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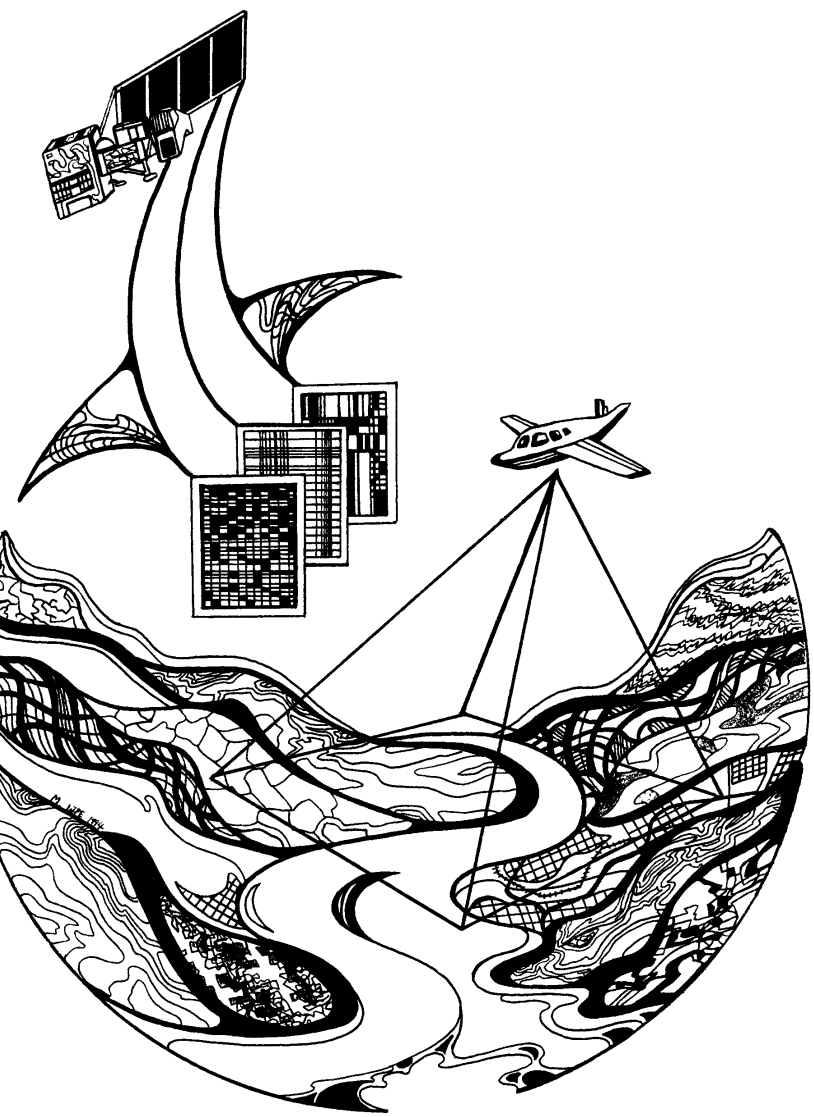
Satellite AVHRR Temperature Measurements of Pools 4, 7, and 8

of the Upper Mississippi River System



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Satellite AVHRR Temperature Measurements of Pools 4, 7, and 8 of the Upper Mississippi River System

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Preface

The Long Term Resource Monitoring Program (LTRMP) was authorized under the Water Resources Development Act of 1986 (Public Law 99-662) as an element of the U.S. Army Corps of Engineers' Environmental Management Program. The LTRMP is being implemented by the Environmental Management Technical Center, a U.S. Geological Survey science center, in cooperation with the five Upper Mississippi River System (UMRS) States of Illinois, Iowa, Minnesota, Missouri, and Wisconsin. The U.S. Army Corps of Engineers provides guidance and has overall Program responsibility. The mode of operation and respective roles of the agencies are outlined in a 1988 Memorandum of Agreement.

The UMRS encompasses the commercially navigable reaches of the Upper Mississippi River, as well as the Illinois River and navigable portions of the Kaskaskia, Black, St. Croix, and Minnesota Rivers. Congress has declared the UMRS to be both a nationally significant ecosystem and a nationally significant commercial navigation system. The mission of the LTRMP is to provide decision makers with information for maintaining the UMRS as a sustainable large river ecosystem given its multiple-use character. The long-term goals of the Program are to understand the system, determine resource trends and effects, develop management alternatives, manage information, and develop useful products.

This report fulfills in part Objective 2.3, *Synthesize and Evaluate Monitoring Data*, as specified in Goal 2 of the Operating Plan (USFWS 1993) and was developed with funding provided by the Long Term Resource Monitoring Program.

Satellite AVHRR Temperature Measurements of Pools 4, 7, and 8 of the Upper Mississippi River System

by

Ronald A. Weinkauf

Abstract

The polar-orbiting Advanced Very High Resolution Radiometer (AVHRR) was evaluated as a means of detecting and measuring surface water temperatures of selected Pools of the Upper Mississippi River System. In summer 1994 Pools 4, 7, and 8 were monitored and, despite heavy cloud cover and fog, useful results were obtained. Satellite mean temperatures were within about 1 Celsius degree of in situ temperature means for nine observation dates for the three pools. A split window procedure, combining the radiance of thermal infrared bands 4 and 5, greatly improved the accuracy of temperature estimates. Routine temperature monitoring could become a reality when some of the logistical problems encountered in this study are addressed. In particular there is a need to establish improved locational control to tie AVHRR pixels more accurately to their surface locations, to provide for systematic surface water data collection on dates of imaging passes, and to link other variables such as water depth and turbidity to the remote temperature measurements.

Introduction

In summer 1993 a study was initiated to explore the feasibility of using satellite thermal radiance data as a source of surface water temperature information for Pools 7 and 8 of the Upper Mississippi River System (UMRS). Conducted under a cooperative agreement between the University of Wisconsin–La Crosse and the U.S.Geological Survey (formerly the National Biological Service) Environmental Management Technical Center, Onalaska, Wisconsin, the initial investigation provided positive results. Satellite Advanced Very High Resolution Radiometer (AVHRR) temperature estimates were within 1.4 Celsius degrees of in situ mean temperatures for eight observing dates for Pool 7 (Lake Onalaska) and within 1 Celsius degree of in situ mean temperatures for Pool 8 (Weinkauf 1997). The 1994 observation period showed improvement, with a 0.23 Celsius degree difference between the means of satellite and in situ readings for the three UMRS pools. Pool 4 (Lake Pepin) was added in the 1994 study. The study also focused attention on several methodological steps that must be improved if satellite measurement of surface temperatures is to become an operational procedure. In particular, the 1993 study defined the following four needs:

- to rectify satellite image data to a standard map projection,
- to normalize pixels to 1.1 km^2 to adjust for variation in off-nadir viewing angles,
- to alert ground personnel of the dates and times of satellite overpasses to provide more accurate correlation between and verification of the remote and in situ readings, and
- to include a larger pool to explore the distribution of temperature in more detail.

Although considerable effort was expended to address these needs, the work during 1994 only partly resolved them. Additional research is therefore required if the procedures documented herein are to become routine practice.

Temperature as a Biophysical Variable

Water temperature is a significant biophysical variable in aquatic ecosystems, with direct bearing on many biological, chemical, and physical processes (Jensen 1983). Moreover, temperature provides a surrogate to other parameters of interest such as water quality, as revealed in total suspended matter, water depth, upwelling, and the presence of cold and warm currents. Under proper conditions, eutrophic state may also be determined (Boland 1976). As concern over the prospect of global warming mounts, an effort to establish the secular trends of pool temperatures could well be an investigative priority in future studies. Retrospective AVHRR data are available since 1985, but initial inquiry suggests that retrieval of the surface temperature information may be a complex task. Although they drew upon current AVHRR data, Lillesand and Wynne (1993) established the value of such study by using lake ice duration in Wisconsin as a signal of a warming trend.

Previous Temperature Studies in the Upper Mississippi River Basin

Only one large, remote surface temperature mapping project has been conducted in the Upper Mississippi River Basin (UMRB). It was carried out in 1971 with an airborne thermal scanner (Tuthill et al. 1973). I believe that satellite-based temperature studies have not been conducted except for the 1993 study discussed here. Although the airborne temperature mapping project provided useful results, it required a major logistical effort to acquire the necessary surface water temperatures and the scanner wavelength sensitivity was not optimal.

Upper Mississippi River

The Mississippi River drains an area of 3.24 million km^2 (1.25 million mi^2) or 41% of the 48 contiguous United States. The present report is concerned with the UMRB lying above the confluence of the Ohio River (Figure 1). Parts of 13 states are drained by the Upper Mississippi River. Some 1,849,260 km^2 (714,000 mi^2) or about 23% of the area of the contiguous United States falls within the basin (Interagency Floodplain Management Review Committee 1994).

The UMRS today consists of a series of 28 locks and dams with a 9-foot navigation channel. Authorized in the 1930s and constructed since about 1940, the impoundments behind the dams create sufficiently large water bodies to fall within the coarse spatial resolution (1.1 km^2) of the AVHRR sensing instrument.

Satellite Thermal Infrared Sensing Systems

Thermal infrared radiance data are acquired by several satellite systems (Table 1). Although two Polar Orbiting Environmental Satellites (POES), NOAA-11 and NOAA-12, operated during the present study, only data acquired by NOAA-12 sensors were used (Table 2). The POES gather data on southbound (descending) and on northbound (ascending) passes. Descending node passes were used because north is at the top of the image, which facilitates the process of georeferencing the image data without having to rotate the image and because the descending node overpass is near 9:00 a.m. local standard time. This provides an opportunity to acquire reflected visible and near infrared as well as emitted thermal infrared radiance data. The satellite's near infrared channel helps to locate and delineate water bodies because of high reflection by ground features, especially vegetated surfaces, and because of high absorption by water in these wavelengths.

Table 1. Orbital sensors used for thermal infrared measurements of the earth's surface.

		Resolution		
Orbital sensor	**Satellite mission**	**Spectral (Fm)**	**Spatial (km)[a]**	**Repeat cycle**
AVHRR	NOAA-11	Band 3 3.53–3.93	1.1	Every 12 h[b]
		Band 4 10.3–11.30	1.1	Every 12 h[b]
		Band 5 11.5–12.50	1.1	Every 12 h[b]
HCMR	HCMM	TIR 10.5–12.5	0.6	5 to 16 days
MSS[c]	Landsat	Band 8 10.5–12.5	0.238	18 days
TM[d]	Landsat	Band 6 10.4–12.6	0.120	16 days

[a] At nadir.

[b] Five to 6 days under actual operation. Data acquired since 1985. Landsat thermal data of the UMRS are available only for selected years. Heat Capacity Mapping Mission thermal data are available from overpasses from 1978 to 1980 (Short and Stuart 1982). It is clear from the table that only the AVHRR is a suitable data source for temperature mapping of past temperature regimes. (In May 1985 the EROS Data Center, Sioux Falls, South Dakota, began to receive real-time AVHRR data. This presents opportunities for future study of the UMRS with AVHRR data.)

[c] Multispectral Scanner System.

[d] Thematic Mapper.

Table 2. AVHRR spectral bands for the NOAA-11 and NOAA-12 satellites.

Channel number	**Wavelengths (Fm)**	**Energy**
1	0.58–0.68	Visible
2	0.725–1.10	Near infrared
3	3.55–3.93	Short wavelength Thermal infrared
4	10.50–11.50	Thermal infrared
5	11.50–12.50	Thermal infrared

The NOAA-11 overpasses in midafternoon (3:00 p.m. local standard time) and early morning (3:00 a.m. local standard time) were not well suited to the observation of water bodies. The late afternoon NOAA-11 overpass time is less desirable than the 9:00 a.m. overpass time because of convective cloud buildup. The early morning pass limits data collection to the thermal infrared portion of the electromagnetic energy spectrum.

The times of data collection are not optimal for the detection and mapping of surface temperatures (Short and Stuart 1982; NASA/EOSAT 1986). Compared with rocks and soils, water has a small diurnal range of temperature. Land and water temperatures are difficult to differentiate between sunrise and midmorning; thus surface water bodies are difficult to isolate by using satellite thermal data.

Methods

The Department of Geography and Earth Science, University of Wisconsin–La Crosse, has established a facility for acquisition, display, and analysis of Geostationary Operational Environmental Satellite (GOES) and POES satellite and associated data. Through a modem satellite image data are accessed in near real-time from the Man computer Interactive Data Access System (McIDAS) on the University of Wisconsin–Madison campus.

Although the early focus of McIDAS was on meteorological applications, increasing attention over the past several years has been directed to terrestrial applications involving surface temperature measurements and the study of vegetation condition (Hastings et al. 1988). The standard procedure is to determine the dates of POES high elevation overpasses covering the upper Midwest. Generally only satellite passes of 70E or higher are considered. Image data acquired at lower elevation angles are degraded by long radiance path lengths through the atmosphere. Observation dates are further limited by days when the upper Midwest is generally cloud-free, but fog or isolated clouds obscure individual pools. The GOES images acquired on 30-min intervals are used to assess cloud cover conditions over the pools of interest preceding the polar-orbiting satellite pass.

When a suitable data set is identified, all five channels of radiance data are transferred from Madison to La Crosse, Wisconsin (Table 3). A cursor box is positioned over the pool of interest and single-channel (band 4) radiometric temperatures are extracted in a 9-line by 9-column matrix of 81 data points. The single-channel temperatures are approximate. Multichannel (bands 4 and 5) manipulation of the thermal data yields much more accurate temperature estimates. These procedures, often referred to as split-window processing, derive from the considerable experience that has accumulated by using AVHRR remote sensing of thermal energy over the oceans of the world, in which accurate sea surface temperatures are routinely mapped (McClain et al. 1985; McClain 1989).

Table 3. AVHRR sensor operational channels.[a]

Band	Wavelengths (Fm)	Typical applications
1	0.58–0.68 Fm	Cloud declination Snow and ice monitoring Weather
2	0.725–1.10 Fm	Location of water bodies Vegetation assessments
3	3.55–3.93 Fm	Landmark extraction Forest fire monitoring Volcanic activity Sea surface temperature (nighttime)
4	10.3–11.3 Fm	Sea surface temperature Weather Soil moisture Volcanic eruptions
5	11.5–12.5 Fm	Sea surface temperature Weather (In combination with band 4 improve surface temperature measurements)

[a]NESDIS Programs, NOAA Satellite Operations, March 1985.

As judged by my 1993 data, I believe that atmospheric adjustments are required if accurate surface water temperatures are to be determined. In essence, the split-window procedure improves the remote surface temperature estimates by removing the contribution of atmospheric radiance to the upwelling radiation. The longer wavelength (band 5) radiance emanates primarily from atmospheric sources. Temperature accuracy is improved by about 5 Celsius degrees by making this atmospheric adjustment.

In keeping with the needs identified in the 1993 study, image data files are now remapped to a Mercator projection and resampled to 1.1 km^2 pixels. These data sets are then imported into IDRISI software on an IBM PC for display and analysis.

Observation Conditions, 1994

Heavy cloud cover in 1994, as in 1993, made data collection a challenge. Fog and haze from forest fires in the western United States contributed to the problem. Suitable data were acquired on nine dates from late June until early September 1994 (Table 4). Cloud cover obscuring Pools 7 and 8 reduced data collection overpasses for those pools to eight dates.

Tabular data for each of the pools were compiled for those dates, but in many instances suitable surface temperature data were not available for comparison.

Table 4. Satellite data collection overpasses, 1994.

Date	Julian date	Universal time	Local standard time
June 25	94176	1408	9:08
June 30	94181	1400	9:00
July 10	94191	1343	8:43
July 15	94196	1343	8:43
July 18	94199	1411	9:11
July 28	94209	1354	8:54
August 2	94214	1346	8:46
August 24	94236	1413	9:13
September 7	94250	1407	9:07

Study Sites

As indicated, Pools 7 and 8 were the focus of attention in the 1993 study. Because of the objective of exploring the distribution of temperature, Pool 4 (Lake Pepin) was added to the sites over which satellite data were acquired for the 1994 study (Figure 1; Table 5).

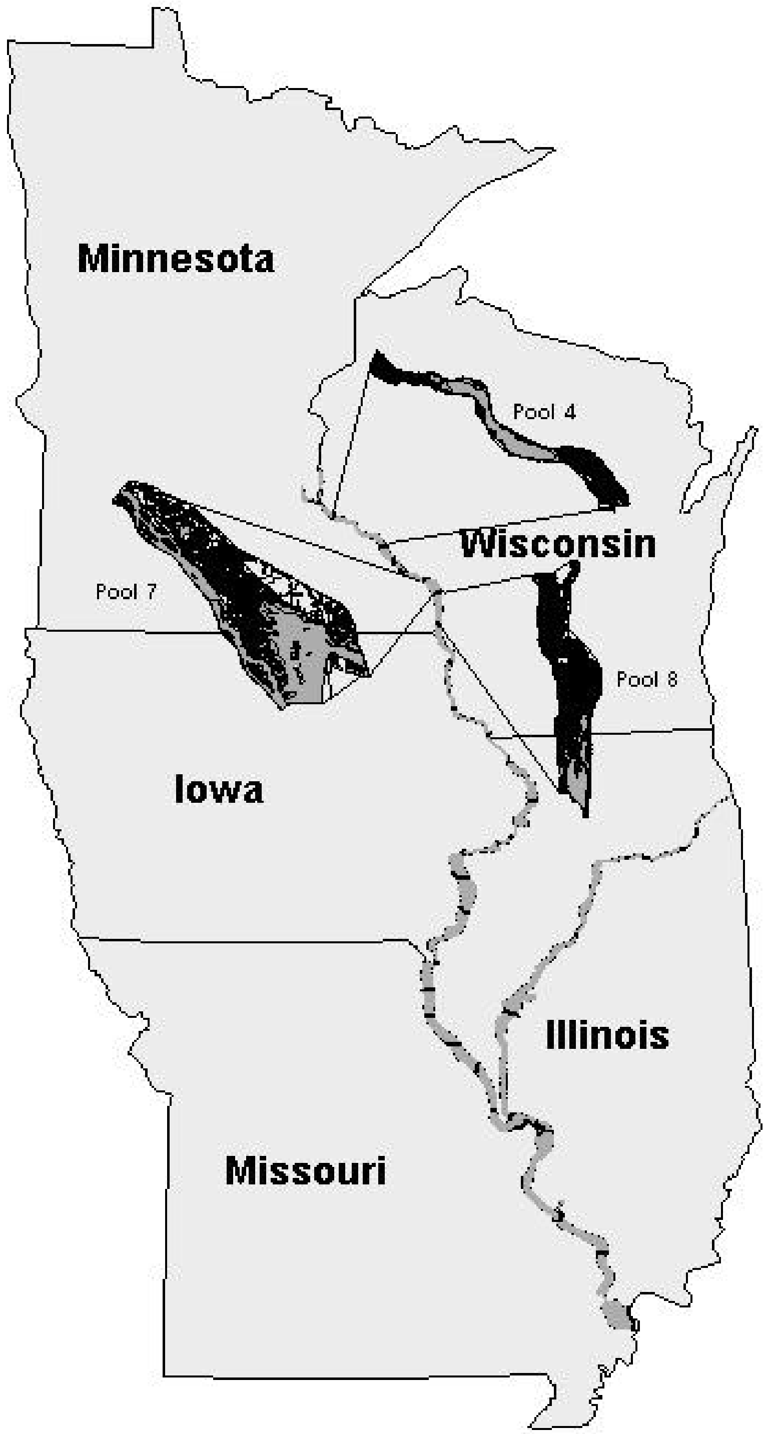

Figure 1. Study sites in the Upper Mississippi River basin.

Table 5. Characteristics of the study pools.

Pool number	Pool name	Acres	Hectares	Number of 1.1 m^2 pixels
4	Lake Pepin	25,408	10,282	94
7	Lake Onalaska	8,965	3,628	33
8	Pool 8	13,870	5,613	50

Pool 4

Lake Pepin, a natural lake on the Mississippi River, is a much larger water body than Pools 7 and 8 and thus is a more suitable target as viewed with a system with 1.1 km^2 spatial resolution (Figure 1). Surface temperature measurements for Pool 4 were available at many sampling sites, making it possible to begin the task of studying the distribution of surface temperatures.

Pool 4, Lake Pepin Temperature Analysis. A mean temperature difference of slightly more than 1EC for the nine observations from late June until early September indicates close correlation between the satellite and the surface readings for Pool 4 (Table 6; Figure 2). In spite of discrepancies during early summer, the general trend of surface temperatures was accurately recorded by the satellite measurements.

Table 6. Pool 4 (Lake Pepin upper segment) satellite and in situ temperate estimates (EC).

Date	Time	Satellite	In situ
June 25	1407	21.7	27.2
June 30	1400	25.0	23.9
July 10	1343	26.3	23.8
July 15	1335	25.3	23.6
July 18	1411	25.5[a]	24.9
July 28	1354	25.4	25.3[b]
August 2	1346	27.3	26.4[c]
August 24	1413	24.4	23.0[d]
September 7	1407	21.4	20.5
Mean		25.30	24.29

[a]Calculated from a single channel reading.
[b]July 29, 1994, reading.
[c]August 5, 1994, reading.
[d]August 23, 1994, reading.

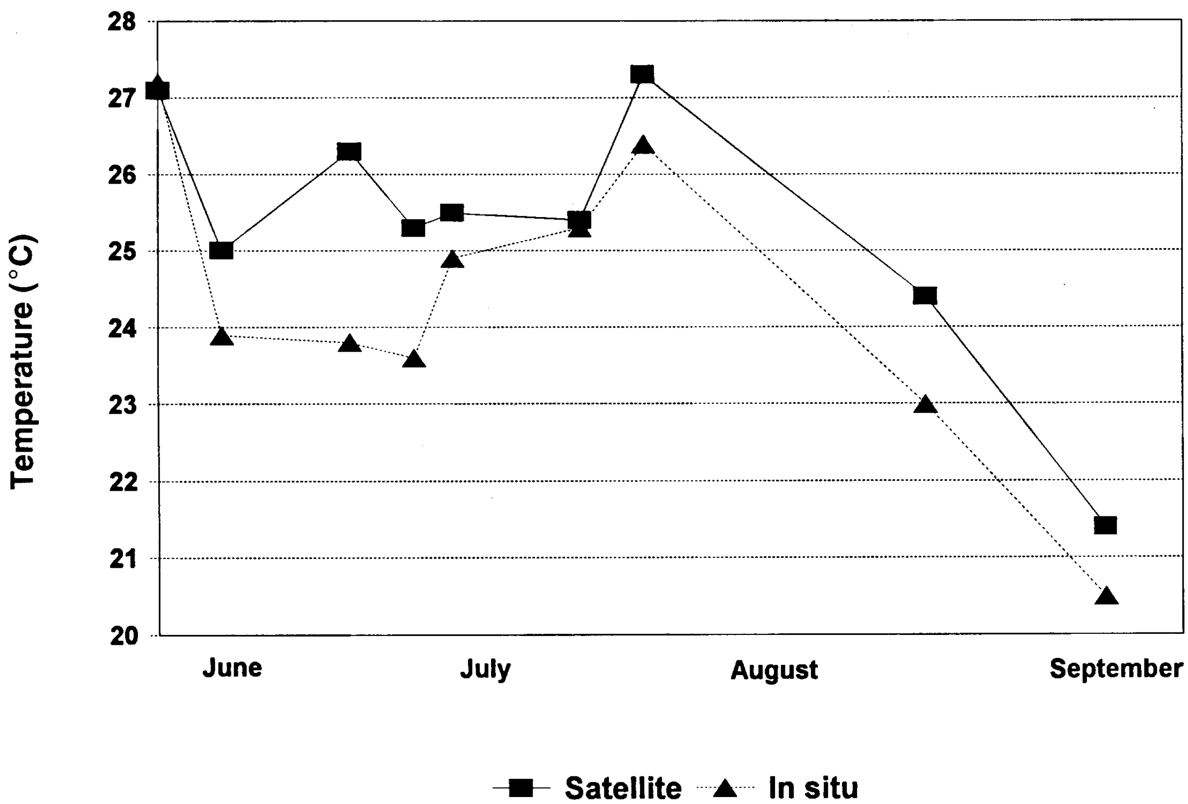

Figure 2. Pool 4, north segment, 1994; satellite and in situ temperatures.

Random sampling of surface water temperatures for July 29, 1994, at 12 sites in the upper segment of Pool 4 yielded a mean of 25.3EC (R. Burdis, personal communication, Minnesota Department of Natural Resources, Lake City, Minnesota, 1994). Satellite estimates for 12 pixels over the Upper Segment of Pool 4 yielded a mean of 25.0EC for July 28, 1994 (Table 7).

Because of the intensive temperature sampling program carried out for Lake Pepin by the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency, the pool could serve as a site for future satellite temperature studies.

Table 7. Pool 4 (Lake Pepin upper segment) random sampling and AVHRR temperatures (EC).

Random sampling	*N*	Mean	Min	Max	SD
7-29-94					
Surface temperature water samples	12	25.3	23.9	27.1	0.77
7-28-94					
Satellite readings	12	25.0	24.9	25.4	0.31

Pool 7

Lake Onalaska is one of the most intensively studied Pools of the UMRS. The effects of recently constructed islands are presently under investigation. Because of the installation of a second temperature recording instrument in the pool, two in situ sites were available for that water body (Figure 1). The south end site near Arrowhead Island is thus designated as the Island Site. The north end site records temperatures over an open-water area and is thus designated as the Open Water site. Surface water temperature measurements for Pool 7 are exceptional in their accuracy, expressed to two decimal points, and in their timing, continuously recorded every minute and integrated at 15-min intervals. The availability of this information makes it possible to match satellite observations with the in situ readings virtually to the minute. It should be stressed that the surface temperatures are point samples and do not express distribution of temperatures.

Pool 7, South End Temperature Analysis. Eight satellite observations yielded a mean temperature difference of slightly more than 1 Celsius degree, similar to that of Pool 4 (Figure 3; Table 8). After a somewhat mixed relation in early summer there was good correlation between the satellite and the surface readings in late summer. One possible explanation for the significant differences in satellite versus in situ estimates in early summer is haze-induced cooling. This supposition requires additional inquiry.

The 31.77EC in situ reading for June 25 (Table 8) was at first treated as invalid, induced perhaps by the recording instrument. A 29.9EC reading for Pool 4 recorded on June 21 and June 22, however, suggests that this is an accurate measurement.

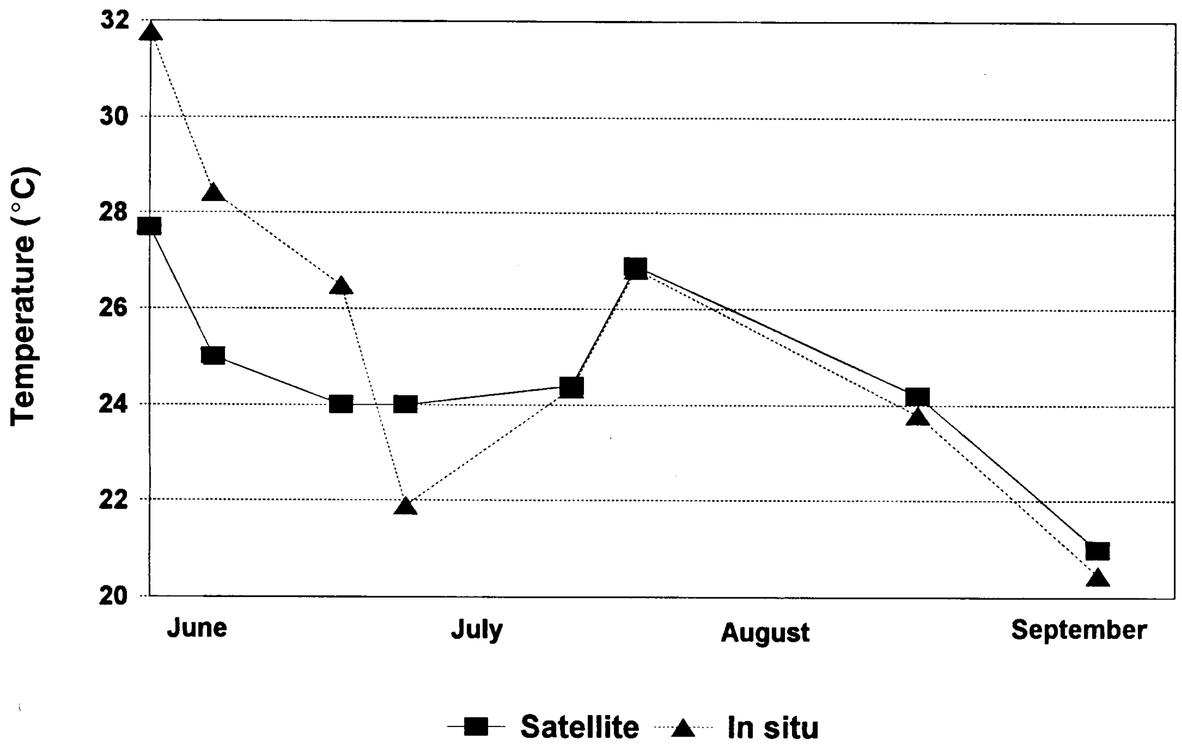

Figure 3. Pool 7, south end, 1994; satellite and in situ temperatures.

Table 8. Pool 7 south end (Island Site) satellite and in situ temperature estimates (EC).

Date	Time	Satellite	In situ
June 25	1408	27.7	31.77
June 30	1400	25.0	28.43
July 10	1343	24.0	26.50[a]
July 15	1335	24.0	21.90[b]
July 18	1411	Cloudy	Not available
July 28	1354	24.4	24.35
August 2	1346	26.9	26.83
August 24	1410	24.2	23.80[c]
September 7	1407	21.0	20.40[d]
Mean		24.65	25.51

[a]Reading on July 5, 1994 at 8:45 a.m.
[b]Lock and Dam #7 estimate from 9:45 reading.
[c]Lock and Dam #7 estimate from 6:00 a.m. reading.
[d]North end of Pool 7 reading at 9:00 a.m.

Pool 7, North End (Open Water) Site. The temperature mean difference at the north end of Pool 7 was only 0.23 Celsius degree for the eight observing dates (Table 9). As with the other sites, poorer correlation in early summer is followed by excellent matching of temperature trends in late summer (Figure 4).

Table 9. Pool 7 north end (Open Water) satellite and in situ temperature estimates (EC).

Date	Time	Satellite	In situ
June 25	1408	27.7	25.20[a]
June 30	1400	25.0	25.83
July 10	1343	24.0	24.00[b]
July 15	1335	24.0	23.09
July 18	1411	Cloudy	Not available
July 28	1354	22.8	24.23
August 2	1346	26.4	26.44
August 24	1410	24.2	23.80[c]
September 7	1407	20.8	20.47
Mean		24.36	24.13

[a]Lock and Dam #7 11:00 (6 a.m.) reading.
[b]Lock and Dam #7 14:45 (9:45 a.m.) reading.
[c]Lock and Dam #7 estimate from 11:00 (6 a.m.) reading.

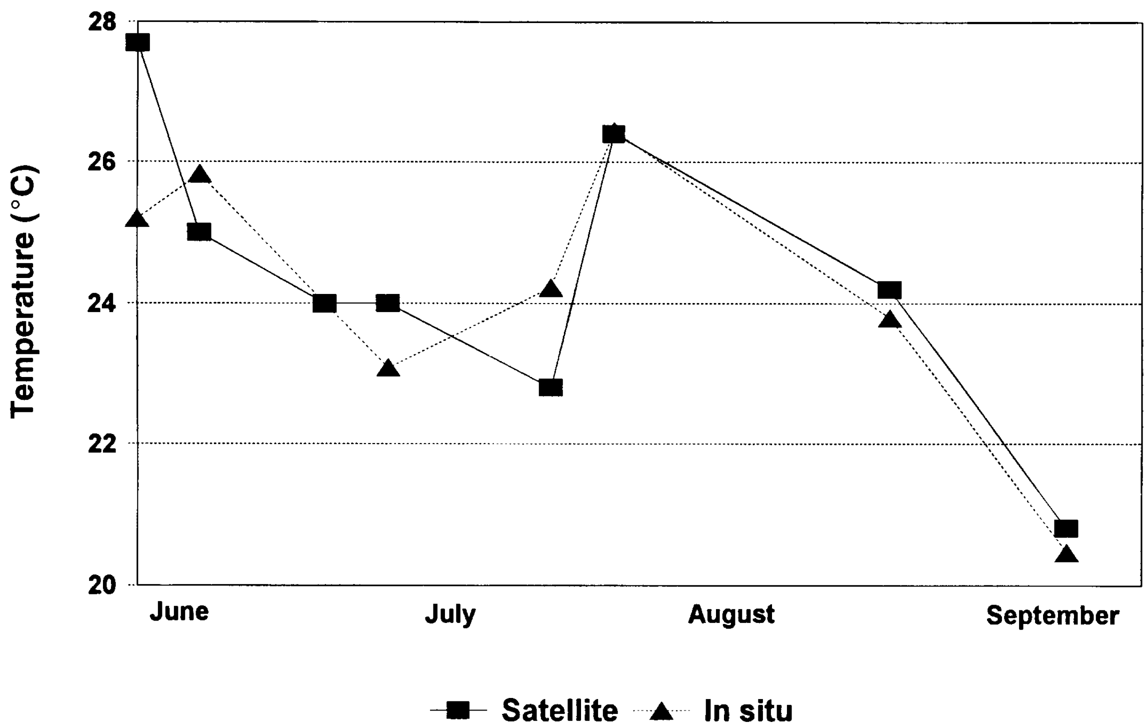

Figure 4. Pool 7, north end, 1994; satellite and in situ temperatures.

Pool 8

The experience with Pool 8 presented difficulties. Eight satellite measurements were acquired but only two in situ readings (Table 10) were available for comparison. The satellite temperature trends closely followed the pattern for Pools 4 and 7, indicating that remote sensing of pool temperatures is a viable technique.

Table 10. Pool 8 satellite and in situ temperature estimates (EC).

Date	Time	Satellite	In situ
June 25	1407	27.3	Not available
June 30	1400	25.8	Not available
July 10	1343	24.5	Not available
July 15	1335	23.6	Not available
July 18	1411	25.4	Not available
July 28	1354	25.4	23.2
August 2	1346	Not available	25.1
August 24	1413	24.2	Not available
September 7	1407	20.6	Not available
Mean		24.6	24.1

When the means are compared for the pools and for the north and south ends of Lake Onalaska, good results are achieved (Table 11). The Pool 8 means may be suspect but the general correspondence with Pool 7 temperatures suggests that the satellite temperatures are valid.

High air temperatures coupled with clear skies (low cloud cover percentages) resulted in the highest water temperatures falling in late June rather than late summer, which is more common. This trend was recorded for all the pools, followed by a return to more seasonal temperatures in July, August, and September.

Table 11. Comparison of temperature means for Pools 4, 7, and 8 (EC).

Pool	Location	Satellite	In situ	Difference
4	Upper segment	25.30	24.29	1.01
7	North end (Open Water)	24.36	24.13	0.23
7	South end (Island Site)	24.65	25.51	–0.86
8	Lower pool	24.60	24.10	0.5
Mean		24.73	24.50	0.23

Procedures

The scheduling of surface reference data collection is a complicated process because of the uncertainty that surrounds the satellite imaging process. Cloud cover or other weather problems such as fog or haze may obscure a given pool, but this information is not known until shortly before the imaging overpass. Operational schedules may be tentative because of a variety of complicating factors inherent, it seems, in satellite or sensor systems linked by computers in several locations. These complications make it difficult to schedule the collection of point data at or near the time that satellite data are collected.

The most challenging aspect of the present temperature mapping project was to link the individual pixel values to their specific surface location sites. Given the large pixel size of about 1 km^2 square, each AVHRR pixel covers nearly 101 ha (250 acres). The size of the UMRS pools is just within the spatial resolution limitations of the system. On the other hand, the high imaging frequency and the inexpensive coverage are advantages of the AVHRR system.

Summary and Conclusion

Although operational procedures are complex and improved spatial resolution is desired, the work accomplished during the 1993 and 1994 observing periods indicates that satellite temperature mapping of water bodies is technically feasible. Aside from the need to improve spatial resolution, consideration must also be given to the acquisition of thermal data closer to the times within the diurnal cycle of maximum and minimum heating and cooling. With respect to spatial resolution, the study of 600-m pixel data of the Heat Capacity Mapping Mission provides greatly improved definition of UMRS pools. If decisions are made to move toward operational status greater involvement is required of field stations to ensure timely and matching point temperature validation of the satellite temperature estimates. When we can place confidence in the satellite temperatures, the need to collect temperature information by conventional point sampling will be greatly reduced. Because of the multitude of factors that control surface temperatures, the exploration of satellite thermal observation of earth is a continuing need. I suggest that airborne sensors that simulate the thermal data characteristics of sensing instruments under the Earth Observing System be employed to further progress toward operational temperature mapping in the Upper Mississippi River (NASA EOS Reference Handbook 1990).

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13. ABSTRACT (Maximum 200 words)

The polar-orbiting Advanced Very High Resolution Radiometer (AVHRR) was evaluated as a means of detecting and measuring surface water temperatures of selected Pools of the Upper Mississippi River System. In summer 1994 Pools 4, 7, and 8 were monitored and, despite heavy cloud cover and fog, useful results were obtained. Satellite mean temperatures were within about 1 Celsius degree of in situ temperature means for nine observation dates for the three pools. A split window procedure, combining the radiance of thermal infrared bands 4 and 5, greatly improved the accuracy of temperature estimates. Routine temperature monitoring could become a reality when some of the logistical problems encountered in this study are addressed. In particular there is a need to establish improved locational control to tie AVHRR pixels more accurately to their surface locations, to provide for systematic surface water data collection on dates of imaging passes, and to link other variables such as water depth and turbidity to the remote temperature measurements.

14. SUBJECT TERMS Advanced very high resolution radiometer (AVHRR), Environmental Management Technical Center, Pools 4, 7, and 8, remote sensing of pool temperatures, satellite remote sensing, Upper Mississippi River System	15. NUMBER OF PAGES 15 pp.
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The Long Term Resource Monitoring Program (LTRMP) for the Upper Mississippi River System was authorized under the Water Resources Development Act of 1986 as an element of the Environmental Management Program. The mission of the LTRMP is to provide river managers with information for maintaining the Upper Mississippi River System as a sustainable large river ecosystem given its multiple-use character. The LTRMP is a cooperative effort by the U.S. Geological Survey, the U.S. Army Corps of Engineers, and the States of Illinois, Iowa, Minnesota, Missouri, and Wisconsin.