MINNESOTA DEPARTMENT OF NATURAL RESOURCES
DIVISION OF FISHERIES

IDENTIFICATION OF GROUND WATER INTRUSION AREAS ON THE LAKE SUPERIOR SHORELINE AND SELECTED TRIBUTARIES IN MINNESOTA

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Acknowlegements

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Abstract

Ground water provides critical spawning habitat for brook trout. Locations of groundwater intrusion areas in the Minnesota waters of Lake Superior and below barrier tributaries are unknown. Aerial thermal remote sensing provides an opportunity to conduct a regional assessment of groundwater intrusion areas over a broad spatial scale. Thermal infrared (TIR) video was shot from a fixed wing aircraft 1300 feet above ground level. Desired conditions for TIR include: high overcast, no precipitation, leaf-free canopy, open water, and maximized temperature differences between groundwater and the local environment. Ideal conditions were rare and when present seldom coincided with contractor availability. TIR data on the Knife River were collected under clear skis during January 2003 when some streams froze completely to the bottom. Field checking indicated stream flow through ice cracks gave “false positive” thermal signatures. Field verification did show TIR effective in identifying one area of ground water intrusion in the Knife River system. Minnesota’s Lake Superior shore was surveyed in April 2003 mostly under clear skies and again in April 2004 under overcast and partly cloudy skies. No significant areas of ground water intrusion were identified along the shore. However, an artesian well at a previously known location was indicated. Lake Superior tributaries were surveyed in December 2003 and in April 2004. A small groundwater intrusion area was located on the Lester River. The success of TIR in detecting groundwater is highly sensitive to weather and environmental conditions. The technique appears sensitive in less than ideal conditions. Multiple datasets were compiled on much of the study area and no areas of groundwater intrusion were located that are likely to be important in the rehabilitation of coaster brook trout.

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Introduction

Locations of groundwater sources, which provide critical habitat for both resident and “coaster” brook trout *Salvelinus fontinalis*, and other migratory fishes are unknown for the Minnesota waters of Lake Superior and its below barrier tributaries. The rehabilitation plan for Lake Superior brook trout published by the Great Lakes Fishery Commission recognizes that successful rehabilitation depends on maintaining and protecting essential within stream spawning and nursery areas (Newman et al. 2003). Shallow areas of headwater streams with strong groundwater flows and gravel substrates are favored spawning areas. Groundwater flow also provides the proper thermal habitat necessary to maintain temperatures below the lethal range for brook trout eggs. In the brook trout chapter of the Fisheries Management Plan for the Minnesota Waters of Lake Superior (Schreiner ed. 1995) one of the objectives is to gather information to determine if rehabilitation of “coaster” brook trout stocks is feasible in Minnesota. One of the specific information needs identified in the plan is to undertake detailed habitat assessments in streams that have the greatest potential for brook trout reproduction. The purpose of this project was to identify springs or ground water sources that if present will be critical to rehabilitation efforts.

The geographical range of potential habitat available to migratory fish species within the Minnesota jurisdiction of Lake Superior and tributaries is expansive. There are over 183 miles of shoreline on the Minnesota coast of Lake Superior and approximately 160 miles of tributaries that are accessible to migratory fish. More traditional approaches to identifying ground water have used in-stream temperature measurements at discrete locations to characterize entire segments of streams. Such measurements would be difficult to obtain over the range of potential habitat in Minnesota. Airborne remote sensing using thermal infrared imaging (TIR) has proven useful in discerning temperature differences over broad spatial scales (Cherkauer et al. 2003, Kay 2001) and in identifying spring locations (Campbell and Singer 2001). An initial exploration of the Minnesota coast of Lake Superior and tributaries for discrete ground water intrusion areas becomes a tractable project using TIR remote sensing. Specific locations of groundwater intrusion areas should be detectible if surveys are conducted under conditions that maximize the differences between ground water temperature and the local surface environment. Identification of groundwater resources is one of the first steps enabling the restoration of coaster brook trout. Since brook trout are dependent on groundwater resources, the extent of successful restoration will be directly related to the abundance of these resources.

Methods

The study area included 177 miles of the Lake Superior shoreline from the Lester River to the Canadian border and below barrier areas of 36 selected tributaries along the Minnesota shoreline that are within state jurisdiction (Figure 1). Seventy river miles of the Knife River system were chosen because the Knife River system has the most water available to anadromous fish of any tributary (Figure 2). Given the constraint of limiting the project to only 40 miles of streams, not including the Knife River and its tributaries, additional streams were prioritized and then selected based on known or suspected importance as potential coaster brook trout habitat (Figure 1). The upstream boundaries of the areas selected for survey coincided with natural barrier falls that impede upstream movement of migratory fish or where no barrier exists, a marker such as a road crossing was used to limit the upstream extent of the survey.

Aerial surveys were conducted by A.W. Research Laboratories, Inc. of Brainerd, Minnesota (AWR) using a fixed-wing "push-type" Lake Buccaneer aircraft (Figure 3). Flight speed and elevation averaged 95 miles per hour and 1300 feet above ground level. The contractor flew preliminary flights over each area taking 35 mm color Fujichrome slides with a handheld SLR camera. Subsequent flights used four wing-mounted video cameras, which were tuned to different wavelengths or bands of the spectrum. These hyperspectral bands were specific to the frequency at which chlorophyll "a" absorbs energy (670 nanometers), a "water-penetrating" frequency (710 nanometers), and a thermal infrared frequency (adjustable from 0.95 to approximately 16 microns). The chlorophyll "a" and "water-penetrating" bands have been used by the contractor in the past to collect additional information about a site's plant community and substrate, but were of little utility in this particular study. The chlorophyll “a” and “water-penetrating” bands were recorded on the same video tape, alternating every second. Regular video in the visible spectrum was also recorded concurrently with the hyperspectral video and included a position stamp with latitude and longitude from the aircraft global positioning (GPS) system.

Video data were transferred to digital versatile disc (DVD) format. Tape counter values in minutes running time on the original video were indexed with positions from the airplane GPS. Arcview coverages of these tape positions were created and projected on a digital orthophoto quadrangle (DOQ) base layer. The tape position was used to label regions of interests. Analyzing the data consisted of reviewing the thermal DVD footage at a slow rate, usually half or quarter speed. Temperature gradients appeared on the thermal footage as areas of contrast with warm areas appearing light and cold areas appearing dark (Figure 4). Since the flights were conducted during the winter and early spring, when ground and water surface temperatures were less than groundwater temperature (approximately 42°F), areas influenced by groundwater should appear light compared to the surrounding environment. Visible slides, visible spectrum video, chlorophyll a, and water penetrating bands were crosschecked with thermal footage to attempt to ascertain the nature of the source of the signal captured by the thermal camera. The visible slides and visible video were useful in identifying areas as “false positive” signals such as water running over the ice in the winter and melt water flowing over warm surfaces in the footage of the Lake Superior shore shot in the spring. These data were especially useful after field experience was gained to correlate the on the ground features with the appearance on the visible images. Areas requiring further explanation were identified and noted by identifying features on a corresponding DOQ and marking waypoints that were loaded into a handheld GPS. Frames from DVD showing areas of interest were captured with a utility packaged in Power DVD, a DVD software. Captured frames were hotlinked to corresponding points on the waypoint coverage.

Field checking or “ground-truthing” areas of interest consisted of locating waypoints and reconnoitering the surrounding area for signs of groundwater influence. Temperature and conductivity measurements were made. Observations of vegetation changes indicative of groundwater presence were noted. Sites were documented with photographs or digital video footage.

Automatic temperature probes were deployed in early November 2003 in selected locations in advance of the aerial data collection of the tributaries. It was hoped that temperature measurements concurrent with the flights would help calibrate the thermal data. Probes were also placed at an area near the headwaters of the Knife River that was identified as a source of groundwater from a field check in the summer of 2003. This area was to serve as a control area for subsequent flights. Unfortunately, flights did not occur in the fall of 2003 as anticipated, so the probes were recovered through the ice in early winter.

Results and discussion

Conditions under which the flights were conducted varied greatly (Table 1). The preliminary flights during which visible slides were shot were conducted under clear skies. The thermal and hyperspectral data covering the main stem of the Knife River and the Lake Superior shoreline north of Two Harbors were initially taken under clear conditions. Sunny conditions created shadows and confounded the interpretation of the thermal data by creating temperature differences from solar warming of dark objects. The Knife River system was surveyed in January 2003, a winter when significant cold periods and little insulating snow cover caused many streams to freeze to the bottom, forcing stream flow on top of the ice. A portion of the mainstem of the Knife River was surveyed again in early December 2003 under overcast to clear conditions. The survey of the Lake Superior shoreline was done in late April 2003 and again in mid April 2004 under varying conditions. The Lake Superior shoreline from Lester River to Two Harbors and associated tributaries were surveyed in early December 2003 under overcast conditions.

Tributaries between Two Harbors and the Canadian border were flown in mid April 2004 during the spring runoff period.

Data collected

The data generated consisted of a composite of approximately five hours of footage for each of the bands of video data and a total of 1602 visible slides covering the Lake Superior shoreline, tributaries and the Knife River. In addition, Arcview shapefile coverages have been generated indexing the thermal, visible, and hyperspectral DVD data from the project to enable finding a location specific video sequence. There are also data with point coverages linked to frame captures from the TIR video for areas of interest.

Conditions for data collection

Our initial supposition of the optimal timing for TIR remote sensing of groundwater intrusion areas is that it is best accomplished when the temperature gradient between groundwater and the surrounding local environment is maximized and the least amount of interference from other sources exists. Confounding factors are a warmer air mass between the ground surface and the thermal sensor on the aircraft, precipitation in the air, ice and snow in the stream channel, and a leafy canopy on stream banks. Solar warming and shadows can also confuse interpretation of TIR images. High overcast conditions present lighting conditions relatively free from shadows. High wind and extreme cold can limit safe operation of the aircraft and limit availability for flights. Conditions appropriate for the TIR data collection on the tributaries merge in the late fall with cooling tributaries and leaf fall. Good conditions for surveying the Lake Superior shore were thought to coincide with early spring after shelf ice melts from the shoreline and when the lake surface water is coldest. This restrictive list of conditions reduced the time for ideal data collection to a small window of opportunity and when merged with the availability of the contractor, combined to be a very limited set of circumstances.

Knife River

The timing for the TIR data collection on the Knife River system, originally scheduled for fall of 2002, was delayed until January and February of 2003 because the contractor was either unavailable or conditions were not suitable. The TIR data from this survey showed multiple warm areas distributed throughout the system, but mostly concentrated in the upper portion of the river system. Field assessment showed these signals to be primarily water flow on top of the ice. At the time TIR data were collected, stream channels were frozen and the bitterly cold winter and sparse insulating snow cover caused cracks in the ice, allowing stream flow on top of the ice creating “false positives,” areas on the TIR data that appeared warm, but were not clearly associated with groundwater (Figure 4). These areas were groundtruthed again in early September 2003 and no evidence of groundwater intrusion was found.

Areas of potential groundwater identified with TIR were investigated, and in all but one case, field assessment failed to find groundwater. At location C, near the intersection of Old Drummond Road and the Knife River (Figure 2), groundwater was positively identified during field assessment. TIR imagery taken on February 29, 2003, showed a possible area of ground water intrusion at this site (Figure 5). This area was initially visited February 19, 2003 and evidence of groundwater consisted of some water on top of the ice, slush and little snow depth. Location C was revisited on September 9, 2003 after a summer of drought. A bryophitic wetland plant community surrounded an off channel spring emanating from the base of a slope (Figure 6). Additional aerial data of the Knife River mainstem were gathered in conjunction with the December 4, 2003 flight of the Lake Superior tributaries. Thermal imagery taken over area C (Figure 2) showed little contrast (Figure 7). It is unclear why the thermal sensor did not detect the presence of groundwater at this site, given the temperature differences that existed at the time of the imaging. This site was visited on December 10, 2003 and showed evidence of groundwater seeping to the surface causing snowmelt (Figure 8).

The other areas that showed contrast in the TIR data from the February 29, 2003 flight displayed similar wintertime characteristics of water or new ice on top of the river ice. However, when these were investigated in the field in summer and fall they showed no evidence of groundwater.

Tributaries A and B (Figure 2) were surveyed April 29, 2003. The streams were open and water temperatures were in the lower 40 °F range (Table 1). TIR data of these tributaries did not show any clearly identifiable point sources of ground water and lacked contrast within the stream channel. With air, water and groundwater temperatures within the same narrow range during this flight, it makes sense that there were no features identified during this flight. If groundwater was influencing these sites, thermal differences with the surrounding environment would have been very small at the time of the TIR data collection and may not have been detectable.

Lake Superior shore

The first thermal data on the Lake Superior shore was gathered on April 29, 2003. The surface temperature of Lake Superior was approximately 35 °F at the time of the survey. The shore from Lester River to Two Harbors was surveyed just after dawn while the sun was low and significant solar warming had not yet occurred. Warm plumes of 40 °F water are visible coming from the tributaries into the lake. A small artesian well in front of the French River appeared as a small bright area just north of the main plume of the river. The groundwater coming out of this well may be thought of as a control area. The warmer effluent from the French River Hatchery also shows up as warm in this image (Figure 9).

For the April 29, 2003 flight, the shore north of Two Harbors was photographed under clear skies once shadows had formed and exposed surfaces, mostly dark diabase bedrock, had the chance to warm in the sun. Cooler runoff from melting snow and ice through intermittent channels were highlighted well under these conditions (Figure 10). While air temperature was recorded as 40 °F, it is uncertain what the substrate temperature was during data collection. With solar warming, the temperatures of surface substrates may have been very close to groundwater temperature. The extent to which groundwater would have contrasted with sun-warmed substrates is unknown.

Once sun-up occurred, a dark shadow appeared along the shoreline from Two Harbors north to the Canadian border (Figure 10). This may have been an artifact of the thermal sensor sampling the junction where the cold lake meets the shore. It does not seem reasonable that a narrow band of surface water colder than the rest of the lake should uniformly follow the shoreline. Shadows likely made the detection of any nearshore upwelling areas of groundwater more difficult to determine from this dataset.

The contractor agreed to resurvey the Lake Superior coastline because of the ambiguity in the interpretation resulting from the shadow artifact following the coastline in the April 29, 2003 dataset. The lower portion from the Lester River to Two Harbors was flown again on December 4, 2003. The TIR imagery of this dataset was without this nearshore shadow and appeared flat with less marked contrast. The data appeared to have fewer artifacts due to solar warming and shadows facilitating interpretation of the data. The hatchery effluent and small artesian well at the French River were indicated (Figure 11).

The shoreline from Two Harbors to the Devil Track River was flown on April 13, 2004 and the remaining shoreline to the Canadian border was flown April 14, 2004. The dataset from April 13, 2004 was shot under partly cloudy to overcast conditions. The TIR data taken on this day did contain the nearshore shadows (Figure 12) that characterized the earlier shoreline flight of April 29, 2003. Shadows seem to be associated with shoreline areas of rock and cobble and appear most distinct under clear skies. An additional dataset of the shoreline from Grand Marais to Two Harbors was flown on April 14, 2004. The data gathered near Grand Marais have greater contrast and show nearshore shadows. Skies became overcast and the TIR imagery had less contrast as the flight progressed toward Two Harbors, but shadow areas on the TIR data persisted, probably the result of solar warming earlier in the day. These shadows were again associated mainly with rock and cobble substrates along the shore. These shadows may have caused minor groundwater intrusions along the shoreline to be undetected. There were no distinct light areas in the TIR footage that would indicate a plume of warm groundwater coming to the surface in the nearshore areas. No areas of groundwater intrusion were identified from the Lake Superior shoreline part of this project, although the hatchery effluent at 42-46°F is clearly indicated (Figure 11).

Below barrier tributaries

The below barrier tributary portions of the Lester River, Talmadge Creek, French and Sucker rivers were flown on December 4, 2003. Streams were partially frozen with an open channel remaining in many areas. The ground and ice surfaces were snow covered. Air temperature was approximately 30 °F. Conditions were mostly overcast on December 4, 2003 resulting in TIR imagery of low contrast and few shadows. A light area appeared in the TIR data on the Lester River from the December 4, 2003 flight indicating a possible groundwater intrusion area from a small side channel (Figure 13, Figure 14). This site was visited on July 9, 2004. The afternoon water temperature in the main river channel was 70 °F, while the temperature of the small side channel was 51 °F indicating the presence of groundwater (Figure 15).

The remaining tributaries from the Stewart River to the Pigeon River were surveyed April 13 and 14, 2004, during the spring runoff period when stream temperatures were approximately 40 °F and air temperatures varied from 30 to 55 °F. An upper section of the Lester River that was omitted from the December 4, 2003 flight was also flown on April 13, 2004. Temperature and sky conditions varied greatly over these two days. The contractor previously stated that difficulty in resolving groundwater intrusions can occur if the temperature of air layer between the ground and sensor is greater than the surface temperature, which was the case for part of the April 13 and 14, 2004 flights. Another factor that likely negatively influenced the ability to identify groundwater intrusions from this dataset was the high springtime flow of the streams, which would act to dilute any groundwater intrusion. No groundwater intrusions were identified from the tributaries or the Lake Superior shoreline from the April 13 and 14, 2004 dataset.

Technique evaluation

This method proved to be sensitive in detecting groundwater intrusions at the Knife River and Lester River sites. Minor flows of warmer water in the example of the artesian well and the hatchery effluent were detected (Figure 9, Figure 11). The technique also detected water flowing over the ice in frozen stream channels.

It is important to remember that TIR technology only registers surface temperature of water bodies (Kay et al, 2001), which may or may not reflect the presence of groundwater. In the case of the nearshore surface of Lake Superior, groundwater would have to be significant enough to well up to the surface and be detectable. Surface mixing may make it difficult to establish a temperature gradient and detect minor amounts of groundwater intrusion. Given a very calm day on the lake under ideal conditions, the technique may work for the nearshore areas of Lake Superior. However, the prerequisite of calm water in addition to the list of restrictive conditions necessary for successful resolution of surficial temperature gradients makes this method difficult to apply to a large lake situation. The lack of groundwater intrusion areas found along Lake Superior's shore in this study does not mean that they do not exist. Minor areas of groundwater intrusion that occur under the lake surface at depth may be important spawning habitat and could remain undetectable. However, based on this study, it appears that significant sources of groundwater do not exist along the Minnesota shoreline.

One limitation to this technology is that it provides temporally discrete information. Although groundwater may be present in a system, the ability to detect its presence through TIR technology varies with the weather and environmental conditions at the time that the survey is conducted. It is very important to identify conditions that will maximize success of detection and facilitate interpretation of the TIR data and survey the area under such conditions. In order to evaluate the prevailing survey conditions, areas known to have groundwater intrusion are important to image as controls. However, detection of known intrusion areas may not always dictate if conditions are suitable for TIR imaging, because controls do not have the same local set of conditions as the unknown intrusion areas. As an example, Site C on the Old Drummond Road and the artesian well at the French River were poorly resolved in the December 4, 2003 dataset (Figure 7 and Figure 11), yet the groundwater intrusion on the Lester River was detected under similar conditions in data gathered on the same day (Figure 13). All three sites appeared to have similar flows of groundwater. The Lester River site seems to be the most clearly resolved. From observing the poor resolution of the known groundwater intrusion sites on this dataset, the Old Drummond Road and artesian well sites, we would incorrectly assume that this dataset offers little resolution of additional sites. Unique characteristics of the local environment at a site such as surrounding substrate, snow and ice conditions influence whether a site is detectable.

Groundwater habitat assessment

The two groundwater intrusion areas identified from this project are unlikely to be of significance to migratory brook trout. The Old Drummond Road site is located far upstream in the Knife River watershed, while the Lester River site is small and located above significant barriers at nearly 2.5 river miles from the mouth.

The results of this survey support the idea that the North Shore of Lake Superior and tributaries have a paucity of groundwater resources. The Knife River system, a focus area of this project, is strongly dependent on runoff to maintain its flow during the summer months and is thought to lack significant groundwater inputs except near some of its headwater areas (Waters 1977). Just one area of groundwater intrusion was identified in the Knife River watershed dataset, one area was identified in the Lester River, and no significant sources were identified from the Lake Superior shoreline data.

The datasets compiled in this project represent a large body of information, which was acquired under a variety of conditions that were at least in part adequate for detection groundwater. The majority of the Lake Superior shoreline was flown on three occasions, the mainstem of the Knife

River was flown twice and the Lake Superior tributaries were flown once. Given that TIR technology used in this study appeared sensitive under less than ideal conditions and that the study areas received adequate coverage, we conclude that significant sources of ground water below barriers along the Minnesota Lake Superior shore and tributaries accessible to migratory salmonids is rare. Minor ground water extrusion areas may have gone undetected, but the number of brook trout they could support in a severe winter would be minimal. The lack of significant ground water will negatively affect coaster brook trout rehabilitation efforts in Minnesota. Winter conditions experienced in 2002-2003 when many stream sections froze completely to the bottom are illustrative of the harsh conditions associate with groundwater poor northshore streams. Stream surveys conducted in the summer of 2003 indicated significant declines in both juvenile rainbow trout and resident brook trout populations. Anglers also reported extremely poor fishing success in areas where brook trout angling is normally good. Streams that have at least some ground water or that have a year round source of water from lakes or large permanent wetlands may be the only realistic candidates for potential coaster brook trout restoration in Minnesota.

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Area Supervisor Date

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Regional Supervisor Date

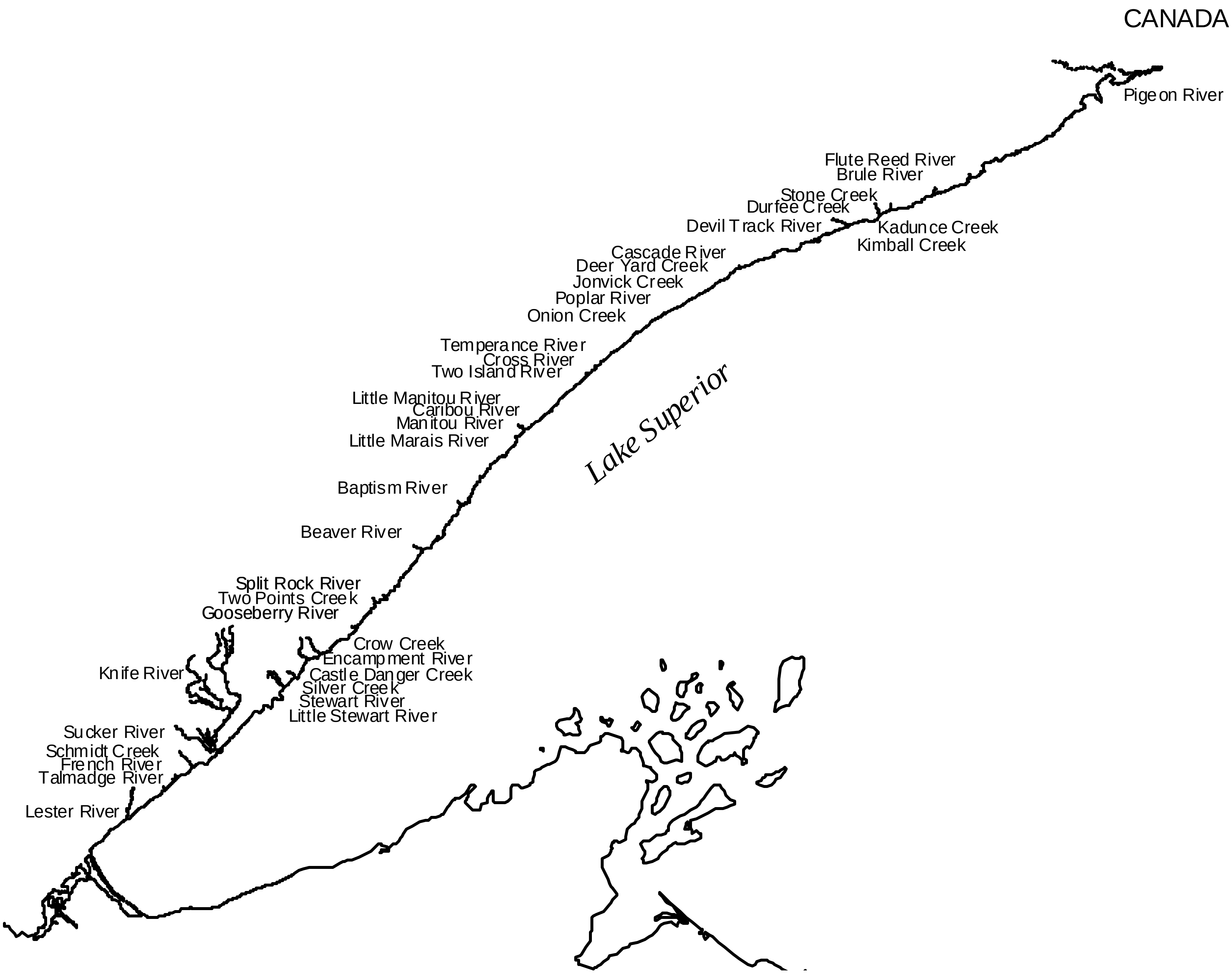

Figure 1. Map of sampled areas.

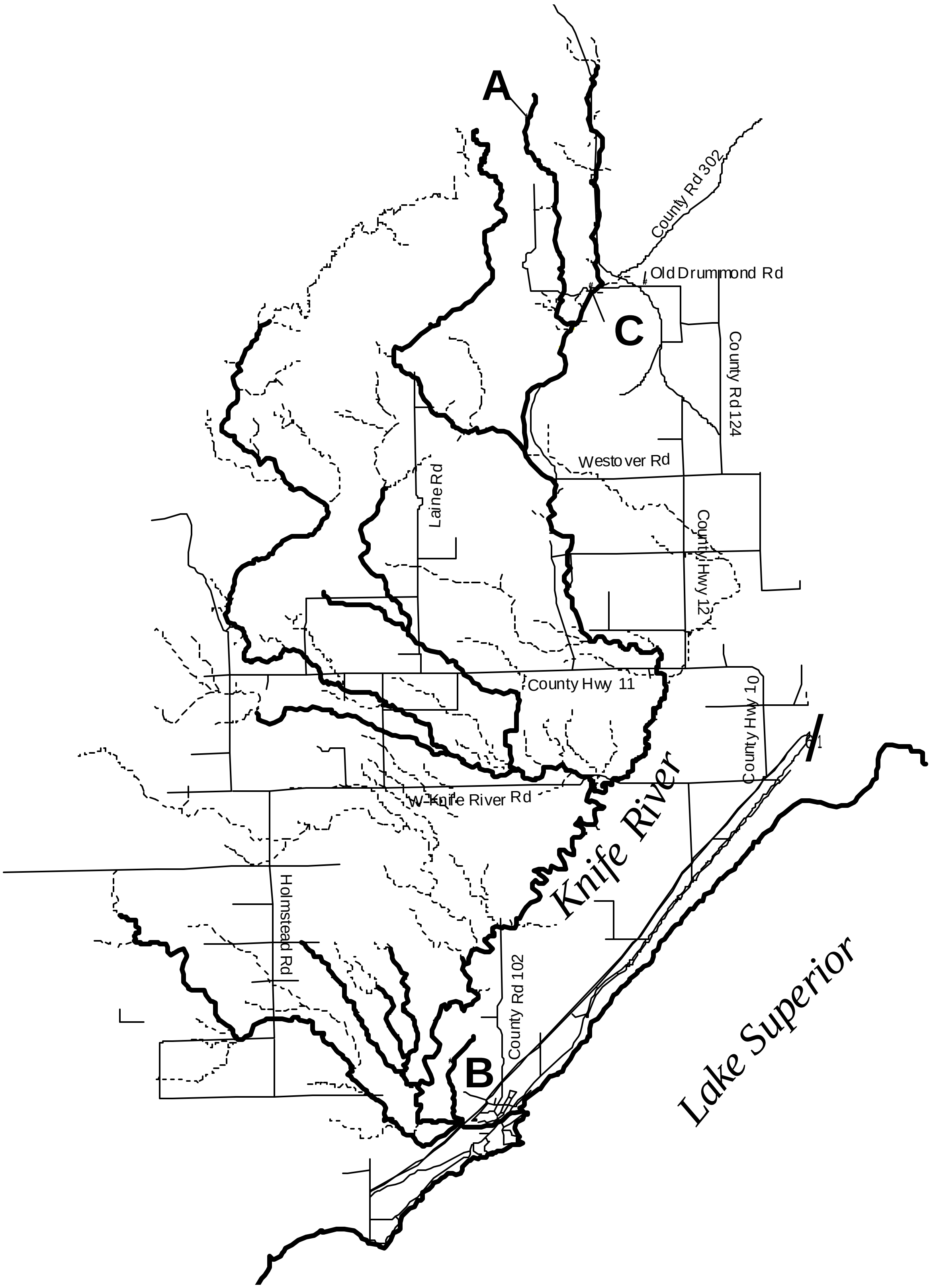

Figure 2. Knife River system indicating surveyed areas in bold. Ground water was detected at site C. .

Figure 3. Lake Buccaneer model, remote sensing aircraft, A.W. Research Laboratories Inc. photo.

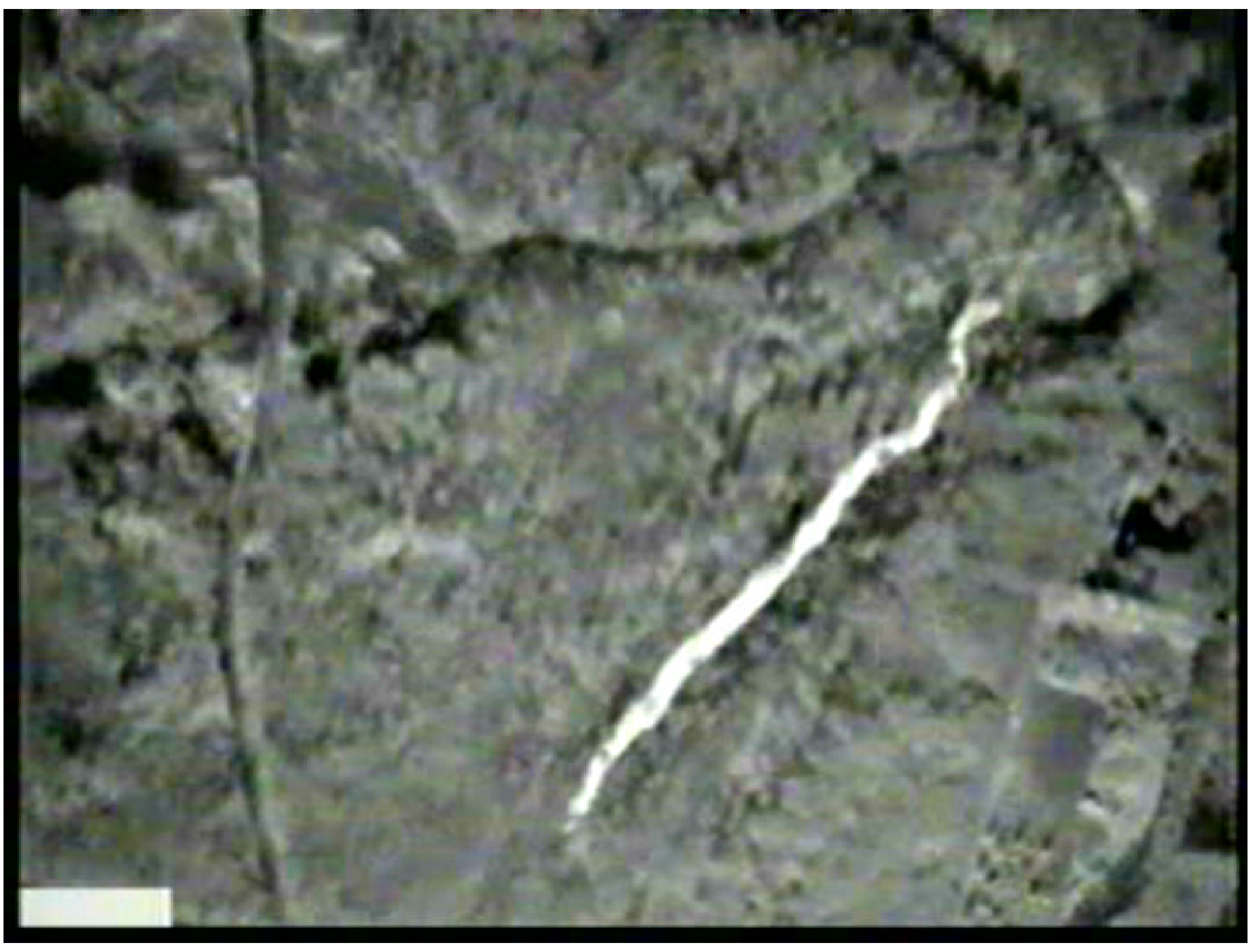

Figure 4. Mainstem Knife River, showing thermal signature of water flowing over the ice, January 2003.

Figure 5. Thermal image of Knife River and Old Drummond Road, C (Figure 2), taken on February 29, 2003, showing a region of ground water intrusion indicated by white.

Figure 6. Groundwater intrusion area near the intersection of Old Drummond Road and the Knife River, site C, showing seeping groundwater feeding a bryophitic plant community. Photo taken on August 9, 2003.

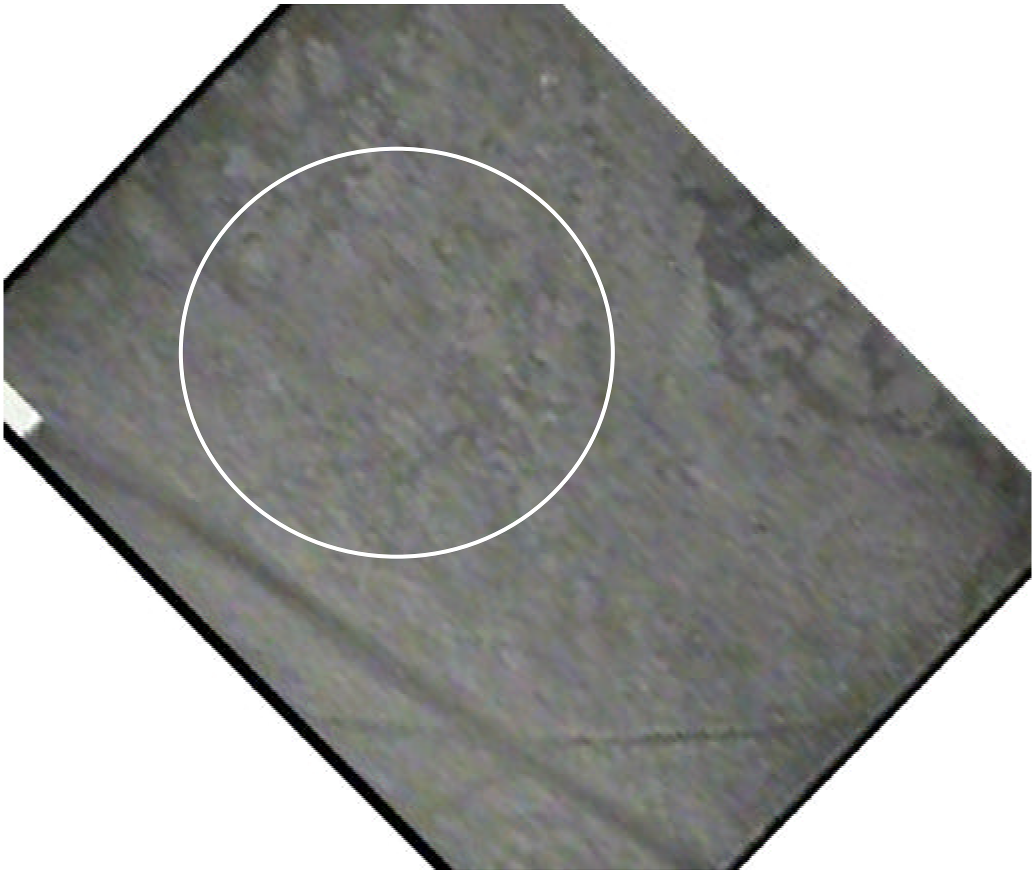

Figure 7. Thermal image of Knife River and Old Drummond Road, C (Figure 2), taken on December 4, 2003, over area of known groundwater intrusion, showing less contrast compared to Figure 5.

Figure 8. Groundwater intrusion area near the intersection of Old Drummond Road and the Knife River, site C, showing exposed ground and seeping groundwater on December 10, 2003.

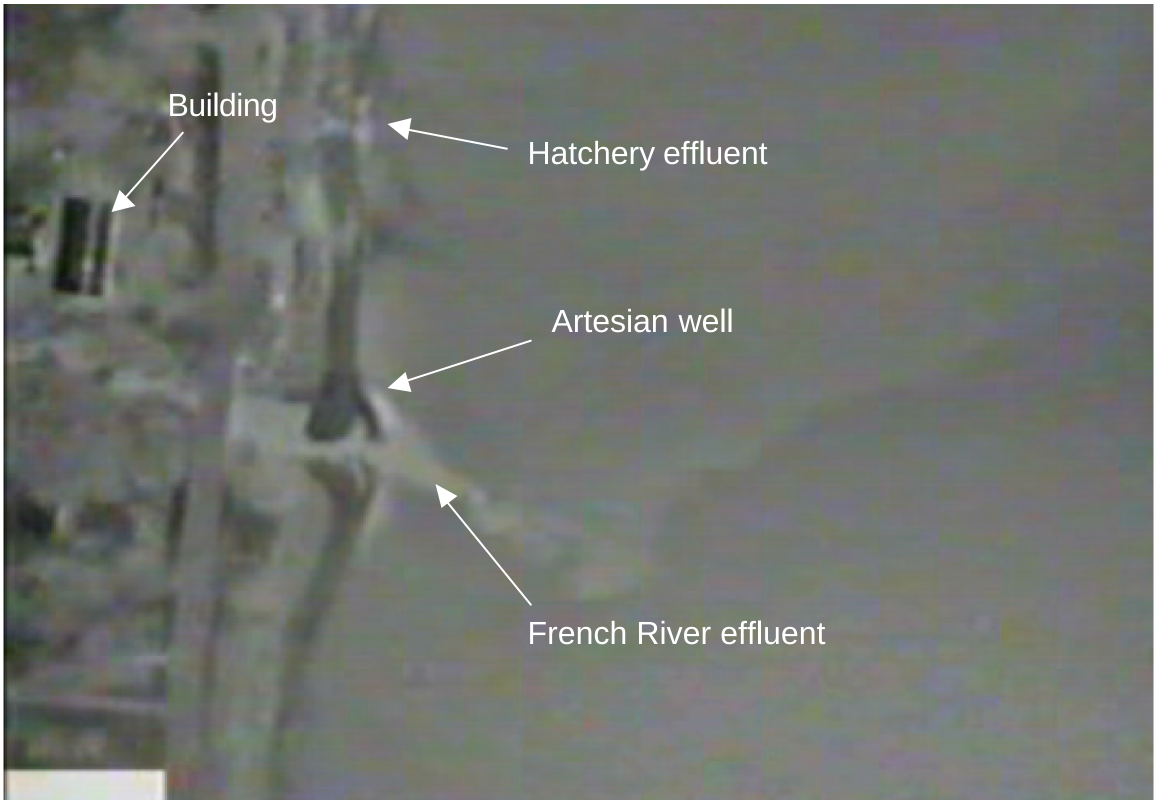

Figure 9. French River showing warm water effluent, artesian well and hatchery effluent taken on April 29, 2003.

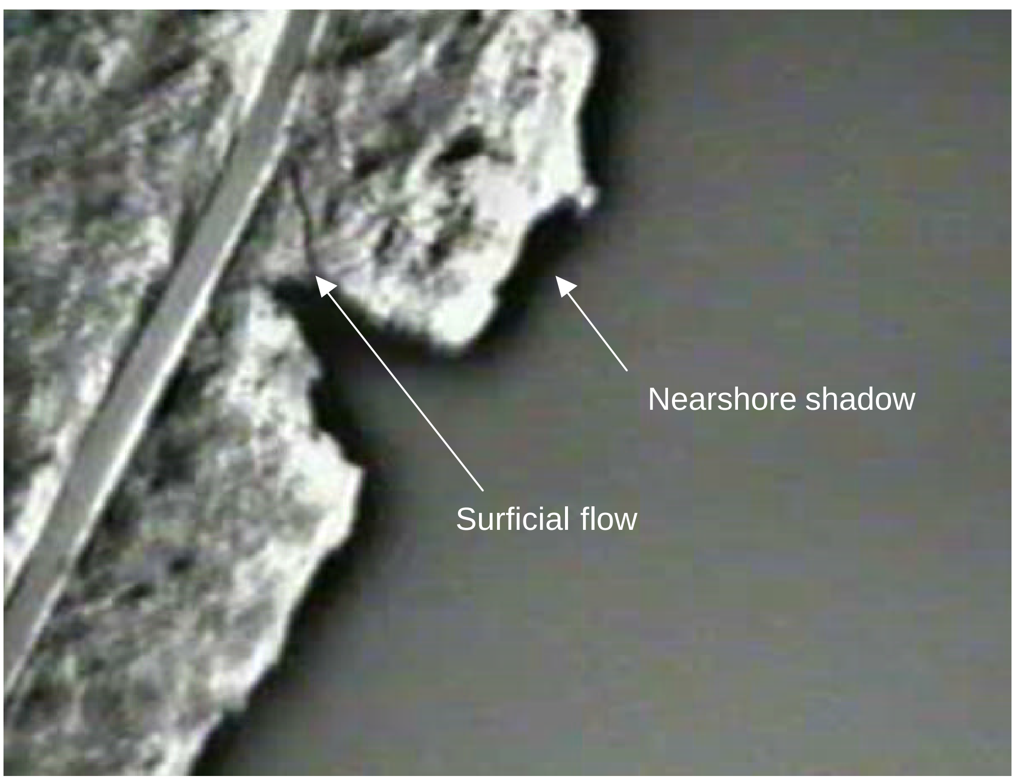

Figure 10. Thermal image near Sugar Loaf Scenic and Natural Area, April 29, 2003, taken under sunny conditions. Cold surficial flow of spring runoff was well highlighted against sun-warmed substrate.

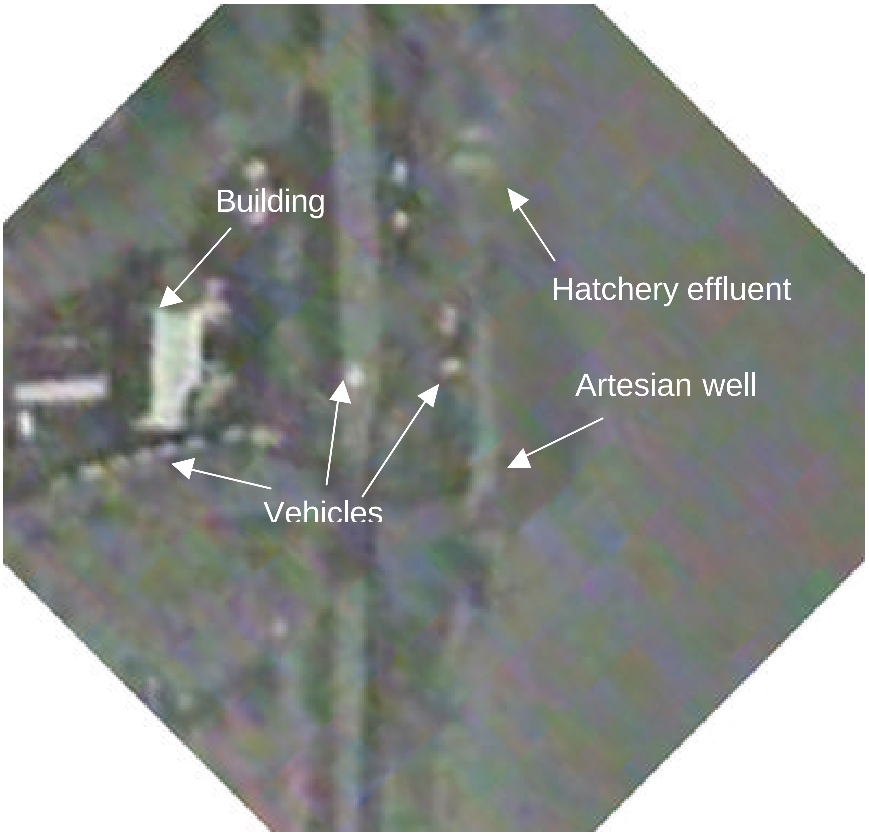

Figure 11. French River showing warm water hatchery effluent and artesian well taken on December 4, 2003.

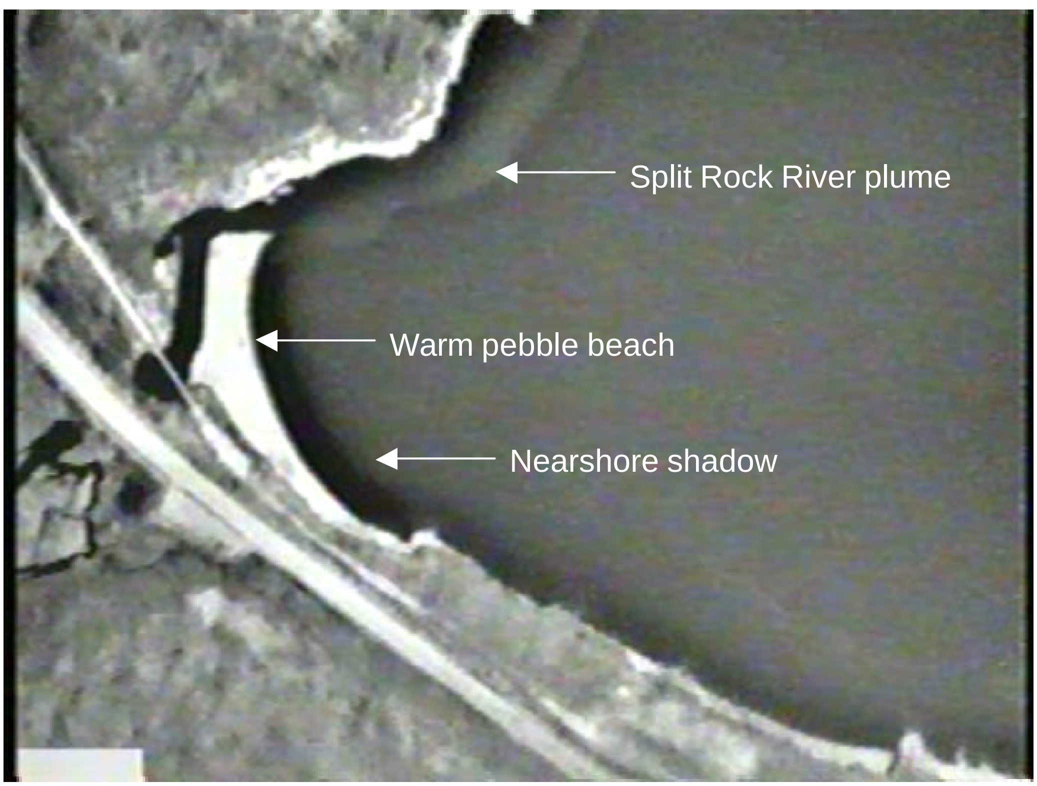

Figure 12. Thermal image of the mouth of the Split Rock River taken on April 13, 2004

Figure 13. Thermal image of small groundwater intrusion area on the Lester River taken December 4, 2003.

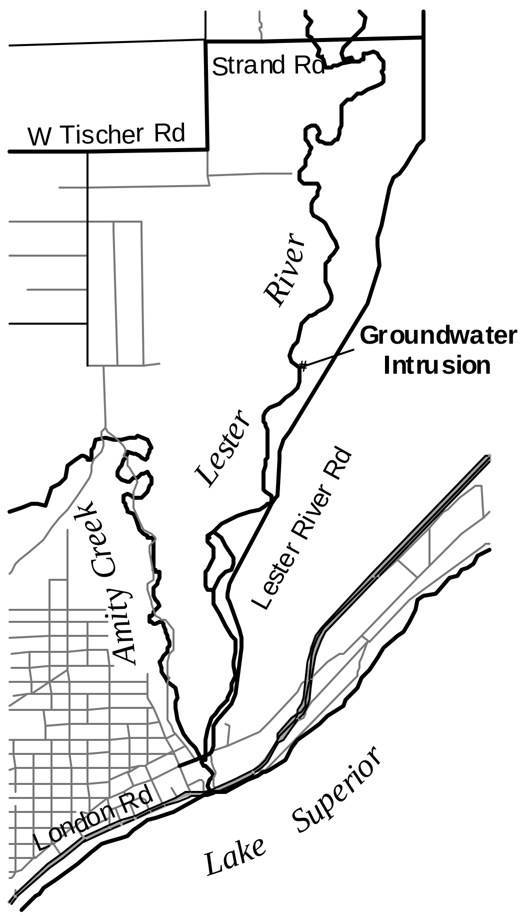

Figure 14. Location of groundwater intrusion area on the Lester River.

Figure 15. Groundwater intrusion area on the Lester River, July 9, 2004.

Table 1. Weather conditions and dates of aerial remote sensing.

Date	Area description	Data	Sky condition	Air temperature
1/20/03	Knife River mainstem	Visible slides	Clear	-5
1/29/03	Knife River tributaries	Visible slides	Clear	8
1/29/03	Knife River mainstem	Thermal, hyperspectral video	Clear	8
2/26/03	Knife River tributaries	Thermal, hyperspectral video	Partly cloudy	20
4/23/03	Lester River to Canadian border	Visible slides	Clear, stattered high clouds	42
4/29/03	Lester River to Canadian border	Thermal, hyperspectral video	Clear, stattered high clouds	40
4/29/03	Knife River tributaries 1 and 12	Thermal, hyperspectral video	Clear, stattered high clouds	40
12/4/03	Lester, Talmadge, French, Schmidt, Sucker rivers; shoreline between Lester and Two Harbors; portion of the Knife River mainstem	Thermal, hyperspectral video, slides	Overcast to clear	30
4/13/04	Upper Lester River, Shoreline and tributaries from Stewart River to Cascade River	Thermal, hyperspectral video	Partly cloudy to overcast	41-55
4/14/04	Shoreline and tributaries from Devil Track River to Pigeon River	Thermal, hyperspectral video	Overcast to clear	32-45