 2 is 0 pixels, the distance between refuges 3 and 4 is 0 pixels, and the distance from refuge 5 to refuge 3 is 6 pixels.

## Split 1-Kilometer River Reaches

For analysis of water temperatures, the study reach was divided into 27 sections along the thalweg, each 1 km long. The east banks of river sections that ran north to south were shaded in the morning by riparian vegetation that allowed exposed rocks within the river to remain cooler than the water during the morning flight. The shading created two potential problems: first, exposed rocks in the morning TIR images appeared as thermal refuges that were absent in the later images when they had become warm from the sun; and second, this shading lowered the water temperature locally and thereby may have obscured genuine refuges, whose temperature is relative to the ambient water temperature. Therefore, each 1-km river section was split in half along the thalweg, and only the temperature data for the half with the lesser amount of morning shade were compiled. Median water temperature, number of refuges, average and maximum refuge size, and average and maximum distance between refuges were calculated for each split 1-km section.

## Tributary Confluences

Five tributaries entering the lower one-third of the study reach (fig. 1) were cooler than the river during at least one flight, as indicated by a large aggregation of cold-water pixels in the TIR images: Boreas River, Raquette Brook, Aldous Brook, Deer Creek, and Thirteenth Lake Outlet. Several other tributaries enter the river as well, but did not have a cooling effect on the Hudson River water temperatures. Small areas around the five cold-water confluences were delineated by hand to isolate the effects of these tributaries on the river temperature at a small scale. Area polygons were drawn such that the cold tributary water represented 15 to 25 percent of their area at base flow. For each confluence, the median water temperature, number of refuges, average and maximum refuge size, and average and maximum distance between refuges were calculated.

## Results

### Water Stage and Temperature at Data Logger Sites in Relation to Reservoir Releases

River stage at each of the seven data-logger sites followed a uniform pattern in the monitoring periods of 2005 and 2006: on release days, river stage increased sharply as the slug of water arrived at each site, then dropped below the starting stage once the slug had passed. On nonrelease days, river stage rose slowly throughout the day as a continued rebound from the sharp rise and decline that followed the previous release. Average increases in stage during releases in June, July, August, and September at the three Indian River sites ranged from 0.36 to 0.65 m in 2005 and from 0.24 to 0.59 m in 2006; stage increases at the four Hudson River sites ranged from 0.35 to 0.96 m in 2005 and from 0.20 to 0.40 m in 2006 (Baldigo and others, 2010). The increase in river stage generally decreased with distance downstream as the river widened, except at HR03, which is in a narrow section of the Hudson River gorge. The return to base flow also slowed downstream as the slug spread out; the high-water period lasted for less than 2.5 hours at the top of the reach (IR01), and nearly 5.5 hours at the lower end (HR05; Baldigo and others, 2010).

Baldigo and others (2010) also compared water temperatures during the release day (August 25, 2005) with those during the previous, nonrelease day to evaluate differences in water temperature patterns. Water temperature at all seven data-logger sites along the reach rose on release days and nonrelease days through the day until 3 or 4 p.m., then began to drop, although the temperature range was larger at most sites on the release day (1.2–8.7  $^{\circ}\text{C}$ ) than on the preceding day (1.2–4.4  $^{\circ}\text{C}$ ) and was larger at the Hudson River sites than at the Indian River sites. No consistent



relation between temperature and stage was noted; water temperature tended to rise less from start to peak of the release than during the same time period on nonrelease days, but this difference between release and nonrelease days was only significant ( $P < 0.05$ ) at three of the seven sites (IR01, IR02, and HR04; Baldigo and others, 2010). Water temperatures did not differ significantly between release and nonrelease days except at HR02 during the first flight (mean difference =  $-1.5^{\circ}\text{C}$ ,  $P=0.042$ ) and at HR03 during the second flight (mean difference =  $+0.8^{\circ}\text{C}$ ,  $P=0.093$ ). Between July 1 and August 1, 2005, means of the daily maximum water temperatures on release days did not differ significantly ( $P>0.05$ ) from those on nonrelease days at any site.

## Longitudinal Temperature Profiles

The longitudinal temperature profiles constructed for the three flight periods on August 25, 2005, indicate that river temperatures increased unevenly during the day. The three flights are as follows:

- *First flight (1012 EST).*—The high-water slug entered kilometers 1 through 5 during this flight. The temperature along most of the thalweg was below  $22^{\circ}\text{C}$  and generally decreased downstream (fig. 3A).
- *Second flight (1239 EST).*—The high-water slug entered kilometers 4 through 19 during this flight. The temperature of most of the river was around  $22^{\circ}\text{C}$ , although the middle part of the study reach (kilometers 6–18) was cooler than the upper (kilometers 1–4) and lower (kilometers 20–27) parts (fig. 3B).
- *Third flight (1542 EST).*—The high-water slug entered kilometers 16 through 27 during this flight. The temperature of most of the river was above  $22^{\circ}\text{C}$ , although the upper part of the study reach (kilometers 3–8) was much warmer than the rest, and the middle part of the study reach (kilometers 15–21) was cooler (fig. 3C).

Radiant temperatures along the thalweg were generally warmer than the median temperatures of the split 1-km sections (fig. 3; table 1), but followed the same general patterns. Thalweg temperatures tended to be cooler than the data-logger values along the banks during the first two flights, but the two were similar during the last flight (fig. 3). The thalweg temperatures correlated moderately well with the data-logger values ( $R^2=0.93$ ), although this correlation may have been lowered because overhanging vegetation made it difficult to locate radiant temperatures exactly at several data-logger sites. Differences between radiant temperatures and in-stream measurements tend to be systematic, but the similarity of trends indicates that radiant temperatures depict the same longitudinal patterns (Cherkauer and others, 2005; Hancock and others, 2005). All three flights showed many

spikes and dips in temperature along the thalweg; although either may reflect spurious data (such as possible from exposed rocks), analyses focused only on the low dips, which might indicate cold-water refuges for fish. None of the five tributary confluences below the Boreas River (fig. 1) were associated with a dip in the longitudinal temperature profile (fig. 3), probably because any cold-water inflows along the bank were too small to affect temperatures in the thalweg.

## Refuge Identification in Split 1-Kilometer Sections

Few cold-water refuges were present along the study reach, regardless of whether or not the high-water slug was present, and most of the refuges were  $1\text{--}2^{\circ}\text{C}$  BMT. Of the 27 1-km sections, 15 sections did not provide refuge  $>2^{\circ}\text{C}$  BMT during any of the 3 flights, and only 5 sections provided refuge  $>2^{\circ}\text{C}$  BMT during more than 1 flight. No part of the study reach was  $>3^{\circ}\text{C}$  BMT (table 1).

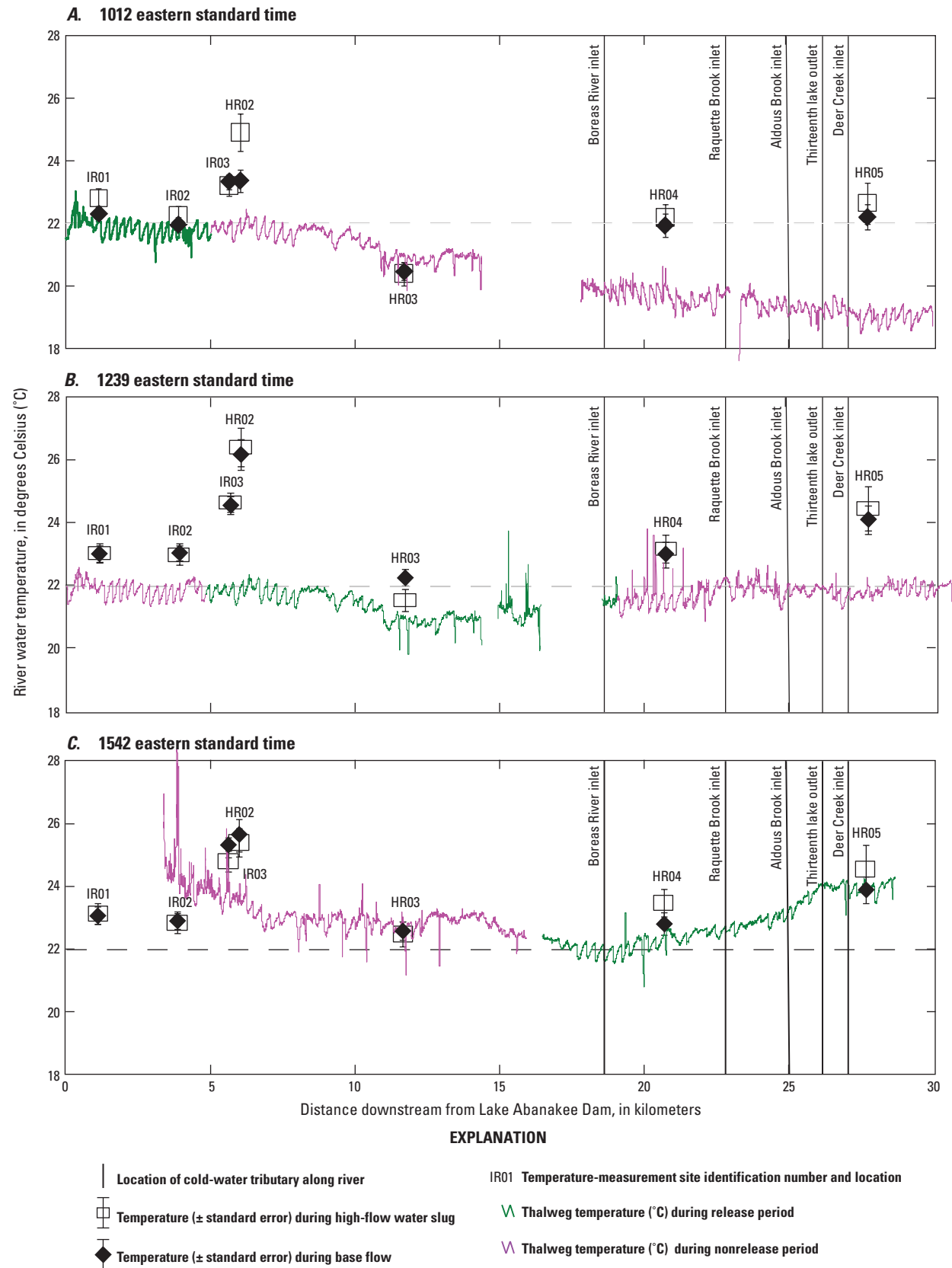
The greatest number and size of cold-water refuges were present during the first and third flights, whereas few refuges were present during the second flight. Overall, the study reach had 254 refuges  $>1^{\circ}\text{C}$  BMT covering  $4,572\text{ m}^2$  during the first flight, and slightly more refuge area during the third flight ( $262$  refuges covering  $6,962\text{ m}^2$ ). More than 10 percent of the refuge area was  $>2^{\circ}\text{C}$  BMT during both of these flights. During the second flight, however, there were only 91 refuges covering  $2,825\text{ m}^2$ , and only 2 refuges (covering  $66\text{ m}^2$ ) were  $>2^{\circ}\text{C}$  BMT (table 1).

The middle section of the study reach (kilometers 6–18) had the fewest available refuges, although this pattern is clearer for refuges  $>2^{\circ}\text{C}$  BMT than for refuges  $>1^{\circ}\text{C}$  BMT. The lack of refuges is partly a result of the lower median temperatures present in the middle section; refuges are defined to local water temps, so cold water is less likely to create a refuge in a cooler section of river, even if its absolute temperature is lower than other refuges.

The number of cold-water refuges was positively related to the median temperature of each 1-km section. Although the scatter of available refuges had a wedge-shaped distribution, the upper boundary of the scatter plot indicates that sections with higher median temperatures tended to have more refuges, which probably is mostly an artifact of the nature of defining cold-water refuges to surrounding water temperatures; however, the presence of many or large refuges may also indicate the presence of a source of cold water.

The high-water slug did not have a uniform effect on cold-water refuges. During the first flight, when river temperatures were coolest, more than one-third of refuges were located in the area of the high-water slug, and all 1-km sections within the slug had some refuge present; however, during the second and third flights, most of the 1-km sections within the high-water slug had no available refuge area. The 1-km sections that had been inundated with the high-water slug for longer were less likely to have refuges present,

## 8 Identifying Trout Refuges in Northern New York Through Airborne Thermal Infrared Remote Sensing



**Figure 3.** Longitudinal thermal infrared temperature profiles along the study reach on August 25, 2005, at *A*, 1012; *B*, 1239; and *C*, 1542 eastern standard time (EST), with box plots showing temperature range and mean (plus or minus  $\pm$ ) standard error at seven sites on release and on nonrelease days from July 21 through September 21, 2005, and locations of five cold-water tributaries. Temperature measurement sites and tributary locations are shown in figure 1.

**Table 1.** Median water temperature for right (R) or left (L) half of each 1-kilometer (km) section of river channel; mean size, standard deviation, and maximum size of refuge areas in which water temperature was 1 to 2 degrees Celsius (°C), and more than (>)2 °C below the median temperature for that section; and mean distance, standard deviation, and median and maximum distances between refuges during three flights over the 27-km study reach of the Indian and Hudson Rivers in northern New York, August 25, 2005.

[Sections were divided into halves to avoid effects of shading. Release from upstream reservoir began at 0930 eastern standard time (EST). Shading denotes high-water conditions during passage of release from the Lake Abanakee Dam (fig. 1). temp, water temperature; m<sup>2</sup>, square meter; m, meter; no., number; SD, standard deviation; Max, maximum; --, no data]

Km	Half	Median temp (°C)	Refuge areas below median temperature (m²)								Distances between refuges (m)			
			1 degree				2 degrees							
			No.	Size	SD	Max	No.	Size	SD	Max	Mean	SD	Median	Max
First flight (1012 EST)														
1	L	20.8	10	23	45	154	1	13	0	13	42	132	0	440
2	L	20.0	20	6	4	15	0	--	--	--	10	16	7	74
3	L	20.2	16	14	24	100	2	5	3	7	30	118	1	503
4	L	20.7	32	12	18	84	6	7	5	15	1	2	0	10
5	L	20.6	2	3	1	3	0	--	--	--	4	0	4	4
6	L	20.1	0	--	--	0	0	--	--	--	--	--	--	--
7	L	19.8	24	3	2	8	0	--	--	--	3	3	1	14
8	L	19.7	11	40	117	410	1	7	0	7	17	30	1	85
9	L	20.0	16	6	7	28	0	--	--	--	19	67	1	271
10	R	19.7	2	5	3	7	0	--	--	--	3	0	3	3
11	L	19.5	19	22	37	144	3	5	3	10	4	8	1	38
12	L	19.5	6	13	10	34	0	--	--	--	125	256	9	644
13	L	19.8	0	--	--	0	0	--	--	--	--	--	--	--
14	L	19.7	1	19	0	19	0	--	--	--	0	.	0	0
15	L	19.7	2	4	2	5	0	--	--	--	2	0	2	2
16	L	20.2	0	--	--	0	0	--	--	--	--	--	--	--
17	L	20.2	5	10	11	32	0	--	--	--	118	199	6	464
18	L	20.0	2	4	1	4	1	2	0	2	0	0	0	0
19	L	19.9	4	268	380	917	9	36	51	163	28	100	0	359
20	R	19.9	3	15	17	38	0	--	--	--	1	0	1	1
21	R	20.0	4	84	50	164	2	36	33	69	7	9	4	23
22	R	20.0	43	4	5	37	0	--	--	--	8	39	1	256
23	R	19.6	0	--	--	0	0	--	--	--	--	--	--	--
24	R	19.4	0	--	--	0	0	--	--	--	--	--	--	--
25	R	19.7	0	--	--	0	0	--	--	--	--	--	--	--
26	R	19.4	4	61	86	208	3	8	9	21	2	2	1	4
27	R	19.2	0	--	--	0	0	--	--	--	--	--	--	--
Overall:		19.9	226	18	71	917	28	18	34	163	16	72	1	644
Second flight (1239 EST)														
1	L	22.3	5	3	1	5	0	--	--	--	35	63	1	145
2	L	22.1	0	--	--	--	0	--	--	--	--	--	--	--
3	L	21.9	0	--	--	--	0	--	--	--	--	--	--	--
4	L	22.1	0	--	--	--	0	--	--	--	--	--	--	--
5	L	21.9	0	--	--	--	0	--	--	--	--	--	--	--
6	L	22.0	0	--	--	--	0	--	--	--	--	--	--	--
7	L	21.8	0	--	--	--	0	--	--	--	--	--	--	--
8	L	21.9	0	--	--	--	0	--	--	--	--	--	--	--
9	L	21.7	1	2	0	2	0	--	--	--	--	.	--	--
10	R	21.4	0	--	--	--	0	--	--	--	--	--	--	--
11	L	21.0	0	--	--	--	0	--	--	--	--	--	--	--
12	L	20.9	0	--	--	--	0	--	--	--	--	--	--	--
13	L	21.2	0	--	--	--	0	--	--	--	--	--	--	--
14	L	21.3	1	360	0	360	0	--	--	--	--	.	--	--

## 10 Identifying Trout Refuges in Northern New York Through Airborne Thermal Infrared Remote Sensing

**Table 1.** Median water temperature for right (R) or left (L) half of each 1-kilometer (km) section of river channel; mean size, standard deviation, and maximum size of refuge areas in which water temperature was 1 to 2 degrees Celsius (°C), and more than (>)2 °C below the median temperature for that section; and mean distance, standard deviation, and median and maximum distances between refuges during three flights over the 27-km study reach of the Indian and Hudson Rivers in northern New York, August 25, 2005.—Continued

[Sections were divided into halves to avoid effects of shading. Release from upstream reservoir began at 0930 eastern standard time (EST). Shading denotes high-water conditions during passage of release from the Lake Abanakee Dam (fig. 1). temp, water temperature; m<sup>2</sup>, square meter; m, meter; no., number; SD, standard deviation; Max, maximum; --, no data]

Km	Half	Median temp (°C)	Refuge areas below median temperature (m²)								Distances between refuges (m)			
			1 degree				2 degrees				Mean	SD	Median	Max
			No.	Size	SD	Max	No.	Size	SD	Max				
Second flight (1239 EST)—Continued														
15	L	21.3	0	--	--	--	0	--	--	--	--	--	--	--
16	L	21.5	0	--	--	--	0	--	--	--	--	--	--	--
17	L	22.2	56	35	202	1,513	0	--	--	--	4	11	1	63
18	L	21.8	0	--	--	--	0	--	--	--	--	--	--	--
19	L	21.9	3	95	120	265	0	--	--	--	3	3	1	7
20	R	22.0	0	--	--	--	0	--	--	--	--	--	--	--
21	R	22.1	2	4	1	5	0	--	--	--	8	0	8	8
22	R	22.2	10	4	3	11	0	--	--	--	4	3	2	9
23	R	22.3	0	--	--	--	0	--	--	--	--	--	--	--
24	R	22.0	2	2	0	2	0	--	--	--	7	0	7	7
25	R	22.1	0	--	--	--	0	--	--	--	--	--	--	--
26	R	22.4	9	11	12	34	2	33	27	59	2	5	0	16
27	R	22.2	0	--	--	--	0	--	--	--	--	--	--	--
Overall:		21.9	89	31	167	1,513	2	33	27	59	5	17	1	63
Third flight (1542 EST)														
1	L	23.2	24	22	40	195	3	107	148	317	11	47	2	247
2	L	23.2	33	17	22	103	0	--	--	--	6	14	1	74
3	L	23.5	44	45	114	756	13	10	15	60	4	9	0	38
4	L	24.1	53	36	70	409	14	7	7	23	3	7	1	41
5	L	24.0	10	6	5	20	1	2	0	2	50	113	8	381
6	L	24.1	9	5	5	16	1	2	0	2	22	68	0	215
7	L	23.4	7	3	1	4	0	--	--	--	97	248	4	660
8	L	23.1	20	42	149	688	3	16	2	19	2	7	1	33
9	L	23.2	4	34	50	120	2	8	4	11	2	2	2	4
10	R	22.8	9	9	5	20	0	--	--	--	93	231	3	699
11	L	23.1	0	--	--	--	0	--	--	--	--	--	--	--
12	L	22.9	0	--	--	--	0	--	--	--	--	--	--	--
13	L	23.2	0	--	--	--	0	--	--	--	--	--	--	--
14	L	23.1	0	--	--	--	0	--	--	--	--	--	--	--
15	L	22.4	10	6	5	21	0	--	--	--	3	3	2	6
16	L	22.4	0	--	--	--	0	--	--	--	--	--	--	--
17	L	22.4	0	--	--	--	0	--	--	--	--	--	--	--
18	L	22.1	0	--	--	--	0	--	--	--	--	--	--	--
19	L	22.2	0	--	--	--	0	--	--	--	--	--	--	--
20	R	22.2	0	--	--	--	0	--	--	--	--	--	--	--
21	R	22.3	0	--	--	--	0	--	--	--	--	--	--	--
22	R	22.6	0	--	--	--	0	--	--	--	--	--	--	--
23	R	22.9	0	--	--	--	0	--	--	--	--	--	--	--
24	R	23.2	0	--	--	--	0	--	--	--	--	--	--	--
25	R	23.5	0	--	--	--	0	--	--	--	--	--	--	--
26	R	23.9	0	--	--	--	0	--	--	--	--	--	--	--
27	R	24.0	2	10	5	14	0	--	--	--	3	0	3	3
Overall:		23.1	225	28	78	756	37	17	51	317	13	67	1	699

compared to sections farther downstream that were more recently inundated at the time of the flight. In addition, several of the 1-km sections just upstream from the high-water slug (and therefore, most recently returning to base flow) also had no available refuge area.

Mean distances between refuges within a section ranged widely, but median distances were generally small for all three flights (table 1). Overall median distance was 1 m for all three flights, and ranged from 0 to 9 m for the first flight, and from 0 to 8 m for the second and third flights. Overall mean distance was smallest for the second flight (5 m) and higher for the first (16 m) and third (13 m) flights. Maximum distance between refuges was also smallest during the second flight (63 m) compared with the first and third flights (644 m and 699 m, respectively). Distance between refuges can be related to refuge number: the more refuges in an area, the shorter the distance between any of them, especially if they are distributed randomly; however, small distances between many refuges can also indicate a cold-water source that is contributing to the creation of several larger refuges in a particular location.

## Cold-Water Contributions From Tributaries

All five cold-water tributaries in the lower part of the study reach (fig. 1) seemed to have a local cooling effect on river water temperatures during the first flight. Two of these tributaries (Boreas River at kilometer 19 and Deer Creek at kilometer 27) enter the Hudson River from the east bank, where the confluences were shaded during the morning flight. For these tributaries, the appearance of more refuge area during the first flight than during the second flight (table 2) can probably be attributed to the shading of exposed rocks. The three other tributaries (Raquette Brook at kilometer 24, Aldous Brook at kilometer 25, and Thirteenth Lake Outlet at kilometer 26) enter from the west bank, and therefore were not shaded during any flight. These three tributaries provided more refuge during the second flight than during the first (table 2). None of the five confluences provided much refuge during the third flight, when the high-water slug was passing through (fig. 4; table 2). Two of the tributaries each provided one refuge  $>1^{\circ}\text{C}$  BMT ( $12\text{ m}^2$  and  $47\text{ m}^2$ , respectively) and

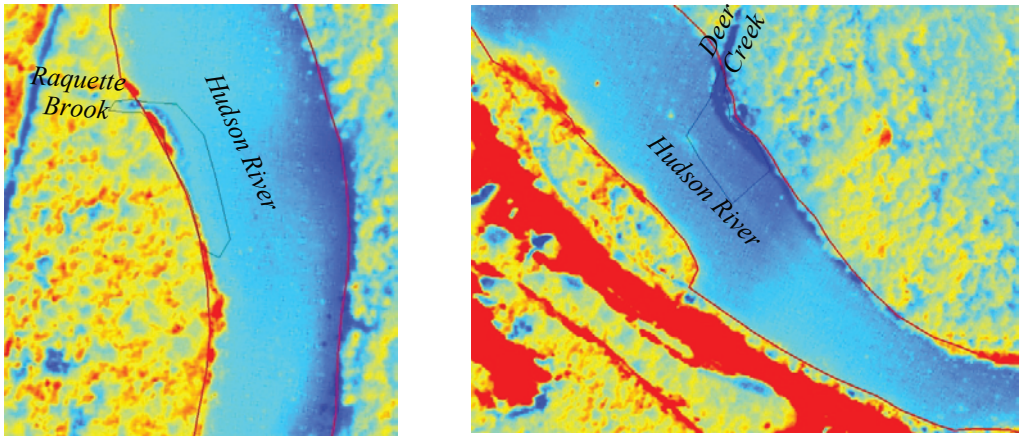
**Table 2.** Median water temperature in five river sections containing a cold-water tributary; mean size, standard deviation, and maximum size of refuge areas in which water temperature was 1 to 2 degrees Celsius ( $^{\circ}\text{C}$ ) and more than ( $>$ )  $2^{\circ}\text{C}$  below the median temperature for that section; and mean distance, standard deviation, and median and maximum distances between refuges during three flights over the 27-kilometer (km) study reach of the Indian and Hudson Rivers in northern New York, August 25, 2005.

[Release from upstream reservoir began at 0930 eastern standard time (EST). Shading denotes high-water conditions during passage of release from the Lake Abanakee Dam (fig. 1). temp, water temperature;  $\text{m}^2$ , square meter; m, meter; SD, standard deviation; Max, maximum; --, no data]

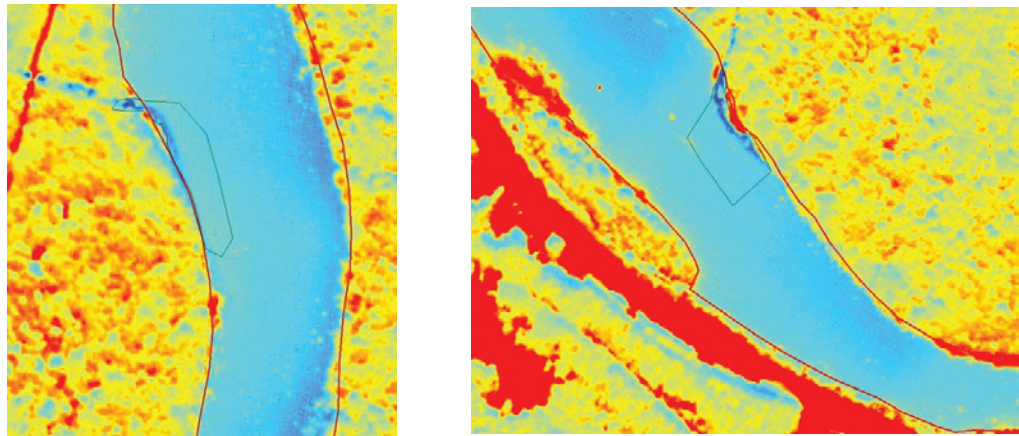
Km	Tributary	Median temp (°C)	Refuge areas below median temperature (m²)								Distances between refuges (m)			
			1 degree				2 degrees							
			No.	Size	SD	Max	No.	Size	SD	Max	Mean	SD	Median	Max
First flight (1012 EST)														
19	Boreas River	19.6	7	179	324	940	6	13	8	24	0	1	0	1
24	Raquette Brook	19.5	0	--	--	--	0	--	--	--	--	--	--	--
25	Aldous Brook	19.9	1	8	0	8	0	--	--	--	0	--	0	0
26	Thirteenth Lake Outlet	19.4	3	113	136	305	5	12	9	24	2	2	1	4
27	Deer Creek	18.8	4	87	144	336	1	11	0	11	0	0	0	0
Second flight (1239 EST)														
19	Boreas River	21.9	4	72	113	268	0	--	--	--	20	33	4	69
24	Raquette Brook	22.3	7	12	11	32	2	4	2	5	1	1	0	4
25	Aldous Brook	22.3	5	9	14	37	1	21	0	21	0	0	0	0
26	Thirteenth Lake Outlet	22.4	16	9	9	33	5	27	28	65	0	1	0	5
27	Deer Creek	22.1	7	27	35	109	3	5	0	5	1	1	0	3
Third flight (1542 EST)														
19	Boreas River	22.4	0	--	--	--	0	--	--	--	--	--	--	--
24	Raquette Brook	23.4	1	47	0	47	0	--	--	--	0	--	0	0
25	Aldous Brook	23.5	1	12	0	12	0	--	--	--	0	--	0	0
26	Thirteenth Lake Outlet	24.0	0	--	--	--	0	--	--	--	--	--	--	--
27	Deer Creek	23.8	0	--	--	--	0	--	--	--	--	--	--	--



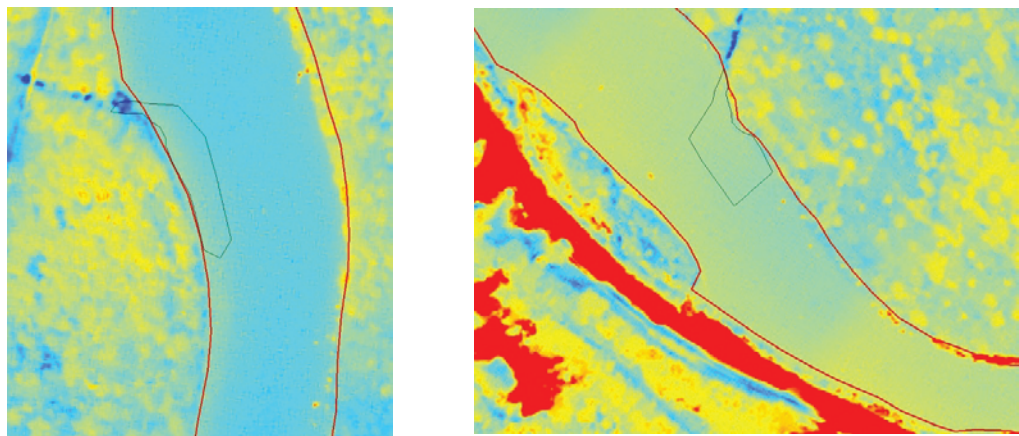
**A. 1012 eastern standard time**



**B. 1239 eastern standard time**

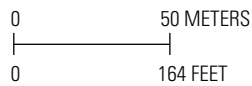


**C. 1542 eastern standard time**



**EXPLANATION**

Red	Warmer (+3 C°)
Light Blue	Mean temperature
Dark Blue	Cooler (-3 C°)
Red line	Potential cold-water refuge boundary



**Figure 4.** False-color thermal infrared images showing cold-water areas at the confluences of Raquette Brook at kilometer 24 and Deer Creek at kilometer 27 with the Hudson River in the Adirondack Mountains, New York, during three overhead flights on August 25, 2005, at *A*, 1012 eastern standard time (EST), *B*, 1239 EST, and *C*, 1542 EST when passage of reservoir release overwhelmed any cooling effect of inflow from tributaries. Tributary locations are shown in figure 1.

no refuges  $>2^{\circ}\text{C}$  BMT, and the three other tributaries did not provide any refuge  $>1^{\circ}\text{C}$  BMT (table 2). During the third flight, the northernmost tributary (Boreas River) was warmer at its mouth than the Hudson River; the other four tributaries, which were cooler at their mouths than the Hudson River, had only a negligible effect on Hudson River temperatures at their confluence. Distances between refuges were small in the areas below these confluences, indicating that cold-water refuges are clumped around the cooler water entering from respective tributaries.

## Discussion

The study reach did not provide much suitable habitat or cold-water refuges for resident cold-water fish species such as brown trout. Only a few areas of the study reach were  $1^{\circ}\text{C}$  BMT at any scale, and there were even fewer and smaller areas that were  $2^{\circ}\text{C}$  BMT, which indicates that the availability of refuges from critically warm temperatures along the 27-km study reach is severely limited, regardless of release flows. A concurrent study on fish movement determined that survival of stocked Brown Trout within the Indian and Hudson Rivers was poor (Boisvert, 2008). Almost no study trout persisted within the Indian and Hudson study reaches for an entire summer, compared to half of the tracked trout in the nearby control system (Cedar River; fig. 1) which was unaffected by recreational releases. This loss of trout in the study reach during the warm summer period supports the finding that suitable cold-water habitats for Brown Trout are scarce. Although a small number of trout may survive and possibly overwinter, it is unlikely that a substantial population of brown trout hold over through the summer in these reaches. Coutant (1985) proposed a similar explanation for summer dieoffs and poor condition of adult striped bass (*Morone saxatilis*) in several North American river basins and reservoirs. Similarly, Sutton and others (2007) determined that main-stem flows in a northern California river could not sustain its salmonid population without the presence of adequate thermal refuges. High temperatures can fragment fish populations within a watershed by isolating suitable thermal habitats (Matthews and Zimmerman, 1990). The entire study reach contains very few and small thermal refuge areas, so it seems to be unable to sustain viable brown trout populations regardless of the releases. Other trout species, which are less tolerant of warm temperatures than brown trout, would also not be expected to maintain resident (year-round) populations.

Recreational flow releases generally decreased the number and size of several small, main-channel refuges by diluting the cold-water areas at tributary mouths in the study reach. In a concurrent study on fish movement, temperature loggers were anchored 6 inches above the stream bottom in the mixing zone of three cold-water tributaries. Water temperatures were generally  $4$  to  $6^{\circ}\text{C}$  lower than surface temperatures at base flow, but this temperature difference

disappeared during releases (Boisvert, 2008). These changes illustrate how warm-water releases can temporarily eliminate thermal refuges. Sutton and others (2007) identified a similar scenario in a stream where localized cold-water patches were diluted by water discharged from upstream reservoirs. This effect may last longer than the period of high-water passage; for example, in Sutton and others (2007), the 16 river sections inundated by high water during the second flight had little refuge area, but only the 8 upstream sections had a greatly increased refuge area during the third flight. Such a delay in the recovery of refuge areas after a release could affect local trout and other species that have a tolerance for high temperature decreases with increasing exposure time (Galbreath and others, 2004). This difference between surface water and stream bottom temperatures also indicates that surface temperatures cannot always accurately identify cold-water refuges, especially if they are at tributary confluences.

The middle part of the study reach (kilometers 6–18) provided more cold-water habitats than many of the refuges in the upper and lower parts of the reach. Water temperatures were cooler in many of the 1-km sections of the middle part of the reach than in some of the refuges in the upper and lower parts of the reach. Thermal remote sensing data from an Oregon river basin indicated that large-scale patterns in the longitudinal temperature profile, such as downstream warming trends and dips in temperature that extended at least 5 km, reflected basin-scale processes (Torgersen and others, 2001). In the study detailed in this report, the lower temperatures in the middle sections of the study reach compared with the upper and lower sections may have resulted from local physical and geomorphic anomalies. The middle sections run east to west and therefore may be more shaded from afternoon sun by riparian vegetation than the upper and lower reaches, which run north to south. The TIR imagery revealed no cold-water tributaries or groundwater seeps in this reach. The drainage area through the Hudson Gorge (middle section) increases by only  $65\text{ km}^2$ , from  $1,626\text{ km}^2$  just below the Indian River confluence to  $1,691\text{ km}^2$  just above the Boreas River confluence, and indicates that a large cold-water inflow is unlikely. Any cold-water tributaries may sink in this region and be undetected by remote thermal sensing, because the banks in this middle reach are steeper than in the lower reaches, and the channel is narrower and deeper (Boisvert, 2008). Alternatively, this greater channel depth could increase hyporheic flow exchange, which in turn could buffer temperature increases (Loheide and Gorelick, 2006), although these explanations are speculative.

The spatial distribution of refuges and trout movement patterns (Boisvert, 2008) in the upper and lower study reaches indicate that brown trout were probably limited in their ability to find refuges and behaviorally thermoregulate. Many studies indicate that salmonids move often, sometimes over long distances (Gowan and Fausch, 1996; Mellina and others, 2005). Garrett and Bennett (1995) found that brown trout in a Michigan reservoir migrated more than 1.7 km upstream into a cold-water tributary to thermoregulate during



high summer temperatures. In the current study, such long-distance movements would allow trout to access cold waters in the middle study reach; however, although brown trout may be capable of long-range movements, they may be less likely to do so during the day when the high-water slug is present, or during the warm summer months. For example, brown trout in a southern Appalachian stream did not seek available thermal refuge in nearby tributaries despite summer water temperatures that approached lethal limits, which increased their mortality (Burrell and others, 2000).

Burrell and others (2000) noted that the study fish had long spawning runs during the fall (up to 7.7 km upstream), but stayed within a small home range during summer, possibly because the stress of high-water temperatures decreased their energy. Matthews and others (1994) also determined that brown trout in a California river commonly limit their movements to a much smaller range during summer low flows, possibly because the elevated temperatures force them to decrease their energy expenditures. In addition, brown trout tend to move significantly less during the day than at night (Young and others, 1997; Diana and others, 2004) and the recreational releases in the Indian and Hudson River only occur during the day. Brown trout in the lower reaches generally used refuges that only occurred within 50 m of their daily position (Boisvert, 2008). The mean distance between adjacent thermal refuges in the upper and lower study reaches was 5 to 16 m during all three flights, and the maximum distance exceeded the 150-m limit for less than one-third of the refuges. In comparison, fish tracked in the middle reach were generally several kilometers away from the nearest refuges. Thus, even though the refuges were within their home range, brown trout may not have used refuges often because of limited access or inadequate energy for movement.

Local thermal refuges near tributaries seem to provide more available habitats to brown trout in the lower study reach. Whether or not periodic decreases in this refuge area caused by the flow releases adversely affect local trout (or other species) depends on the use of refuges by trout during thermally stressful periods and the amount of refuge area that is lost during the releases. If most fish rely on small-scale refuges to escape thermal stress, then the reservoir releases may have a strongly negative effect on their survival. Transmitter-implanted trout in a concurrent study on fish movement exploited thermal refuges, but the low rate of use indicates that these areas of cold water were limited (Boisvert, 2008). Small, infrequent thermal refuges may be difficult for stressed individuals to locate, or they may simply be inadequate to support a self-sustaining (naturalized) brown trout population.

## Study Limitations

Logistics and funding and time constraints created several limitations that could have affected some findings in the present study. The main limitation of this study was the

lack of a control flight on a nonrelease day to separate the effects of increased daytime solar radiation from the dam release on water temperature. The dam release clearly affected refuge areas because the top of the reach (kilometers 1–9) showed more refuge area during the afternoon flight than the flight at 1239 EST, which is inconsistent with the idea that solar radiation was the only impact on river temperature. Comparisons showing that (1) water temperatures did not differ substantially between release and nonrelease days and (2) the peaks in river stage associated with the high-water slug were not correlated with water temperature changes (Baldigo and others, 2010) indicate that the high-water slug does not affect the overall temperature patterns of the river, which helped compensate for the lack of control flight. Despite these compensations, the utility of remote thermal sensing in this study was limited by two characteristics of the TIR images.

The first characteristic was the inability to consistently differentiate land from water where riparian vegetation was abundant and crowded the edge of the water; overhanging riparian vegetation obscured 11 to 15 percent of the stream banks in the visible-spectrum and TIR images, and therefore required visual estimation techniques for these areas. Given that all thermal refuges identified in this study were small and were located along a stream bank (primarily at tributary confluences), the estimated location of the edge of the water may have skewed the measurement of thermal refuge area.

The second major limitation of thermal remote sensing in this study was the inability to detect groundwater seeps. Remote sensing measures only surface water temperatures, and cold groundwater upflow into a stream channel is denser than warmer main-stem water and not likely to rise to the surface. Both of these limitations could be decreased or eliminated if additional thermal remote sensing data were collected during late fall or early spring when deciduous stream-edge vegetation is absent and groundwater flowing into streams is warmer than the river and more easily detected (Torgersen and others, 2001). Such cold-weather data would not have addressed the primary objective of this study, which was to quantify the effect of summer recreational releases on the number, size, and distribution of thermal (cold-water) refuge areas.

Some study methods may have also increased the error rate of the data. For example, estimates of mean distances between refuges were probably underestimated in most sections. Although refuge-interval (distance) measures are fairly straightforward, other techniques used to evaluate water temperature patterns (mask out the land on TIR images, and then calculate averages from all pixels within the stream boundary) vary across similar studies, which involve a visual inspection of TIR images (for example, Torgersen and others, 1999, 2001). Visual inspection can be used to exclude rocks and large woody debris when selecting sample points in the main stream. The methods used in this study may have increased the error rate, affecting the longitudinal profile more than the calculation of section medians, as evidenced by the spiky longitudinal profile patterns. Black and others (2003)



analyzed stream temperatures in a Washington stream using methods similar to those of this study and determined that remote thermal sensing of streams in which some areas were obscured by vegetation and other areas had open canopy might promote misinterpretation, with higher temperatures throughout the reach rather than solely within the open canopy areas. Thus, shaded sections of stream in the present study may have lower temperatures than indicated by thermal remote sensing data. If so, parts of the reach may actually provide more cold-water habitats, but because cooler water tends to have fewer refuges, the number and size of refuges (and distances between refuges) could differ from those described herein.

## Summary

In 2005, the U.S. Geological Survey, in cooperation with the New York State Department of Environmental Conservation and Cornell University, initiated an assessment of the natural resources in the Indian and Hudson Rivers along a reach that receives regular recreational releases from an upstream reservoir to support whitewater rafting. The main objective of the study was to evaluate the potential effects of these releases on the resident and stocked brown trout (*Salmo trutta*) fishery. A related goal, and the focus of this report, was to identify cold-water areas that could provide refuges possibly critical to the survival of stocked and resident trout during periods of thermal stress (the warm summer months). Stream temperature data from seven continuous loggers and TIR remote sensing data from the 27-kilometer (km) reach affected by release flows were analyzed to (1) assess the effectiveness of thermal remote sensing to detect spatial patterns in stream temperatures at multiple spatial scales, (2) identify potential thermal refuges at base flow and during release flows, (3) define how the release flows affect the size and temperature of the identified refuges, and (4) compare the results of thermal refuge identification made at several spatial scales. We evaluated hypotheses that the size and number of thermal refuges were diminished by recreational flow releases.

Although high temperatures can fragment fish populations within a watershed by isolating suitable thermal habitats, the TIR data indicate that thermal (cold-water) refuges may be too small and widely distributed to have any real effect on local trout populations in the study reach. The identification of only a few potential thermal refuge areas in the Hudson Gorge probably reflects the typically warm, low-flow summer conditions that would prevail even in the absence of recreational releases from the warm reservoir. Although indirect effects of the releases probably increased trout stress and mortality (for example, by physically displacing individuals or temporarily eliminating low-velocity resting areas), summer temperatures along the study reach were stressful, regardless of the pulsed discharge events. Adult brown trout living under these thermally stressful conditions

may not be able to fulfill normal metabolic needs. Remote thermal sensing can be an effective way to map spatial patterns and variations in river temperatures; however, the drawbacks of the method require consideration when small thermal refuges are to be characterized. Choosing an appropriate scale is critical and depends on both stream-system geomorphology and the movement patterns (and thermal requirements) of the fish that potentially use cold-water refuges. The 27-km river reach in this study provided both small-scale thermal refuges at tributary confluences and large-scale refuges that extended along several kilometers of river that remain cooler than the rest of the study reach. In summary, the limited size and number of thermal refuges (and the inability of brown trout to utilize cold-water refuges that are more than 50 meters [m] away) indicates that self-sustaining (naturalized) brown trout populations are unlikely to persist in the lower Indian and upper Hudson Rivers.

In general, the release flows overwhelmed the small number of thermal refuges that were detected and greatly decreased their numbers and their sizes. Mean water temperatures were unaffected by the releases, but small-scale heterogeneity was diminished. At the river-reach scale, water temperatures in the upper and lower segments of the reach were consistently warmer than in the middle segment, even during passage of release waters. Most important, the limited number of thermal refuges may be inadequate to sustain local brown trout populations in the upper Hudson and Indian Rivers considering findings from published literature and academic research indicate trout must have nearby (within about 50 m) cold-water refuges to survive extended periods of thermal stress. The inability of remote thermal images to consistently distinguish land from water (in shaded areas) and to detect groundwater seeps (away from the shallow edges of the stream), however, hampered our ability to identify and assess potential thermal refuge areas in this report.

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