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Evaluation of Factors Affecting Ice Forces at Selected Bridges in South Dakota

Water-Resources Investigations Report 02-4158

U.S. Department of the Interior
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
cubic foot (ft^3)	28.32	cubic decimeter
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch	2.54	centimeter
inch	25.4	millimeter
inch per second (in/sec)	2.54	centimeter per second
mile (mi)	1.609	kilometer
pound, avoirdupois (lb)	0.4536	kilogram
pound per square inch (lb/in^2)	6.895	kilopascal
square inch (in^2)	6.452	square centimeter
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Evaluation of Factors Affecting Ice Forces at Selected Bridges in South Dakota

By Colin A. Niehus

ABSTRACT

During 1998-2002, the U.S. Geological Survey, in cooperation with the South Dakota Department of Transportation (SDDOT), conducted a study to evaluate factors affecting ice forces at selected bridges in South Dakota. The focus of this ice-force evaluation was on maximum ice thickness and ice-crushing strength, which are the most important variables in the SDDOT bridge-design equations for ice forces in South Dakota.

Six sites, the James River at Huron, the James River near Scotland, the White River near Oacoma/Presho, the Grand River at Little Eagle, the Oahe Reservoir near Mobridge, and the Lake Francis Case at the Platte-Winner Bridge, were selected for collection of ice-thickness and ice-crushing-strength data. Ice thickness was measured at the six sites from February 1999 until April 2001. This period is representative of the climate extremes of record in South Dakota because it included both one of the warmest and one of the coldest winters on record. The 2000 and 2001 winters were the 8th warmest and 11th coldest winters, respectively, on record at Sioux Falls, South Dakota, which was used to represent the climate at all bridges in South Dakota.

Ice thickness measured at the James River sites at Huron and Scotland during 1999-2001 ranged from 0.7 to 2.3 feet and 0 to 1.7 feet, respectively, and ice thickness measured at the White River near Oacoma/Presho site during 2000-01 ranged from 0.1 to 1.5 feet. At the Grand River at Little Eagle site, ice thickness was measured at 1.2 feet in 1999, ranged from 0.5 to 1.2 feet in 2000, and ranged from 0.2 to 1.4 feet in 2001. Ice thickness measured at the Oahe Reservoir near Mobridge site ranged from 1.7 to 1.8 feet in 1999, 0.9 to 1.2 feet in 2000, and 0 to 2.2 feet in 2001. At the Lake Francis Case at the Platte-Winner Bridge site, ice thickness ranged from 1.2 to 1.8 feet in 2001.

Historical ice-thickness data measured by the U.S. Geological Survey (USGS) at eight selected streamflow-gaging stations in South Dakota were compiled for 1970-97. The gaging stations included the Grand River at Little Eagle, the White River near Oacoma, the James River near Scotland, the James River near Yankton, the Vermillion River near Wakonda, the Vermillion River near Vermillion, the Big Sioux River near Brookings, and the Big Sioux River near Dell Rapids.

Three ice-thickness-estimation equations that potentially could be used for bridge design in South Dakota were selected and included the

Accumulative Freezing Degree Day (AFDD), Incremental Accumulative Freezing Degree Day (IAFDD), and Simplified Energy Budget (SEB) equations. These three equations were evaluated by comparing study-collected and historical ice-thickness measurements to equation-estimated ice thicknesses. Input data required by the equations either were collected or compiled for the study or were obtained from the National Weather Service (NWS). An analysis of the data indicated that the AFDD equation best estimated ice thickness in South Dakota using available data sources with an average variation about the measured value of about 0.4 foot.

Maximum potential ice thickness was estimated using the AFDD equation at 19 NWS stations located throughout South Dakota. The 1979 winter (the coldest winter on record at Sioux Falls) was the winter used to estimate the maximum potential ice thickness. The estimated maximum potential ice thicknesses generally are largest in northeastern South Dakota at about 3 feet and are smallest in southwestern and south-central South Dakota at about 2 feet.

From 1999 to 2001, ice-crushing strength was measured at the same six sites where ice thickness was measured. Ice-crushing-strength measurements were done both in the middle of the winter and near spring breakup. The maximum ice-crushing strengths were measured in the mid- to late winter before the spring thaw. Measured ice-crushing strengths were much smaller near spring breakup.

Ice-crushing strength measured at the six sites ranged from 58 to greater than 1,046 lb/in^2 (pounds per square inch). The largest ice-crushing-strength measurements were from samples collected at the Oahe Reservoir near Mobridge and the James River at Huron sites. The smallest ice-crushing-strength measurement was from a sample collected at the Oahe Reservoir near Mobridge site near spring breakup. Maximum ice-crushing strengths averaged from about 475 lb/in^2 from samples collected at the White River near Oacoma/Presho site to about 950 lb/in^2 at the James River at Huron site. From an analysis of the ice-crushing-strength data, ice-crushing strengths of about 1,000 lb/in^2 could be expected at any site in South Dakota if enough water is available for freezing and if the winter is as cold as the 2001 winter.

Ice-crushing-strength data were evaluated to a limited degree to see how the ice-crushing strengths compared to the strengths used in bridge design in South Dakota. The ice-crushing strengths measured during spring breakup probably are the most applicable values for bridge design. American Association of State Highway and Transportation Officials (AASHTO) bridge-design values for ice-crushing strength range from 100 to 400 lb/in^2, which could result in large variations in bridge design. In the bridge-design criteria used by the SDDOT, ice-crushing strength is set at 100 lb/in^2. Even if the assumption is made that ice does not put extensive force on bridge structures except when it breaks up in the spring and is driven by flow or wind against the structures, measured ice-crushing strength near breakup usually was much greater than 100 lb/in^2. The average ice-crushing strength measured near breakup at the six ice-data collection sites in South Dakota ranged from 75 to 300 lb/in^2. An ice-crushing strength of 250 lb/in^2 would not be anomalous for expected ice-crushing strengths near spring breakup in South Dakota.

INTRODUCTION

Estimating the magnitude of ice forces that act on bridge piers and abutments in northern climates is a major concern in the design of new bridges and in the evaluation of the structural stability of existing bridges. Ice-load evaluation is complex because the ice forces acting on bridges tend to be related to many factors including ice thickness, ice-crushing strength, water depth, streamflow, and wind. Furthermore, ice thickness and ice-crushing strength can be influenced by other factors including snow cover, water and air temperature, and water specific conductivity. The problem is compounded by the wide variety of river and lake or reservoir conditions in South Dakota. These conditions can range from bridges on large rivers with high flows to lakes or reservoirs subjected to strong winds.

Inappropriate design for ice forces on bridges can be costly. Overdesign leads to more expensive bridge structures, whereas underdesign can result in bridge damage leading to costly repairs, disruptions of traffic, and safety hazards to the public. The ice damage at the State Highway 44 Bridge across Lake Francis Case (a Missouri River reservoir) between Platte and Winner during the winter of 1996-97 is a recent example of how costly ice damage can be. This bridge was closed for several months while repairs were made, which resulted in substantial repair costs, disruption to travel, and impacts to local economies. The damage probably was related to ice flows in conjunction with rising water levels in Lake Francis Case (Collins Engineers, Inc., 1997).

Existing equations for estimating ice forces are necessarily conservative due to the many factors involved. Although bridge-design equations for estimating ice forces address ice thickness and ice-crushing strength, the estimated ice forces may not be conservative because the ice-thickness and ice-crushing-strength values used in these equations may not be the maximum values that could occur at bridges in South Dakota. Estimates for maximum ice thickness and ice-crushing strength are used because the values for these variables are not well known for different parts of the State.

The U.S. Geological Survey (USGS), in cooperation with the South Dakota Department of Transportation (SDDOT), conducted a study to evaluate factors affecting ice forces at selected bridges in South Dakota. The period of the study was originally set from June 1998 to September 2001. However, this period was later extended to September 2002. The focus of the study was to evaluate maximum ice thickness and ice-crushing strength, which are the most important variables in bridge-design equations for ice forces in South Dakota. Additional objectives of the study are:

1. To identify a model that will predict ice thickness in South Dakota,

2. To begin development of a database that will aid in the prediction of ice thickness in South Dakota, and

3. To estimate maximum ice thickness and ice-crushing strength properties on major rivers and lakes or reservoirs in South Dakota in order to minimize risk and uncertainty in the design of bridge substructures.

The results of this study may aid in a more effective design for ice forces at new bridges and in the evaluation of potential ice problems at existing bridges. This should result in better protection of the public while minimizing the costs to construct and repair bridges that have damage from ice forces.

Purpose and Scope

The purpose of this report is to present the results from a study of factors affecting ice forces at selected bridges in South Dakota. Maximum ice thickness and ice-crushing strength are evaluated in this report.

Ice thickness and ice-crushing strength were measured at six sites during 1999-2001. Historical data and ice-thickness estimation equations were used to estimate the maximum potential ice thickness on rivers and lakes or reservoirs throughout South Dakota.

Acknowledgments

The author thanks the SDDOT for providing reference materials in connection with the study and for their assistance in ice-data collection at the Oahe Reservoir near Mobridge site. The author also appreciated the cooperation and access to the sites provided by personnel from the U.S Army Corps of Engineers at the Oahe Reservoir near Mobridge site and from the South Dakota Game, Fish and Parks at the Lake Francis Case site.

ICE-DATA COLLECTION SITES AND METHODS

The six sites selected and methods used for collection of ice data, which included thickness and ice-crushing strength, are described in this section. The selected sites include two sites located on the James River (at Huron and near Scotland), one site on the White River (near Oacoma/Presho), one site on the Grand River (at Little Eagle), and two sites on the Missouri River reservoirs (Oahe Reservoir near Mobridge and Lake Francis Case at the Platte-Winner Bridge).

Both river and lake or reservoir sites were selected for ice-data collection because there may be important differences critical to bridge design in the ice characteristics between these site types (Ashton, 1986). River ice initially can be formed as frazil transported by flow, whereas lake or reservoir ice is formed mainly in place. Also, ice cover on smaller, shallower lakes generally forms and melts earlier than ice cover on larger, deeper lakes. The thickness of river ice may vary more than lake or reservoir ice because of flow-induced transport and accumulation. Dynamic impact of ice during breakup may be more critical for bridge design on rivers than on lakes or reservoirs. Thermal ice pressure is more important on lakes or reservoirs. Wind action also generally is greater on lakes or reservoirs than rivers due to longer wind fetch length.

Description of Sites

The six sites selected for ice-data collection, including ice-thickness and ice-crushing-strength data, are presented in table 1 and shown in figure 1. The sites were organized by the following site numbers, which were used throughout the study and this report:

site 1, James River at Huron,
site 2, James River near Scotland,
site 3, White River near Oacoma/Presho,
site 4, Grand River at Little Eagle,
site 5, Oahe Reservoir near Mobridge, and
site 6, Lake Francis Case at the Platte-Winner Bridge.

The six sites are representative of the major rivers and lakes or reservoirs in South Dakota. If possible, sites were selected near USGS streamflow-gaging stations and National Weather Service (NWS) meteorological stations. The selected sites had easy access and were reasonably safe for collection of ice data.

Site 1 (James River at Huron), which is shown in figure 2A, is located on the nearly flat gradient James River in the central part of eastern South Dakota. Ice data collected at the site were used to represent the middle part of eastern South Dakota. The site was selected because it is located at a USGS streamflow-gaging station (06476000) and near an NWS station at Huron. This site also was selected because a small overflow structure located just downstream of the ice-data collection site ponds water upstream, which assures an adequate supply of water for maximum ice formation. The lowest flows of the James River typically occur during the winter months, which correspond to the greatest ice formation months. In the spring during March and April, the James River flows increase substantially aiding in deterioration of any formed ice mass. Ice jams rarely occur at site 1.

Site 2 (James River near Scotland), which is shown in figure 2B, is located about 80 mi downstream of site 1 (James River at Huron). Site 2 is the most southern data-collection site for this study and was used, along with the Lake Francis Case at the Platte-Winner Bridge site, to represent ice formation in southern South Dakota. This site also was selected because it is at a USGS streamflow-gaging station (06478500) and near an NWS station at Yankton. The James River at this site has flow characteristics similar to those of the James River at site 1. Ice jams rarely occur at site 2.

Site 3 (White River near Oacoma/Presho) is at two separate locations—at the U.S. Highway 183 bridge south of Presho and at the State Highway 47 bridge near Oacoma. The Oacoma site is within a few miles of the intersection of the White River with Lake Francis Case. Most of the ice data were collected at the Oacoma site shown in figure 2C; ice data were collected about 25 mi upstream at the Presho site once due to a miscommunication. The two locations were treated as one site because ice conditions were assumed to be similar at the two sites. Site 3 and the Lake Francis Case site were used to represent ice formation in south-central South Dakota. Site 3 was selected because it is located at a USGS streamflow-gaging station (06452000) and near an NWS station at Gann Valley. The White River at the site has flow characteristics similar to those of the James River at sites 1 and 2. The lowest flows occur during the months of greatest ice formation, and in the spring, the flows typically increase substantially, which contributes to the deterioration of the ice mass. The White River often has ice breakups that cause ice jams at bridges on the river. One problem associated with ice-data collection at site 3 is that sometimes inadequate water is available for ice formation limiting ice-data collection. At these times, it is not possible to measure the maximum potential ice thickness because the water freezes to the streambed and thus cannot get any thicker.

Site 4 (Grand River at Little Eagle), which is shown in figure 2D, is the most northern ice-data collection site and was used to represent ice formation on rivers in northern South Dakota. The site also was chosen because it is located at a USGS streamflow-gaging station (06357800) and near an NWS station at Eureka. At this site, the Grand River typically has the lowest flows during the months of greatest ice formation, and the flows increase substantially in March and April, which contributes to the deterioration of any formed ice mass. Similar to the White River at site 3, the Grand River sometimes has ice breakups that cause ice jams at bridges on the river. One problem for ice-data collection at site 4 is that, like site 3, sometimes inadequate water is available for maximum ice formation.

Table 1. Selected information for ice-data collection sites

[USGS, U.S. Geological Survey; --, not applicable or not collected]

Site number	Site name or USGS streamflow-gaging station name	USGS streamflow-gaging station number at or near the site	Site description	Approximate stream or reservoir width at site during data collection (feet)	Applicable National Weather Service Station
			Sites Where Data were Collected for the Study		
1	James River at Huron	06476000	Upstream of 3rd Street and railroad bridges in Huron	250	Huron
2	James River near Scotland	06478500	At a county road bridge near the Maxwell Colony near Scotland	150	Yankton
3	White River near Oacoma/Presho	06452000	At a U.S. Highway 183 Bridge south of Presho and at a State Highway 47 Bridge near Oacoma	125 to 250	Gann Valley
4	Grand River at Little Eagle	06357800	At a State Highway 63 Bridge at Little Eagle	100	Eureka
5	Oahe Reservoir near Mobridge	--	At Indian Creek Recreation Area south of Mobridge	6,500	Eureka
6	Lake Francis Case at the Platte-Winner Bridge	--	At a State Highway 44 Bridge south the Platte-Winner Bridge	5,000	Academy
			Sites Where Data were Collected Prior to the Study		
--	Grand River at Little Eagle	06357800	At USGS streamflow-gaging station	--	--
--	White River near Oacoma	06452000	At USGS streamflow-gaging station	--	--
--	James River near Scotland	06478500	At USGS streamflow-gaging station	--	--
--	James River near Yankton	06478513	At USGS streamflow-gaging station	--	--
--	Vermillion River near Wakonda	06479000	At USGS streamflow-gaging station	--	--
--	Vermillion River near Vermillion	06479010	At USGS streamflow-gaging station	--	--
--	Big Sioux River near Brookings	06480000	At USGS streamflow-gaging station	--	--
--	Big Sioux River near Dell Rapids	06481000	At USGS streamflow-gaging station	--	--

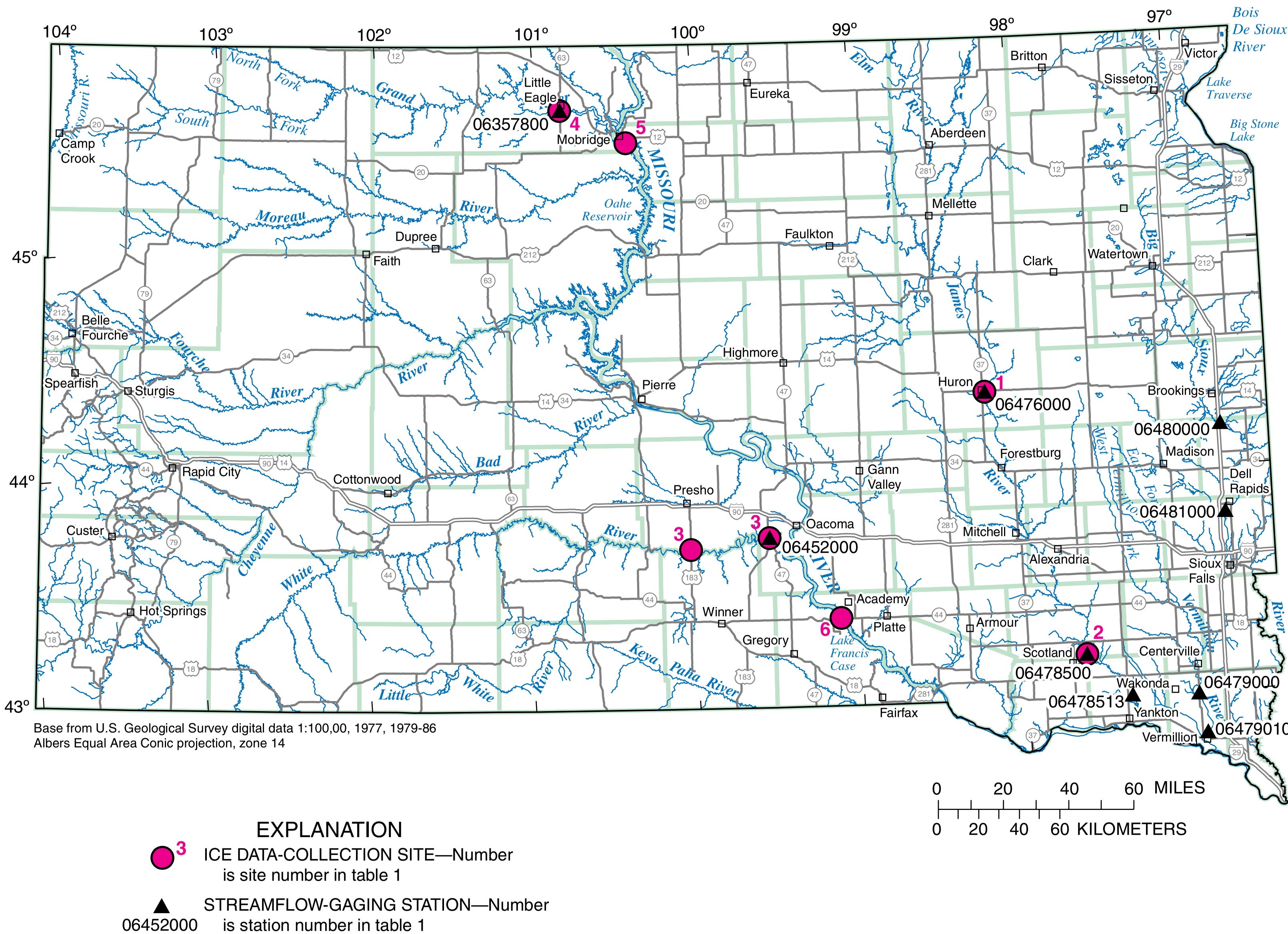


Figure 1. Location of the ice-data collection sites and selected U.S. Geological Survey streamflow-gaging stations in South Dakota.

A Site 1 (James River at Huron) looking south, upstream of the railroad crossing on April 2, 2001

B Site 2 (James River near Scotland) looking upstream, 200 feet downstream of bridge on February 11, 1999

Figure 2. Photographs of the ice-data collection sites in South Dakota.

C Site 3 (White River near Oacoma) looking west, 150 feet downstream of the bridge on February 24, 2000

D Site 4 (Grand River at Little Eagle) looking west, 300 feet downstream of the bridge on February 25, 2000

Figure 2. Photographs of the ice-data collection sites in South Dakota.—Continued

E Site 5 (Oahe Reservoir near Mobridge) looking west from Indian Creek Recreation Area on March 21, 2001

F Site 6 (Lake Francis Case at Platte-Winner bridge) looking west on January 9, 2001

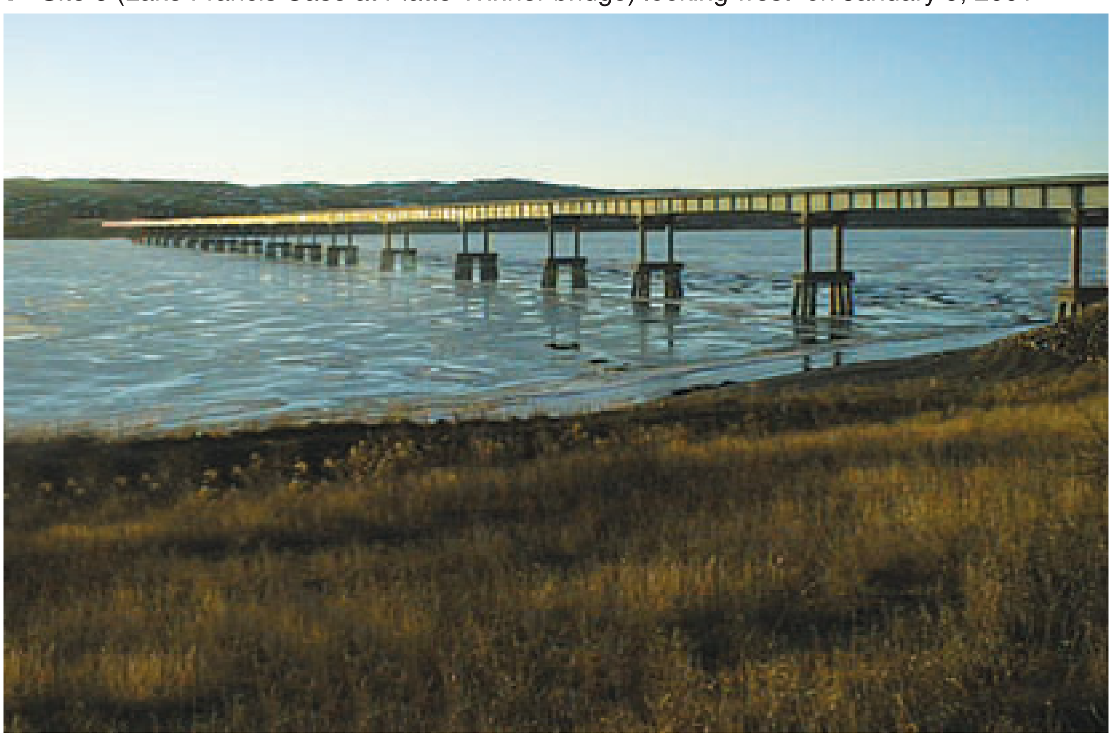


Figure 2. Photographs of the ice-data collection sites in South Dakota.—Continued

Site 5 (Oahe Reservoir near Mobridge), which is shown in figure 2E, is located at the Indian Creek Recreation Area and was used to represent ice formation on large lakes or reservoirs in northern South Dakota. Water levels of Oahe Reservoir, which is managed by the U.S. Army Corps of Engineers (COE), generally are stable during the winter months relative to water levels at the Lake Francis Case site. Site 5 is the only one of the six sites that does not have a bridge over the water body at the site. There is a bridge over the Oahe Reservoir several miles upstream at Mobridge; however, this bridge was not selected for an ice-data collection site because it is near where the Grand River discharges into Oahe Reservoir, which contributes to unpredictable and unsafe ice conditions. Site 5 is located near an NWS station at Eureka.

Site 6 (Lake Francis Case at the Platte-Winner Bridge), which is shown in figure 2F, is located at the State Highway 44 Bridge between Platte and Winner and was used to represent ice formation on large lakes or reservoirs in southern South Dakota. In addition to its desirable ice data-collection location, this site was selected because of the previous ice damage to this bridge during the 1996-97 winter and the site's proximity to an NWS station at Academy. Lake Francis Case, a Missouri River reservoir, typically has highly variable water levels with the lowest water levels in the fall and highest water levels in the spring. The large variation in water levels causes ice-data collection at this site to be extremely difficult and potentially dangerous. Because the climate at the site is milder than the climate in central and northern South Dakota, the reservoir usually doesn't have a complete ice cover until the middle of winter. Then, early in the spring before the ice mass begins to deteriorate, the water level begins to rise from upstream Missouri River reservoir discharges. This causes large areas of open water at the shoreline and makes it extremely difficult to get on the ice mass.

Description of Collection Methods

Equipment used to make ice-thickness measurements was similar to the equipment in the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory's (CRREL) ice-thickness kits. These kits consist of a 2.5-inch-diameter auger and a tape for measuring ice thickness. The measuring tape used in the study was obtained from the CRREL and is shown in figure 3C. Ice-thickness data collection began by carefully walking on the ice, using an ice chisel bar to test the ice for adequate thickness to support walking. Because of safety considerations and for adequate ice thickness for samples, no ice less than 6 inches thick was measured except on small rivers where it was known that the water depth was less than 4 ft. A minimum of two people were involved in ice-data collection at all sites. For the Missouri River reservoir sites (sites 5 and 6), one of the two-person crew (with a rope attached to them) walked about 100 ft ahead of the other person.

Once the ice was deemed safe for ice-data collection, a 6-inch diameter hole for measuring ice thickness was drilled using a small-engine powered ice auger as shown in figures 3A and 3B. The diameter of the drilled hole was 6 inches because it had to be smaller than the hinged bar of the measuring tape (fig. 3C). The measuring tape with the hinged bar was lowered through the 6-inch-diameter hole in such a manner that the bar remained straight across the hinge. Once the bar was below the ice, the measuring tape was pulled up until the hinged bar met adequate resistance from the ice. The ice thickness was then measured using the tape. Then, the measuring tape was pulled hard enough until the hinged bar folded together, allowing the measuring line and hinged bar to be pulled through the 6-inch diameter hole in the ice.

At each site, ice thickness usually was measured at three to five locations along a transect perpendicular to the direction of flow. The actual number of locations for data collection depended on the widths of the rivers or reservoirs, ice conditions, and safety considerations. The transect was located at a cross section of the river or reservoir that was assumed to be representative of the site's maximum ice thickness. The data-collection locations were referenced to a map coordinate system using a Global Positioning System (GPS). The GPS data are not presented in this report because the data were collected mostly on the two large reservoirs and only were used to determine distance between ice-data collection holes. However, the data are available at the USGS office in Huron, South Dakota.

Samples for measuring ice-crushing strength were collected at the same time that the ice-thickness measurements were made. Using a portable electric-core drill with a 3.5- or 4-inch-diameter hollow bit (figs. 4A and 4B) powered by a gasoline-driven portable generator, 6- to 12-inch-length samples were collected. Six-inch extensions were added to the hollow bits as needed to collect samples from the entire vertical section of the ice mass. The samples were put in plastic bags, labeled, and stored in an ice cooler for safe transportation back to shore for later crushing. The ice was crushed as soon after collection as feasible because temperature can cause significant ice-crushing-strength variation.

A Drilling hole for measuring ice thickness at site 5 (Oahe Reservoir near Mobridge) on February 12, 1999

Photograph by Franklin D. Amundson

B Measuring ice thickness at site 5 (Oahe Reservoir near Mobridge) on February 12, 1999

Photograph by Franklin D. Amundson

C Tape used to measure ice thickness (note hinged bar at end of tape)

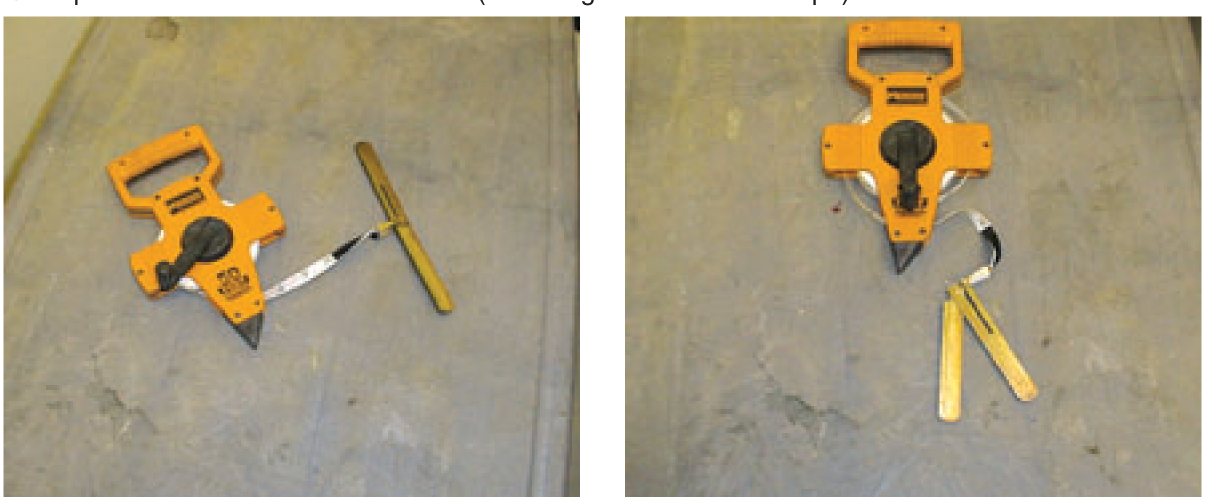


Figure 3. Photographs of equipment used to collect ice-thickness data for the study.

A Ice-coring machine with 4-inch coring bit attached at site 5 (Oahe Reservoirs near Mobridge) on February 12, 1999

B Sample collection with ice-coring machine at site 5 (Oahe Reservoir near Mobridge) on February 12, 1999

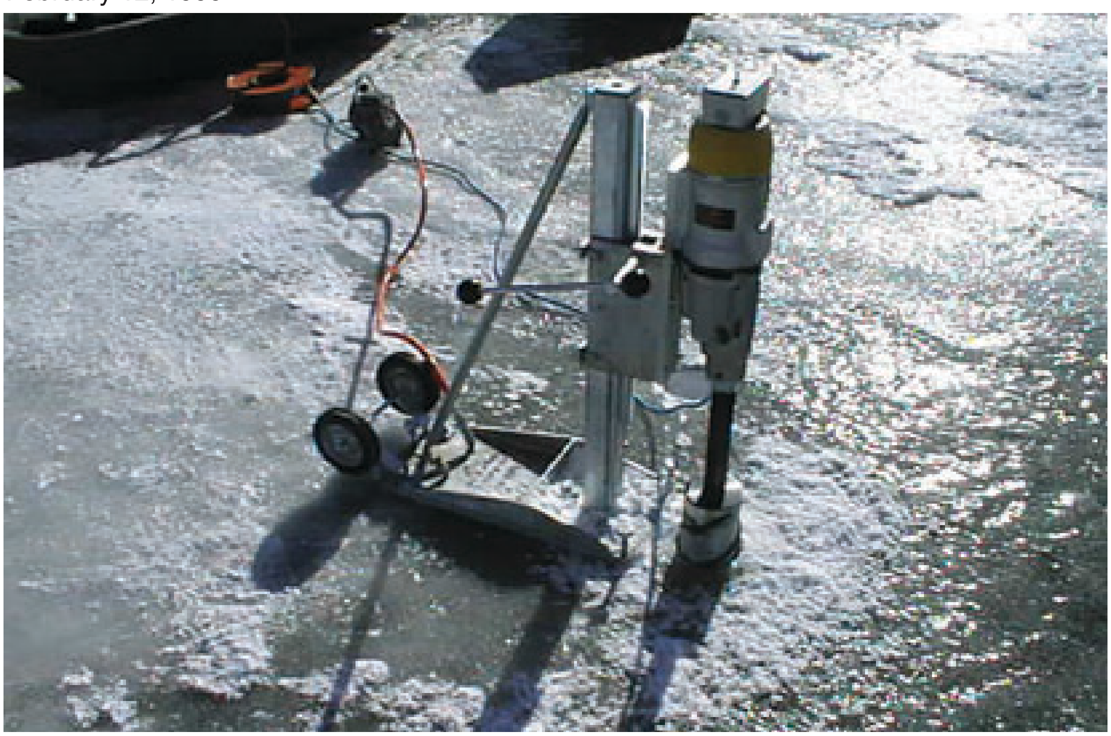


Figure 4. Photographs of equipment used to collect samples and measure ice-crushing strength for the study.

C Measurement of ice-crushing strength with ice-compression machine at site 5 (Oahe Reservoir near Mobridge) on January 10, 2001

D Measurement of ice-crushing strength (note strain gage used to measure loading rate) at site 1 (James River at Huron) on April 2, 2001

Figure 4. Photographs of equipment used to collect samples and measure ice-crushing strength for the study—Continued

Samples for measuring ice-crushing strength usually were collected at about three to five locations along a transect perpendicular to the direction of flow at each river or reservoir site and at locations representative of the site's ice conditions. The actual number of locations depended on the width of the river or reservoir at the data-collection site and safety considerations. Samples from the river sites usually were collected across the entire reach. Samples from the Missouri River reservoir sites usually were collected from near the shorelines to only the midpoints of the reservoirs because of the large reach length and safety considerations.

Multiple ice samples were collected at each core hole from various depths in the vertical section to obtain a representative ice-crushing strength of the entire vertical section. For quality-assurance purposes, nearly identical samples were collected and crushed, and the results were compared for multiple samples from each site. It was not feasible to collect samples to send to an outside laboratory to obtain ice-crushing-strength data because the properties of the ice could change significantly before the laboratory analysis was done. Thus, nearly identical samples were collected to analyze the consistency of the ice-crushing-strength collection method that was used.

On shore, the samples were prepared for crushing by carefully sawing off both sample ends to obtain about a 6- to 9-inch-length representative sample. When feasible, a sample length of about twice the diameter was prepared. This sometimes could not be done because of problems with the ice-coring machine or when the ice was exceptionally brittle. The prepared samples were placed between compliant-constrained platens and loaded into the portable crushing machine (fig. 4C). Using compliant-constrained platens allowed the force applied from the compression machine to be evenly distributed over the entire ice sample cross section. The samples were crushed at rates between 0.0005 to 0.0013 in/sec, measured using a strain gage (fig. 4D) and stop watch.

To measure the maximum ice-crushing strength, the samples were crushed until failure. Failure of the ice sample often occurred when the sample fractured and exploded into many fragments. In other more ductile samples, failure of the ice occurred when the sample would not take any more load. In rare instances, the maximum ice-crushing strength could not be measured because the ice sample was exceptionally strong, and the limit (about 1,000 lb/in^2) of the compression machine was reached during loading.

Other data collected at the sites, potentially important to the evaluation of ice-force factors at bridges in South Dakota, included air temperature, snow depth, water depth below the ice, and specific conductance of the water. If the site was at or near a USGS streamflow-gaging station, discharge data were obtained from the USGS's Automatic Data Processing System (ADAPS) data base.

EVALUATION OF FACTORS AFFECTING ICE FORCES

Many factors including ice thickness, ice-crushing strength, water depth, streamflow, and wind, can affect ice forces at bridges in South Dakota. The most important of these factors are ice thickness and ice-crushing strength. An evaluation of both of these factors, which can be influenced by snow cover, water and air temperature, and water specific conductivity, was performed.

Ice Thickness

Ice thickness was evaluated at specific sites in South Dakota and estimated across South Dakota. Ice-thickness data at six selected sites were collected for the study. Historical ice-thickness data were compiled for 1970-97 for eight sites. The historical data and ice-thickness estimation equations were used to estimate the maximum potential ice thickness throughout South Dakota.

Data Summary

This section of the report contains a summary of ice-thickness data collected and compiled for the study. Ice-thickness data were collected at six selected sites. Other data collected at the sites, including air temperature, snow depth, water depth below the ice, specific conductance of the water, and discharge, also are summarized. Historical ice-thickness data for 1970-97 are compiled for eight sites.

Data Collected for the Study

Maximum ice thickness was measured at the six sites shown in figure 1. Ice-thickness measurements didn't begin until early February 1999 because of the mild winter of 1999 leading to a lack of adequate ice formation. The winter measurements continued until April 2001. The period of ice-data collection was longer than originally planned because of the mild winter experienced in 1999 and to a lesser extent in 2000 (especially in the southern part of the State). These mild winters caused limited ice formation and consequently limited the ice-data collection.

The 1999-2001 winters are reasonably representative of the climate extremes in South Dakota because this period included both one of the warmest and one of the coldest winters on record as shown in table 2. The 2000 and 2001 winters were the 8th warmest and 11th coldest winters, respectively, on record at Sioux Falls, South Dakota. This temperature variation allowed a large range of ice thickness to be measured. All references to the coldest or warmest winters in this report are for Sioux Falls, which is assumed to adequately represent the general climate for all of South Dakota.

Although the primary emphasis of the ice-thickness data collection focused on maximum ice thickness, which typically occurs in mid- to late winter, ice data also were collected as close to ice breakup as feasible. At the request of the SDDOT, ice-data collection during the 2001 winter especially focused on the collection of ice data near breakup. The process of ice breakup in a river or lake or reservoir is further discussed in a following section.

Ice-thickness and associated data collected at the six sites from 1999-2001 are presented in table 4 in the Supplemental Information section at the end of the report. The ice-thickness data are summarized in figure 5, which shows boxplots for each of the six sites. Because of a colder, more ice-producing climate in northern South Dakota during the study, more data were collected at the more northern sites (site 1, James River at Huron, and site 5, Oahe Reservoir near Mobridge) than at some of the more southern sites (site 2, James River near Scotland, and site 6, Lake Francis Case at the Platte-Winner Bridge).

Ice-thickness data were collected at site 1 (James River at Huron) once in 1999, twice in 2000, and three times in 2001. Ice thickness measured at site 1 ranged from 1.1 to 1.3 ft in 1999, 0.7 to 1.2 ft in 2000, and 1.4 to 2.3 ft in 2001. Because the 2001 winter was the 11th coldest winter of record, ice-thickness measurements collected during 2001 probably are near the maximum ice thickness that could occur due to in-place, thermal growth at this site. Snow depth during ice-data collection at site 1 ranged from 0 inch in 1999 and 2000 to 24 inches in 2001. On February 12, 2001, the snow depth on the ice during ice-data collection ranged from 14 to 24 inches (fig. 6A). Specific conductance of water in the James River at this site (table 4) was measured only in 2001 and ranged from 1,868 to 2,280 µS/cm (microsiemens per centimeter) in the middle of the winter to 915 and 1,115 µS/cm during the spring thaw as more fresh water flowed into the James River. Discharge (daily mean flow) at streamflow-gaging station 06476000 near the site during ice-data collection ranged from about 65 to 771 ft^3/s. Maximum water depths measured at the site were fairly stable and ranged from 10.7 to 12.1 ft during ice-data collection.

Table 2. Coldest and warmest winters on record (1891-2001) at Sioux Falls, South Dakota

[From National Oceanic and Atmospheric Administration, 2001. A winter is defined as December through February; for example, 1979 winter is December 1978 through February 1979]

Rank	Average temperature (degrees Fahrenheit)	Winter
Coldest Winters on Record		
1	7.97	1979
2	8.93	1978
3	9.33	1917
4	9.37	1936
5	9.40	1918
6	11.07	1904
7	11.60	1899
8	12.03	1894
9	12.27	1997
9	12.27	1956
11	12.53	2001
12	12.60	1972
Warmest Winters on Record		
1	28.73	1931
2	27.50	1992
3	27.33	1987
4	26.13	1919
5	26.03	1921
6	25.83	1998
7	25.00	1944
8	24.27	2000
9	24.03	1906
10	23.60	1983

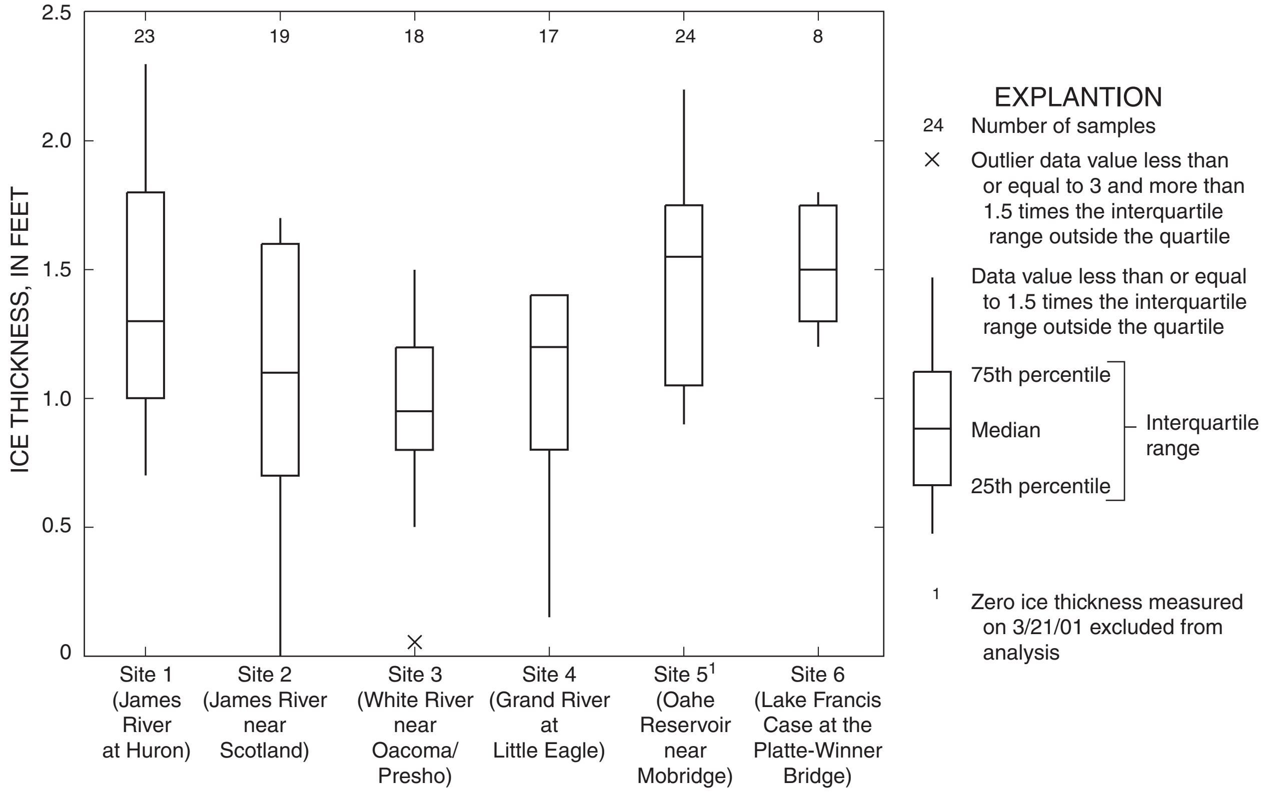


Figure 5. Boxplots of measured ice thickness at ice-data collection sites for the study, 1999-2001.

Ice-thickness data were collected at site 2 (James River near Scotland) once in 1999 and 2000 and three times in 2001. Ice thickness measured at site 2 ranged from 0.7 to 0.9 ft in 1999, 0.5 to 1.0 ft in 2000, and 0 to 1.7 ft in 2001. Snow depth during ice-data collection at site 2 ranged from 0 inch in 1999 and 2000 to 5 inches in 2001. Specific conductance of water in the James River was measured only in 2001 at this site and ranged from 1,897 to 2,490 µS/cm in the middle of the winter to 1,060 µS/cm during the spring thaw as more fresh water flowed into the James River. Specific conductance of water on top of the ice on March 20, 2001, was 145 µS/cm, as compared to 1,060 µS/cm for open water along the James River shore. Discharge (daily mean flow) at streamflow-gaging station 06478500 at the site during ice-data collection ranged from about 155 to 1,800 ft^3/s. Maximum water depths measured at the site were fairly uniform and ranged from 6.0 to 7.6 ft during ice-data collection.

Ice-thickness data were collected at site 3 (White River near Oacoma/Presho) once in 2000 at both the Presho and Oacoma locations and three times in 2001 at the Oacoma location. Ice thickness measured at site 3 ranged from 0.5 to 1.0 ft in 2000 and 0.1 to 1.5 ft in 2001. This site had limited water and little corresponding ice (0.1 ft) when data were collected on February 13, 2001. Snow depth at the site was about 0 inch in 2000 and 2001. On March 13, 2001, specific conductance was 614 µS/cm at the site. Discharge (daily mean flow) at streamflow-gaging station 06452000, which is located near the Oacoma location, ranged from about 116 to 6,500 ft^3/s during ice-data collection. Maximum water depths measured at the site ranged from 2.0 to 2.6 ft. No water-depth data were collected on February 13 and March 13, 2001, because of safety considerations.

A Two feet of snow cover during ice-data collection at site 1 (James River at Huron) on February 12, 2001

B Pressure ridge located about 1,500 feet from north shore of the reservoir at site 5 (Oahe Reservoir near Mobridge) on February 12, 1999

C Pressure ridge at site 5 (Oahe Reservoir near Mobridge) on January 1, 2001

Figure 6. Photographs of ice-data collection site 1 (James River at Huron) and site 5 (Oahe Reservoir near Mobridge).

Ice-thickness data were collected at site 4 (Grand River at Little Eagle) once in 1999, twice in 2000, and three times in 2001. Ice thickness measured at site 4 was 1.2 ft in 1999, ranged from 0.5 to 1.2 ft in 2000, and ranged from 0.2 to 1.4 ft in 2001. Little water in the Grand River was available for freezing during January and February of 2001 resulting in little ice formation. There was no snow on the ice at site 4 during sample collection. Specific conductance was measured once at the site and was 314 µS/cm on March 14, 2001. Discharge (daily mean flow) at streamflow-gaging station 06357800 at the site during sample collection ranged from about 14 to 4,500 ft^3/s. Maximum water depths measured at the site were 2.1 and 2.2 ft during ice-data collection; water depths were not measured on three sampling dates.

Ice-thickness data were collected at site 5 (Oahe Reservoir near Mobridge) once in 1999, twice in 2000, and three times in 2001. Ice thickness measured at site 5 ranged from 1.7 to 1.8 ft in 1999, 0.9 to 1.2 ft in 2000, and 0 to 2.2 ft in 2001. Snow depth at the site ranged from 0 inch in 1999 and 2000 to 4 inches in 2001. Specific conductance of water in the Oahe Reservoir was only measured in 2001 at this site and ranged from 215 to 694 µS/cm. Maximum water depths measured at the site ranged from about 70 to 79 ft during ice-data collection. Because of safety concerns and because it was assumed that sampling from shoreline to near the center of the reservoir was representative of the entire section, ice data were not collected across the entire reservoir. A pressure ridge, shown in figures 6B and 6C, was present in the middle section of the Oahe Reservoir at the ice-data collection site. The ridge sometimes was crossed to collect ice-data on the west side of the reservoir. At other times, there was open water at the ridge, and it was not safe to cross.

Ice-thickness data were collected at site 6 (Lake Francis Case at the Platte-Winner Bridge) only in 2001. Because of the large variation in water levels and the mild winters of 1999 and 2000 and corresponding unsafe ice, no ice data were collected at the site during 1999 and 2000. In 2001, ice thickness measured at site 6 ranged from 1.2 to 1.8 ft, and snow depth ranged from 0 to 2 inches. Specific conductance of water in the reservoir was measured on February 13, 2001, and ranged from 527 to 707 µS/cm. No flow data were collected because the site is on a large reservoir that has little or no flow. Maximum water depths measured at the site during two visits were about 58 and 62 ft. For the same reasons described for the Oahe Reservoir near Mobridge site (site 5), ice data were not collected across the entire reservoir at site 6. Ice data were collected starting from the eastern shore on January 9, 2001, and starting from the western shore on February 13, 2001.

Historical Data

When making discharge measurements during the winter at gaging stations, USGS personnel must drill holes through the ice mass across the entire cross section. The ice thickness often will be noted in the USGS discharge-measurement field notes. These data are not published in the USGS annual data reports, but can be obtained by manually going through the discharge-measurement field notes. The ice thicknesses measured during discharge measurements are not necessarily as dependable or as accurate as ice thicknesses measured for this study because the focus is not on ice thickness. However, these data were useful to supplement the ice-thickness data collected for the limited period of this study. Limitations of the historical ice-thickness data are that the data were not necessarily collected at the time of maximum ice-thickness cover, and the data were not necessarily collected at a cross section representative of the site's maximum ice thickness.

Historical ice-thickness data are available for many streamflow-gaging stations in South Dakota. Eight gaging stations (fig. 1, table 1), including three that also were data-collection sites for the study, were selected for compilation of historical ice-thickness data based on the needs of the SDDOT. For each discharge measurement with corresponding ice-thickness data, the maximum ice thicknesses were compiled for 1970-97 for the selected gaging stations and are presented in table 5 in the Supplemental Information Section and shown in figure 7. The following are the selected USGS gaging stations with ice-thickness data that were compiled and used in this study: Grand River at Little Eagle (06357800), White River near Oacoma (06452000), James River near Scotland (06478500), James River near Yankton (06478513), Vermillion River near Wakonda (06479000), Vermillion River near Vermillion (06479010), Big Sioux River near Brookings (06480000), and Big Sioux River near Dell Rapids (06481000).

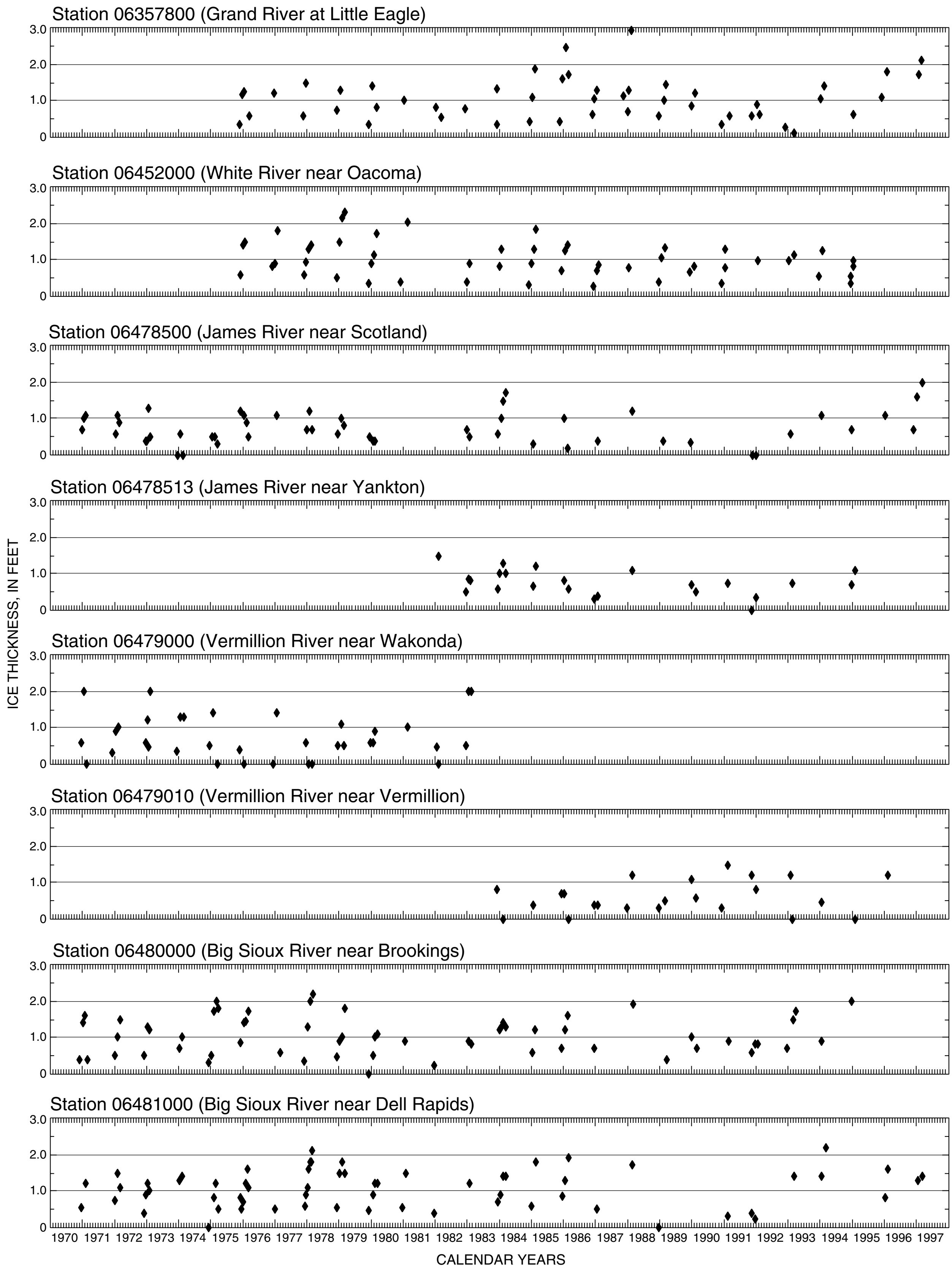


Figure 7. Maximum measured historical ice thickness at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97.

The Grand River at Little Eagle, White River near Oacoma, and James River near Scotland gaging stations also were ice-data collection sites for this study (sites 4, 3, and 2, respectively). The maximum measured historical ice thickness at the Grand River at Little Eagle station was 2.9 ft in February 1988. Another large ice thickness of 2.1 ft was measured in February 1997 during the ninth coldest winter on record. No ice data were collected during the middle of the 1979 and 1978 winters, which are the coldest winters on record. The maximum historical ice thickness at the White River at Oacoma station was 2.3 ft in March 1979, which was during the coldest winter on record. Other large ice-thickness measurements at the White River at Oacoma station were 2.2 and 1.8 ft in February 1979 and January 1977. The maximum measured historical ice thickness at the James River near Scotland station was 2.0 ft in March 1997, which was during the ninth coldest winter on record. Ice data were collected during the middle of the winter for 1979 and 1978, which are the coldest winters on record; however, surprisingly, only about 1 ft of ice thickness was measured. Only 0.4 ft of ice thickness was measured in January 1987, which was during the third warmest winter on record.

The maximum historical ice thickness at the James River near Yankton station measured was 1.5 ft in February 1982, which was not during one of the twelve coldest winters on record. No data were available at this site for any of the twelve coldest winters. The maximum historical ice thickness at the Vermillion River near Wakonda station was 2.0 ft, which was measured in January 1971, February 1973, January 1983, and February 1983, none of which were during one of the twelve coldest winters on record. Surprisingly, the maximum ice thickness was only 1.1 ft in the middle of 1979, which was during the coldest winter on record, and 0 ft in March 1978, which was during the second coldest winter. The maximum historical ice thickness at the Vermillion River near Vermillion station was 1.5 ft in February 1991, which was not during one of the twelve coldest winters on record.

The maximum historical ice thickness of 2.2 ft at the Big Sioux River near Brookings station was measured in March 1978. Additional maximum ice thicknesses of about 2.0 ft (1.8 to 2.0 ft) were measured in March and April 1975, February 1978, March 1979, and February 1988. Of these dates, the February 1978 and March 1979 measurements were during the two coldest winters on record. The maximum historical ice thickness measured at the Big Sioux River near Dell Rapids station was 2.2 ft in March 1994. Other large maximum ice thicknesses of 1.8 to 2.1 ft were measured in February and March 1978, February 1979, February 1985, and February 1986.

Methods for Estimation of Ice Thickness

Existing methods for estimating ice thickness that potentially could be used for bridge design in South Dakota were identified through a review of literature applicable to the estimation of ice thickness for design of bridge substructures and communication with experts in ice-thickness estimation methods. Of the methods identified, three equations were selected for further evaluation. A discussion of the applicability of these equations for ice-thickness estimation follows.

Ice formation on rivers and lakes or reservoirs occurs under either static or dynamic conditions (U.S. Army Corps of Engineers, 1996). Ice formation on water in which flow velocity plays almost no role is called static-ice formation. Static-ice growth starts in a very thin layer of super-cooled water at the water surface. The ice grows at the ice/water interface as a result of heat transfer upwards through the ice to the air. Static-ice formation occurs on rivers during periods of low-flow velocities and on lakes or reservoirs during periods of low winds. Snow ice, created during static-ice formation, forms when the weight of snow on the ice depresses the ice and causes water to flow upward through cracks in the ice and mix with the snow. Dynamic-ice formation occurs on rivers during periods of higher flow velocities when the ice growth is dominated by the interaction between transported ice pieces and flowing water. Almost all large-river ice covers partly are formed dynamically; however, during times of low flow that typically occur in the winters in South Dakota, periods when the ice itself slows the flow, or after the initial cover of ice forms, static-ice formation is the predominant mechanism on both rivers and lakes or reservoirs. The equations that were evaluated for this study only are applicable for static-ice formation, which probably is the predominant ice formation mechanism during the winter months in South Dakota.

The three selected equations were evaluated by comparing study-collected and historical ice-thickness data to equation-estimated ice thickness. Input data required by the equations were either collected for the study or obtained from the NWS.

Description of Equations

Three ice-thickness estimation equations that potentially could be used for bridge design in South Dakota were selected. No new equations were developed from existing or study-collected ice-thickness data. The three equations are described in this section.

The first equation is the Accumulative Freezing Degree Day (AFDD) equation (U.S. Army Corps of Engineers, 1981):

$$h = \alpha \times \sqrt{\sum (T_m - T_s) \times t} \qquad (1)$$

where:

h = ice thickness, in inches;
α = coefficient that ranges from 0.4 to 0.9;
T_m = bottom surface temperature of the ice, in degrees Fahrenheit;
T_s = top surface temperature of the ice, in degrees Fahrenheit; and
t = time, in days.

The AFDD equation is a simple equation that assumes that ice thickness is a function of air temperature. The estimated ice thickness is proportional to the square root of the accumulated freezing degree-days. This equation estimates the total ice thickness since ice formation began. If ice-thickness data are available, the coefficient α can be estimated by solving for α in equation 1. If no data are available, a value of 0.6 for α can be assumed (U.S. Army Corps of Engineers, 1981).

The second equation is the Incremental Accumulative Freezing Degree Day (IAFDD) equation (U.S. Army Corps of Engineers, 1981):

$$\Delta h = \alpha^2 \times \left(\frac{k_i}{\rho_i \times \lambda}\right) \times \left(\frac{T_m - T_s}{h}\right) \times \Delta t \qquad (2)$$

where:

Δh = incremental ice thickness, in inches expected over time;
α = coefficient that ranges from 0.6 to 0.7;
k_i = thermal conductivity of ice, in British thermal units per inch per degrees Fahrenheit per day;
ρ_i = density of ice, in pounds per cubic inch;
λ = heat of fusion, in British thermal units per pound;
T_m = bottom surface temperature of the ice, in degrees Fahrenheit;
T_s = top surface temperature of the ice, in degrees Fahrenheit;
h = initial ice thickness, in inches; and
Δt = time increment, in days.

The IAFDD equation, while similar to the AFDD equation, calculates the change in ice thickness from an initial ice thickness rather than the total ice thickness since ice formation began. It is used when the accumulative freezing degree-days since initial ice-cover formation are unknown or difficult to calculate. The coefficient α can be calculated using past records of ice-thickness data. If data are unavailable, a value of 0.6 or 0.7 is recommended (U.S. Army Corps of Engineers, 1981).

The third equation is the Simplified Energy Budget (SEB) equation (U.S. Army Corps of Engineers, 1981):

$$\Delta h = \left(\frac{1}{\rho_i \times \lambda}\right) \times \left(\frac{T_m - T_s}{\left(\frac{h_i}{k_i}\right) + \left(\frac{h_s}{k_s}\right) + \left(\frac{1}{h_{ia}}\right)}\right) \times \Delta t \qquad (3)$$

where:

Δh = incremental ice thickness, in inches over time;
ρ_i = density of ice, in pounds per cubic inch;
λ = heat of fusion, in British thermal units per pound;
T_m = bottom surface temperature of the ice, in degrees Fahrenheit;
T_s = top surface temperature of the ice, in degrees Fahrenheit;
h_i = existing ice thickness, in inches;
k_i = thermal conductivity of ice, in British thermal units per inch per degrees Fahrenheit per day;
h_s = existing snow cover thickness on the ice, in inches;
k_s = thermal conductivity of snow, in British thermal units per inch per degrees Fahrenheit per day;
h_{ia} = overall heat transfer coefficient, in British thermal units per inch per degrees Fahrenheit per day; and
Δt = time increment, in days.

The SEB equation incorporates, more directly than the previous two equations, the effects of the temperature difference between the top surface of the ice and the air and the insulating effects of snow cover on the solid ice mass. As in the IAFDD equation, the incremental change in ice thickness is estimated using this equation rather than the total ice thickness since ice formation began.

Evaluation of Equations

The three selected equations were evaluated by comparing study-collected and historical ice-thickness data to equation-estimated ice thickness. Existing ice-thickness data that are used in this comparison (table 5) included historical data available at selected USGS streamflow-gaging stations. However, the main focus of the comparison involved using ice-thickness data collected for this study (table 4).

In the AFDD equation (equation 1), the α coefficient was estimated at 0.6 as recommended (U.S. Army Corps of Engineers, 1981). Because ice-thickness data were available, an analysis was performed to fit the data by varying the α coefficient. From this analysis, it was determined that the value of 0.6 was reasonable for the sites. Data for the T_s variable, which represents the top surface temperature of the ice, was estimated by averaging maximum and minimum daily air temperatures from available NWS meteorological stations. The T_m variable, which represents the bottom surface temperature of the ice, was set at 32° F as recommended (U.S. Army Corps of Engineers, 1981). As stated in the previous section, this equation estimates total ice thickness since ice formation began. The beginning of ice formation is best set using water-temperature data; however, these data were not readily available. Consequently, air-temperature data, which were readily available, were used to set the beginning of ice formation. Estimated ice thickness was compared to measured ice thickness at each site to ensure that a reasonable beginning date was selected.

In the IAFDD equation (equation 2), the α coefficient was estimated at 0.6 as recommended (U.S. Army Corps of Engineers, 1981). This value was determined reasonable based on an analysis using available ice-thickness data. The k_i variable, which represents the thermal conductivity of ice, was set at 2.59 Btu/inch-°F-day (British thermal units per inch per degrees Fahrenheit per day); the ρ_i variable, which represents the density of ice, was set at 0.0331 lb/in^3 (pounds per cubic inch); and the λ variable, which represents the heat of fusion, was set at 143.6 Btu/lb (British thermal units per pound) (U.S. Army Corps of Engineers, 1981). The T_s variable, which represents the top surface temperature of the ice, was estimated by averaging the maximum and minimum daily air temperatures from available NWS meteorological stations. The T_m variable, which represents the bottom surface temperature of the ice in the AFDD equation, was set at 32°F (U.S. Army Corps of Engineers, 1981).

In the SEB equation (equation 3), the ρ_i variable, which represents the density of ice, was set at 0.0331 lb/in^3; the λ variable, which represents the heat of fusion, was set at 143.6 Btu/lb, the k_i variable, which represents the thermal conductivity of ice, was set at 2.59 Btu/in-°F-day; and the k_s variable, which represents the thermal conductivity of ice, was set at 0.3 Btu/in-°F-day (U.S. Army Corps of Engineers, 1981). The T_s variable, which represents the top surface temperature of the ice, was estimated by averaging the maximum and minimum daily air temperatures from available NWS meteorological stations. The T_m variable, which represents the bottom surface temperature of the ice, was set at 32°F (U.S. Army Corps of Engineers, 1981). The h_s variable, which represents the existing snow-cover thickness on the ice, was estimated using snowfall data from NWS meteorological stations. This snowfall data probably overestimates the actual ice snow-cover thickness.

Additional information needed for the evaluation of the ice-thickness equations was obtained from the NWS. The periods of record for selected meteorological stations in South Dakota that were used for this study are shown in figure 8. The meteorological stations used for the evaluation of the ice-thickness estimation equations included sites at Academy, Brookings, Eureka, Gann Valley, Huron, Mobridge, and Yankton (see fig. 1 for location). These stations had daily minimum and maximum temperature and snowfall data available for most days in the winters during which ice-thickness data were collected. No meteorological data were available for a small number of days, for which estimates were needed for use in equations. Estimates for these days were made either by using the closest NWS meteorological station with data or by interpolating between days with data.

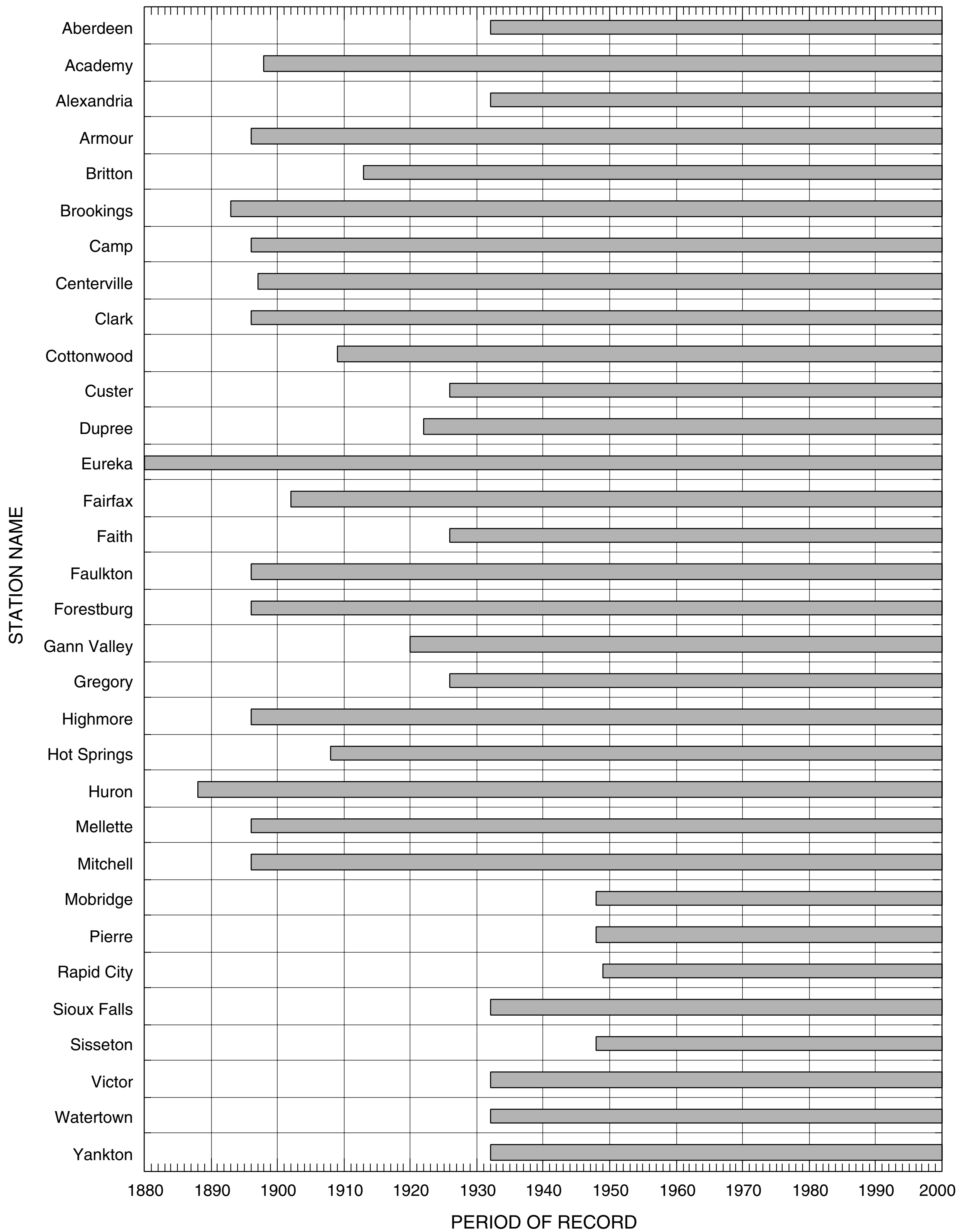


Figure 8. Period of record for selected National Weather Service stations in South Dakota.

Of the three selected equations, the AFDD equation (equation 1) best estimated maximum ice thickness in South Dakota using available data sources based on an ice-thickness data comparison between measured and estimated thicknesses. Five comparisons are summarized in table 3, which references more specific data sets in subsequent tables 6-10 in the Supplemental Information section. Both data collected for this study and historical ice-thickness data were used to make the evaluation.

The results of five comparisons using selected ice-thickness data (summarized in table 3) are presented in tables 6-10 and figures 9-13. In figures 9-13, points that plot close to the 1:1-slope reference line indicate a close relation between the ice-thickness-estimation equation and the actual measured ice thickness. In the comparison shown in table 6 and figure 9, ice-thickness data for this study and the compiled historical ice-thickness data were used; about 200 ice-thickness measurements used in the comparison. Three of the ice-thickness measurements done for this study were excluded from the comparison (table 6) because representative maximum ice-thickness data were not obtained due to unsafe ice conditions; samples were collected only near shore. Absolute differences between the measured and estimated values were calculated to evaluate the accuracy of the equations. The AFDD equation best estimated the measured ice thickness with an average variation about the measured value of about 0.4 ft. The average variation about the measured value was about 0.5 ft for the IAFDD equation, and about 0.6 ft for the SEB equation. Most of the points for the AFDD and IAFDD equations presented in figure 9 plot above the 1:1-slope reference line, indicating that these equations tend to overestimate the ice thickness. The SEB equation points plot both above and below the reference line (fig. 9), indicating that the equation tends to both overestimate and underestimate the ice thickness.

Table 3. Summary of comparisons between measured and equation-estimated ice thickness at selected sites in South Dakota

[AFDD, Accumulative Freezing Degree Day equation; IAFDD, Incremental Accumulative Freezing Degree Day equation; SEB, Simplified Energy Budget equation]

Average difference between measured and equation-estimated ice thickness			Description of data set used to compute averages
AFDD (feet)	IAFDD (feet)	SEB (feet)	
0.4	0.5	0.6	Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data (table 6).
.2	0	.6	Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using only study-collected ice-thickness data (table 7).
.4	.4	.6	Comparison between greater-than-1.0-foot measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data (table 8).
.3	.3	.6	Comparison between greater-than-1.5-foot measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data (table 9).
.2	.2	([1])	Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using only study-collected ice-thickness data using an α coefficient of 0.55 (table 10).

[1]Not applicable because α is not a variable in this equation.

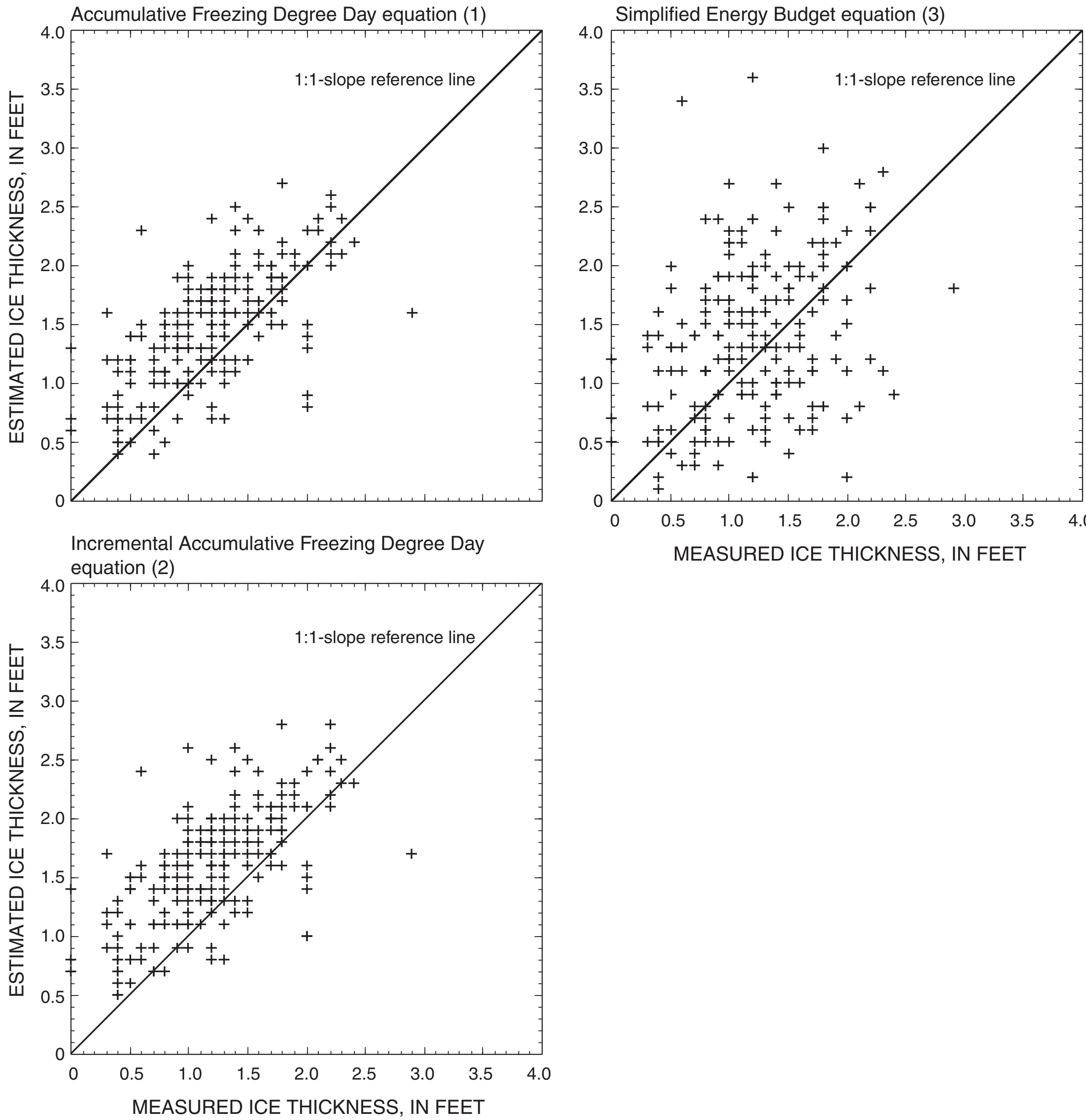


Figure 9. Equation-estimated versus measured ice thickness using both historical and study-collected ice-thickness data at selected sites in South Dakota (see table 6).

To avoid a possible bias from using the existing historical ice-thickness data that may not be as accurate as ice-thickness data collected for this study, a comparison was done using only study-collected data with 26 ice-thickness measurements used in the comparison. The results are presented in table 7, which also indicates that three of the ice-thickness measurements were excluded from the comparison, and in figure 10. The AFDD equation again best estimated the measured ice thickness with an average variation about the measured value of about 0.2 ft. The AFDD equation estimate using only study-collected data was much better than the 0.4-ft variation about the measured value using all of the available ice-thickness data. The IAFDD equation estimated ice thickness comparatively well with an average variation about the measured value of about 0.3 ft. Most of the points for the AFDD and IAFDD equations presented in figure 10 plot above the 1:1-slope reference line, indicating that these equations tend to overestimate the ice thickness. Applying the SEB equation resulted in ice-thickness estimates that were considerably different from ice-thickness measurements, with an average variation about the measured value of about 0.6 ft. The SEB equation points plot both above and below the reference line (fig. 10), indicating that the equation tends to both overestimate and underestimate the ice thickness. Additionally, the SEB equation ice-thickness variation about the measured value has a much larger standard deviation (0.4 ft) than the AFDD and IAFDD equation variations (0.2 ft). The SEB equation takes into account the effect of snow cover, which would be expected to cause the underprediction of maximum ice thickness because the snow cover would have an insulating effect. However, an analysis of the points plotted in figure 10 contradicts this expectation as most of the points plot above the 1:1-slope reference line, indicating that the SEB equation overestimates the ice thickness. Inaccurate representation of the ice snow-cover thickness may be the source of this error. The ice snow-cover thickness was estimated using snowfall data at NWS stations, which may not represent the actual ice snow cover.

An additional comparison using both study-collected and historical ice-thickness data was performed excluding ice-thickness measurements of less than 1.0 and 1.5 ft. The small values of measured ice thickness were excluded because one of the major focuses of this study is to estimate maximum potential ice thickness in South Dakota. It was expected that maximum ice thickness in South Dakota probably would be 1.0 to 1.5 ft during most winters. The results of a comparison excluding ice-thickness measurements of less than 1.0 ft are presented in table 8 and figure 11. About 140 ice-thickness measurements were used in the comparison. The AFDD and IAFDD equations again best estimated the measured ice thickness with an average variation about the measured value of about 0.4 ft for both. The SEB equation resulted in ice-thickness data with an average variation about the measured value of about 0.6 ft, which is the same as results of the comparisons summarized in tables 6 and 7. Again, most of the points for the AFDD and IAFDD equations presented in figure 11 plot above the 1:1-slope reference line, indicating that these equations tend to overestimate the ice thickness. The SEB equation points plot both above and below the reference line (fig. 11), indicating that the equation tends to both overestimate and underestimate the ice thickness.

The results of a comparison excluding ice-thickness measurements of less than 1.5 ft are shown in table 9 and figure 12. Sixty ice-thickness measurements were used in the comparison. The AFDD and IAFDD equations again best estimated the measured ice thickness with an average variation about the measured value of about 0.3 ft. The SEB equation resulted in ice-thickness data with an average variation about the measured value of about 0.6 ft, which is the same as results of the comparisons summarized in tables 6-8. Most of the points for the AFDD and IAFDD equations presented in figure 12 plot above the 1:1-slope reference line, indicating that these equations tend to overestimate the ice thickness. The SEB equation plotted points in figure 12 indicate that the equation tends to both overestimate and underestimate the ice thickness.

Another comparison was performed for the AFDD and IAFDD equations by changing the α variable from 0.6 to 0.55. The SEB equation was not used in this comparison because α is not a variable in that equation. To avoid a possible bias from using historical ice-thickness data that may not be as accurate as ice-thickness data collected for this study, the comparison was done using only study-collected data. The variation about the measured value results, which are shown in table 10 and figure 13, were not very different from the results using the 0.6 value for α (table 7). The average variation about the measured value was 0.2 ft for both equations. However, the points in figure 13 plotted much closer to the 1:1-slope reference line indicating a closer fit between the equations and the measured values.

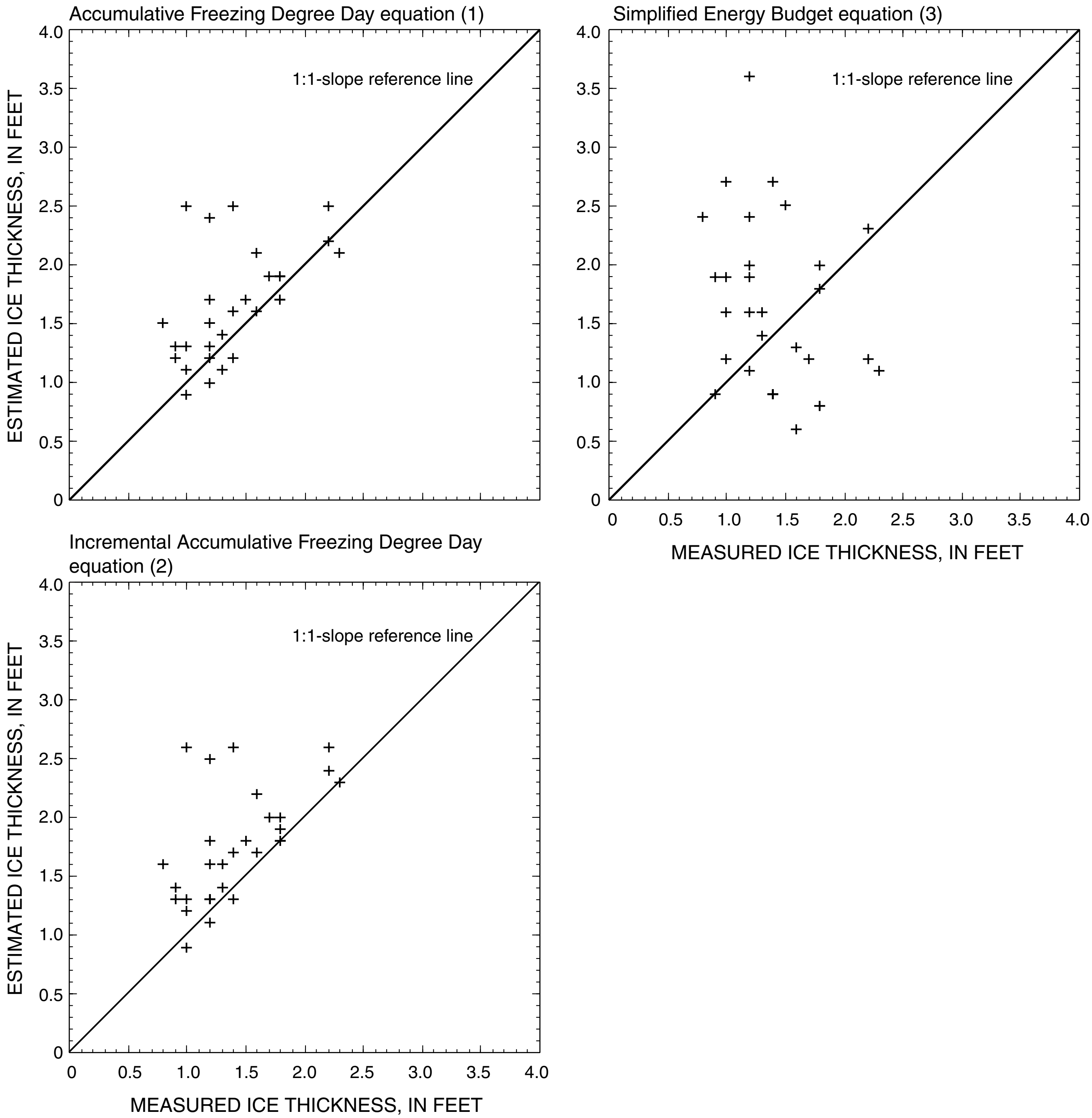


Figure 10. Equation-estimated versus measured ice thickness using only study-collected ice-thickness data at selected sites in South Dakota (see table 7).

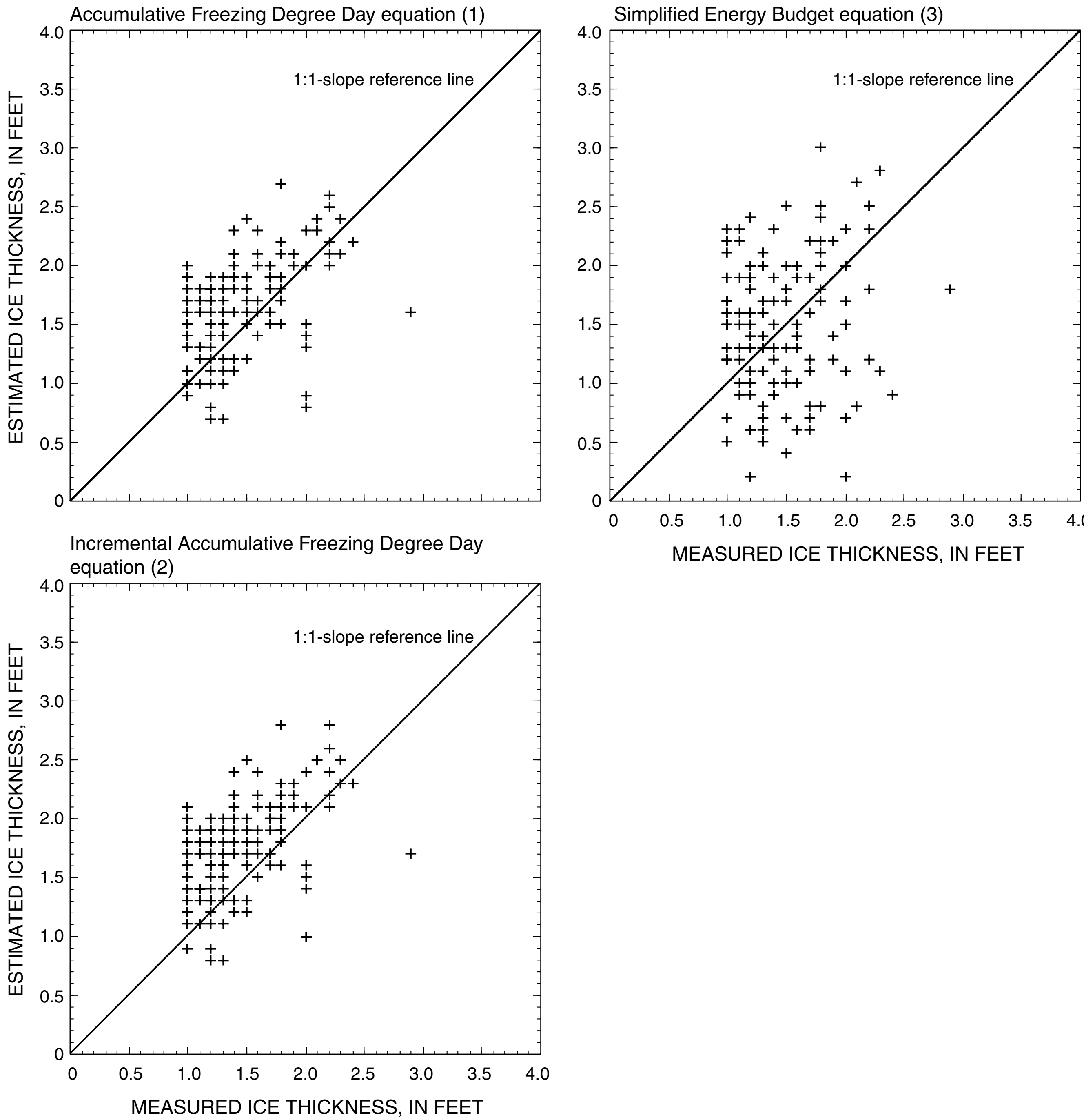


Figure 11. Equation-estimated versus equal or greater-than-1-foot measured ice thickness using both historical and study-collected ice-thickness data at selected sites in South Dakota (see table 8).

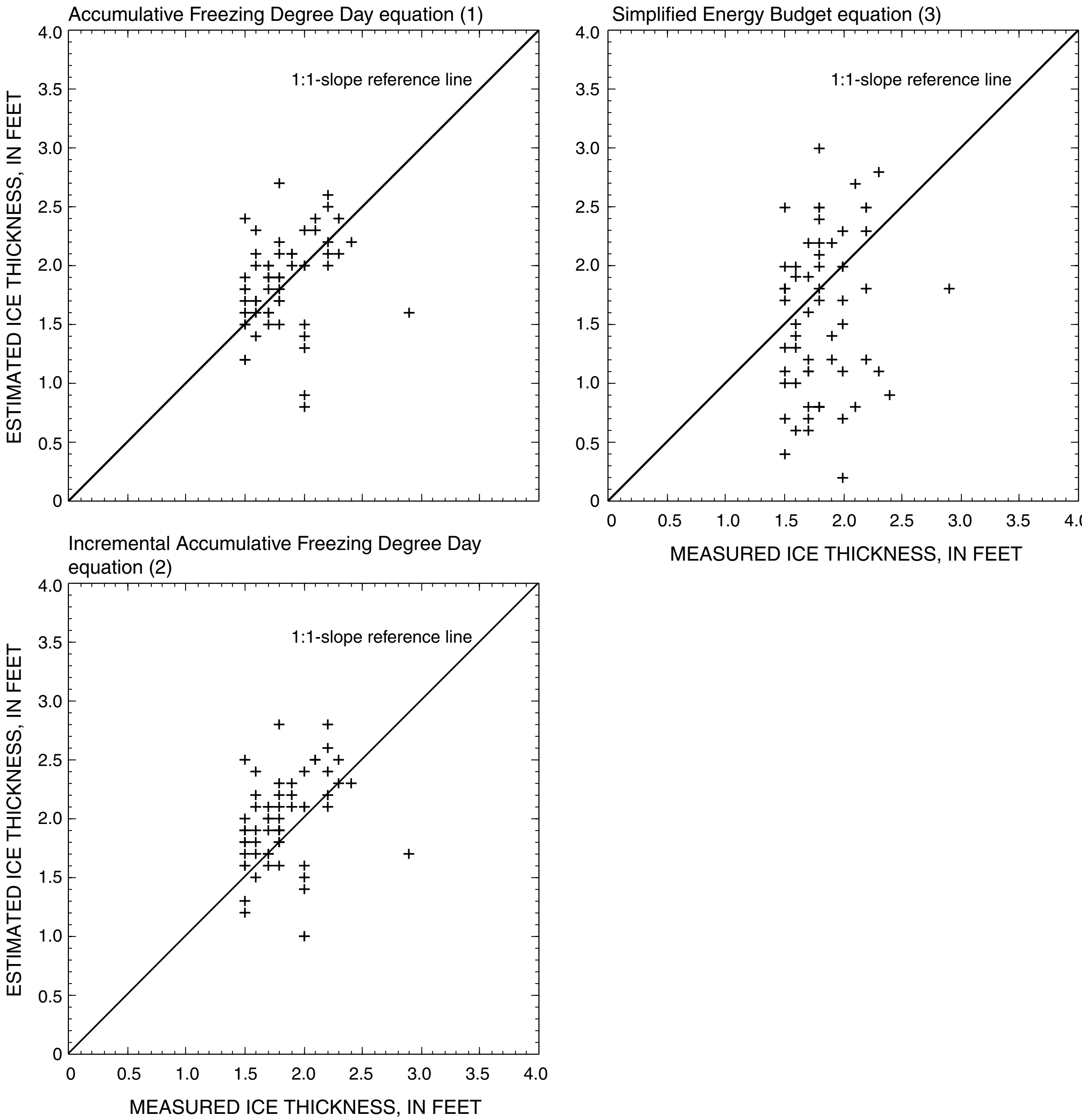


Figure 12. Equation-estimated versus equal or greater-than-1.5-foot measured ice thickness using both historical and study-collected ice thickness data at selected sites in South Dakota (see table 9).

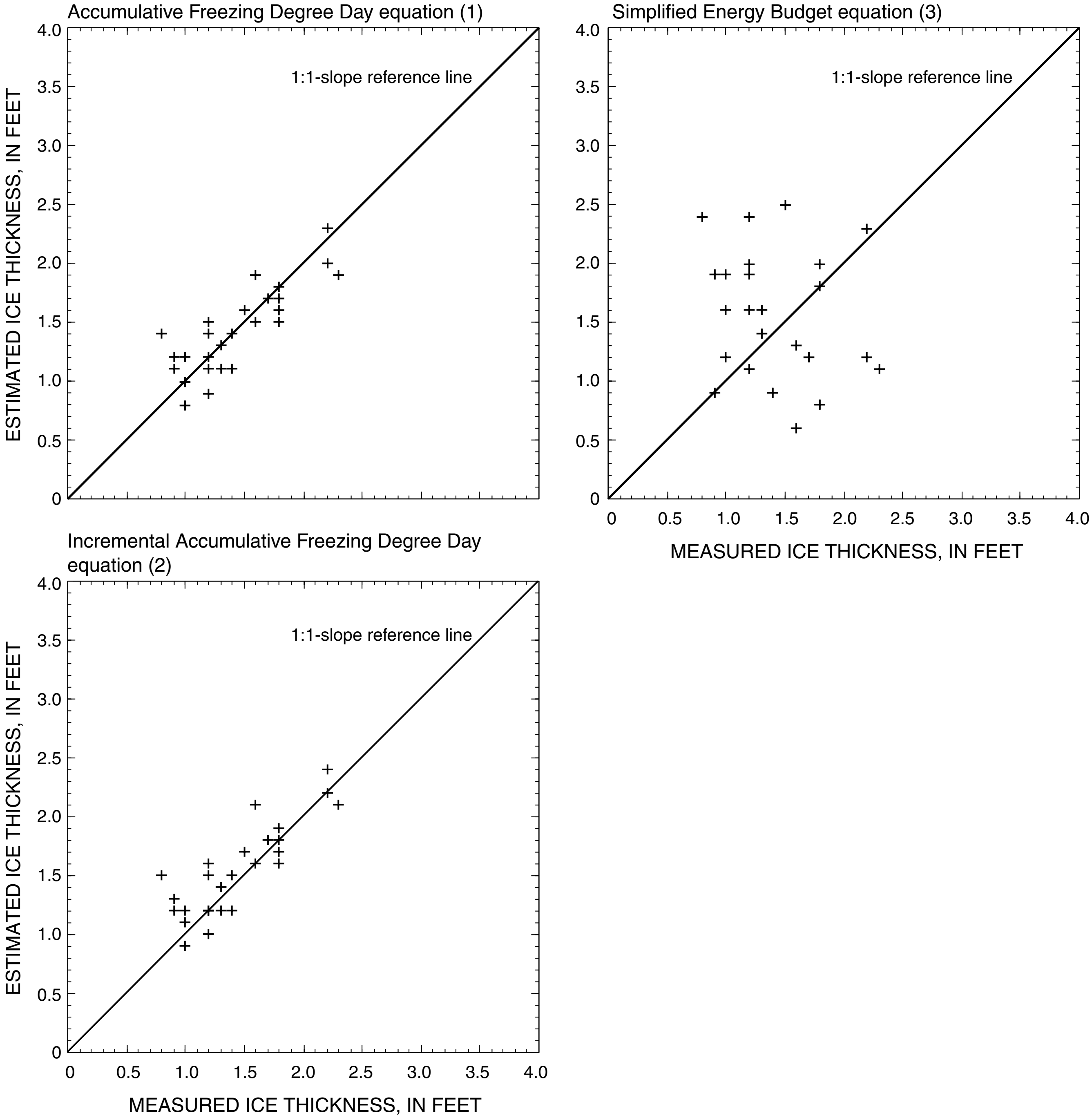


Figure 13. Equation-estimated versus measured ice thickness using only study-collected ice-thickness data with an α coefficient of 0.55 at selected sites in South Dakota (see table 10).

The progression from the AFDD to the IAFDD to the SEB equations would be expected to increase accuracy (James Wuebben, U.S. Army Corps of Engineers, written commun., 2002). However, the additional data or term values needed for the IAFDD and SEB equations often are not available or accurate for the site (for example, snowfall does not equal snow accumulation, and snow accumulation at an NWS meteorological station may not be the same as snow cover on the ice). Uncertainty in these additional terms can lead to uncertainty in the predicted values. The AFDD equation lumps many effects, and, at least for estimation of maximum ice thickness, performs well when α is set appropriately. If the focus was on estimating ice thickness early in the winter or if ice snow cover and other necessary ice-thickness-equation data were available, application of the SEB equation probably would result in the best estimation of ice thickness. For practical estimation of maximum ice thickness, the AFDD equation works well.

Estimation of Maximum Potential Ice Thickness

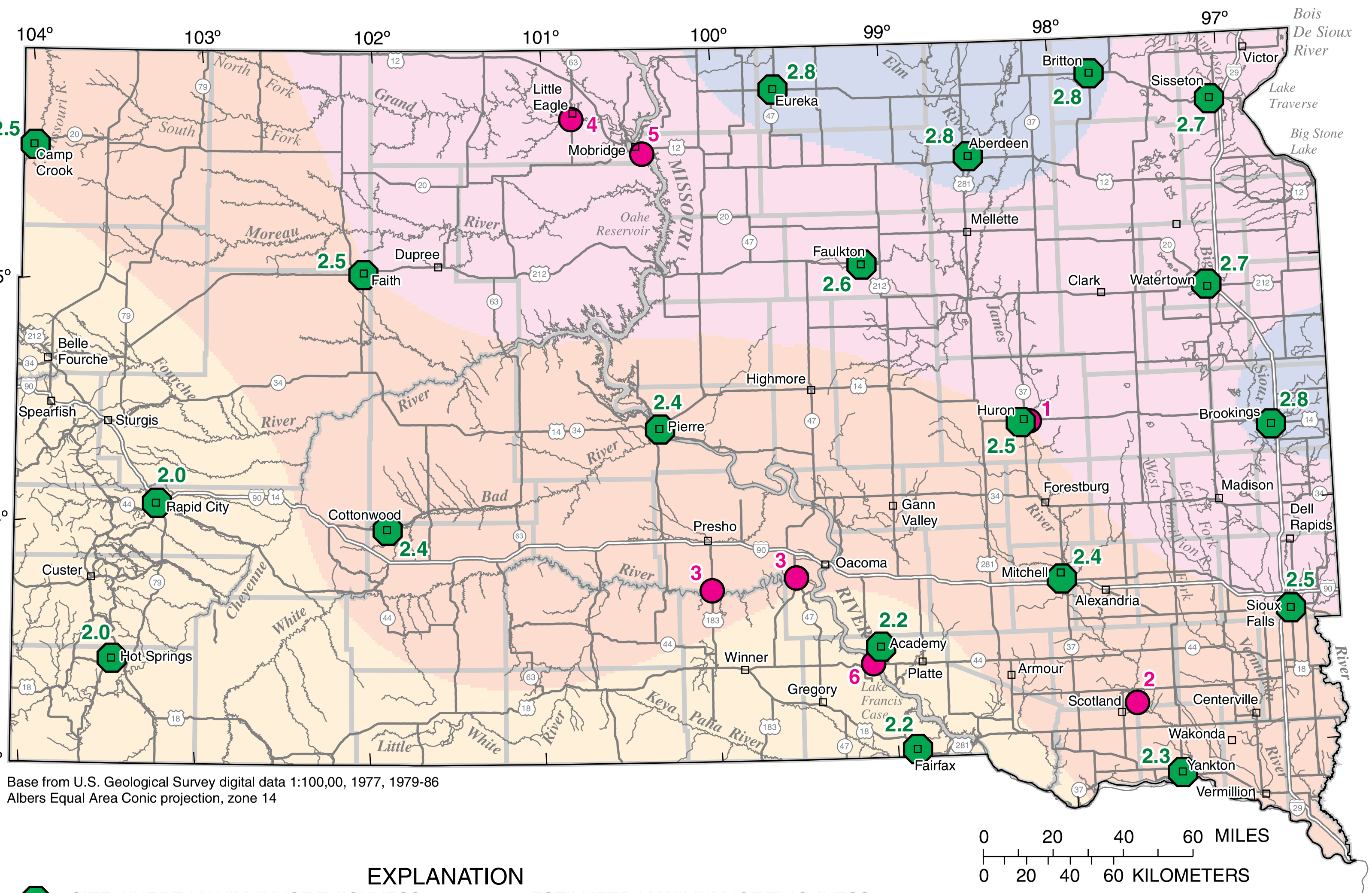
Maximum potential ice thickness was estimated for major rivers and lakes or reservoirs throughout South Dakota using the Accumulative Freezing Degree Day (AFDD) equation (equation 1), which resulted in the most accurate estimated ice thickness of the three selected equations using readily available meteorological data. The actual number of sites where maximum potential ice thickness was estimated was based on available historical NWS meteorological data and discussions with SDDOT representatives.

The maximum potential ice thicknesses are not predictions, but rather are the best estimate of future maximum ice thicknesses based on past data. By their nature, equations are imperfect and all have limitations, as do the actual data input into the equations. It is cautioned that the AFDD equation primarily is applicable to slow-moving rivers and lakes or reservoirs not subject to sustained high winds during ice formation (U.S. Army Corps of Engineers, 1981). When rivers have large discharges and associated high water velocities under the ice cover or when warm water from basins discharge into the ice-covered rivers, the results from this equation during these periods may not be applicable and consequently not accurate. Also, use of the AFDD equation is applicable only when ice is forming, not when it is melting. However, this error probably is not large because the equations were applied to obtain maximum potential ice thickness during the coldest winters on record that probably did not have extended periods of melting prior to the formation of the maximum ice thickness.

The estimated maximum potential ice thicknesses at 19 sites throughout South Dakota using the AFDD equation ranged from 2.0 to 2.8 ft and are listed in table 11 in the Supplemental Information section and shown in figure 14. For comparison, the estimated maximum potential ice thicknesses from applying the IAFDD and SEB equations also are included in table 11.

The 19 sites are located at NWS stations with extensive meteorological data. The necessary equation data included maximum and minimum daily air temperature and snowfall data for periods in the past that had very cold winters. The coldest winters on record at the Sioux Falls NWS station are listed in table 2. The Sioux Falls site was used to select the winters with the coldest temperatures for South Dakota (a winter is defined as December through February). The 1979 winter, the coldest winter on record according to the NWS, was the winter used to estimate maximum potential ice thickness. Other winters, including the 1978, 1917, 1936, 1899, 1997, and 1972 winters, also were used when data for the 1979 winter were not available or as a comparison to the maximum ice thickness estimated using the AFDD equation for the 1979 winter.

To estimate maximum potential ice thickness throughout South Dakota, the maximum ice-thickness estimates at the 19 NWS stations were contoured using mathematical and manual-editing methods as shown in figure 14. Generally, the estimated maximum potential ice thicknesses are the largest in northeastern South Dakota at about 3 ft and are smallest in southwestern and south-central South Dakota at about 2 ft. The ice-thickness estimations are based on the assumption that the AFDD equation accurately represents past measured ice thickness; however, little or no data were available or collected in northwestern and southwestern South Dakota to check the accuracy of this equation. Also, only large rivers and reservoirs were used in the evaluation of the equations. Applying these results to smaller rivers and lakes may not be valid. As previously stated, the AFDD equation is not applicable when the rivers have high flow velocities or when the lakes or reservoirs have significant wind that can result in dynamic accumulation. It also is important to consider the amount of water available for ice formation. Smaller rivers may never reach their maximum potential ice thickness because of this limiting factor.



Base from U.S. Geological Survey digital data 1:100,00, 1977, 1979-86
Albers Equal Area Conic projection, zone 14

EXPLANATION

SITE WHERE MAXIMUM ICE THICKNESS WAS ESTIMATED—Number is maximum ice thickness, in feet (2.0)

ICE DATA-COLLECTION SITE—Number is site number in table 1 (3)

ESTIMATED MAXIMUM ICE THICKNESS, IN FEET

- 2.0 to 2.2
- 2.2 to 2.5
- 2.5 to 2.8
- 2.8 to 3.0

Figure 14. Estimated maximum potential ice thickness on rivers and lakes or reservoirs in South Dakota.

Ice-Crushing Strength

Ice-crushing strength was measured at the six sites shown in figure 1. Ice-crushing-strength measurements didn't begin until early February 1999 because of the mild winter of 1999, and continued until April 2001. As previously discussed in the ice-thickness section of this report, the 1999-2001 data-collection winters included both one of the warmest and one of the coldest winters on record. The 2000 winter was the 8th warmest winter, and the 2001 winter was the 11th coldest winter in a period of 111 years of record. This winter temperature variation allowed a wide range of measured ice-crushing strengths, as ice strength is very dependent on the temperature of the ice during testing.

Ice-crushing strength was measured both in the winter and in the spring as close to ice breakup as feasible. The maximum ice-crushing strengths were measured in mid- to late winter when the ice was the coldest. Ice-crushing strengths measured at and near breakup during the spring thaw were much less. The magnitude of ice-crushing strength when the ice breaks up and sometimes flows down a river or moves by wind across a lake or reservoir is important because this ice-crushing strength may be more applicable to use in bridge-design equations.

Ice breakup transforms an ice-covered river or lake or reservoir into an open river or lake or reservoir. The breakup may involve two possible extremes, thermal meltout and mechanical breakup. Thermal melt out occurs when the ice mass deteriorates through warming and absorption of solar radiation and melts in place with no increase in flow and little or no ice movement. Mechanical breakup occurs when the ice mass breaks up due to an increase in flow entering the river. This breakup can be rapid because no deterioration of the ice mass is necessary. The introduced water creates stresses in the ice mass that cause cracks to form, leading to the breakup of the ice into chunks. Ice moves much like sediment, which moves through high energy reaches and deposits in lower energy locations. Bridges generally do not slow or stop ice flow unless pier spacing is narrow in relation to ice flow size or unless the bridge holds the winter sheet ice in place. Ice jams occur at locations where the ice is obstructed as the ice chunks flow downstream or where the energy slope of the river decreases. These ice jams impede the flow causing upstream flooding and subsequent downstream flooding when the jams suddenly release.

Many rivers in South Dakota undergo a combination of thermal meltout and mechanical breakup. The ice mass deteriorates during a warm-up period, while at the same time the warm up causes increased flow into the river. Lakes or reservoirs also can undergo a combination of thermal meltout and mechanical breakup as the lake or reservoir ice typically melts in place, but before complete melting, ice chunks can be moved by high winds against bridge structures. At the two James River and two Missouri River reservoir sites, observed breakup was closer to thermal meltout than mechanical breakup. A combination of the two breakup extremes occurred at the White River and Grand River sites.

Ice-crushing strengths used in bridge design in South Dakota were evaluated in a limited way by comparing ice-crushing strengths used in bridge design to ice-crushing strengths measured at the data-collection sites. A more extensive study, involving direct measurement of ice forces at bridge structures, would be useful. This would allow a measurement of the magnitude of the force applied by ice on bridge structures at both the time of maximum ice-crushing strength in mid- to late winter and of the ice force applied during spring breakup. Literature applicable to the ice-crushing strength was researched to gain an understanding of how ice-crushing strength develops. This was done in conjunction with the literature search on ice-thickness estimation.

Data Summary

Ice-crushing strength measured at the six sites from February 1999 to April 2001 ranged from 58 lb/in^2 to greater than 1,046 lb/in^2 (table 4). The samples collected for measurements of ice-crushing strength varied from very-clear columnar ice collected near the bottom of the ice mass (fig. 15A) to milky-colored snow ice (fig. 15B) to sediment-layered ice (fig. 15C). Columnar ice is ice that consists of column-shaped grains (U.S. Army Corps of Engineers, 1996). Snow ice is ice that forms when snow slush freezes on an ice cover. The presence of air bubbles makes it appear white (U.S. Army Corps of Engineers, 1996). Boxplots summarizing the collected ice-crushing-strength data are shown in figure 16. Crushing-strength data used that were greater than specific values were set equal to those values for purpose of the boxplots. The largest ice-crushing strengths were measured from samples collected from

A Clear ice sample taken from the bottom section of the ice mass at site 5 (Oahe Reservoir near Mobridge) on January 11, 2001

B Milky-colored ice sample after removed from ice-crushing machine at site 1 (James River at Huron) on April 2, 2001

C Ice sample with alternating clear and sediment-mixed layers at site 3 (White River near Oacoma) on January 10, 2001

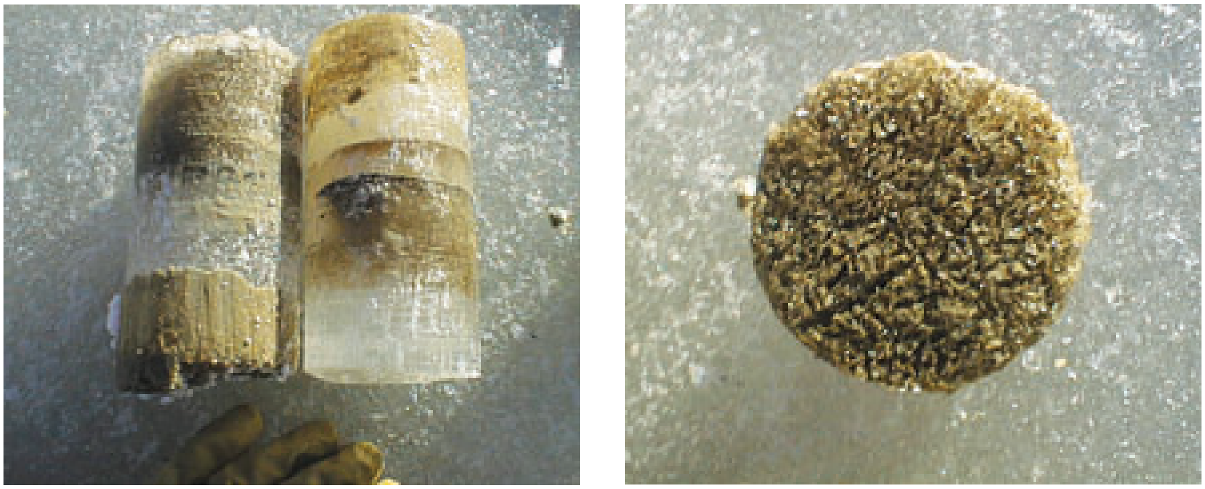


Figure 15. Photographs of samples collected for measuring ice-crushing strength at ice-data collection sites in South Dakota.

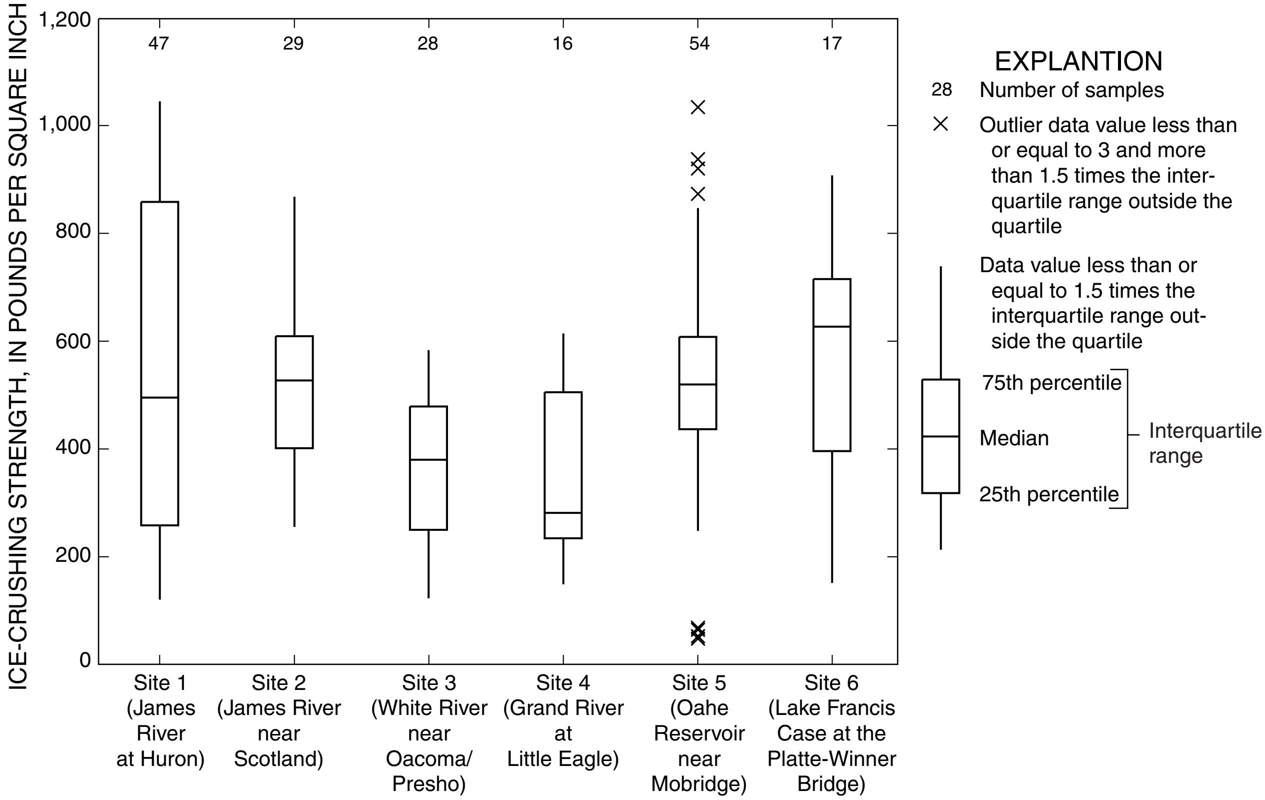


Figure 16. Boxplots of measured ice-crushing strength at ice-data collection sites for the study, 1999-2001.

site 5 (Oahe Reservoir near Mobridge) and site 1 (James River at Huron). The smallest ice-crushing-strength measurement was 58 lb/in^2 from a sample collected from site 5. The initial plan for data collection was to collect data at all six sites each year of the study in early January, February, and March. This initial plan was modified depending on ice conditions encountered at each site. The colder climate in northern South Dakota provided more opportunities to measure ice; thus, more data were collected at sites 1 (James River at Huron) and 5 (Oahe Reservoir near Mobridge) than the other sites.

Ice-crushing strength was measured once at site 1 (James River at Huron) in 1999, twice in 2000, and four times in 2001. Ice-crushing strength measured at site 1 was highly variable and ranged from 228 to 522 lb/in^2 in 1999, 180 lb/in^2 to greater than 1,042 lb/in^2 in 2000, and 207 lb/in^2 to greater than 1,046 lb/in^2 in 2001. The maximum ice-crushing strength of greater than 1,046 lb/in^2 was measured in the winter of 2001, which was the 11th coldest winter of record (table 2). Surprisingly, a similar large maximum ice-crushing strength of greater than 1,042 lb/in^2 was measured in the 2000 winter, which was a much milder winter than the 2001 winter. The largest ice-crushing strengths were measured in the middle of the winter in January and early February. In January 2000, the average ice-crushing strength was about 950 lb/in^2, and in January and February 2001, the average ice-crushing strength was about 800 and 850 lb/in^2, respectively. As expected, the smallest ice-crushing strengths were measured during the spring near breakup. In 2001, the average ice-crushing strength measured near breakup was about 200 lb/in^2.

For all samples collected at site 1, the ice was crushed at rates between 0.0006 and 0.0013 in/sec, and sample sizes (diameter by length) varied from 3.5 by 6 inches to 3.5 by 8.25 inches and from 4 by 4.5 inches to 4 by 8.5 inches. The ice-crushing strengths measured using samples that are not close to the ideal length-to-diameter ratio of 2 to 1 should be used with caution. For quality-assurance purposes, ice-crushing strength usually was measured at this same location using other samples that were at or near this ratio.

During the study, breakup at site 1 was more of a thermal meltout than a mechanical breakup. A series of photographs in figure 17 illustrates spring breakup at this site in April 2001. Due to warmer temperatures and input of "warm" upstream tributary water, the measured maximum ice thickness decreased from about 2 ft on April 2 to less than 1 ft by April 4. A 2-inch rain on April 6 further deteriorated the ice mass. Based on shore observation on April 6 (ice was unsafe for a direct measurement), the thickness of the ice mass at the site decreased to only a few inches. By April 9, the ice mass was completely gone.

Ice-crushing strength was measured at site 2 (James River near Scotland) once in 1999 and 2000 and three times in 2001. Ice-crushing strength measured at site 2 ranged from 417 to 603 lb/in^2 in 1999, 565 to 694 lb/in^2 in 2000, and 255 to 869 lb/in^2 in 2001. The maximum ice-crushing strength of 869 lb/in^2 was measured during the winter of 2001 (the 11th coldest winter of record). The largest ice-crushing strengths were measured in the middle of the winter in January and early February. The largest ice-crushing strengths at site 2 didn't vary nearly as much as ice-crushing strengths measured at site 1 (James River at Huron). For January and February measurements, average ice-crushing strength ranged from about 475 to 625 lb/in^2 at site 2, as compared to the range of about 300 to 950 lb/in^2 at site 1. The smallest ice-crushing strengths at site 2 were measured in the spring near breakup. In 2001, average ice-crushing strength measured near breakup was about 275 lb/in^2. For all samples, the ice was crushed at rates between 0.0005 and 0.0011 in/sec, and sample sizes (diameter by length) varied from 3.5 by 6.25 inches to 3.5 by 8 inches and from 4 by 5 inches to 4 by 8 inches.

Like site 1, breakup at site 2 was more of a thermal meltout than a mechanical breakup. During the spring breakup in March 2001, the ice mass first deteriorated at the shoreline (fig. 18A). By March 20, there was about 10 ft of open water on both sides of the James River at the site. A ladder was used to get on the ice to collect samples over the open water as shown in figure 18B. The ice-mass top was very slushy with some open water in areas on top of the ice. The maximum ice thickness ranged from about 1 to 1.5 ft for the western one-half of the James River at this site. Ice on the eastern one-half was less than 1 ft thick and deemed unsafe for data collection.

Ice-crushing strength was measured at site 3 (White River near Oacoma/Presho) once in 2000 at the Presho and Oacoma locations and twice in 2001 at the Oacoma location. Ice-crushing strength measured during the winter months at site 3 ranged from 180 to 579 lb/in^2 in 2000 and from 214 to 585 lb/in^2 in 2001. On February 13, 2001, the White River at the site had limited water and corresponding little ice (0.1 ft). Consequently, no ice-crushing-strength data were collected. The maximum ice-crushing strength of 585 lb/in^2 was measured in the 2001 winter, the 11th coldest winter of record; however, a similar large ice-crushing strength of 579 lb/in^2 was measured in the 2000 winter, which was a much milder winter than the 2001 winter. The largest ice-crushing strengths were measured in the middle of the winter in January and early February. The average ice-crushing strengths measured during the middle of winter (450 to 475 lb/in^2) varied similarly to the ice-crushing strengths measured at site 2 (James River near Scotland). The smallest ice-crushing strengths were measured during the spring near breakup. In 2000 and 2001, the average ice-crushing strength was measured at 225 lb/in^2 near breakup. For all samples, the ice was crushed at rates between 0.0008 and 0.0010 in/sec, and sample sizes (diameter by length) varied from 3.5 by 5 inches to 3.5 by 8 inches and from 4 by 4.5 inches to 4 by 6 inches.

Breakup at site 3 usually was more of a mechanical breakup than a thermal meltout. Breakup in 2001 occurred near March 13 when the ice broke into chunks and flowed down the White River. The ice chunks intermittently were jammed at site 3 as shown in figures 19A and 19B. The samples needed for ice-crushing-strength measurement were collected by walking on this ice jam (when it wasn't moving) and manually collecting ice chunks that were large enough for use in the ice-coring machine (figs. 19C and 19D). The samples collected on March 13 were obtained very near the start of the breakup, before the samples were changed by spring temperature variations.

Figure 17. Sequence of photographs showing breakup at ice-data collection site 1 (James River at Huron), April 2001.

A Open water looking downstream at site 2 (James River near Scotland) on March 20, 2001

B Open water was crossed to collect samples on upstream side of bridge at site 2 (James River near Scotland) on March 20, 2001

Photograph by Franklin D. Amundson

Figure 18. Photographs showing the breakup at ice-data collection site 2 (James River near Scotland), site 4 (Grand River at Little Eagle), and site 5 (Oahe Reservoir near Mobridge).

C Remnants of ice jam near shore at site 4 (Grand River at Little Eagle) on February 12, 1999

D Open water near shore at site 5 (Oahe Reservoir near Mobridge) on March 21, 2001. Ice chunks were collected by wading out to the ice mass. Samples were collected using the core drill on collected ice chunks.

Photograph by Franklin D. Amundson

Figure 18. Photographs showing the breakup at ice-data collection site 2 (James River near Scotland), site 4 (Grand River at Little Eagle), and site 5 (Oahe Reservoir near Mobridge).—Continued

A Ice jam (no movement of ice) looking upstream of bridge

B Ice breakup dowstream of bridge with flowing ice

Figure 19. Photographs showing the mechanical breakup on March 13, 2001, at ice-data collection site 3 (White River near Oacoma).

C Ice chunks collected from the ice jam

D Ice chunks with samples already drilled out

Figure 19. Photographs showing the mechanical breakup on March 13, 2001, at ice-data collection site 3 (White River near Oacoma).—Continued

Ice-crushing strength was measured at site 4 (Grand River at Little Eagle) once in 1999, twice in 2000, and once in 2001. Ice-crushing strength measured at site 4 ranged from 229 to 577 lb/in^2 in 1999, 148 to 615 lb/in^2 in 2000, and 236 to 411 lb/in^2 in 2001. Little water in the Grand River was available for freezing during January and February 2001, and thus little ice was formed and no samples collected for measurement of ice-crushing strength. The maximum ice-crushing strength of 615 lb/in^2 was measured in the winter of 2000. The smallest ice-crushing strengths were measured in the spring near breakup. In 1999, 2000, and 2001, average ice-crushing strength measured near breakup was about 400, 300, and 300 lb/in^2, respectively. The samples measured for ice-crushing strength in both 1999 and 2001 were taken from ice chunks near the shore. The 400-lb/in^2 ice-crushing strength measured in 1999 probably was an overestimation because the ice chunks that were sampled from probably had been refrozen after deposition. For all samples, the ice was crushed at rates between 0.0007and 0.0011 in/sec, and sample sizes (diameter by length) varied from 3.5 by 7 inches to 3.5 by 8 inches and from 4 by 5 inches to 4 by 7.5 inches.

Breakup at site 4 usually was a combination of a thermal meltout and mechanical breakup. Breakup in 1999 occurred in February when ice broke up into chunks and flowed down the river. On February 12, 1999, ice samples were collected from the remnants of this ice breakup (fig. 18C) by using the core machine to drill samples from ice chunks near the shoreline. Some of the ice chunks were almost 2 ft thick.

Ice-crushing strength was measured at site 5 (Oahe Reservoir near Mobridge) once in 1999, twice in 2000, and three times in 2001. Ice-crushing strength measured at site 5 was highly variable and ranged from 387 to 685 lb/in^2 in 1999, 247 to 883 lb/in^2 in 2000, and 58 to greater than 1,046 lb/in^2 in 2001. The maximum ice-crushing strength of greater than 1,046 lb/in^2 was measured in the winter of 2001 (11th coldest winter of record). As at the other sites, the largest ice-crushing strengths were measured in the middle of the winter in January and early February. Average ice-crushing-strength measurements in January and February ranged from about 500 to 650 lb/in^2 as compared to an average ice-crushing strength of 75 lb/in^2 near the 2001 spring breakup. For all samples, the ice was crushed at rates between 0.0008 and 0.0010 in/sec, and sample sizes (diameter by length) varied from 3.5 by 5.5 inches to 3.5 by 8.25 inches and from 4 by 5 inches to 4 by 8 inches. Because of the large area to obtain ice samples (greater that 1 mile) and northern location in South Dakota, more samples were collected at this site than any other site. This large number of samples was used to assess the quality of the ice-crushing-strength data and to measure any variation between top and bottom samples. The results of the assessment are discussed in the next section.

Breakup at site 5 was more of a thermal meltout than a mechanical breakup. The ice mass broke up near shore where the depths were shallower and water was warmer from runoff. This resulted in an increasingly larger area of open water near shore. For the 2001 breakup, ice samples were collected by wading through 20 ft of open water to the ice mass and chipping off ice blocks using an ice chisel as shown in figure 18D. These ice blocks were then transferred to shore, and samples were collected for crushing using the ice-coring machine.

Ice-crushing strength was measured at site 6 (Lake Francis Case at the Platte-Winner Bridge) only in 2001. Because of large variations in water levels and the mild winters of 1999 and 2000 and corresponding unsafe ice, no ice data were collected at the site in 1999 and 2000. Ice-crushing strength measured at site 6 in 2001 ranged from 151 to 907 lb/in^2. Average ice-crushing strength was estimated as 725 lb/in^2 on February 13, 2001. No data were collected during spring breakup because it was not possible to collect samples from the ice mass in March, as an open shoreline rapidly formed in early March. This open water was too extensive and too deep to wade out to the ice mass to collect samples. The best estimates of ice-crushing strength for this site during breakup probably are the ice-crushing strengths ranging from 151 to 428 lb/in^2 with an average of about 250 lb/in^2 measured in January 2001. These samples were collected by wading through open water to the ice mass. For all samples, the ice was crushed at rates between 0.0010 and 0.0013 in/sec, and sample sizes (diameter by length) varied from 3.5 by 6 inches to 3.5 by 8 inches.

Evaluation of Ice-Crushing Strength

Ice-crushing-strength data collected in the field were evaluated to a limited degree to see how they compared to ice-crushing strengths used in bridge design in South Dakota. There are ice-crushing-strength estimation equations available to use for comparisons with measured strength; however, these equations require extensive data that are hard to collect or not readily available. The ice-crushing strengths measured during spring breakups probably are the most applicable values for bridge design.

A summary of the maximum ice-crushing strengths is presented in figure 20, which shows both the individual maximum ice-crushing strength and the maximum average ice-crushing strength measured at each site during the data-collection period. For example, the maximum ice-crushing strength measured at site 2 (James River near Scotland) from 1999 to 2001 was 869 lb/in^2 on February 12, 2001, from a sample collected 100 ft from the shoreline. The maximum average ice-crushing strength at this site was 625 lb/in^2 on January 24, 2000. The average ice-crushing strengths at this site ranged from 275 to 625 lb/in^2 during the data-collection period.

Potential maximum ice-crushing strengths across South Dakota were not estimated because no ice-crushing-strength estimation equations were evaluated. However, based on data collected, maximum ice-crushing strengths averaged from about 475 lb/in^2 at site 3 (White River near Oacoma/Presho) to about 950 lb/in^2 at site 1 (James River at Huron). Individual maximum ice-crushing-strength measurements were the lowest at site 3 (White River near Oacoma/Presho) and site 4 (Grand River at Little Eagle) (585 and 615 lb/in^2, respectively). The individual maximum ice-crushing strengths were 869 and 907 lb/in^2 at site 2 (James River near Scotland) and site 6 (Lake Francis Case at the Platte-Winner Bridge), respectively, and greater than 1,046 lb/in^2 at both site 1 (James River at Huron) and site 5 (Oahe Reservoir near Mobridge). Based on an analysis of this limited ice-crushing-strength data, ice-crushing strengths of about 1,000 lb/in^2 could be expected at any site in South Dakota if enough water is available for freezing and if the winter is as cold as the 2001 winter.

American Association of State Highway and Transportation Officials (AASHTO) design values for the ice-crushing strength of ice range from 100 to 400 lb/in^2 (Daris Ormesher, South Dakota Department of Transportation, written commun., 1999), which could result in large variations in bridge design. The design criteria (AASHTO Design Method) used by the SDDOT Bridge Section sets ice-crushing strength at 100 lb/in^2 for purposes of bridge design. Even if the assumption is made that ice does not put extensive force on bridge structures except when it breaks up in the spring and is driven by flow or wind against the structures, measured ice-crushing strength near spring breakup usually was much greater than 100 lb/in^2. The average ice-crushing strength measured near breakup at the six ice-data collection sites in South Dakota ranged from 75 to 300 lb/in^2 (fig. 21). An ice-crushing strength of 250 lb/in^2 would not be anomalous for expected ice-crushing strengths during spring breakup in South Dakota. Site 3 (White River near Oacoma/Presho) provided the most applicable data for an analysis of mechanical breakup because the samples for ice-crushing on March 13, 2001, were taken from ice that had broken up and started to flow downstream into the bridge piers. The average ice-crushing strength for samples collected on this date was about 225 lb/in^2 and ranged from 214 to 271 lb/in^2. Site 1 (James River at Huron) provided the most applicable data for an analysis of ice-crushing strength for a breakup representative of a thermal meltout and with extensive available data. This site was monitored extensively near the breakup during 2001. Ice-crushing strength was about 200 lb/in^2 just before the final breakup in April 2001.

As previously stated, the samples collected for ice-crushing-strength measurement varied from very-clear columnar ice collected near the bottom of the ice to milky-colored snow ice to sediment-layered ice. A description of the ice samples is included in table 4 along with the measured ice-crushing strengths. No conclusions could be reached from an analysis of the ice-crushing strength data as related to the different types of ice because data collection was not tailored to ice type. Limited specific conductance data, which was measured only in 2001, also are included in this table. The location in the vertical column of the ice mass from which the sample was taken also is presented in table 4. If there was sufficient ice thickness, samples were taken in the upper, middle, and lower part of the ice columns. An analysis was done to see if the magnitude of the ice-crushing strength depended on the location the sample was taken in the vertical column. There were 22 instances where ice-crushing strength was measured at the same time and location for both an upper or middle and lower sample. The ice-crushing strength of the sample from the upper or middle column was equal to or greater than that from the lower column in about 45 percent of the sample pairs and was lower in about 55 percent of the sample pairs, so the results were inconclusive. The magnitude of the difference between the lower sample ice-crushing-strength values as compared to the upper or middle sample ice-crushing-strength values averaged about 22 percent. Variation in strength near the top or middle of the ice cover versus the bottom could depend on air temperature or ice type. If the air temperature is well below freezing, the upper or middle portion of the ice would be colder and therefore stronger than the bottom, which would be at about 32°F where in contact with the underlying water. Ice type also results in strength variation as columnar ice is stronger than the snow ice.

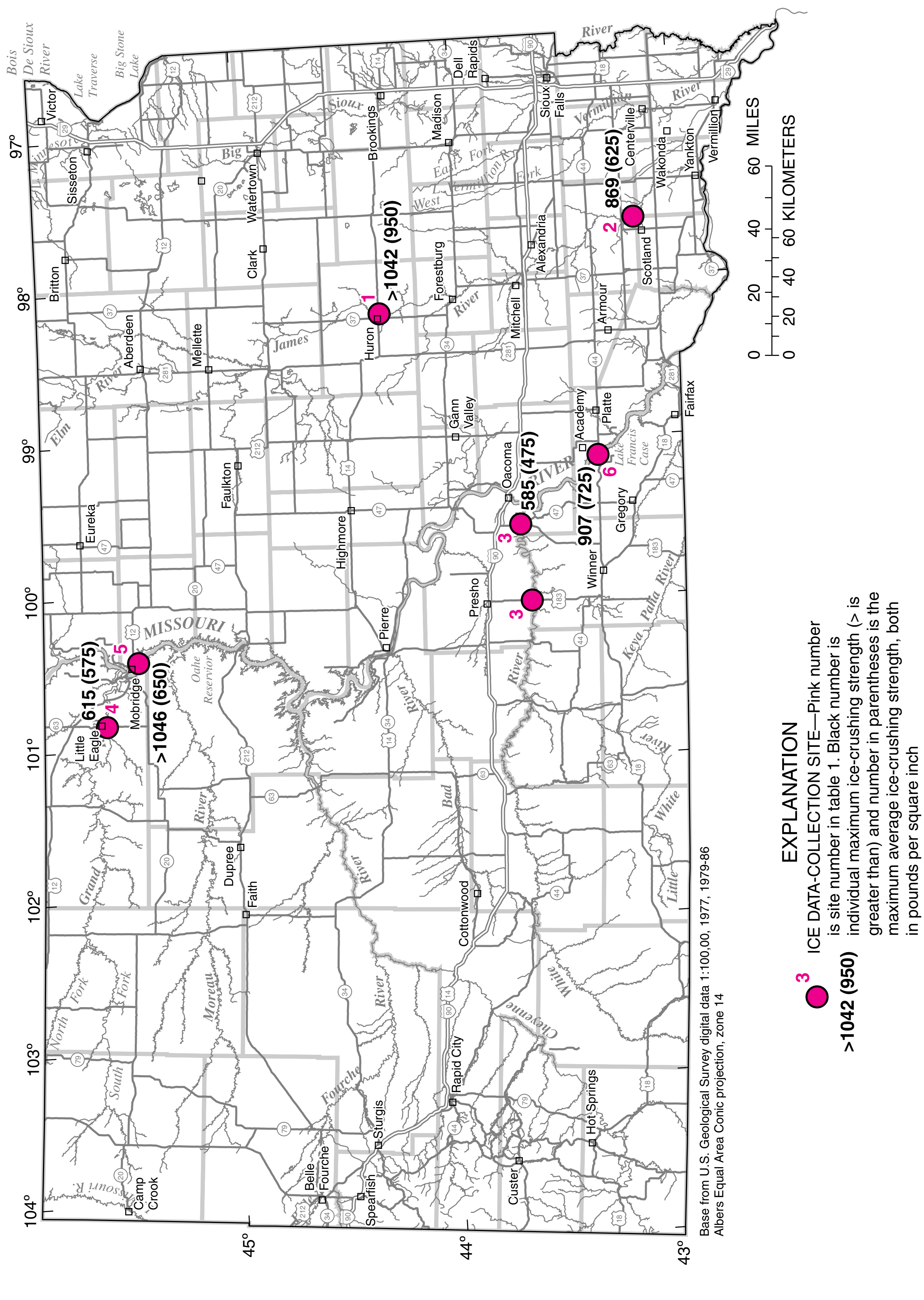


Figure 20. Maximum ice-crushing strength measured at ice-data collection sites in South Dakota.

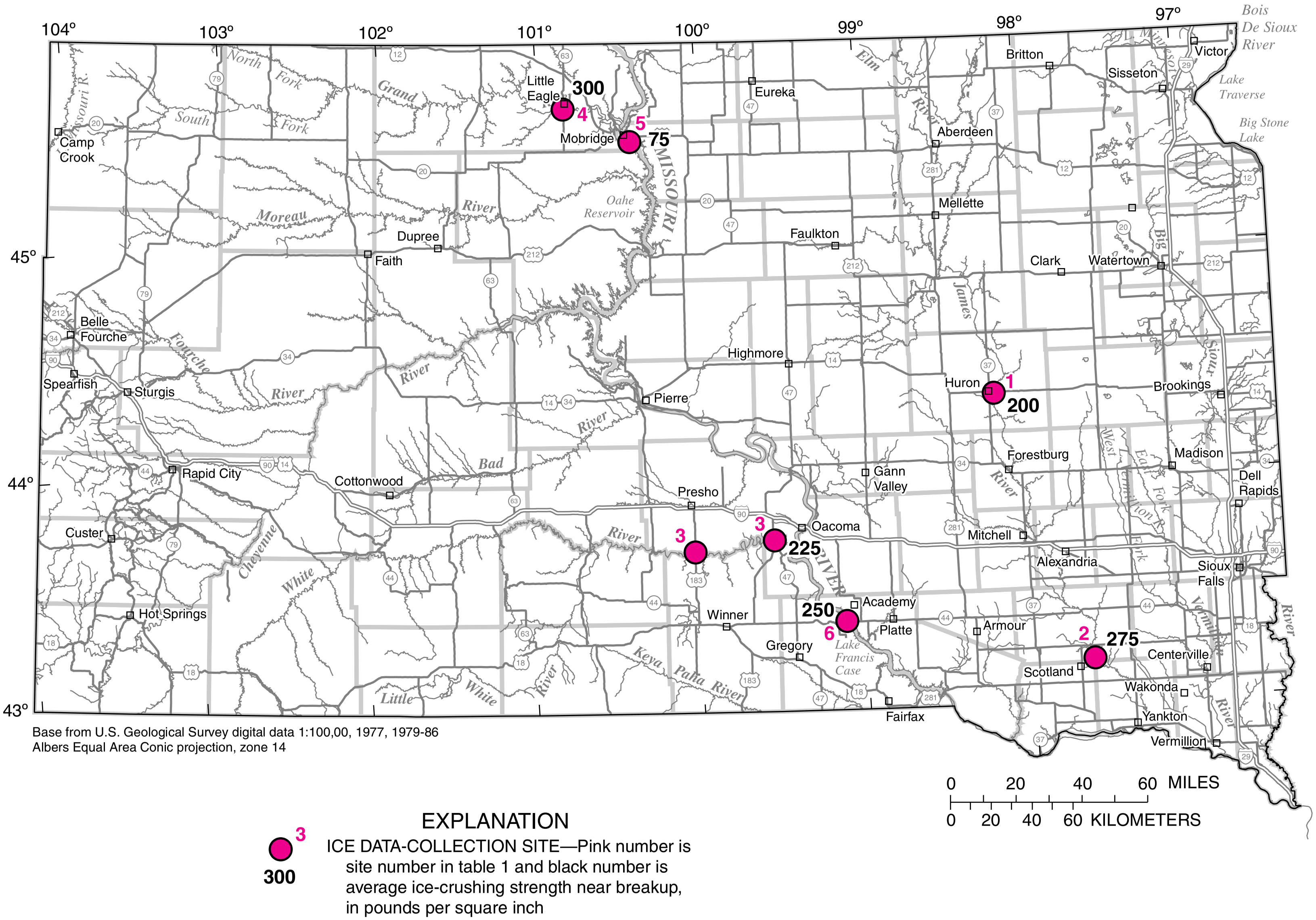


Figure 21. Average ice-crushing strength measured near breakup at the ice-data collection sites in South Dakota.

The evaluation of ice-crushing strength presented in this report is limited by the data collected for the study. The collection of additional data at the six sites used in this study could provide better estimates of ice-crushing strengths. For practical application, the collection of data from more sites, especially in the northeast, northwest, and southwest parts of South Dakota, would be beneficial.

SUMMARY

Estimating the magnitude of ice forces that act on bridge piers and abutments in northern climates is a major concern in the design of new bridges and in the evaluation of the structural stability of existing bridges. Although ice-force estimation equations typically are used for bridge design that address ice thickness and ice-crushing strength, which are the most important variables in the bridge design equations, the estimated ice forces may not be conservative because the ice-thickness and ice-crushing-strength values used in these equations may not be the maximum values that could occur in South Dakota. In response to these concerns, the U.S. Geological Survey (USGS), in cooperation with the South Dakota Department of Transportation, conducted a study to evaluate factors affecting ice forces at selected bridges in South Dakota from June 1998 to September 2002.

Six sites in South Dakota were selected for ice-data collection, which included ice-thickness and ice-crushing-strength data. Ice thickness generally was measured at each site at three to five locations along a transect perpendicular to the direction of flow. Ice-crushing strength was measured at the same six sites where ice-thickness data were collected. Samples with 6- to 12-inch lengths were collected for ice-crushing-strength analyses. Multiple ice samples were collected at each location along the transect to obtain representative samples from the entire vertical section. The samples were crushed at each site using a portable ice-crushing machine until failure was achieved.

Ice thickness measured at the James River at Huron site ranged from 1.1 to 1.3 feet in 1999, 0.7 to 1.2 feet in 2000, and 1.4 to 2.3 feet in 2001. Because the 2001 winter was the 11th coldest winter of record at Sioux Falls, ice-thickness measurements collected during this winter probably are near the maximum ice thicknesses that could occur at this site in the future. Ice thickness measured at the James River near Scotland site ranged from near 0 to 0.9 ft in 1999, 0.5 to 1.0 ft in 2000, and 0 to 1.7 ft in 2001. Ice thickness measured at the White River near Oacoma/Presho site ranged from 0.5 to 1.0 ft in 2000 and from 0.1 to 1.5 ft in 2001. This site had limited water and corresponding little ice (0.1 ft) when data were collected in February 2001. Ice thickness measured at the Grand River at Little Eagle site was 1.2 ft in 1999, ranged from 0.5 to 1.2 ft in 2000, and ranged from 0.2 to 1.4 ft in 2001. Little water was available at the site for freezing in January and February 2001, resulting in little ice formation. Ice thickness measured at the Oahe Reservoir near Mobridge site ranged from 1.7 to 1.8 ft in 1999, 0.9 to 1.2 ft in 2000, and 0 to 2.2 ft in 2001. Ice thickness measured at the Lake Francis Case at the Platte-Winner Bridge site ranged from 1.2 to 1.8 ft in 2001. Because of the large variation in water levels at this site and the mild winters of 1999 and 2000, no ice data were collected in 1999 and 2000.

Historical ice-thickness data measured by the USGS at eight selected streamflow-gaging stations for 1970-97 were compiled. The maximum measured ice thickness at the Grand River at Little Eagle station was 2.9 ft from November 1975 to February 1997, and the maximum measured ice thickness at the White River at Oacoma station was 2.2 ft from December 1975 to January 1995. The maximum ice thickness measured at the two James River stations was 2.0 ft from December 1970 to March 1997 near Scotland and 1.5 ft from February 1982 to January 1995 near Yankton. Maximum ice thickness measured at the two Vermillion River stations was 2.0 ft from December 1970 to February 1983 near Wakonda and 1.5 ft from December 1983 to February 1996 near Vermillion. The maximum ice thickness measured at the two Big Sioux River stations was 2.0 ft from November 1970 to December 1994 near Brookings and 2.2 ft from December 1970 to March 1997 near Dell Rapids.

Three ice-thickness-estimation equations that potentially could be used for bridge design in South Dakota were selected. The three equations included the Accumulative Freezing Degree Day (AFDD), Incremental Accumulative Freezing Degree Day (IAFDD), and Simplified Energy Budget (SEB) equations. The AFDD equation is a simple equation that assumes that ice thickness is a function of air temperature. The IAFDD equation, while similar to the AFDD equation, calculates the change in ice thickness from an initial ice thickness rather than the total ice thickness since ice formation began. The SEB equation incorporates more

directly the effects of the temperature difference between the top surface of the ice and the air and the insulating effects of snow cover on the solid ice cover.

The three equations were evaluated by comparing study-collected and historical ice-thickness measurements to equation-estimated ice thicknesses. Additional information needed for the evaluation of the ice-thickness equations was obtained from the National Weather Service (NWS).

Of the three selected equations, the AFDD equation best estimated maximum ice thickness in South Dakota using available data sources with an average variation about the measured value of about 0.4 ft. The IAFDD equation, a similar equation to the AFDD equation, estimated ice thickness nearly as well with an average variation about the measured value of about 0.5 ft. The SEB equation estimated ice thickness slightly more in error with an average variation about the measured value of about 0.6 ft. To avoid a possible bias from using the historical ice-thickness data that may not be as accurate as study-collected ice-thickness data, a comparison was done using only study-collected data. The AFDD equation again best estimated the measured ice thickness with an average variation about the measured value of about 0.2 ft. Additional comparisons were done using both existing historical and study-collected ice-thickness data, but excluding measured ice thickness of less than 1.0 and 1.5 ft. For measured ice thickness greater than 1.0 ft, the AFDD and IAFDD equations again best estimated the measured ice thickness with average variations about the measured values of 0.4 ft for both.

Maximum potential ice thickness was estimated at 19 NWS stations located throughout South Dakota using the AFDD equation. The 1979 winter, which is the coldest winter on record at Sioux Falls, was the winter used to estimate maximum potential ice thickness. To estimate maximum potential ice thickness at rivers and lakes or reservoirs throughout South Dakota, the maximum ice-thickness estimates at the 19 NWS stations were contoured. The maximum potential estimated ice thicknesses generally are the largest in northeastern South Dakota at about 3 ft and are smallest in southwestern and south-central South Dakota at about 2 ft.

Ice-crushing strength was measured from February 1999 to April 2001 at the same six sites where ice-thickness data were collected. Ice-crushing strength was measured both in the winter and spring near ice breakup. The maximum ice-crushing strengths were measured in mid- to late winter, while ice-crushing strengths measured during the spring at and near ice breakup were much less. These lesser strengths that were measured at or near breakup in the spring may be more applicable to use in bridge design equations.

Ice-crushing-strength data measured at the six sites ranged from 58 to greater than 1,046 lb/in^2. The largest ice-crushing strengths measured were from samples collected at the Oahe Reservoir near Mobridge and the James River at Huron sites. The smallest ice-crushing-strength measurement was 58 lb/in^2 from samples collected at the Oahe Reservoir near Mobridge site during spring breakup.

Ice-crushing strength measured at the James River at Huron site was highly variable and ranged from 228 to 522 lb/in^2 in 1999, 180 lb/in^2 to greater than 1,042 lb/in^2 in 2000, and 207 lb/in^2 to greater than 1,046 lb/in^2 in 2001. The maximum ice-crushing strength of greater than 1,046 lb/in^2 was measured in the winter of 2001, the 11th coldest winter of record. Ice-crushing strength measured at the James River near Scotland site ranged from 417 to 603 lb/in^2 in 1999, 565 to 694 lb/in^2 in 2000, and 255 to 869 lb/in^2 in 2001. Ice-crushing strength measured at the White River near Oacoma/Presho site ranged from 180 to 579 lb/in^2 in 2000 and 214 to 585 lb/in^2 in 2001, and ice-crushing strength measured at the Grand River at Little Eagle site ranged from 229 to 577 lb/in^2 in 1999, 148 to 615 lb/in^2 in 2000, and 236 to 411 lb/in^2 in 2001. Ice-crushing strength measured at the Oahe Reservoir near Mobridge site was highly variable and ranged from 387 to 685 lb/in^2 in 1999, 247 to 883 lb/in^2 in 2000, and 58 to greater than 1,046 lb/in^2 in 2001. Ice-crushing strength measured at the Lake Francis Case at the Platte-Winner Bridge also was highly variable and ranged from 151 to 907 lb/in^2 in 2001.

Measured ice-crushing strengths were evaluated to see how they compared to ice-crushing strengths used in bridge design in South Dakota. The ice-crushing strengths measured during spring breakup probably are the most applicable values for bridge design.

Maximum ice-crushing strengths averaged from about 475 lb/in^2 at the White River near Oacoma/Presho site to about 950 lb/in^2 at the James River at Huron site. Individual maximum ice-crushing-strength measurements were the lowest at the White River near Oacoma/Presho and Grand River at Little Eagle sites (585 and 615 lb/in^2, respectively). The individual maximum ice-crushing strengths measured at the James River near Scotland and Lake

Francis Case near the Platte-Winner Bridge sites were 869 and 907 lb/in^2, respectively, and at both the James River at Huron and Oahe Reservoir near Mobridge sites the strengths were greater than 1,046 lb/in^2. From an analysis of this limited ice-crushing-strength data, ice-crushing strengths of about 1,000 lb/in^2 could be expected at any site in South Dakota if enough water is available for freezing and if the winter is as cold as the 2001 winter.

Measured ice-crushing strength during spring breakup usually was greater than 100 lb/in^2, and the average ice-crushing strength measured near breakup at the six ice-data collection sites in South Dakota ranged from 75 to 300 lb/in^2. An ice-crushing strength of 250 lb/in^2 would not be anomalous for expected ice-crushing strengths during the spring breakup in South Dakota.

SELECTED REFERENCES

Ashton, G.D., ed., 1986, River and lake ice engineering: Littleton, Colo., Water Resources Publications, 485 p.

Collins Engineers, Inc., 1997, Emergency underwater investigation of bents 16 and 17 at Bridge No. 12-085-080 SD 44 Over the Missouri River: Chicago, Collins Engineers, Inc., 5 p.

Committee on Ice Problems of the International Association of Hydraulic Research, 1975, Report of Task Committee on Standardizing Testing Methods for Ice, Appendix B: Hanover, N.H., p. 607-618.

Daly, S.F., 1998, Thermal ice growth: real-time estimation: Hanover, N.H., USA Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers, 25 p.

Fish, A. M., and Zaretsky, Y.K., 1997, Ice strength as a function of hydrostatic pressure and temperature: Hanover, N.H., Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers, 14 p.

Kay, L.K., and White, K.D., 1997, River ice data instrumentation: Hanover, N.H., Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers, 40 p.

National Oceanic and Atmospheric Administration, 2001, Climatic extremes and record events: accessed August 27, 2001, at URL http://www.crh.noaa.gov/fsd/archive2.htm

Tuthill, A.M., 1995, Structural ice control—Review of existing methods: Hanover, N.H., Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers, 31 p.

U.S. Army Corp of Engineers, 1981, Prediction and calculation of incremental ice thickening, 6 p.

———1996, Ice engineering: Hanover, N.H., Cold Regions Research and Engineering Laboratory, 80 p.

U.S. Geological Survey, 2000, Water resources data, South Dakota, water year 1999: U.S. Geological Survey Water-Data Report SD-99-1, 501 p.

———2001, Water resources data, South Dakota, water year 2000: U.S. Geological Survey Water-Data Report SD-00-1, 461 p.

———2002, Water resources data, South Dakota, water year 2001: U.S. Geological Survey Water-Data Report SD-01-1, 476 p.

White, K.D., and Zufelt, J.E., 1994, Ice jam data collection: Hanover, N.H., Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers, 37 p.

Wuebben, J.L., and Gagnon, J.J., 1995, Ice jam flooding on the Missouri River near Williston, North Dakota: Hanover, N.H., Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers, 25 p.

Zabilansky, L.J., 1996, Ice force and scour instrumentation for the White River, Vermont: Hanover, N.H., Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers, 53 p.

Zufelt, J.E., and Ettema, R., 1996, Model ice properties: Hanover, NH, USA Cold Regions Research and Engineering Laboratory, U.S. Army; Corps of Engineers, 19 p.

SUPPLEMENTAL INFORMATION

Table 4. Summary of ice data collected at selected sites in South Dakota, 1999-2001

[°C, degrees Celsius; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; sec, seconds; in/sec, inches per second; lb/in^2, pounds per square inch; >, greater than; --, no data or not applicable]

Date of ice-data collection	Air temper-ature (°C)	Daily mean discharge (ft^3/s)	Description of ice sample	Total distance across transect (feet)	Distance from shore (feet)	Ice thickness (feet)
			Site 1, James River at Huron			
02-06-99	0.0	222	Clear ice (columnar ice)	[1]250	40	1.1
			Clear ice (columnar ice)		80	1.1
			Clear ice (columnar ice)		80	--
			Clear ice (columnar ice)		120	1.1
			Clear ice (columnar ice)		120	--
			Clear ice (columnar ice)		160	1.3
			Clear ice (columnar ice)		160	--
			Clear ice (columnar ice)		160	--
			Clear ice (columnar ice)		200	1.3
			Clear ice (columnar ice)		200	--
			Clear ice (columnar ice)		230	1.3
			Clear ice (columnar ice)		230	--
01-20-00	-5.0	139	Cloudy ice (snow ice)	[1]241	50	.7
			Cloudy ice (snow ice)		100	.9
			Cloudy ice (snow ice)		150	1.0
			Cloudy ice (snow ice)		200	1.2
02-24-00	3.0	99	Cloudy ice (deteriorated columnar and snow ice); 0.40-inch rain fell on 02-23-00	[1]235	50	.7
			Cloudy ice (deteriorated columnar and snow ice); 0.40-inch rain fell on 02-23-00		50	--
			Cloudy ice (deteriorated columnar and snow ice); 0.40-inch rain fell on 02-23-00		122	.7
			Cloudy ice (deteriorated columnar and snow ice); 0.40-inch rain fell on 02-23-00		122	--
			Cloudy ice (deteriorated columnar and snow ice); 0.40-inch rain fell on 02-23-00		122	--
			Cloudy ice (deteriorated columnar and snow ice); 0.40-inch rain fell on 02-23-00		182	1.0
			Cloudy ice (deteriorated columnar and snow ice); 0.40-inch rain fell on 02-23-00		182	--
01-08-01	-4.0	[2]260	Top 3 inches cloudy ice (snow ice), then very clear ice (columnar ice)	[1]250	50	1.4
			Top 3 inches cloudy ice (snow ice), then very clear ice (columnar ice)		50	--
			Top 3 inches cloudy ice (snow ice), then very clear ice (columnar ice)		100	1.6
			Top 3 inches cloudy ice (snow ice), then very clear ice (columnar ice)		100	--

Snow depth (inches)	Depth of water (feet)	Specific conduc-tance (μS/cm)	Ice sample diameter by height (inches)	Where sample taken in column	Ice-crushing rate (in/sec)	Ice-crushing strength (lb/in^2)	Average ice-crushing strength at section (lb/in^2)	Average ice-crushing strength at site (rounded to nearest 25 lb/in^2)
0.0	7.8	--	4x8	Middle	0.0010	474	474	[2]400
.0	11.1	--	4x8	Middle	.0010	466	465	--
--	--	--	4x5	Middle	.0010	465	--	--
.0	9.3	--	4x8	Middle	.0010	455	437	--
--	--	--	4x5.5	Middle	.0010	418	--	--
.0	6.2	--	4x6.75	Middle	.0010	228	238	--
--	--	--	4x6.5	Middle	.0010	244	--	--
--	--	--	4x6.5	Middle	.0010	243	--	--
.0	4.5	--	4x8	Middle	.0010	381	336	--
--	--	--	3.5x7	Middle	.0006	290	--	--
.0	2.0	--	4x8.5	Middle	.0010	522	[2]500	--
--	--	--	3.5x7	Middle	.0010	>381	--	--
.5	12.0	--	4x7	Middle	.0010	875	875	[2]950
.0	10.8	--	4x7	Middle	.0010	>883	[2]900	--
.0	6.8	--	4x6	Middle	.0010	>1,042	[2]1,050	--
1.5	1.6	--	4x7	Middle	--	--	--	--
.0	10.7	--	3.5x6	Middle	.0010	258	288	[2]300
--	--	--	3.5x7	Middle	.0010	317	--	--
.0	9.4	--	3.5x7	Middle	.0013	>172	[2]175	--
--	--	--	3.5x7	Middle	.0010	>120	--	--
--	--	--	4x4.5	Middle	.0010	180	--	--
.0	4.7	--	3.5x6.25	Middle	.0013	>495	[2]450	--
--	--	--	3.5x6.5	Middle	.0010	380	--	--
.0	10.7	--	3.5x8	Upper	.0010	744	802	[2]800
--	--	--	3.5x8	Upper	.0010	859	--	--
.0	10.7	--	3.5x8	Upper	.0010	>1,046	[2]1,010	--
--	--	--	3.5x8	Upper	.0010	973	--	--

Table 4. Summary of ice data collected at selected sites in South Dakota, 1999-2001—Continued

[°C, degrees Celsius; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; sec, seconds; in/sec, inches per second; lb/in^2, pounds per square inch; >, greater than; --, no data or not applicable]

Date of ice-data collection	Air temper-ature (°C)	Daily mean discharge (ft^3/s)	Description of ice sample	Total distance across transect (feet)	Distance from shore (feet)	Ice thickness (feet)
			Site 1, James River at Huron—Continued			
01-08-01			Top 3 inches cloudy ice (snow ice), then very clear ice (columnar ice)		150	1.7
			Top 3 inches cloudy ice (snow ice), then very clear ice (columnar ice)		150	--
			Top 3 inches cloudy ice (snow ice), then very clear ice (columnar ice)		150	--
			Very clear ice (columnar ice)		200	1.8
			Very clear ice (columnar ice)		200	--
02-12-01	-8.3	[2]65	Semi-cloudy ice	[3]250	50	2.3
			Semi-cloudy ice		50	--
			Clear ice (columnar ice)		50	--
			Clear ice (columnar ice)		50	--
			Top 2 inches cloudy/milky ice (snow ice), then clear ice (columnar ice)		100	1.8
			Top 2 inches cloudy/milky ice (snow ice), then clear ice (columnar ice)		100	--
			Clear ice (columnar ice)		100	--
			Clear ice (columnar ice)		100	1.8
			Semi-cloudy ice; water on ice		150	--
			Semi-cloudy ice; water on ice		150	--
			4 inches of water on ice		200	--
04-02-01	3.0	[2]472	Top 3 inches slushy ice (deteriorated columnar and snow ice), then clear ice (columnar ice)	[1]250	70	1.8
			Top 3 inches slushy ice (deteriorated columnar and snow ice), then clear ice (columnar ice)		70	--
			Top 4 inches slushy ice (deteriorated columnar and snow ice), then clear ice (columnar ice)		130	1.8
			Top 4 inches slushy ice (deteriorated columnar and snow ice), then clear ice (columnar ice)		130	--
			Top 4 inches hard blueish/gray ice (columnar ice), then weak ice (deteriorated columnar ice)		205	2.2
			Top 4 inches hard blueish/gray ice (columnar ice), then weak ice (deteriorated columnar ice)		205	--
04-03-01	--	[2]771	Top 7 inches water/slush, then cloudy/slushy ice (deteriorated columnar and snow ice)	[1]250	50	--
			Top 7 inches water/slush, then cloudy/slushy ice (deteriorated columnar and snow ice)		50	--

Snow depth (inches)	Depth of water (feet)	Specific conduc-tance (µS/cm)	Ice sample diameter by height (inches)	Where sample taken in column	Ice-crushing rate (in/sec)	Ice-crushing strength (lb/in^2)	Average ice-crushing strength at section (lb/in^2)	Average ice-crushing strength at site (rounded to nearest 25 lb/in^2)
0.0	7.7	--	3.5x8	Upper	0.0011	838	789	--
--	--	--	3.5x7	Lower	.0010	661	--	--
--	5.2	--	3.5x7	Lower	.0010	869	--	--
.0	--	--	3.5x8	Upper	.0010	578	638	--
--	--	--	3.5x8	Upper	.0010	697	--	--
24.0	3.6	1,900	3.5x8	Upper	.0013	968	924	[2]850
--	--	--	3.5x8	Upper	.0013	988	--	--
--	--	--	3.5x7	Lower	.0013	744	--	--
--	--	--	3.5x8	Lower	.0013	994	--	--
14.0	10.2	1,868	3.5x8	Upper	.0013	>859	[2]825	--
--	--	--	3.5x8	Upper	.0013	979	--	--
--	--	--	3.5x8	Lower	.0013	754	--	--
--	--	--	3.5x8	Lower	.0013	703	--	--
14.0	11.5	2,280	3.5x8	Upper	.0013	942	780	--
--	--	--	3.5x8.25	Upper	.0013	619	--	--
--	--	--	--	--	--	--	--	--
.0	12.1	--	3.5x7.5	Middle	.0009	245	[2]240	[2]250
--	--	--	3.5x7.5	Middle	.0009	>146	--	--
.0	9.1	915	3.5x8	Middle-bottom	.0009	250	258	--
--	--	--	3.5x8	Middle-bottom	.0009	266	--	--
.0	6.2	1,115	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--
--	--	--	3.5x7.5	Lower	.0010	207	[2]200	[2]200
--	--	--	3.5x7.5	Lower	.0010	>172	--	--

Table 4. Summary of ice data collected at selected sites in South Dakota, 1999-2001—Continued

[°C, degrees Celsius; ft^3/s, cubic feet per second; μS/cm, microsiemens per centimeter at 25 degrees Celsius; sec, seconds; in/sec, inches per second; lb/in^2, pounds per square inch; >, greater than; --, no data or not applicable]

Date of ice-data collection	Air temper-ature (°C)	Daily mean discharge (ft^3/s)	Description of ice sample	Total distance across transect (feet)	Distance from shore (feet)	Ice thickness (feet)
			Site 2, James River near Scotland			
02-11-99	-5.0	[2]550	Clear ice (columnar ice)	[3]120	30	0.7
			Clear ice (columnar ice)		50	--
			Clear ice (columnar ice)		50	--
			Clear ice (columnar ice)		50	--
			Clear ice (columnar ice)		50	--
			Clear ice (columnar ice)		55	.9
			Very thin ice		60-120	--
01-24-00	-5.0	[2]206	Cloudy ice (snow ice)	[3]122	30	1.0
			Cloudy ice (snow ice)		75	.5
			Cloudy ice (snow ice)		90	.5
			Cloudy ice (snow ice)		90	--
01-09-01	-3.0	[2]360	7 inches of cloudy/milky ice (snow ice), then clear ice (columnar ice)	[3]120	35	1.4
			8 inches of cloudy/milky ice (snow ice), then clear ice (columnar ice)		35	--
			9 inches of cloudy/milky ice (snow ice), then clear ice (columnar ice)		35	--
			4.5 inches of cloudy/milky ice (snow ice), then clear ice (columnar ice)		70	1.1
			4.5 inches of cloudy/milky ice (snow ice), then clear ice (columnar ice)		70	--
			4.5 inches of cloudy/milky ice (snow ice), then clear ice (columnar ice)		105	1.2
			4.5 inches of cloudy/milky ice (snow ice), then clear ice (columnar ice)		105	--
02-12-01	-8.3	[2]155	Slushy ice (deteriorated columnar and snow ice)	[3]135	50	1.7
			Slushy ice (deteriorated columnar and snow ice)		50	--
			Semi-clear ice (columnar ice)		50	--
			Semi-clear ice (columnar ice)		50	--
			Clear ice (columnar ice)		75	1.7
			Clear ice (columnar ice)		75	--
			Semi-clear ice (columnar ice)		100	1.6
			Semi-clear ice (columnar ice)		100	--
			Semi-clear ice (columnar ice)		100	--
			Semi-clear ice (columnar ice)		100	--

Snow depth (inches)	Depth of water (feet)	Specific conductance (µS/cm)	Ice sample diameter by height (inches)	Where sample taken in column	Ice-crushing rate (in/sec)	Ice-crushing strength (lb/in^2)	Average ice-crushing strength at section (lb/in^2)	Average ice-crushing strength at site (rounded to nearest 25 lb/in^2)
0.0	0.7	--	--	--	--	--	--	475
--	--	--	4x8	Middle	0.0010	417	484	--
--	--	--	4x8	Middle	.0006	447	--	--
--	--	--	3.5x8	Middle	.0010	603	--	--
--	--	--	3.5x7	Middle	.0010	470	--	--
.0	.7	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--
.0	1.3	--	4x6.5	Middle	.0008	694	694	625
.0	7.6	--	4x5	Middle	.0008	565	565	--
.0	4.9	--	4x6.5	Middle	.0008	605	634	--
--	--	--	4x5	--	.0005	663	--	--
.0	7.5	--	3.5x8	Upper	.0010	630	588	[2]500
--	--	--	3.5x8	Upper	.0010	609	--	--
--	--	--	3.5x6.25	Lower	.0010	526	--	--
.0	7.4	--	3.5x8	Upper	.0011	>359	[2]325	--
--	--	--	3.5x8	Upper	.0011	287	--	--
.0	2.4	--	3.5x8	Upper	.0010	578	620	--
--	--	--	3.5x8	Upper	.0010	661	--	--
2.0	6.6	2,490	3.5x7.5	Upper	.0010	401	444	500
--	--	--	3.5x7.5	Upper	.0010	411	--	--
--	--	--	3.5x7.5	Lower	.0010	552	--	--
--	--	--	3.5x7.5	Lower	.0010	411	--	--
2.0	6.0	1,907	3.5x8	Upper	.0010	318	370	--
--	--	--	3.5x8	Lower	.0010	422	--	--
5.0	4.0	1,897	3.5x7.5	Upper	.0010	869	692	--
--	--	--	3.5x7	Upper	.0010	578	--	--
--	--	--	3.5x7.75	Lower	.0010	614	--	--
--	--	--	3.5x7.75	Lower	.0010	705	--	--

Table 4. Summary of ice data collected at selected sites in South Dakota, 1999-2001—Continued

[°C, degrees Celsius; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; sec, seconds; in/sec, inches per second; lb/in^2, pounds per square inch; >, greater than; --, no data or not applicable]

Date of ice-data collection	Air temper-ature (°C)	Daily mean discharge (ft^3/s)	Description of ice sample	Total distance across transect (feet)	Distance from shore (feet)	Ice thickness (feet)
			Site 2, James River near Scotland—Continued			
03-20-01	12.0	[2]1,800	Open water	[3]150	0-10	0.0
			Slushy ice; very soft ice (deteriorated columnar and snow ice); 3 inches water/slush over ice		20	1.2
			Slushy ice; very soft ice (deteriorated columnar and snow ice); 3 inches water/slush over ice		25	1.4
			Clear to cloudy ice (columnar and snow ice); 3 inches water/slush over ice		33	1.6
			Clear to cloudy ice (columnar and snow ice); 3 inches water/slush over ice		35	--
			Clear to cloudy ice (columnar and snow ice); 3 inches water/slush over ice		40	1.6
			Clear to fractured ice (columnar ice); 3 inches water/slush over ice		45	--
			Slushy ice; very soft ice (deteriorated columnar and snow ice); 3 inches water/slush over ice		50	1.1
			Slushy ice; very soft ice (deteriorated columnar and snow ice); 3 inches water/slush over ice		60	.9
			Open water		140-150	.0
			Site 3, White River near Oacoma/Presho			
[4]01-28-00	-1	[5]160	Lot of sediment in ice (columnar ice)	[6]242	108	.7
			Much sediment in ice (columnar ice)		108	--
			Much sediment in ice (columnar ice)		108	--
			Much sediment in ice (columnar ice)		108	--
			Much sediment in ice (columnar ice)		160	1.0
			Much sediment in ice (columnar ice)		160	--
			Much sediment in ice (columnar ice)		202	1.0
			Much sediment in ice (columnar ice)		202	--
			Much sediment in ice (columnar ice)		202	--
			Much sediment in ice (columnar ice)		202	--
			Much sediment in ice (columnar ice)		202	--
[7]02-24-00	7.0	[2]700	Clear ice (columnar ice); some sediment in ice	[8]125	11	.9
			Clear ice; some sediment in ice		40	.7
			Clear ice; some sediment in ice		40	--

Snow depth (inches)	Depth of water (feet)	Specific conduc-tance (μS/cm)	Ice sample diameter by height (inches)	Where sample taken in column	Ice-crushing rate (in/sec)	Ice-crushing strength (lb/in^2)	Average ice-crushing strength at section (lb/in^2)	Average ice-crushing strength at site (rounded to nearest 25 lb/in^2)
0.0	--	1,060 (from open water along shore)	--	--	--	--	--	275
.0	--	145 (from water on top of ice)	--	--	--	--	--	--
.0	--	--	3.5x8	Middle	0.0010	276	276	--
.0	--	--	--	--	--	--	--	--
--	6.0	--	3.5x8	Middle	.0010	276	276	--
.0	--	--	--	--	--	--	--	--
--	4.0	--	3.5x7.25	Middle	.0010	255	255	--
.0	--	--	--	--	--	--	--	--
.0	--	--	3.5x7.25	Middle	.0010	297	297	--
.0	--	--	--	--	--	--	--	--
1.5	1.0	--	4x5	Middle	.0010	395	[2]450	[2]450
--	--	--	4x5	Middle	.0008	488	--	--
--	--	--	4x4.5	Middle	.0010	>419	--	--
--	--	--	4x4.5	Middle	.0008	475	--	--
1.5	1.2	--	4x4.5	Middle	.0010	482	530	--
--	--	--	4x4.5	Middle	.0008	579	--	--
1.5	2.6	--	4.x6	Middle	.0010	375	365	--
--	--	--	4x6	Middle	.0010	383	--	--
--	--	--	4x5.5	Middle	.0010	355	--	--
--	--	--	4.x6	Middle	.0008	371	--	--
--	--	--	4.4.5	Middle	.0008	342	--	--
.0	1.5	--	3.5x6	Middle	.0010	292	292	[2]225
.0	2.2	--	3.5x5	Middle	.0010	180	180	--
--	--	--	3.5x5	Middle	.0010	>122	[2]180	--

Table 4. Summary of ice data collected at selected sites in South Dakota, 1999-2001—Continued

[°C, degrees Celsius; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; sec, seconds; in/sec, inches per second; lb/in^2, pounds per square inch; >, greater than; --, no data or not applicable]

Date of ice-data collection	Air temper-ature (°C)	Daily mean discharge (ft^3/s)	Description of ice sample	Total distance across transect (feet)	Distance from shore (feet)	Ice thickness (feet)
			Site 3,White River near Oacoma/Presho—Continued			
[7]02-24-00			Clear ice; some sediment in ice		50	0.5
			Thin ice to open water		60-110	--
[7]01-10-01	-2.0	[2]116	Cloudy ice (snow ice)	[6]265	9.5	.8
			3.5 inches cloudy (snow ice), then 3 inches sediment-loaded, then 3.5 inches clear ice (columnar ice)		42	.8
			3.5 inches cloudy (snow ice), then 3 inches sediment-loaded, then 3.5 inches clear ice (columnar ice)		42	--
			2 inches cloudy (snow ice), then 4.5 inches sediment-loaded, then 3.5 inches clear ice (columnar ice)		69	1.2
			Cloudy ice (snow ice)		102	1.5
			Cloudy ice (snow ice)		102	--
			Cloudy ice (snow ice)		138	1.2
			4 inches cloudy (snow ice), then 1 inch sediment-loaded, then 5 inches clear ice (columnar ice)		142	--
			5 inches cloudy (snow ice), then 1 inch sediment-loaded, then 5 inches clear ice (columnar ice)		142	--
			Cloudy ice (snow ice)		185	1.3
			5 inches cloudy (snow ice), then 3.5 inches sediment-loaded, then 1.5 inches clear ice (columnar ice)		200	--
			Cloudy ice (snow ice)		215	1.0
			Cloudy ice (snow ice)		240	.8
			Cloudy ice (snow ice)		255	--
[7]02-13-01	--	[2]320	Thin ice; not much water	--	--	.1
[7,9]03-13-01	12.0	[2]6,500	Semi-clear ice (columnar ice)	[6]--	10	1.0
			Semi-clear ice (columnar ice)		10	1.2
			Semi-clear ice (columnar ice)		10	.9
			Semi-clear ice (columnar ice)		10	--
			Semi-clear ice (columnar ice)		10	--
			Semi-clear ice (columnar ice)		10	--
			Site 4, Grand River at Little Eagle			
[10]02-12-99	-4.0	[2]4,500	Semi-clear ice (columnar ice)	[6]--	5	1.2
			Milky-colored ice (snow ice)		5	1.2
			Clear ice (columnar ice)		5	1.2

Snow depth (inches)	Depth of water (feet)	Specific conduc-tance (μS/cm)	Ice sample diameter by height (inches)	Where sample taken in column	Ice-crushing rate (in/sec)	Ice-crushing strength (lb/in^2)	Average ice-crushing strength at section (lb/in^2)	Average ice-crushing strength at site (rounded to nearest 25 lb/in^2)
0.0	1.3	--	--	--	0.0010	--	--	--
.0	--	--	--	--	--	--	--	--
.0	1.8	--	--	--	--	--	--	[2]475
.0	1.7	--	3.5x7.25	Upper	.0010	422	431	--
--	--	--	3.5x8	Upper	.0010	440	--	--
.0	1.5	--	3.5x7.75	Upper	.0010	>318	[2]400	--
.0	1.6	--	3.5x7	Upper	.0010	585	585	--
--	--	--	3.5x6.75	Lower	.0010	585	--	--
.0	2.0	--	--	--	--	--	--	--
--	--	--	3.5x8	Upper	.0010	536	510	--
--	--	--	3.5x8	Upper	.0010	484	--	--
.0	1.7	--	--	--	--	--	--	--
--	--	--	3.5x8	Upper	.0010	474	474	--
.0	1.1	--	--	--	--	--	--	--
.0	1.7	--	--	--	--	--	--	--
--	1.5	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--
.0	--	614	3.5x7	Middle	.0010	>157	[2]229	[2]225
.0	--	--	3.5x8	Middle	.0010	224	--	--
.0	--	--	3.5x8	Middle	.0010	224	--	--
--	--	--	3.5x6.5	Middle	.0010	271	--	--
--	--	--	3.5x7	Middle	.0010	229	--	--
--	--	--	3x5.7	Middle	.0010	214	--	--
.0	--	--	4x7.5	Middle	.0010	369	392	400
.0	--	--	3.5x7	Middle	.0010	229	--	--
.0	--	--	4x7	Middle	.0010	577	--	--

Table 4. Summary of ice data collected at selected sites in South Dakota, 1999-2001—Continued

[°C, degrees Celsius; ft^3/s, cubic feet per second; μS/cm, microsiemens per centimeter at 25 degrees Celsius; sec, seconds; in/sec, inches per second; lb/in^2, pounds per square inch; >, greater than; --, no data or not applicable]

Date of ice-data collection	Air temper-ature (°C)	Daily mean discharge (ft^3/s)	Description of ice sample	Total distance across transect (feet)	Distance from shore (feet)	Ice thickness (feet)
			Site 4, Grand River at Little Eagle—Continued			
01-25-00	-5.0	[2]56	Cloudy ice (snow ice)	[6]115	20	1.2
			Clear ice (columnar ice)		50	1.0
			Cloudy ice (snow ice)		75	.9
			Cloudy ice (snow ice)		95	.8
02-25-00	5.0	[2]120	Water on ice in lot of spots; cloudy ice (snow ice)	[6]102	15	.5
			Water on ice in lot of spots; cloudy ice (snow ice)		15	--
			Water on ice in lot of spots; cloudy ice (snow ice)		45	.8
			Water on ice in lot of spots; cloudy ice (snow ice)		45	--
			Water on ice in lot of spots; cloudy ice (snow ice)		70	--
			Water on ice in lot of spots; cloudy ice (snow ice)		70	--
			Water on ice in lot of spots; cloudy ice (snow ice)		77	.6
			Some open water		77-102	--
01-10-01	--	[2]14	Thin ice; not much water	--	--	.2
02-14-01	--	[2]17	Thin ice; not much water	--	--	.2
[10]03-14-01	4.0	[2]3,000	Dirty-looking/soft ice (deteriorated columnar and snow ice)	[6]--	5-30	1.4
			Dirty-looking/soft ice (deteriorated columnar and snow ice)		5-30	1.4
			Clear/cloudy ice (columnar and snow ice)		5-30	1.4
			Dirty-looking/soft ice (deteriorated columnar and snow ice)		5-30	1.4
			Dirty-looking/soft ice (deteriorated columnar and snow ice)		5-30	1.4
			Site 5, Oahe Reservoir near Mobridge			
02-12-99	--	--	Clear ice (columnar ice)	[6]6,500	300	1.8
			Clear ice (columnar ice)		300	--
			Clear ice (columnar ice)		300	--
			Clear ice (columnar ice)		600	1.7
			Clear ice (columnar ice)		600	--
			Clear ice (columnar ice)		600	--
			Clear ice (columnar ice)		900	1.7
			Clear ice (columnar ice)		900	--
			Clear ice (columnar ice)		1,200	1.8
			Clear ice (columnar ice)		1,200	--
			Clear ice (columnar ice)		1,500	1.7
			Clear ice (columnar ice)		1,500	--

Snow depth (inches)	Depth of water (feet)	Specific conduc-tance (µS/cm)	Ice sample diameter by height (inches)	Where sample taken in column	Ice-crushing rate (in/sec)	Ice-crushing strength (lb/in^2)	Average ice-crushing strength at section (lb/in^2)	Average ice-crushing strength at site (rounded to nearest 25 lb/in^2)
0.0	1.2	--	--	--	--	--	--	575
.0	1.7	--	4x7.5	Middle	0.0008	615	615	--
.0	2.1	--	--	--	--	--	--	--
.0	2.1	--	4x5	Middle	.0008	554	554	--
.0	1.4	--	--	Middle	.0007	526	505	300
--	--	--	--	Middle	.0007	484	--	--
.0	1.7	--	--	Middle	.0010	148	212	--
--	--	--	--	Middle	.0010	275	--	--
--	--	--	--	Middle	.0011	185	197	--
--	--	--	--	Middle	.0011	209	--	--
.0	2.2	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--
.0	--	--	--	--	--	--	--	--
.0	--	--	--	--	--	--	--	--
.0	--	314	3.5x8	Middle	.0010	289	291	[2]300
.0	--	--	3.5x8	Middle	.0010	269	--	--
.0	--	--	3.5x8	Middle	.0010	411	--	--
.0	--	--	3.5x8	Middle	.0010	250	--	--
.0	--	--	3.5x7	Middle	.0010	236	--	--
.0	55.5	--	4x6.5	Middle	.0010	483	449	[2]500
--	--	--	4x8	Middle	.0010	463	--	--
--	--	--	3.5x7	Middle	.0010	402	--	--
.0	72.5	--	4x8	Middle	.0010	387	473	--
--	--	--	4x8	Middle	.0010	473	--	--
--	--	--	4x6	Lower	.0010	559	--	--
.0	75.0	--	4x7	Middle	.0010	566	626	--
--	--	--	4x5	Lower	.0010	685	--	--
.0	79.0	--	4x7.5	Middle	.0010	522	479	--
--	--	--	4x8	Middle	.0010	436	--	--
.0	76.5	--	4x8	Middle	.0010	465	[2]430	--
--	--	--	4x5.5	Lower	.0010	>369	--	--

Table 4. Summary of ice data collected at selected sites in South Dakota, 1999-2001—Continued

[°C, degrees Celsius; ft^3/s, cubic feet per second; μS/cm, microsiemens per centimeter at 25 degrees Celsius; sec, seconds; in/sec, inches per second; lb/in^2, pounds per square inch; >, greater than; --, no data or not applicable]

Date of ice-data collection	Air temperature (°C)	Daily mean discharge (ft^3/s)	Description of ice sample	Total distance across transect (feet)	Distance from shore (feet)	Ice thickness (feet)
			Site 5, Oahe Reservoir near Mobridge—Continued			
01-25-00	-1.0	--	Clear ice (columnar ice)	[6]6,500	800	0.9
			Clear ice (columnar ice)		1,300	.9
			Clear ice (columnar ice)		1,750	1.0
			Clear ice (columnar ice)		2,350	.9
02-25-00	7.2	--	Ice deteriorating due to rain previous day	[6]6,500	500	1.1
			Ice crushed on 02-26-00		1,000	1.1
					2,000	1.2
					2,000	--
					3,000	.9
					3,000	--
					3,000	--
01-11-01	-4.0	--	Clear ice (columnar ice)	[6]6,500	650	1.7
			Clear ice (columnar ice)		650	--
			Clear ice (columnar ice)		1,200	1.7
			Clear ice (columnar ice)		1,200	--
			Clear ice (columnar ice)		1,200	--
			Clear ice (columnar ice)		1,200	--
			Clear ice (columnar ice)		2,300	1.8
			Clear ice (columnar ice)		2,300	--
			Clear ice (columnar ice)		3,300	1.7
			Clear ice (columnar ice)		3,300	--
			Clear ice (columnar ice)		3,300	--
			Clear ice (columnar ice)		4,300	1.4
			Clear ice (columnar ice)		4,300	--
			Clear ice (columnar ice)		4,300	--
			Clear ice (columnar ice)		4,300	--
02-14-01	-1.0	--	Clear ice (columnar ice)	[6]6,500	800	2.2
			Clear ice (columnar ice)		800	--
			Clear ice (columnar ice)		800	--
			Clear ice (columnar ice)		800	--
			Clear ice (columnar ice)		1,500	2.1
			Clear ice (columnar ice)		1,500	--
			Clear ice (columnar ice)		1,500	--
			Clear ice (columnar ice)		1,500	--

Snow depth (inches)	Depth of water (feet)	Specific conduc-tance (μS/cm)	Ice sample diameter by height (inches)	Where sample taken in column	Ice-crushing rate (in/sec)	Ice-crushing strength (lb/in^2)	Average ice-crushing strength at section (lb/in^2)	Average ice-crushing strength at site (rounded to nearest 25 lb/in^2)
0.0	71.2	--	4x5	Middle	0.0010	472	472	600
.0	71.2	--	4x8	Middle	.0010	883	883	--
.0	75.1	--	4x7.5	Middle	.0010	475	475	--
.0	71.1	--	4x7	Middle	.0010	531	531	--
.0	>70	--	3.5x6	Middle	.0010	571	571	[2]525
.0	>70	--	3.5x6	Middle	.0010	247	247	--
.0	>70	--	3.5x6	Middle	.0010	573	581	--
--	--	--	3.5x6.5	Middle	.0010	588	--	--
.0	>70	--	3.5x6	Middle	.0008	633	707	--
--	--	--	3.5x6	Middle	.0010	754	--	--
--	--	--	3.5x5.5	Middle	.0010	735	--	--
.0	57.0	--	3.5x8	Upper	.0010	474	546	[2]550
--	--	--	3.5x6.25	Lower	.0010	619	--	--
.0	62.0	--	3.5x6.5	Upper	.0008	462	596	--
--	--	--	3.5x7.25	Upper	.0008	401	--	--
--	--	--	3.5x8	Lower	.0008	474	--	--
--	--	--	3.5x8	Lower	.0008	>1,046	--	--
.0	65.0	--	3.5x8	Upper	.0010	391	669	--
--	--	--	3.5x6.5	Lower	.0010	947	--	--
.0	64.0	--	3.5x8	Upper	.0010	453	548	--
--	--	--	3.5x7.5	Lower	.0010	583	--	--
--	--	--	3.5x7.5	Upper	.0010	607	--	--
.0	70.0	--	3.5x8	Upper	.0010	474	439	--
--	--	--	3.5x8	Upper	.0010	375	--	--
--	--	--	3.5x8	Lower	.0010	391	--	--
--	--	--	3.5x7.25	Lower	.0010	517	--	--
4.0	61.4	694	3.5x7	Upper	.0010	848	665	[2]650
--	--	--	3.5x7	Upper	.0010	931	--	--
--	--	--	3.5x7.5	Lower	.0010	318	--	--
--	--	--	3.5x7.5	Lower	.0010	562	--	--
4.0	70.3	587	3.5x8	Upper	.0010	739	[2]675	--
--	--	--	3.5x8	Upper	.0010	599	--	--
--	--	--	3.5x7.5	Lower	.0010	>573	--	--
--	--	--	3.5x8	Lower	.0010	723	--	--

Table 4. Summary of ice data collected at selected sites in South Dakota, 1999-2001—Continued

[°C, degrees Celsius; ft^3/s, cubic feet per second; μS/cm, microsiemens per centimeter at 25 degrees Celsius; sec, seconds; in/sec, inches per second; lb/in^2, pounds per square inch; >, greater than; --, no data or not applicable]

Date of ice-data collection	Air temper-ature (°C)	Daily mean discharge (ft^3/s)	Description of ice sample	Total distance across transect (feet)	Distance from shore (feet)	Ice thickness (feet)
			Site 5, Oahe Reservoir near Mobridge—Continued			
02-14-01			Clear ice (columnar ice)		2,100	1.9
			Clear ice (columnar ice)		2,100	--
			Clear ice (columnar ice)		2,100	--
			Clear ice (columnar ice)		2,100	--
03-21-01	2.0	--	Samples taken from ice mass (deteriorated columnar ice); 10-20 feet open water	[6]6,500	10	.0
					20	.7-1.0
					20	1.1
					20	1.2
					20	--
			Site 6, Lake Francis Case at the Platte-Winner Bridge			
01-09-01	7.0	--	Clear ice (columnar ice)	[1]5,000	100	1.3
			Snowy/milky ice (snow ice)		200	1.6
			Greenish clear ice (columnar ice)		500	1.3
			Greenish clear ice (columnar ice)		1,000	1.4
			Greenish clear ice (columnar ice)		1,000	--
			Greenish clear ice (columnar ice)		2,000	1.2
			Greenish clear ice (columnar ice)		2,000	--
02-13-01	-4.0	--	Top 2.5 inches cloudy; rest clear ice	[3]5,000	900	1.7
			Top 2.5 inches cloudy; rest clear ice		900	--
			Top 2.5 inches cloudy; rest clear ice		900	--
			Clear ice (columnar ice)		1,800	1.8
			Clear ice (columnar ice)		1,800	--
			Clear ice (columnar ice)		1,800	--
			Clear ice (columnar ice)		2,700	1.8
			Clear ice (columnar ice)		2,700	--
			Clear ice (columnar ice)		2,700	--
			Clear ice (columnar ice)		2,700	--

[1]Distance measured from east shore.
[2]Estimated.
[3]Distance measured from west shore.
[4]Measured near Presho (25 miles upstream of Oacoma site).
[5]Estimated using Oacoma site.
[6]Distance measured from north shore.
[7]Measured near Oacoma.
[8]Distance measured from south shore.
[9]Sampled from ice jam.
[10]From shore from ice breakup.

Snow depth (inches)	Depth of water (feet)	Specific conduc-tance (µS/cm)	Ice sample diameter by height (inches)	Where sample taken in column	Ice-crushing rate (in/sec)	Ice-crushing strength (lb/in^2)	Average ice-crushing strength at section (lb/in^2)	Average ice-crushing strength at site (rounded to nearest 25 lb/in^2)
4.0	65.3	538	3.5x8.25	Upper	0.0010	578	614	--
--	--	--	3.5x6.5	Upper	.0010	593	--	--
--	--	--	3.5x8	Lower	.0010	786	--	--
--	--	--	3.5x7.75	Lower	.0010	500	--	--
--	--	--	--	--	--	--	--	75
.0	--	215	3.5x7	Middle	.0010	58	68	--
.0	>70	--	3.5x7.25	Middle	.0010	79	--	--
.0	>70	--	3.5x7.25	Middle	.0010	73	--	--
--	--	--	3.5x6.5	Middle	.0010	63	--	--
.0	6.5	--	3.5x8	Upper	.0010	157	157	[2]250
.0	9.5	--	3.5x8	Upper	.0010	151	151	--
.0	30.5	--	3.5x6	Upper	.0010	396	396	--
.0	46.0	--	3.5x8	Upper	.0013	428	326	--
--	--	--	3.5x8	Upper	.0013	224	--	--
.0	58.0	--	3.5x8	Upper	.0010	162	282	--
--	--	--	3.5x8	Upper	.0010	401	--	--
2.0	30.0	527	3.5x7.5	Upper	.0010	709	705	[2]725
--	--	--	3.5x8	Upper	.0010	635	--	--
--	--	--	3.5x7	Lower	.0010	771	--	--
2.0	43.6	624	3.5x7	Upper	.0010	593	794	--
--	--	--	3.5x7	Upper	.0010	907	--	--
--	--	--	3.5x7.25	Lower	.0010	881	--	--
2.0	62.3	707	3.5x8	Upper	.0010	715	692	--
--	--	--	3.5x7.75	Upper	.0010	737	--	--
--	--	--	3.5x7.5	Lower	.0010	627	--	--
--	--	--	3.5x6.5	Lower	.0010	687	--	--

Table 5. Summary of historical ice-thickness data measured at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97

[ft, feet; ft^3/s, cubic feet per second; mi, miles; --, no data]

Date	Ice thickness (ft)			Daily mean discharge (ft^3/s)	Additional location information
	Left	Center	Right		
Station 06357800 (Grand River at Little Eagle) Period of Record 11-24-75 to 02-27-97					
11-24-75	--	--	0.4	19	1,000 ft above gage
12-22-75	1.1	1.0	1.2	9	500 ft above gage
01-19-76	1.3	1.1	1.2	11	500 ft above gage
03-16-76	.3	.3	.6	90	800 ft above gage
12-21-76	1.2	1.2	1.2	.56	100 ft below gage
11-23-77	.6	.5	.6	0	--
12-19-77	1.5	1.2	1.2	0	--
12-06-78	.6	.8	.7	37	At gage
01-12-79	1.3	.7	.8	3.3	At gage
12-06-79	.3	.3	.4	25	400 ft above gage
01-10-80	1.4	1.3	1.3	2.9	300 ft above gage
03-05-80	.5	.8	.7	13	800 ft above gage
01-07-81	1.0	.6	.5	5	300 ft below gage
01-06-82	.8	.6	.7	1.5	600 ft below gage
03-03-82	.3	.5	.5	102	300 ft below gage
12-07-82	.6	.8	.6	140	75 ft below gage
11-30-83	.3	.3	.4	15	200 ft below gage
12-05-83	1.2	1.3	1.3	12	--
12-05-84	.4	.2	.3	12	100 ft below gage
01-10-85	1.1	.9	.9	3.4	100 ft below gage
02-06-85	1.6	1.9	1.6	0	At gage
11-20-85	.4	.4	.4	11	250 ft below gage
12-18-85	1.5	1.0	1.6	20	50 ft below gage
01-23-86	1.6	1.7	1.0	26	100 ft below gage
02-20-86	2.4	1.9	2.1	14	50 ft below gage
11-19-86	.6	.6	.6	82	900 ft below gage
12-17-86	.9	.9	1.0	52	600 ft below gage
01-14-87	.9	1.0	1.3	55	900 ft below gage
11-11-87	.9	1.0	1.1	62	125 ft below gage
12-29-87	.7	.6	.4	31	500 ft below gage
01-14-88	1.1	1.1	1.3	.5	600 ft below gage
02-10-88	2.9	2.5	2.8	4.1	750 ft below gage
12-20-88	.5	.3	.6	18	250 ft below gage
02-14-89	.9	1.0	.7	5.7	400 ft below gage
03-08-89	1.0	1.1	1.4	5.3	300 ft below gage

Table 5. Summary of historical ice-thickness data measured at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97–Continued

[ft, feet; ft^3/s, cubic feet per second; mi, miles; --, no data]

Date	Ice thickness (ft)			Daily mean discharge (ft^3/s)	Additional location information
	Left	Center	Right		
Station 06357800 (Grand River at Little Eagle) Period of Record 11-24-75 to 02-27-97—Continued					
12-20-89	0.6	0.8	0.8	0.7	150 ft below gage
02-01-90	1.1	1.1	1.2	13	150 ft below gage
12-04-90	.3	.4	.3	4.5	150 ft below gage
03-04-91	.3	.6	.4	28	250 ft below gage
11-07-91	.6	.4	.6	2.5	150 ft below gage
01-06-92	.9	.6	.8	4	200 ft below gage
02-11-92	.2	.6	.3	24	250 ft below gage
11-30-92	--	.3	.3	9.5	300 ft below gage
03-01-93	.1	--	.1	3.7	250 ft below gage
01-04-94	1.1	.9	1.0	50	400 ft below gage
02-15-94	1.2	1.2	1.4	49	400 ft below gage
01-10-95	1.1	.9	1.0	30	300 ft below gage
12-01-95	.6	--	.6	102	300 ft below gage
01-24-96	1.6	1.2	1.8	56	350 ft below gage
01-21-97	1.6	1.5	1.7	69	250 ft below gage
02-27-97	2.1	1.6	1.8	113	250 ft below gage
Station 06452000 (White River near Oacoma) Period of Record 12-05-75 to 01-13-95					
12-05-75	.4	.5	.6	6.5	500 ft below gage
01-09-76	1.3	1.4	.8	11	At gage
01-29-76	1.5	1.1	1.2	38	200 ft above gage
12-03-76	.8	.7	.8	7	300 ft above gage
01-03-77	.9	.8	.7	11	0.5 mi below gage
01-27-77	1.8	1.6	1.7	10	At gage
11-29-77	.6	.5	.4	90	100 ft below gage
12-22-77	1.0	.8	.8	90	400 ft below gage
01-16-78	1.3	1.0	.9	70	600 ft from gage
02-21-78	1.4	1.1	.9	55	600 ft below gage
12-04-78	.5	.5	.3	40	500 ft below gage
01-08-79	1.5	1.4	1.5	13	400 ft below gage
02-05-79	2.2	1.8	2.0	25	300 ft below gage
03-05-79	1.0	2.3	2.2	36	300 ft below gage
12-04-79	.3	.3	.3	66	50 ft below gage
01-07-80	.7	.9	.7	30	0.5 mi below gage
02-05-80	1.1	1.0	1.1	56	0.5 mi below gage
03-03-80	1.7	1.1	1.6	295	300 ft above gage

Table 5. Summary of historical ice-thickness data measured at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97–Continued

[ft, feet; ft^3/s, cubic feet per second; mi, miles; --, no data]

Date	Ice thickness (ft)			Daily mean discharge (ft^3/s)	Additional location information
	Left	Center	Right		
Station 06452000 (White River near Oacoma) Period of Record 12-05-75 to 01-13-95—Continued					
12-03-80	0.3	0.4	0.4	32	500 ft above gage
02-17-81	1.9	2.0	1.6	110	300 ft below gage
12-23-82	.2	.3	.4	160	50 ft below gage
01-20-83	.8	.9	.9	230	250 ft below gage
12-27-83	.8	.6	.7	85	50 ft below gage
01-23-84	1.3	1.3	1.2	85	30 ft below gage
12-03-84	.2	.2	.3	41	50 ft below gage
12-28-84	.9	.8	.7	25	30 ft below gage
01-25-85	1.3	1.3	1.2	49	75 ft below gage
02-21-85	1.7	1.8		65	300 ft above gage
12-10-85	.7	.5	.6	59	10 ft above gage
01-14-86	.8	.9	1.2	54	75 ft below gage
02-18-86	.9	1.4	1.2	160	100 ft above gage
12-05-86	.3	--	.2	75	150 ft below gage
01-08-87	.7	.5	.7	190	50 ft below gage
01-30-87	.9	.6	.8	170	125 ft below gage
01-07-88	.8	.6	.7	22	100 ft below gage
12-16-88	.3	.4	.4	81	60 ft below gage
01-18-89	1.0	.9	1.0	32	100 ft below gage
02-27-89	1.3	1.3	1.3	81	100 ft above gage
12-08-89	.4	.5	.7	104	150 ft below wire-weight gage
01-23-90	.4	.8	.5	187	125 ft below wire-weight gage
11-29-90	.2	.3	.3	21	120 ft below gage
01-07-91	.8	.7	.8	.05	30 ft below gage
01-14-91	1.3	1.1	1.2	.34	800 ft below gage
01-16-92	.8	.5	1.0	75	125 ft below gage
01-08-93	1.0	.8	.8	14	At gage
03-02-93	.6	1.1	1.1	68	600 ft below gage
12-08-93	.5	.5	.5	280	700 ft below gage
01-24-94	1.1	1.3	.8	85	700 ft below gage
12-09-94	.4	.3	.3	58	100 ft below gage
12-09-94	.5	.5	.5	58	--
01-13-95	.8	.8	.6	71	At gage
01-13-95	1.0	.8	.8	71	--

Table 5. Summary of historical ice-thickness data measured at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97–Continued

[ft, feet; ft^3/s, cubic feet per second; mi, miles; --, no data]

Date	Ice thickness (ft)			Daily mean discharge (ft^3/s)	Additional location information
	Left	Center	Right		
Station 06478500 (James River near Scotland) Period of Record 12-28-70 to 03-04-97					
12-28-70	0.7	0.4	0.4	24	800 ft below gage
01-21-71	1.0	.4	.3	14	800 ft below gage
02-11-71	1.1	.4	.5	14	400 ft below gage
01-12-72	.6	.3	.4	96	800 ft below gage
02-01-72	1.1	.6	.6	46	300 ft below gage
02-23-72	.9	.2	.4	52	500 ft below gage
12-20-72	.4	.0	.3	81	1/4 mi below gage
01-03-73	.3	.0	.4	96	1/4 mi below gage
01-24-73	1.2	1.1	1.3	250	At gage
02-12-73	.3	.4	.5	87	1/4 mi below gage
12-19-73	.0	.0	.0	32	1/4 mi below gage
01-17-74	.6	.0	.0	26	300 ft below gage
02-22-74	.0	.0	.0	118	1/4 mi below gage
01-15-75	.5	.5	.3	14	300 ft below gage
02-12-75	.5	.4	.4	15	300 ft below gage
03-14-75	.3	.0	.3	30	300 ft below gage
12-09-75	1.2	.7	.7	260	10 ft above bridge
01-12-76	.8	.9	1.1	113	300 ft below gage
02-11-76	.4	.4	.9	79	250 ft below gage
03-09-76	.0	.0	.5	160	300 ft below gage
01-20-77	.3	.3	1.1	3.3	300 ft below gage
12-29-77	.5	.0	.7	22	400 ft below gage
01-30-78	1.1	.7	1.2	20	300 ft below gage
02-27-78	.7	.6	.7	22	250 ft below gage
12-20-78	.5	.0	.6	65	400 ft below gage
01-22-79	.9	1.0	1.0	38	Below gage
02-20-79	.4	.8	.8	31	Below gage
12-17-79	.5	.0	.4	226	Below gage
01-22-80	.0	.0	.4	104	Below gage
02-12-80	.1	.3	.4	42	Below gage
12-27-82	.5	.6	.7	173	30 ft below gage
01-27-83	.3	.5	.5	92	1/4 mi below gage
12-13-83	.6	.4	.5	188	300 ft below gage
01-18-84	.6	.4	1.0	73	100 ft below gage
02-15-84	1.5	1.2	1.4	107	400 ft above gage

Table 5. Summary of historical ice-thickness data measured at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97–Continued

[ft, feet; ft^3/s, cubic feet per second; mi, miles; --, no data]

Date	Ice thickness (ft)			Daily mean discharge (ft^3/s)	Additional location information
	Left	Center	Right		
Station 06478500 (James River near Scotland) Period of Record 12-28-70 to 03-04-97—Continued					
03-14-84	1.3	1.3	1.7	590	150 ft below gage
01-14-85	.3	.2	.3	68	1/2 mi below gage
01-06-86	.3	.3	1.0	65	200 ft below dam
02-18-86	.1	.2	.2	55	200 ft below dam
01-20-87	.0	.0	.4	177	200 ft below dam
02-18-88	1.2	.5	1.0	80	300 ft below gage
02-07-89	.4	.3	.3	20	300 ft below gage
12-13-89	.3	.0	.4	30	100 ft below gage
11-14-91	.0	.0	.0	50	200 ft below gage
12-26-91	.0	.0	.0	34	200 ft below gage
01-21-93	.6	.5	.6	40	350 ft below gage
01-14-94	1.1	1.0	1.1	470	400 ft below gage
12-19-94	.7	.6	.5	432	20 ft below gage
01-09-96	.6	1.0	1.1	233	1/2 mi below gage
11-25-96	.7	.5	.6	540	60 ft below gage
01-07-97	1.6	.7	1.3	215	500 ft below gage
03-04-97	1.7	1.3	2.0	160	200 ft below gage
Station 06478513 (James River near Yankton) Period of Record 02-02-82 to 01-31-95					
02-02-82	1.3	1.5	.2	14	500 ft below gage
12-16-82	.5	.4	.3	190	--
01-12-83	.7	.9	.8	185	500 ft below gage
02-04-83	.7	.8	.8	80	1/3 mi below gage
12-07-83	.6	.4	.4	190	50 ft above gage
01-05-84	.9	1.0	.4	130	100 ft above gage
02-08-84	1.2	1.3	.5	85	30 ft above gage
03-08-84	1.0	1.0	.6	620	20 ft above bridge
01-15-85	.6	.7	.5	85	100 ft above gage
02-20-85	1.2	1.0	.7	100	At gage
01-07-86	.8	.8	.4	72	50 ft below gage
02-20-86	.5	.6	.4	60	50 ft above gage
12-16-86	.3	.0	.0	290	100 ft above gage
01-21-87	.4	.0	.0	200	50 ft above gage
02-16-88	.7	1.1	.8	80	50 ft above gage
12-28-89	.7	.7	.6	15	30 ft above gage
02-13-90	.5	.2	.0	29	50 ft above gage

Table 5. Summary of historical ice-thickness data measured at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97–Continued

[ft, feet; ft^3/s, cubic feet per second; mi, miles; --, no data]

Date	Ice thickness (ft)			Daily mean discharge (ft^3/s)	Additional location information
	Left	Center	Right		
Station 06478513 (James River near Yankton) Period of Record 02-02-82 to 01-31-95—Continued					
02-05-91	0.6	0.8	0.4	25	25 ft above gage
11-12-91	.0	.0	.0	42	50 ft above gage
12-27-91	.3	.4	.0	29	75 ft above gage
02-09-93	.0	.8	.0	260	30 ft above gage
12-19-94	.6	.6	.7	410	100 ft above gage
01-31-95	.8	1.0	1.1	140	100 ft above gage
Station 06479000 (Vermillion River near Wakonda) Period of Record 12-16-70 to 02-08-83					
12-16-70	.5	.6	.6	6.2	25 ft below gage
01-14-71	1.8	1.8	2.0	2.5	75 ft below gage
02-18-71	.0	.0	.0	35	75 ft below gage
12-10-71	.3	.3	.3	9.9	300 ft below gage
01-12-72	.9	.6	.8	4.7	700 ft above gage
02-11-72	1.0	1.0	.9	1.8	300 ft below gage
12-19-72	.6	.6	.5	12	150 ft below gage
01-16-73	1.1	1.0	1.2	10	100 ft below gage
01-24-73	.0	.0	.5	65	50 ft below gage
02-13-73	1.5	1.6	2.0	20	40 ft below gage
12-12-73	.3	.4	.3	18	800 ft above gage
01-17-74	1.3	1.2	1.2	6.7	800 ft above gage
02-25-74	1.3	.9	1.2	48	800 ft above gage
12-17-74	.3	.3	.5	4.9	1/4 mi below gage
01-22-75	.8	1.4	1.0	2	200 ft below gage
03-19-75	.0	.0	.0	4.6	1/4 mi below gage
11-25-75	.4	.4	.4	3.9	Below gage
01-15-76	.0	.0	.0	1.6	1/4 mi below gage
12-16-76	.0	.0	.0	.59	1/4 mi below gage
01-20-77	.0	1.4	.0	.01	1/4 mi below gage
12-14-77	.4	.5	.6	7.6	1/8 mi below gage
01-20-78	.0	.0	.0	.43	1/8 mi below control
03-01-78	.0	.0	.0	.47	1/8 mi below gage
12-12-78	.5	.4	.2	14	Beaver dam
01-23-79	1.1	1.0	1.1	6.9	1/4 mi below gage
02-21-79	.5	.0	.0	6.8	Below gage
12-19-79	.3	.6	.5	47	Below gage
01-23-80	.6	.5	.6	32	--

Table 5. Summary of historical ice-thickness data measured at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97–Continued

[ft, feet; ft^3/s, cubic feet per second; mi, miles; --, no data]

Date	Ice thickness (ft)			Daily mean discharge (ft^3/s)	Additional location information
	Left	Center	Right		
Station 06479000 (Vermillion River near Wakonda) Period of Record 12-16-70 to 02-08-83—Continued					
02-13-80	0.8	0.9	0.8	21	Below gage, control
02-18-81	.5	.9	1.0	8.1	1,000 ft below gage
01-13-82	.5	.3	.3	1	3/4 mi below gage
02-01-82	.0	.0	.0	.8	1/2 mi below gage
12-14-82	.5	.5	.4	177	500 ft above gage
01-13-83	2.0	1.2	1.0	75	At gage
02-08-83	1.8	1.9	2.0	50	At gage
Station 06479010 (Vermillion River near Vermillion) Period of Record 12-06-83 to 02-07-96					
12-06-83	.5	.2	.8	85	100 ft above gage
02-09-84	.0	.0	.0	64	100 ft above gage
01-16-85	.4	.3	.3	65	300 ft above gage
12-05-85	.4	.7	.3	50	100 ft from gage
01-08-86	.0	.6	.7	45	100 ft above gage
02-20-86	.0	.0	.0	35	50 ft below gage
12-16-86	.4	.4	.4	150	200 ft above gage
01-22-87	.4	.3	.3	50	200 ft below gage
12-17-87	.3	.3	.3	37	200 ft above gage
02-18-88	.0	.0	1.2	24	300 ft above gage
12-20-88	.0	.0	.3	22	75 ft above gage
02-28-89	.3	.0	.5	8	150 ft above gage
12-28-89	.8	1.0	1.1	7.5	40 ft above gage
02-13-90	.0	.6	.5	15	75 ft above gage
12-06-90	.0	.3	.3	8.5	75 ft above gage
02-06-91	.5	1.4	1.5	8.8	200 ft above gage
11-13-91	1.2	.9	1.2	15	50 ft above gage
12-27-91	.8	.6	.7	7.5	50 ft above gage
01-20-93	1.0	1.2	.8	60	50 ft above gage
02-11-93	.0	.0	.0	102	75 ft above gage
01-14-94	.5	.4	.4	50	100 ft above gage
02-01-95	.0	.0	.0	39	150 ft above gage
02-07-96	.8	.4	1.2	120	150 ft above gage
Station 06480000 (Big Sioux River near Brookings) Period of Record 11-30-78 to 12-16-94					
11-30-70	.3	.3	.4	48	300 ft below gage
01-05-71	1.3	1.3	1.4	14	200 ft below gage
02-02-71	1.4	1.3	1.6	4.5	200 ft below gage

Table 5. Summary of historical ice-thickness data measured at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97–Continued

[ft, feet; ft^3/s, cubic feet per second; mi, miles; --, no data]

Date	Ice thickness (ft)			Daily mean discharge (ft^3/s)	Additional location information
	Left	Center	Right		
Station 06480000 (Big Sioux River near Brookings) Period of Record 11-30-78 to 12-16-94—Continued					
03-03-71	0.4	0.3	0.3	190	150 ft below gage
01-03-72	.4	.5	.5	30	300 ft below gage
02-07-72	1.0	1.0	.8	6.1	300 ft below gage
03-06-72	1.5	1.3	.7	5.8	300 ft below gage
12-04-72	.5	.0	.4	92	300 ft below gage
01-11-73	.6	1.3	.6	32	150 ft below gage
01-30-73	.3	1.2	.9	53	300 ft below gage
01-09-74	.7	.5	.6	6.5	300 ft below gage
02-12-74	.9	.8	1.0	6.8	300 ft below gage
12-04-74	.3	.3	.3	5.8	200 ft below gage
01-07-75	.5	.5	.3	4.1	150 ft below gage
02-03-75	1.7	1.5	1.7	.71	150 ft above gage
03-04-75	2.0	1.8	1.6	.57	100 ft above gage
04-02-75	1.8	1.7	1.1	3.1	100 ft above bridge
12-02-75	.6	.8	.9	3.3	--
01-12-76	1.4	1.4	1.1	2.3	75 ft above gage
02-02-76	1.4	1.5	1.2	2.5	75 ft above gage
03-01-76	1.7	1.5	1.1	37	50 ft below gage
03-01-77	.6	.5	.6	0	300 ft below gage
11-30-77	.3	.3	.4	109	150 ft above gage
01-04-78	1.2	1.3	1.0	37	150 ft above gage
02-06-78	1.8	2.0	1.0	12	150 ft above gage
03-07-78	.7	1.1	2.2	12	150 ft above gage
12-06-78	.5	.3	.3	20	200 ft below gage
01-10-79	.9	.0	.4	3.8	200 ft below gage
02-07-79	.7	1.0	.9	2.9	250 ft below gage
03-06-79	1.8	.9	1.2	2.5	200 ft below gage
12-05-79	.0	.0	.0	91	200 ft below gage
01-22-80	.4	.5	.3	37	200 ft below gage
02-13-80	.6	1.0	.7	20	150 ft below gage
03-12-80	.4	1.1	.6	21	200 ft below gage
01-15-81	.6	.8	.9	6.2	100 ft below gage
12-16-81	.0	.0	.3	11	200 ft below gage
01-18-83	.9	.8	.5	50	150 ft below gage
02-17-83	.8	.6	.0	50	100 ft above gage

Table 5. Summary of historical ice-thickness data measured at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97–Continued

[ft, feet; ft^3/s, cubic feet per second; mi, miles; --, no data]

Date	Ice thickness (ft)			Daily mean discharge (ft^3/s)	Additional location information
	Left	Center	Right		
Station 06480000 (Big Sioux River near Brookings) Period of Record 11-30-78 to 12-16-94—Continued					
12-27-83	1.2	1.0	0.5	28	150 ft below gage
01-09-84	.4	1.3	.9	45	200 ft above gage
02-08-84	.4	1.4	.4	29	200 ft above gage
03-08-84	.7	1.3	.5	530	400 ft below gage
01-07-85	.6	.4	.5	90	200 ft below gage
02-05-85	.5	1.2	.6	45	200 ft below gage
12-10-85	.7	.7	.7	175	120 ft below gage
01-13-86	.7	1.2	1.0	120	100 ft below gage
02-18-86	.7	1.6	1.1	88	150 ft below gage
12-17-86	.7	.5	.4	210	100 ft below gage
02-24-88	.0	1.9	1.8	15	150 ft below gage
03-22-89	.4	.2	.3	69	100 ft below gage
12-27-89	.8	.8	1.0	3	200 ft below gage
02-20-90	.7	.4	.5	5.7	200 ft below gage
02-21-91	.5	.7	.9	22	250 ft below gage
11-08-91	.6	.5	.5	44	375 ft below gage
12-19-91	.4	.7	.8	40	275 ft below gage
01-23-92	.5	.7	.8	40	100 ft below gage
12-17-92	.3	.0	.7	127	150 ft below gage
02-24-93	.5	1.5	1.3	60	150 ft below gage
03-25-93	.4	1.3	1.7	100	100 ft below gage
01-13-94	.7	.8	.9	160	100 ft below gage
12-16-94	2.0	.0	.7	190	200 ft below gage
Station 06481000 (Big Sioux River near Dell Rapids) Period of record 12-17-70 to 03-06-97					
12-17-70	.6	.3	.4	50	800 ft below gage
02-03-71	.6	1.1	1.2	10	600 ft below gage
01-10-72	.5	.8	.2	38	800 ft below gage
01-31-72	1.0	1.5	.4	14	600 ft below gage
03-03-72	1.0	1.1	.2	14	600 ft below gage
12-07-72	.4	.3	.4	122	800 ft below gage
12-20-72	.6	.9	.8	80	600 ft below gage
01-11-73	.7	1.2	1.0	47	600 ft below gage
01-31-73	.6	.9	1.0	95	1/4 mi below gage
01-10-74	.9	1.3	1.0	14	300 ft above gage
02-12-74	1.0	1.4	1.3	13	300 ft above gage

Table 5. Summary of historical ice-thickness data measured at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97–Continued

[ft, feet; ft^3/s, cubic feet per second; mi, miles; --, no data]

Date	Ice thickness (ft)			Daily mean discharge (ft^3/s)	Additional location information
	Left	Center	Right		
Station 06481000 (Big Sioux River near Dell Rapids) Period of record 12-17-70 to 03-06-97—Continued					
12-03-74	0.0	0.0	0.0	15	1 3/4 mi above gage
02-06-75	.5	.8	.8	5.6	1 1/2 mi above gage
03-03-75	.1	.5	1.2	6.6	1 1/2 mi above gage
04-02-75	.5	.4	.4	20	300 ft below gage
12-02-75	.8	.0	.5	13	1 1/2 mi above gage
12-19-75	.3	.4	.5	7.5	1 1/2 mi above gage
01-05-76	.6	.5	.7	9.7	1 1/4 mi above gage
02-05-76	1.2	1.0	.3	8	Above gage
02-19-76	1.2	1.6	1.3	20	300 ft above gage
03-01-76	.5	1.1	.3	220	300 ft above gage
01-04-77	.5	.4	.5	1.7	250 ft below gage
12-07-77	.5	.6	.6	111	300 ft above gage
12-22-77	.9	.8	.8	114	300 ft above gage
01-05-78	1.0	1.1	.9	56	300 ft above gage
01-23-78	1.3	1.6	1.2	32	300 ft above gage
02-06-78	1.3	1.8	1.6	22	300 ft above gage
02-14-78	1.2	1.8	1.5	20	300 ft above gage
03-03-78	1.5	2.1	1.4	18	300 ft above gage
12-04-78	.5	.6	.4	33	200 ft above gage
01-09-79	1.0	1.5	1.4	12	200 ft above gage
02-06-79	1.0	1.8	1.3	10	300 ft above gage
03-05-79	.9	1.5	1.3	13	200 ft above gage
12-05-79	.4	.0	.4	155	300 ft above gage
01-21-80	.8	.7	.9	65	200 ft above gage
02-12-80	1.0	1.1	1.2	40	200 ft above gage
03-13-80	1.2	1.0	.9	46	200 ft above gage
12-22-80	.5	.6	.5	20	600 ft below gage
01-29-81	1.4	1.2	1.5	17	500 ft above gage
12-17-81	.3	.4	.4	21	400 ft below gage
01-25-83	1.0	.9	1.2	83	300 ft below gage
12-15-83	.7	.7	.5	150	--
01-16-84	.9	.8	.5	65	--
02-13-84	1.4	1.0	.8	78	--
03-16-84	.8	1.2	1.4	280	--
01-02-85	.6	.0	.2	130	--

Table 5. Summary of historical ice-thickness data measured at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97–Continued

[ft, feet; ft^3/s, cubic feet per second; mi, miles; --, no data]

Date	Ice thickness (ft)			Daily mean discharge (ft^3/s)	Additional location information
	Left	Center	Right		
Station 06481000 (Big Sioux River near Dell Rapids) Period of record 12-17-70 to 03-06-97—Continued					
02-13-85	0.8	1.0	1.8	65	500 ft below gage
12-18-85	.7	.6	.8	200	300 ft below gage
01-15-86	.8	.6	1.3	150	300 ft below gage
02-20-86	1.8	1.9	1.4	120	200 ft below gage
01-09-87	.5	.0	.2	250	250 ft below gage
02-16-88	1.5	1.7	1.3	17	700 ft below gage
12-13-88	.0	.0	.0	20	300 ft below gage
02-05-91	.0	.0	.3	14	400 ft below gage
11-06-91	.4	.0	.4	190	300 ft below gage
12-19-91	.2	.0	.2	375	400 ft below gage
03-01-93	1.0	1.4	.7	390	300 ft below gage
01-14-94	1.3	1.4	1.0	160	150 ft above gage
03-04-94	2.2	2.0	1.3	80	300 ft above gage
01-05-96	.8	.8	.4	120	800 ft below gage
02-06-96	1.6	1.6	1.2	160	700 ft below gage
01-16-97	1.0	1.3	1.0	80	500 ft below gage
03-06-97	1.4	1.2	1.3	120	700 ft below gage

Table 6. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
					Study-Collected Data						
Huron	James River	02-06-99	1	Huron	1.3	1.4	0.1	1.6	0.3	1.4	0.1
Huron	James River	01-20-00	1	Huron	1.0	1.0	.0	1.1	.1	1.1	.1
Huron	James River	02-24-00	1	Huron	1.3	1.1	.2	1.4	.1	1.6	.3
Huron	James River	01-08-01	1	Huron	1.8	1.7	.1	1.8	.0	.8	1.0
Huron	James River	02-12-01	1	Huron	2.3	2.1	.2	2.3	.0	1.1	1.2
Huron	James River	04-02-01	1	Huron	2.2	2.5	.3	2.6	.4	1.2	1.0
Scotland	James River	02-11-99	2	Yankton	.9	1.2	.3	1.3	.4	.9	.0
Scotland	James River	01-24-00	2	Yankton	1.0	.9	.1	.9	.1	1.2	.2
Scotland	James River	01-09-01	2	Yankton	1.4	1.6	.2	1.7	.3	.9	.5
Scotland	James River	02-12-01	2	Yankton	1.7	1.9	.2	2.0	.3	1.2	.5
Scotland	James River	03-20-01	2	Yankton	1.6	2.1	.5	2.2	.6	1.3	.3
Presho	White River	01-28-00	3	Gann Valley	1.0	1.1	.1	1.2	.2	1.6	.6
Oacoma	White River	02-24-00	3	Gann Valley	.9	1.3	.4	1.4	.5	1.9	1.0
Oacoma	White River	01-10-01	3	Gann Valley	1.5	1.7	.2	1.8	.3	2.5	1.0
Oacoma	White River	03-13-01	3	Gann Valley	1.2	2.4	([1])	2.5	([1])	3.6	([1])
Oacoma	White River	03-13-01	3	Gann Valley	1.2	1.2	.0	1.3	.1	1.6	.4
Little Eagle	Grand River	02-12-99	4	Eureka	1.2	1.7	.5	1.8	.6	2.0	.8
Little Eagle	Grand River	01-25-00	4	Eureka	1.2	1.3	.1	1.3	.1	1.9	.7
Little Eagle	Grand River	02-25-00	4	Eureka	.8	1.5	.7	1.6	.8	2.4	1.6
Little Eagle	Grand River	03-14-01	4	Eureka	1.4	2.5	([1])	2.6	([1])	2.7	([1])
Little Eagle	Grand River	03-14-01	4	Eureka	1.4	1.2	.2	1.3	.1	.9	.5
near Mobridge	Oahe Reservoir	02-12-99	5	Eureka	1.8	1.7	.1	1.8	.0	2.0	.2

Table 6. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Study-Collected Data—Continued											
near Mobridge	Oahe Reservoir	01-25-00	5	Eureka	1.0	1.3	0.3	1.3	0.3	1.9	0.9
near Mobridge	Oahe Reservoir	02-25-00	5	Eureka	1.2	1.5	.3	1.6	.4	2.4	1.2
near Mobridge	Oahe Reservoir	01-11-01	5	Eureka	1.8	1.9	.1	1.9	.1	1.8	.0
near Mobridge	Oahe Reservoir	02-14-01	5	Eureka	2.2	2.2	.0	2.4	.2	2.3	.1
near Mobridge	Oahe Reservoir	03-21-01	5	Eureka	1.0	2.5	([1])	2.6	([1])	2.7	([1])
Platte-Winner	Lake Francis Case	01-09-01	6	Academy	1.6	1.6	.0	1.7	.1	.6	1.0
Platte-Winner	Lake Francis Case	02-13-01	6	Academy	1.8	1.9	.1	2.0	.2	.8	1.0
Historical Data											
Little Eagle	Grand River	01-19-76	06357800	Mobridge	1.3	1.5	.2	1.6	.3	1.6	.3
Little Eagle	Grand River	12-21-76	06357800	Mobridge	1.2	1.1	.1	1.2	.0	1.4	.2
Little Eagle	Grand River	12-19-77	06357800	Mobridge	1.5	1.2	.3	1.2	.3	.4	1.1
Little Eagle	Grand River	12-06-78	06357800	Mobridge	.8	1.1	.3	1.1	.3	.6	.2
Little Eagle	Grand River	01-10-80	06357800	Mobridge	1.4	1.1	.3	1.2	.2	1.3	.1
Little Eagle	Grand River	01-07-81	06357800	Mobridge	1.0	1.0	.0	1.1	.1	1.3	.3
Little Eagle	Grand River	01-06-82	06357800	Mobridge	.8	1.3	.5	1.4	.6	1.1	.3
Little Eagle	Grand River	12-07-82	06357800	Mobridge	.8	.5	.3	.7	.1	.6	.2
Little Eagle	Grand River	12-05-83	06357800	Mobridge	1.3	.7	.6	.8	.5	.5	.8
Little Eagle	Grand River	02-06-85	06357800	Mobridge	1.9	2.0	.1	2.1	.2	2.2	.3
Little Eagle	Grand River	01-20-86	06357800	Mobridge	1.7	1.8	.1	1.9	.2	.6	1.1
Little Eagle	Grand River	02-20-86	06357800	Mobridge	2.4	2.2	.2	2.3	.1	.9	1.5
Little Eagle	Grand River	01-14-87	06357800	Mobridge	1.3	1.0	.3	1.1	.2	.6	.7
Little Eagle	Grand River	01-14-88	06357800	Mobridge	1.3	1.2	.1	1.3	.0	1.3	.0
Little Eagle	Grand River	02-10-88	06357800	Mobridge	2.9	1.6	1.3	1.7	1.2	1.8	1.1
Little Eagle	Grand River	02-14-89	06357800	Mobridge	1.0	1.7	.7	1.8	.8	1.2	.2
Little Eagle	Grand River	02-01-90	06357800	Mobridge	1.2	1.5	.3	1.6	.4	1.9	.7

Table 6. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
					Historical Data—Continued						
Little Eagle	Grand River	12-04-90	06357800	Mobridge	0.4	0.5	0.1	0.5	0.1	0.5	0.1
Little Eagle	Grand River	01-06-92	06357800	Mobridge	.8	1.0	.2	1.1	.3	1.1	.3
Little Eagle	Grand River	02-15-94	06357800	Mobridge	1.4	2.1	.7	2.2	.8	1.0	.4
Little Eagle	Grand River	01-10-95	06357800	Mobridge	1.1	1.3	.2	1.4	.3	.9	.2
Little Eagle	Grand River	01-24-96	06357800	Mobridge	1.8	1.5	.3	1.6	.2	1.7	.1
Little Eagle	Grand River	01-21-97	06357800	Mobridge	1.7	2.0	.3	2.1	.4	.8	.9
Little Eagle	Grand River	02-27-97	06357800	Mobridge	2.1	2.3	.2	2.5	.4	.8	1.3
Oacoma	White River	01-29-76	06452000	Gann Valley	1.5	1.5	.0	1.6	.1	1.7	.2
Oacoma	White River	01-27-77	06452000	Gann Valley	1.8	1.7	.1	1.9	.1	2.4	.6
Oacoma	White River	02-21-78	06452000	Gann Valley	1.4	2.3	.9	2.4	1.0	1.9	.5
Oacoma	White River	02-05-79	06452000	Gann Valley	2.2	2.1	.1	2.2	.0	2.5	.3
Oacoma	White River	03-05-79	06452000	Gann Valley	2.3	2.4	.1	2.5	.2	2.8	.5
Oacoma	White River	03-03-80	06452000	Gann Valley	1.7	1.5	.2	1.6	.1	2.2	.5
Oacoma	White River	12-03-80	06452000	Gann Valley	.4	.4	.0	.5	.1	.2	.2
Oacoma	White River	02-17-81	06452000	Gann Valley	2.0	1.3	.7	1.4	.6	1.7	.3
Oacoma	White River	01-20-83	06452000	Gann Valley	.9	1.0	.1	1.1	.2	1.2	.3
Oacoma	White River	01-23-84	06452000	Gann Valley	1.3	1.9	.6	2.0	.7	.8	.5
Oacoma	White River	02-21-85	06452000	Gann Valley	1.8	1.9	.1	2.1	.3	2.1	.3
Oacoma	White River	01-14-86	06452000	Gann Valley	1.2	1.8	.6	1.9	.7	.6	.6
Oacoma	White River	01-30-87	06452000	Gann Valley	.9	1.0	.1	1.1	.2	1.4	.5
Oacoma	White River	01-07-88	06452000	Gann Valley	.8	1.1	.3	1.2	.4	.7	.1
Oacoma	White River	02-27-89	06452000	Gann Valley	1.3	1.8	.5	1.9	.6	1.6	.3
Oacoma	White River	01-23-90	06452000	Gann Valley	.8	1.4	.6	1.5	.7	1.8	1.0
Oacoma	White River	01-14-91	06452000	Gann Valley	1.3	1.6	.3	1.7	.4	2.1	.8
Oacoma	White River	01-08-93	06452000	Gann Valley	1.0	1.4	.4	1.5	.5	2.1	1.1

Table 6. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Historical Data—Continued											
Oacoma	White River	01-24-94	06452000	Gann Valley	1.3	1.7	0.4	1.8	0.5	1.7	0.4
Oacoma	White River	01-13-95	06452000	Gann Valley	1.0	1.3	.3	1.4	.4	1.5	.5
Scotland	James River	02-11-71	06478500	Yankton	1.1	1.8	.7	1.9	.8	1.9	.8
Scotland	James River	02-01-72	06478500	Yankton	1.1	1.6	.5	1.7	.6	1.5	.4
Scotland	James River	01-24-73	06478500	Yankton	1.3	1.4	.1	1.5	.2	1.3	.0
Scotland	James River	01-17-74	06478500	Yankton	.6	1.5	.9	1.6	1.0	1.3	.7
Scotland	James River	01-15-75	06478500	Yankton	.5	1.2	.7	1.1	.6	1.1	.6
Scotland	James River	12-09-75	06478500	Yankton	1.2	.8	.4	.9	.3	.2	1.0
Scotland	James River	01-20-77	06478500	Yankton	1.1	1.6	.5	1.7	.6	2.3	1.2
Scotland	James River	01-30-78	06478500	Yankton	1.2	1.8	.6	1.9	.7	1.9	.7
Scotland	James River	01-22-79	06478500	Yankton	1.0	1.7	.7	1.8	.8	2.2	1.2
Scotland	James River	12-17-79	06478500	Yankton	.5	.7	.2	.8	.3	.6	.1
Scotland	James River	12-27-82	06478500	Yankton	.7	.4	.3	.7	.0	.4	.3
Scotland	James River	02-15-84	06478500	Yankton	1.5	1.8	.3	1.9	.4	.7	.8
Scotland	James River	03-14-84	06478500	Yankton	1.7	1.9	.2	2.0	.3	.7	1.0
Scotland	James River	01-14-85	06478500	Yankton	.3	1.2	.9	1.2	.9	1.4	1.1
Scotland	James River	01-06-86	06478500	Yankton	1.0	1.6	.6	1.7	.7	1.5	.5
Scotland	James River	01-20-87	06478500	Yankton	.4	.8	.4	.9	.5	1.1	.7
Scotland	James River	02-18-88	06478500	Yankton	1.2	1.7	.5	1.8	.6	1.6	.4
Scotland	James River	02-07-89	06478500	Yankton	.4	1.1	.7	1.2	.8	1.6	1.2
Scotland	James River	12-13-89	06478500	Yankton	.4	.7	.3	.8	.4	.5	.1
Scotland	James River	12-26-91	06478500	Yankton	.0	.7	.7	.8	.8	.5	.5
Scotland	James River	01-21-93	06478500	Yankton	.6	1.4	.8	1.5	.9	1.5	.9
Scotland	James River	01-14-94	06478500	Yankton	1.1	1.2	.1	1.3	.2	1.3	.2
Scotland	James River	12-19-94	06478500	Yankton	.7	.8	.1	.9	.2	.3	.4

Table 6. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Historical Data—Continued											
Scotland	James River	01-09-96	06478500	Yankton	1.1	1.0	0.1	1.1	0.0	1.0	0.1
Scotland	James River	11-25-96	06478500	Yankton	.7	.6	.1	.7	.0	.5	.2
Scotland	James River	01-07-97	06478500	Yankton	1.6	1.4	.2	1.5	.1	1.5	.1
Scotland	James River	03-04-97	06478500	Yankton	2.0	2.0	.0	2.1	.1	2.0	.0
Yankton	James River	02-02-82	06478513	Yankton	1.5	1.6	.1	1.8	.3	1.1	.4
Yankton	James River	12-16-82	06478513	Yankton	.5	.5	.0	.6	.1	.4	.1
Yankton	James River	01-12-83	06478513	Yankton	.9	.7	.2	.9	.0	.3	.6
Yankton	James River	02-04-83	06478513	Yankton	.8	1.1	.3	1.2	.4	.5	.3
Yankton	James River	12-07-83	06478513	Yankton	.6	.7	.1	.8	.2	.3	.3
Yankton	James River	01-05-84	06478513	Yankton	1.0	1.5	.5	1.6	.6	.5	.5
Yankton	James River	02-08-84	06478513	Yankton	1.3	1.8	.5	1.9	.6	.7	.6
Yankton	James River	03-08-84	06478513	Yankton	1.0	1.9	.9	2.0	1.0	.7	.3
Yankton	James River	01-15-85	06478513	Yankton	.7	1.2	.5	1.3	.6	1.4	.7
Yankton	James River	02-20-85	06478513	Yankton	1.2	1.7	.5	1.8	.6	1.9	.7
Yankton	James River	01-07-86	06478513	Yankton	.8	1.6	.8	1.7	.9	1.6	.8
Yankton	James River	01-21-87	06478513	Yankton	.4	.7	.3	.7	.3	.8	.4
Yankton	James River	02-16-88	06478513	Yankton	1.1	1.7	.6	1.8	.7	1.6	.5
Yankton	James River	12-28-89	06478513	Yankton	.7	1.3	.6	1.4	.7	.7	.0
Yankton	James River	02-05-91	06478513	Yankton	.8	1.5	.7	1.6	.8	1.7	.9
Yankton	James River	12-27-91	06478513	Yankton	.4	.9	.5	1.0	.6	.5	.1
Yankton	James River	02-09-93	06478513	Yankton	.8	1.4	.6	1.6	.8	1.5	.7
Yankton	James River	01-31-95	06478513	Yankton	1.1	1.3	.2	1.4	.3	1.2	.1
Wakonda	Vermillion River	01-14-71	06479000	Yankton	2.0	1.4	.6	1.5	.5	1.1	.9
Wakonda	Vermillion River	02-11-72	06479000	Yankton	1.0	1.8	.8	1.9	.9	1.7	.7

Table 6. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Historical Data—Continued											
Wakonda	Vermillion River	01-16-73	06479000	Yankton	1.2	1.4	0.2	1.5	0.3	1.3	0.1
Wakonda	Vermillion River	02-13-73	06479000	Yankton	2.0	1.5	.5	1.6	.4	1.5	.5
Wakonda	Vermillion River	01-17-74	06479000	Yankton	1.3	1.5	.2	1.6	.3	1.3	.0
Wakonda	Vermillion River	01-22-75	06479000	Yankton	1.0	1.1	.1	1.2	.2	1.2	.2
Wakonda	Vermillion River	11-25-75	06479000	Yankton	.4	.5	.1	.6	.2	.1	.3
Wakonda	Vermillion River	01-20-77	06479000	Yankton	1.4	1.6	.2	1.7	.3	2.3	.9
Wakonda	Vermillion River	12-14-77	06479000	Yankton	.6	.8	.2	.9	.3	1.1	.5
Wakonda	Vermillion River	01-23-79	06479000	Yankton	1.1	1.7	.6	1.8	.7	2.2	1.1
Wakonda	Vermillion River	02-13-80	06479000	Yankton	.9	1.4	.5	1.5	.6	1.7	.8
Wakonda	Vermillion River	02-18-81	06479000	Yankton	1.0	1.3	.3	1.4	.4	1.7	.7
Wakonda	Vermillion River	01-13-82	06479000	Yankton	.5	1.1	.6	1.4	.9	.9	.4
Wakonda	Vermillion River	01-13-83	06479000	Yankton	2.0	.8	1.2	1.0	1.0	.2	1.8
Vermillion	Vermillion River	01-05-84	06479010	Yankton	.9	1.5	.6	1.6	.7	.5	.4
Vermillion	Vermillion River	01-16-85	06479010	Yankton	.4	1.2	.8	1.3	.9	1.4	1.0
Vermillion	Vermillion River	12-05-85	06479010	Yankton	.7	1.1	.4	1.1	.4	.8	.1
Vermillion	Vermillion River	12-16-86	06479010	Yankton	.4	.6	.2	.7	.3	.6	.2
Vermillion	Vermillion River	02-18-88	06479010	Yankton	1.2	1.7	.5	1.8	.6	1.6	.4
Vermillion	Vermillion River	02-28-89	06479010	Yankton	.5	1.4	.9	1.5	1.0	2.0	1.5
Vermillion	Vermillion River	12-28-89	06479010	Yankton	1.1	1.3	.2	1.4	.3	.9	.2
Vermillion	Vermillion River	02-06-91	06479010	Yankton	1.5	1.5	.0	1.6	.1	1.8	.3
Vermillion	Vermillion River	11-13-91	06479010	Yankton	1.2	.7	.5	.8	.4	.2	1.0
Vermillion	Vermillion River	01-20-93	06479010	Yankton	1.2	1.4	.2	1.4	.2	1.5	.3
Vermillion	Vermillion River	01-14-94	06479010	Yankton	.5	1.2	.7	1.4	.9	1.3	.8
Vermillion	Vermillion River	02-01-95	06479010	Yankton	.0	1.3	1.3	1.4	1.4	1.2	1.2
Vermillion	Vermillion River	02-07-96	06479010	Yankton	1.2	1.5	.3	1.6	.4	1.9	.7

Table 6. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
					Historical Data—Continued						
Brookings	Big Sioux River	02-02-71	06480000	Brookings	1.6	2.0	0.4	2.1	0.5	1.9	0.3
Brookings	Big Sioux River	03-06-72	06480000	Brookings	1.5	2.4	.9	2.5	1.0	1.8	.3
Brookings	Big Sioux River	01-11-73	06480000	Brookings	1.3	1.6	.3	1.7	.4	2.0	.7
Brookings	Big Sioux River	02-12-74	06480000	Brookings	1.0	2.0	1.0	2.1	1.1	1.6	.6
Brookings	Big Sioux River	02-03-75	06480000	Brookings	1.7	1.6	.1	1.7	.0	1.6	.1
Brookings	Big Sioux River	03-04-75	06480000	Brookings	2.0	2.0	.0	2.1	.1	2.0	.0
Brookings	Big Sioux River	01-12-76	06480000	Brookings	1.4	1.6	.2	1.8	.4	.9	.5
Brookings	Big Sioux River	02-02-76	06480000	Brookings	1.5	1.9	.4	2.0	.5	1.0	.5
Brookings	Big Sioux River	03-01-76	06480000	Brookings	1.7	2.0	.3	2.1	.4	1.1	.6
Brookings	Big Sioux River	03-01-77	06480000	Brookings	.6	2.3	1.7	2.4	1.8	3.4	2.8
Brookings	Big Sioux River	02-06-78	06480000	Brookings	2.0	2.3	.3	2.4	.4	2.3	.3
Brookings	Big Sioux River	03-07-78	06480000	Brookings	2.2	2.6	.4	2.8	.6	2.5	.3
Brookings	Big Sioux River	03-06-79	06480000	Brookings	1.8	2.7	.9	2.8	1.0	3.0	1.2
Brookings	Big Sioux River	02-13-80	06480000	Brookings	1.0	1.7	.7	1.8	.8	2.3	1.3
Brookings	Big Sioux River	01-15-81	06480000	Brookings	.9	1.3	.4	1.4	.5	1.9	1.0
Brookings	Big Sioux River	12-16-81	06480000	Brookings	.3	.8	.5	.9	.6	.5	.2
Brookings	Big Sioux River	01-18-83	06480000	Brookings	.9	1.3	.4	1.4	.5	1.4	.5
Brookings	Big Sioux River	12-27-83	06480000	Brookings	1.2	1.6	.4	1.7	.5	.6	.6
Brookings	Big Sioux River	02-08-84	06480000	Brookings	1.4	2.1	.7	2.2	.8	1.2	.2
Brookings	Big Sioux River	02-05-85	06480000	Brookings	1.2	1.9	.7	2.0	.8	2.4	1.2
Brookings	Big Sioux River	02-18-86	06480000	Brookings	1.6	2.3	.7	2.4	.8	1.4	.2
Brookings	Big Sioux River	12-17-86	06480000	Brookings	.7	1.0	.3	1.1	.4	1.4	.7
Brookings	Big Sioux River	02-24-88	06480000	Brookings	1.9	2.1	.2	2.3	.4	1.4	.5
Brookings	Big Sioux River	12-27-89	06480000	Brookings	1.0	1.5	.5	1.6	.6	2.2	1.2
Brookings	Big Sioux River	02-21-91	06480000	Brookings	.9	1.9	1.0	2.0	1.1	2.4	1.5
Brookings	Big Sioux River	02-24-92	06480000	Brookings	1.5	1.6	.1	1.7	.2	2.0	.5

Table 6. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Historical Data—Continued											
Brookings	Big Sioux River	03-25-92	06480000	Brookings	1.7	1.6	0.1	1.7	0.0	1.9	0.2
Brookings	Big Sioux River	01-13-94	06480000	Brookings	.9	1.6	.7	1.7	.8	.9	.0
Brookings	Big Sioux River	12-16-94	06480000	Brookings	2.0	.9	1.1	1.0	1.0	.7	1.3
Dell Rapids	Big Sioux River	02-03-71	06481000	Sioux Falls	1.2	1.8	.6	2.0	.8	1.6	.4
Dell Rapids	Big Sioux River	01-10-72	06481000	Sioux Falls	.8	1.5	.7	1.5	.7	.8	.0
Dell Rapids	Big Sioux River	01-31-72	06481000	Sioux Falls	1.5	1.8	.3	1.9	.4	1.3	.2
Dell Rapids	Big Sioux River	01-11-73	06481000	Sioux Falls	1.2	1.5	.3	1.6	.4	1.8	.6
Dell Rapids	Big Sioux River	02-12-74	06481000	Sioux Falls	1.4	1.8	.4	1.9	.5	1.5	.1
Dell Rapids	Big Sioux River	03-03-75	06481000	Sioux Falls	1.2	1.8	.6	1.9	.7	1.8	.6
Dell Rapids	Big Sioux River	02-05-76	06481000	Sioux Falls	1.2	1.7	.5	1.8	.6	1.0	.2
Dell Rapids	Big Sioux River	02-19-76	06481000	Sioux Falls	1.6	1.7	.1	1.8	.2	1.0	.6
Dell Rapids	Big Sioux River	01-04-77	06481000	Sioux Falls	.5	1.4	.9	1.5	1.0	1.8	1.3
Dell Rapids	Big Sioux River	02-06-78	06481000	Sioux Falls	1.8	2.1	.3	2.2	.4	2.5	.7
Dell Rapids	Big Sioux River	03-03-78	06481000	Sioux Falls	2.1	2.4	.3	2.5	.4	2.7	.6
Dell Rapids	Big Sioux River	02-06-79	06481000	Sioux Falls	1.8	2.2	.4	2.3	.5	2.2	.4
Dell Rapids	Big Sioux River	02-12-80	06481000	Sioux Falls	1.2	1.6	.4	1.6	.4	1.9	.7
Dell Rapids	Big Sioux River	01-29-81	06481000	Sioux Falls	1.5	1.2	.3	1.3	.2	1.8	.3
Dell Rapids	Big Sioux River	12-17-81	06481000	Sioux Falls	.4	.7	.3	.8	.4	.5	.1
Dell Rapids	Big Sioux River	01-25-83	06481000	Sioux Falls	1.2	1.2	.0	1.3	.1	.9	.3
Dell Rapids	Big Sioux River	02-13-84	06481000	Sioux Falls	1.4	2.0	.6	2.1	.7	1.0	.4
Dell Rapids	Big Sioux River	02-13-85	06481000	Sioux Falls	1.8	1.8	.0	1.9	.1	2.5	.7
Dell Rapids	Big Sioux River	02-20-86	06481000	Sioux Falls	1.9	2.1	.2	2.2	.3	1.2	.7
Dell Rapids	Big Sioux River	01-09-87	06481000	Sioux Falls	.5	1.0	.5	1.1	.6	1.3	.8
Dell Rapids	Big Sioux River	02-16-88	06481000	Sioux Falls	1.7	1.9	.2	2.0	.3	1.1	.6
Dell Rapids	Big Sioux River	12-13-88	06481000	Sioux Falls	.0	.6	.6	.7	.7	.7	.7

Table 6. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Historical Data—Continued											
Dell Rapids	Big Sioux River	02-05-91	06481000	Sioux Falls	0.3	1.6	1.3	1.7	1.4	1.3	1.0
Dell Rapids	Big Sioux River	12-19-91	06481000	Sioux Falls	.3	.7	.4	1.1	.8	.8	.5
Dell Rapids	Big Sioux River	03-01-93	06481000	Sioux Falls	1.4	1.9	.5	2.0	.6	1.7	.3
Dell Rapids	Big Sioux River	03-04-94	06481000	Sioux Falls	2.2	2.0	.2	2.1	.1	1.8	.4
Dell Rapids	Big Sioux River	02-06-96	06481000	Sioux Falls	1.6	1.7	.1	1.9	.3	2.0	.4
Dell Rapids	Big Sioux River	01-16-97	06481000	Sioux Falls	1.3	1.6	.3	1.7	.4	1.1	.2
				Average difference, in feet			.4		.5		.6
				Number of samples used in analysis			199		199		199
				Standard deviation			.3		.3		.4

[1]Not calculated because representative maximum ice thickness was not obtained due to unsafe ice conditions; samples collected only near shore.

Table 7. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using only study-collected ice-thickness data

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Huron	James River	02-06-99	1	Huron	1.3	1.4	0.1	1.6	0.3	1.4	0.1
Huron	James River	01-20-00	1	Huron	1.2	1.0	.2	1.1	.1	1.1	.1
Huron	James River	02-24-00	1	Huron	1.3	1.1	.2	1.4	.1	1.6	.3
Huron	James River	01-08-01	1	Huron	1.8	1.7	.1	1.8	.0	.8	1.0
Huron	James River	02-12-01	1	Huron	2.3	2.1	.2	2.3	.0	1.1	1.2
Huron	James River	04-02-01	1	Huron	2.2	2.5	.3	2.6	.4	1.2	1.0
Scotland	James River	02-11-99	2	Yankton	.9	1.2	.3	1.3	.4	.9	.0
Scotland	James River	01-24-00	2	Yankton	1.0	.9	.1	.9	.1	1.2	.2
Scotland	James River	01-09-01	2	Yankton	1.4	1.6	.2	1.7	.3	.9	.5
Scotland	James River	02-12-01	2	Yankton	1.7	1.9	.2	2.0	.3	1.2	.5
Scotland	James River	03-20-01	2	Yankton	1.6	2.1	.5	2.2	.6	1.3	.3
Presho	White River	01-28-00	3	Gann Valley	1.0	1.1	.1	1.2	.2	1.6	.6
Oacoma	White River	02-24-00	3	Gann Valley	.9	1.3	.4	1.4	.5	1.9	1.0
Oacoma	White River	01-10-01	3	Gann Valley	1.5	1.7	.2	1.8	.3	2.5	1.0
Oacoma	White River	03-13-01	3	Gann Valley	1.2	2.4	([1])	2.5	([1])	3.6	([1])
Oacoma	White River	03-13-01	3	Gann Valley	1.2	1.2	.0	1.3	.1	1.6	.4
Little Eagle	Grand River	02-12-99	4	Eureka	1.2	1.7	.5	1.8	.6	2.0	.8
Little Eagle	Grand River	01-25-00	4	Eureka	1.2	1.3	.1	1.3	.1	1.9	.7
Little Eagle	Grand River	02-25-00	4	Eureka	.8	1.5	.7	1.6	.8	2.4	1.6

Table 7. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using only study-collected ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Little Eagle	Grand River	03-14-01	4	Eureka	1.4	2.5	([1])	2.6	([1])	2.7	([1])
Little Eagle	Grand River	03-14-01	4	Eureka	1.4	1.2	0.2	1.3	0.1	.9	0.5
near Mobridge	Oahe Reservoir	02-12-99	5	Eureka	1.8	1.7	.1	1.8	.0	2.0	.2
near Mobridge	Oahe Reservoir	01-25-00	5	Eureka	1.0	1.3	.3	1.3	.3	1.9	.9
near Mobridge	Oahe Reservoir	02-25-00	5	Eureka	1.2	1.5	.3	1.6	.4	2.4	1.2
near Mobridge	Oahe Reservoir	01-11-01	5	Eureka	1.8	1.9	.1	1.9	.1	1.8	.0
near Mobridge	Oahe Reservoir	02-14-01	5	Eureka	2.2	2.2	.0	2.4	.2	2.3	.1
near Mobridge	Oahe Reservoir	03-21-01	5	Eureka	1.0	2.5	([1])	2.6	([1])	2.7	([1])
Platte-Winner	Lake Francis Case	01-09-01	6	Academy	1.6	1.6	.0	1.7	.1	.6	1.0
Platte-Winner	Lake Francis Case	02-13-01	6	Academy	1.8	1.9	.1	2.0	.2	.8	1.0
				Average difference, in feet			.2		.3		.6
				Number of samples used in analysis			26		26		26
				Standard deviation			.2		.2		.4

[1]Not calculated because representative maximum ice thickness was not obtained due to unsafe ice conditions; samples collected only near shore.

Table 8. Comparison between equal or greater-than-1.0-foot measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Study-Collected Data											
Huron	James River	02-06-99	1	Huron	1.3	1.4	0.1	1.6	0.3	1.4	0.1
Huron	James River	01-20-00	1	Huron	1.2	1.0	.2	1.1	.1	1.1	.1
Huron	James River	02-24-00	1	Huron	1.3	1.1	.2	1.4	.1	1.6	.3
Huron	James River	01-08-01	1	Huron	1.8	1.7	.1	1.8	.0	.8	1.0
Huron	James River	02-12-01	1	Huron	2.3	2.1	.2	2.3	.0	1.1	1.2
Huron	James River	04-02-01	1	Huron	2.2	2.5	.3	2.6	.4	1.2	1.0
Scotland	James River	01-24-00	2	Yankton	1.0	.9	.1	.9	.1	1.2	.2
Scotland	James River	01-09-01	2	Yankton	1.4	1.6	.2	1.7	.3	.9	.5
Scotland	James River	02-12-01	2	Yankton	1.7	1.9	.2	2.0	.3	1.2	.5
Scotland	James River	03-20-01	2	Yankton	1.6	2.1	.5	2.2	.6	1.3	.3
Presho	White River	01-28-00	3	Gann Valley	1.0	1.1	.1	1.2	.2	1.6	.6
Oacoma	White River	01-10-01	3	Gann Valley	1.5	1.7	.2	1.8	.3	2.5	1.0
Oacoma	White River	03-13-01	3	Gann Valley	1.2	1.2	.0	1.3	.1	1.6	.4
Little Eagle	Grand River	02-12-99	4	Eureka	1.2	1.7	.5	1.8	.6	2.0	.8
Little Eagle	Grand River	01-25-00	4	Eureka	1.2	1.3	.1	1.3	.1	1.9	.7
Little Eagle	Grand River	03-14-01	4	Eureka	1.4	1.2	.2	1.3	.1	.9	.5
near Mobridge	Oahe Reservoir	02-12-99	5	Eureka	1.8	1.7	.1	1.8	.0	2.0	.2
near Mobridge	Oahe Reservoir	01-25-00	5	Eureka	1.0	1.3	.3	1.3	.3	1.9	.9
near Mobridge	Oahe Reservoir	02-25-00	5	Eureka	1.2	1.5	.3	1.6	.4	2.4	1.2
near Mobridge	Oahe Reservoir	01-11-01	5	Eureka	1.8	1.9	.1	1.9	.1	1.8	.0
near Mobridge	Oahe Reservoir	02-14-01	5	Eureka	2.2	2.2	.0	2.4	.2	2.3	.1

Table 8. Comparison between equal or greater-than-1.0-foot measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Study-Collected Data—Continued											
Platte-Winner	Lake Francis Case	01-09-01	6	Academy	1.6	1.6	0.0	1.7	0.1	0.6	1.0
Platte-Winner	Lake Francis Case	02-13-01	6	Academy	1.8	1.9	.1	2.0	.2	.8	1.0
Historical Data											
Little Eagle	Grand River	01-19-76	06357800	Mobridge	1.3	1.5	.2	1.6	.3	1.6	.3
Little Eagle	Grand River	12-21-76	06357800	Mobridge	1.2	1.1	.1	1.2	.0	1.4	.2
Little Eagle	Grand River	12-19-77	06357800	Mobridge	1.5	1.2	.3	1.2	.3	.4	1.1
Little Eagle	Grand River	01-10-80	06357800	Mobridge	1.4	1.1	.3	1.2	.2	1.3	.1
Little Eagle	Grand River	01-07-81	06357800	Mobridge	1.0	1.0	.0	1.1	.1	1.3	.3
Little Eagle	Grand River	12-05-83	06357800	Mobridge	1.3	.7	.6	.8	.5	.5	.8
Little Eagle	Grand River	02-06-85	06357800	Mobridge	1.9	2.0	.1	2.1	.2	2.2	.3
Little Eagle	Grand River	01-20-86	06357800	Mobridge	1.7	1.8	.1	1.9	.2	.6	1.1
Little Eagle	Grand River	02-20-86	06357800	Mobridge	2.4	2.2	.2	2.3	.1	.9	1.5
Little Eagle	Grand River	01-14-87	06357800	Mobridge	1.3	1.0	.3	1.1	.2	.6	.7
Little Eagle	Grand River	01-14-88	06357800	Mobridge	1.3	1.2	.1	1.3	.0	1.3	.0
Little Eagle	Grand River	02-10-88	06357800	Mobridge	2.9	1.6	1.3	1.7	1.2	1.8	1.1
Little Eagle	Grand River	02-14-89	06357800	Mobridge	1.0	1.7	.7	1.8	.8	1.2	.2
Little Eagle	Grand River	02-01-90	06357800	Mobridge	1.2	1.5	.3	1.6	.4	1.9	.7
Little Eagle	Grand River	02-15-94	06357800	Mobridge	1.4	2.1	.7	2.2	.8	1.0	.4
Little Eagle	Grand River	01-10-95	06357800	Mobridge	1.1	1.3	.2	1.4	.3	.9	.2
Little Eagle	Grand River	01-24-96	06357800	Mobridge	1.8	1.5	.3	1.6	.2	1.7	.1
Little Eagle	Grand River	01-21-97	06357800	Mobridge	1.7	2.0	.3	2.1	.4	.8	.9
Little Eagle	Grand River	02-27-97	06357800	Mobridge	2.1	2.3	.2	2.5	.4	.8	1.3
Oacoma	White River	01-29-76	06452000	Gann Valley	1.5	1.5	.0	1.6	.1	1.7	.2
Oacoma	White River	01-27-77	06452000	Gann Valley	1.8	1.7	.1	1.9	.1	2.4	.6
Oacoma	White River	02-21-78	06452000	Gann Valley	1.4	2.3	.9	2.4	1.0	1.9	.5

Table 8. Comparison between equal or greater-than-1.0-foot measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Historical Data—Continued											
Oacoma	White River	02-05-79	06452000	Gann Valley	2.2	2.1	0.1	2.2	0.0	2.5	0.3
Oacoma	White River	03-05-79	06452000	Gann Valley	2.3	2.4	.1	2.5	.2	2.8	.5
Oacoma	White River	03-03-80	06452000	Gann Valley	1.7	1.5	.2	1.6	.1	2.2	.5
Oacoma	White River	02-17-81	06452000	Gann Valley	2.0	1.3	.7	1.4	.6	1.7	.3
Oacoma	White River	01-23-84	06452000	Gann Valley	1.3	1.9	.6	2.0	.7	.8	.5
Oacoma	White River	02-21-85	06452000	Gann Valley	1.8	1.9	.1	2.1	.3	2.1	.3
Oacoma	White River	01-14-86	06452000	Gann Valley	1.2	1.8	.6	1.9	.7	.6	.6
Oacoma	White River	02-27-89	06452000	Gann Valley	1.3	1.8	.5	1.9	.6	1.6	.3
Oacoma	White River	01-14-91	06452000	Gann Valley	1.3	1.6	.3	1.7	.4	2.1	.8
Oacoma	White River	01-08-93	06452000	Gann Valley	1.0	1.4	.4	1.5	.5	2.1	1.1
Oacoma	White River	01-24-94	06452000	Gann Valley	1.3	1.7	.4	1.8	.5	1.7	.4
Oacoma	White River	01-13-95	06452000	Gann Valley	1.0	1.3	.3	1.4	.4	1.5	.5
Scotland	James River	02-11-71	06478500	Yankton	1.1	1.8	.7	1.9	.8	1.9	.8
Scotland	James River	02-01-72	06478500	Yankton	1.1	1.6	.5	1.7	.6	1.5	.4
Scotland	James River	01-24-73	06478500	Yankton	1.3	1.4	.1	1.5	.2	1.3	.0
Scotland	James River	12-09-75	06478500	Yankton	1.2	.8	.4	.9	.3	.2	1.0
Scotland	James River	01-20-77	06478500	Yankton	1.1	1.6	.5	1.7	.6	2.3	1.2
Scotland	James River	01-30-78	06478500	Yankton	1.2	1.8	.6	1.9	.7	1.9	.7
Scotland	James River	01-22-79	06478500	Yankton	1.0	1.7	.7	1.8	.8	2.2	1.2
Scotland	James River	02-15-84	06478500	Yankton	1.5	1.8	.3	1.9	.4	.7	.8
Scotland	James River	03-14-84	06478500	Yankton	1.7	1.9	.2	2.0	.3	.7	1.0
Scotland	James River	01-06-86	06478500	Yankton	1.0	1.6	.6	1.7	.7	1.5	.5
Scotland	James River	02-18-88	06478500	Yankton	1.2	1.7	.5	1.8	.6	1.6	.4
Scotland	James River	01-14-94	06478500	Yankton	1.1	1.2	.1	1.3	.2	1.3	.2
Scotland	James River	01-09-96	06478500	Yankton	1.1	1.0	.1	1.1	.0	1.0	.1

Table 8. Comparison between equal or greater-than-1.0-foot measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Historical Data—Continued											
Scotland	James River	01-07-97	06478500	Yankton	1.6	1.4	0.2	1.5	0.1	1.5	0.1
Scotland	James River	03-04-97	06478500	Yankton	2.0	2.0	.0	2.1	.1	2.0	.0
Yankton	James River	02-02-82	06478513	Yankton	1.5	1.6	.1	1.8	.3	1.1	.4
Yankton	James River	01-05-84	06478513	Yankton	1.0	1.5	.5	1.6	.6	.5	.5
Yankton	James River	02-08-84	06478513	Yankton	1.3	1.8	.5	1.9	.6	.7	.6
Yankton	James River	03-08-84	06478513	Yankton	1.0	1.9	.9	2.0	1.0	.7	.3
Yankton	James River	02-20-85	06478513	Yankton	1.2	1.7	.5	1.8	.6	1.9	.7
Yankton	James River	02-16-88	06478513	Yankton	1.1	1.7	.6	1.8	.7	1.6	.5
Yankton	James River	01-31-95	06478513	Yankton	1.1	1.3	.2	1.4	.3	1.2	.1
Wakonda	Vermillion River	01-14-71	06479000	Yankton	2.0	1.4	.6	1.5	.5	1.1	.9
Wakonda	Vermillion River	02-11-72	06479000	Yankton	1.0	1.8	.8	1.9	.9	1.7	.7
Wakonda	Vermillion River	01-16-73	06479000	Yankton	1.2	1.4	.2	1.5	.3	1.3	.1
Wakonda	Vermillion River	02-13-73	06479000	Yankton	2.0	1.5	.5	1.6	.4	1.5	.5
Wakonda	Vermillion River	01-17-74	06479000	Yankton	1.3	1.5	.2	1.6	.3	1.3	.0
Wakonda	Vermillion River	01-22-75	06479000	Yankton	1.0	1.1	.1	1.2	.2	1.2	.2
Wakonda	Vermillion River	01-20-77	06479000	Yankton	1.4	1.6	.2	1.7	.3	2.3	.9
Wakonda	Vermillion River	01-23-79	06479000	Yankton	1.1	1.7	.6	1.8	.7	2.2	1.1
Wakonda	Vermillion River	02-18-81	06479000	Yankton	1.0	1.3	.3	1.4	.4	1.7	.7
Wakonda	Vermillion River	01-13-83	06479000	Yankton	2.0	.8	1.2	1.0	1.0	.2	1.8
Vermillion	Vermillion River	02-18-88	06479010	Yankton	1.2	1.7	.5	1.8	.6	1.6	.4
Vermillion	Vermillion River	12-28-89	06479010	Yankton	1.1	1.3	.2	1.4	.3	.9	.2
Vermillion	Vermillion River	02-06-91	06479010	Yankton	1.5	1.5	.0	1.6	.1	1.8	.3
Vermillion	Vermillion River	11-13-91	06479010	Yankton	1.2	.7	.5	.8	.4	.2	1.0

Table 8. Comparison between equal or greater-than-1.0-foot measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Historical Data—Continued											
Vermillion	Vermillion River	01-20-93	06479010	Yankton	1.2	1.4	0.2	1.4	0.2	1.5	0.3
Vermillion	Vermillion River	02-07-96	06479010	Yankton	1.2	1.5	.3	1.6	.4	1.9	.7
Brookings	Big Sioux River	02-02-71	06480000	Brookings	1.6	2.0	.4	2.1	.5	1.9	.3
Brookings	Big Sioux River	03-06-72	06480000	Brookings	1.5	2.4	.9	2.5	1.0	1.8	.3
Brookings	Big Sioux River	01-11-73	06480000	Brookings	1.3	1.6	.3	1.7	.4	2.0	.7
Brookings	Big Sioux River	02-12-74	06480000	Brookings	1.0	2.0	1.0	2.1	1.1	1.6	.6
Brookings	Big Sioux River	02-03-75	06480000	Brookings	1.7	1.6	.1	1.7	.0	1.6	.1
Brookings	Big Sioux River	03-04-75	06480000	Brookings	2.0	2.0	.0	2.1	.1	2.0	.0
Brookings	Big Sioux River	01-12-76	06480000	Brookings	1.4	1.6	.2	1.8	.4	.9	.5
Brookings	Big Sioux River	02-02-76	06480000	Brookings	1.5	1.9	.4	2.0	.5	1.0	.5
Brookings	Big Sioux River	03-01-76	06480000	Brookings	1.7	2.0	.3	2.1	.4	1.1	.6
Brookings	Big Sioux River	02-06-78	06480000	Brookings	2.0	2.3	.3	2.4	.4	2.3	.3
Brookings	Big Sioux River	03-07-78	06480000	Brookings	2.2	2.6	.4	2.8	.6	2.5	.3
Brookings	Big Sioux River	03-06-79	06480000	Brookings	1.8	2.7	.9	2.8	1.0	3.0	1.2
Brookings	Big Sioux River	02-13-80	06480000	Brookings	1.0	1.7	.7	1.8	.8	2.3	1.3
Brookings	Big Sioux River	12-27-83	06480000	Brookings	1.2	1.6	.4	1.7	.5	.6	.6
Brookings	Big Sioux River	02-08-84	06480000	Brookings	1.4	2.1	.7	2.2	.8	1.2	.2
Brookings	Big Sioux River	02-05-85	06480000	Brookings	1.2	1.9	.7	2.0	.8	2.4	1.2
Brookings	Big Sioux River	02-18-86	06480000	Brookings	1.6	2.3	.7	2.4	.8	1.4	.2
Brookings	Big Sioux River	02-24-88	06480000	Brookings	1.9	2.1	.2	2.3	.4	1.4	.5
Brookings	Big Sioux River	12-27-89	06480000	Brookings	1.0	1.5	.5	1.6	.6	2.2	1.2
Brookings	Big Sioux River	02-24-92	06480000	Brookings	1.5	1.6	.1	1.7	.2	2.0	.5
Brookings	Big Sioux River	03-25-92	06480000	Brookings	1.7	1.6	.1	1.7	.0	1.9	.2
Brookings	Big Sioux River	12-16-94	06480000	Brookings	2.0	.9	1.1	1.0	1.0	.7	1.3

Table 8. Comparison between equal or greater-than-1.0-foot measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Historical Data—Continued											
Dell Rapids	Big Sioux River	02-03-71	06481000	Sioux Falls	1.2	1.8	0.6	2.0	0.8	1.6	0.4
Dell Rapids	Big Sioux River	01-31-72	06481000	Sioux Falls	1.5	1.8	.3	1.9	.4	1.3	.2
Dell Rapids	Big Sioux River	01-11-73	06481000	Sioux Falls	1.2	1.5	.3	1.6	.4	1.8	.6
Dell Rapids	Big Sioux River	02-12-74	06481000	Sioux Falls	1.4	1.8	.4	1.9	.5	1.5	.1
Dell Rapids	Big Sioux River	03-03-75	06481000	Sioux Falls	1.2	1.8	.6	1.9	.7	1.8	.6
Dell Rapids	Big Sioux River	02-05-76	06481000	Sioux Falls	1.2	1.7	.5	1.8	.6	1.0	.2
Dell Rapids	Big Sioux River	02-19-76	06481000	Sioux Falls	1.6	1.7	.1	1.8	.2	1.0	.6
Dell Rapids	Big Sioux River	02-06-78	06481000	Sioux Falls	1.8	2.1	.3	2.2	.4	2.5	.7
Dell Rapids	Big Sioux River	03-03-78	06481000	Sioux Falls	2.1	2.4	.3	2.5	.4	2.7	.6
Dell Rapids	Big Sioux River	02-06-79	06481000	Sioux Falls	1.8	2.2	.4	2.3	.5	2.2	.4
Dell Rapids	Big Sioux River	02-12-80	06481000	Sioux Falls	1.2	1.6	.4	1.6	.4	1.9	.7
Dell Rapids	Big Sioux River	01-29-81	06481000	Sioux Falls	1.5	1.2	.3	1.3	.2	1.8	.3
Dell Rapids	Big Sioux River	01-25-83	06481000	Sioux Falls	1.2	1.2	.0	1.3	.1	.9	.3
Dell Rapids	Big Sioux River	02-13-84	06481000	Sioux Falls	1.4	2.0	.6	2.1	.7	1.0	.4
Dell Rapids	Big Sioux River	02-13-85	06481000	Sioux Falls	1.8	1.8	.0	1.9	.1	2.5	.7
Dell Rapids	Big Sioux River	02-20-86	06481000	Sioux Falls	1.9	2.1	.2	2.2	.3	1.2	.7
Dell Rapids	Big Sioux River	02-16-88	06481000	Sioux Falls	1.7	1.9	.2	2.0	.3	1.1	.6
Dell Rapids	Big Sioux River	03-01-93	06481000	Sioux Falls	1.4	1.9	.5	2.0	.6	1.7	.3
Dell Rapids	Big Sioux River	03-04-94	06481000	Sioux Falls	2.2	2.0	.2	2.1	.1	1.8	.4
Dell Rapids	Big Sioux River	02-06-96	06481000	Sioux Falls	1.6	1.7	.1	1.9	.3	2.0	.4
Dell Rapids	Big Sioux River	01-16-97	06481000	Sioux Falls	1.3	1.6	.3	1.7	.4	1.1	.2
				Average difference, in feet			.4		.4		.6
				Number of samples used in analysis			138		138		138
				Standard deviation			.3		.3		.4

Table 9. Comparison between equal or greater-than-1.5-foot measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Study-Collected Data											
Huron	James River	01-08-01	1	Huron	1.8	1.7	0.1	1.8	0.0	0.8	1.0
Huron	James River	02-12-01	1	Huron	2.3	2.1	.2	2.3	.0	1.1	1.2
Huron	James River	04-02-01	1	Huron	2.2	2.5	.3	2.6	.4	1.2	1.0
Scotland	James River	02-12-01	2	Yankton	1.7	1.9	.2	2.0	.3	1.2	.5
Scotland	James River	03-20-01	2	Yankton	1.6	2.1	.5	2.2	.6	1.3	.3
Oacoma	White River	01-10-01	3	Gann Valley	1.5	1.7	.2	1.8	.3	2.5	1.0
near Mobridge	Oahe Res.	02-12-99	5	Eureka	1.8	1.7	.1	1.8	.0	2.0	.2
near Mobridge	Oahe Res.	01-11-01	5	Eureka	1.8	1.9	.1	1.9	.1	1.8	.0
near Mobridge	Oahe Res.	02-14-01	5	Eureka	2.2	2.2	.0	2.4	.2	2.3	.1
Platte-Winner	Lake Francis Case	01-09-01	6	Academy	1.6	1.6	.0	1.7	.1	.6	1.0
Platte-Winner	Lake Francis Case	02-13-01	6	Academy	1.8	1.9	.1	2.0	.2	.8	1.0
Little Eagle	Grand River	12-19-77	06357800	Mobridge	1.5	1.2	.3	1.2	.3	.4	1.1
Little Eagle	Grand River	02-06-85	06357800	Mobridge	1.9	2.0	.1	2.1	.2	2.2	.3
Little Eagle	Grand River	01-20-86	06357800	Mobridge	1.7	1.8	.1	1.9	.2	.6	1.1
Little Eagle	Grand River	02-20-86	06357800	Mobridge	2.4	2.2	.2	2.3	.1	.9	1.5
Little Eagle	Grand River	02-10-88	06357800	Mobridge	2.9	1.6	1.3	1.7	1.2	1.8	1.1
Little Eagle	Grand River	01-24-96	06357800	Mobridge	1.8	1.5	.3	1.6	.2	1.7	.1
Little Eagle	Grand River	01-21-97	06357800	Mobridge	1.7	2.0	.3	2.1	.4	.8	.9
Little Eagle	Grand River	02-27-97	06357800	Mobridge	2.1	2.3	.2	2.5	.4	.8	1.3
Historical Data											
Oacoma	White River	01-29-76	06452000	Gann Valley	1.5	1.5	.0	1.6	.1	1.7	.2

Table 9. Comparison between equal or greater-than-1.5-foot measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
					Historical Data—Continued						
Oacoma	White River	01-27-77	06452000	Gann Valley	1.8	1.7	0.1	1.9	0.1	2.4	0.6
Oacoma	White River	02-05-79	06452000	Gann Valley	2.2	2.1	.1	2.2	.0	2.5	.3
Oacoma	White River	03-05-79	06452000	Gann Valley	2.3	2.4	.1	2.5	.2	2.8	.5
Oacoma	White River	03-03-80	06452000	Gann Valley	1.7	1.5	.2	1.6	.1	2.2	.5
Oacoma	White River	02-17-81	06452000	Gann Valley	2.0	1.3	.7	1.4	.6	1.7	.3
Oacoma	White River	02-21-85	06452000	Gann Valley	1.8	1.9	.1	2.1	.3	2.1	.3
			06452000								
Scotland	James River	02-15-84	06478500	Yankton	1.5	1.8	.3	1.9	.4	.7	.8
Scotland	James River	03-14-84	06478500	Yankton	1.7	1.9	.2	2.0	.3	.7	1.0
Scotland	James River	01-07-97	06478500	Yankton	1.6	1.4	.2	1.5	.1	1.5	.1
Scotland	James River	03-04-97	06478500	Yankton	2.0	2.0	.0	2.1	.1	2.0	.0
Yankton	James River	02-02-82	06478513	Yankton	1.5	1.6	.1	1.8	.3	1.1	.4
Wakonda	Vermillion River	01-14-71	06479000	Yankton	2.0	1.4	.6	1.5	.5	1.1	.9
Wakonda	Vermillion River	02-13-73	06479000	Yankton	2.0	1.5	.5	1.6	.4	1.5	.5
Wakonda	Vermillion River	01-13-83	06479000	Yankton	2.0	.8	1.2	1.0	1.0	.2	1.8
Vermillion	Vermillion River	02-06-91	06479010	Yankton	1.5	1.5	.0	1.6	.1	1.8	.3
Brookings	Big Sioux River	02-02-71	06480000	Brookings	1.6	2.0	.4	2.1	.5	1.9	.3
Brookings	Big Sioux River	03-06-72	06480000	Brookings	1.5	2.4	.9	2.5	1.0	1.8	.3
Brookings	Big Sioux River	02-03-75	06480000	Brookings	1.7	1.6	.1	1.7	.0	1.6	.1
Brookings	Big Sioux River	03-04-75	06480000	Brookings	2.0	2.0	.0	2.1	.1	2.0	.0
Brookings	Big Sioux River	02-02-76	06480000	Brookings	1.5	1.9	.4	2.0	.5	1.0	.5
Brookings	Big Sioux River	03-01-76	06480000	Brookings	1.7	2.0	.3	2.1	.4	1.1	.6

Table 9. Comparison between equal or greater-than-1.5-foot measured and equation-estimated ice thickness at selected sites in South Dakota using both study-collected and historical ice-thickness data–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day, Incremental Accumulative Freezing Degree Day, and Simplified Energy Budget equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site or USGS streamflow-gaging station number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2		Equation 3	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Historical Data—Continued											
Brookings	Big Sioux River	02-06-78	06480000	Brookings	2.0	2.3	0.3	2.4	0.4	2.3	0.3
Brookings	Big Sioux River	03-07-78	06480000	Brookings	2.2	2.6	.4	2.8	.6	2.5	.3
Brookings	Big Sioux River	03-06-79	06480000	Brookings	1.8	2.7	.9	2.8	1.0	3.0	1.2
Brookings	Big Sioux River	02-18-86	06480000	Brookings	1.6	2.3	.7	2.4	.8	1.4	.2
Brookings	Big Sioux River	02-24-88	06480000	Brookings	1.9	2.1	.2	2.3	.4	1.4	.5
Brookings	Big Sioux River	02-24-92	06480000	Brookings	1.5	1.6	.1	1.7	.2	2.0	.5
Brookings	Big Sioux River	03-25-92	06480000	Brookings	1.7	1.6	.1	1.7	.0	1.9	.2
Brookings	Big Sioux River	12-16-94	06480000	Brookings	2.0	.9	1.1	1.0	1.0	.7	1.3
Dell Rapids	Big Sioux River	01-31-72	06481000	Sioux Falls	1.5	1.8	.3	1.9	.4	1.3	.2
Dell Rapids	Big Sioux River	02-19-76	06481000	Sioux Falls	1.6	1.7	.1	1.8	.2	1.0	.6
Dell Rapids	Big Sioux River	02-06-78	06481000	Sioux Falls	1.8	2.1	.3	2.2	.4	2.5	.7
Dell Rapids	Big Sioux River	03-03-78	06481000	Sioux Falls	2.1	2.4	.3	2.5	.4	2.7	.6
Dell Rapids	Big Sioux River	02-06-79	06481000	Sioux Falls	1.8	2.2	.4	2.3	.5	2.2	.4
Dell Rapids	Big Sioux River	01-29-81	06481000	Sioux Falls	1.5	1.2	.3	1.3	.2	1.8	.3
Dell Rapids	Big Sioux River	02-13-85	06481000	Sioux Falls	1.8	1.8	.0	1.9	.1	2.5	.7
Dell Rapids	Big Sioux River	02-20-86	06481000	Sioux Falls	1.9	2.1	.2	2.2	.3	1.2	.7
Dell Rapids	Big Sioux River	02-16-88	06481000	Sioux Falls	1.7	1.9	.2	2.0	.3	1.1	.6
Dell Rapids	Big Sioux River	03-04-94	06481000	Sioux Falls	2.2	2.0	.2	2.1	.1	1.8	.4
Dell Rapids	Big Sioux River	02-06-96	06481000	Sioux Falls	1.6	1.7	.1	1.9	.3	2.0	.4
				Average difference, in feet			.3		.3		.6
				Number of samples used in analysis			60		60		60
				Standard deviation			.3		.3		.4

Table 10. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using only study-collected ice-thickness data using an α coefficient of 0.55

[Equations 1 and 2 are the Accumulative Freezing Degree Day and Incremental Accumulative Freezing Degree Day equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
Huron	James River	02-06-99	1	Huron	1.3	1.3	0.0	1.4	0.1
Huron	James River	01-20-00	1	Huron	1.2	.9	.3	1.0	.2
Huron	James River	02-24-00	1	Huron	1.3	1.1	.2	1.2	.1
Huron	James River	01-08-01	1	Huron	1.8	1.6	.2	1.7	.1
Huron	James River	02-12-01	1	Huron	2.3	1.9	.4	2.1	.2
Huron	James River	04-02-01	1	Huron	2.2	2.3	.1	2.4	.2
Scotland	James River	02-11-99	2	Yankton	.9	1.1	.2	1.2	.3
Scotland	James River	01-24-00	2	Yankton	1.0	.8	.2	.9	.1
Scotland	James River	01-09-01	2	Yankton	1.4	1.4	.0	1.5	.1
Scotland	James River	02-12-01	2	Yankton	1.7	1.7	.0	1.8	.1
Scotland	James River	03-20-01	2	Yankton	1.6	1.9	.3	2.1	.5
Presho	White River	01-28-00	3	Gann Valley	1.0	1.0	.0	1.1	.1
Oacoma	White River	02-24-00	3	Gann Valley	.9	1.2	.3	1.3	.4
Oacoma	White River	01-10-01	3	Gann Valley	1.5	1.6	.1	1.7	.2
Oacoma	White River	03-13-01	3	Gann Valley	1.2	1.1	.1	1.2	.0
Little Eagle	Grand River	02-12-99	4	Eureka	1.2	1.5	.3	1.6	.4
Little Eagle	Grand River	01-25-00	4	Eureka	1.2	1.2	.0	1.2	.0
Little Eagle	Grand River	02-25-00	4	Eureka	.8	1.4	.6	1.5	.7
Little Eagle	Grand River	03-14-01	4	Eureka	1.4	1.1	.3	1.2	.2

Table 10. Comparison between measured and equation-estimated ice thickness at selected sites in South Dakota using only study-collected ice-thickness data using an α coefficient of 0.55–Continued

[Equations 1 and 2 are the Accumulative Freezing Degree Day and Incremental Accumulative Freezing Degree Day equations, respectively; USGS, U.S. Geological Survey; NWS, National Weather Service; Diff, absolute difference between measured and estimated]

Location	Water body	Date	Site number	NWS station	Measured maximum ice thickness (feet)	Equation 1		Equation 2	
						Estimated ice thickness (feet)	Diff (feet)	Estimated ice thickness (feet)	Diff (feet)
near Mobridge	Oahe Reservoir	02-12-99	5	Eureka	1.8	1.5	0.3	1.6	0.2
near Mobridge	Oahe Reservoir	01-25-00	5	Eureka	1.0	1.2	.2	1.2	.2
near Mobridge	Oahe Reservoir	02-25-00	5	Eureka	1.2	1.4	.2	1.5	.3
near Mobridge	Oahe Reservoir	01-11-01	5	Eureka	1.8	1.7	.1	1.8	.0
near Mobridge	Oahe Reservoir	02-14-01	5	Eureka	2.2	2.0	.2	2.2	.0
Platte-Winner	Lake Francis Case	01-09-01	6	Academy	1.6	1.5	.1	1.6	.0
Platte-Winner	Lake Francis Case	02-13-01	6	Academy	1.8	1.8	.0	1.9	.1
				Average difference, in feet			.2		.2
				Number of samples used in analysis			26		26
				Standard deviation			.2		.2

Table 11. Estimated maximum potential ice thickness using three equations at selected sites in South Dakota

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day equation; Incremental Accumulative Freezing Degree Day; and Simplified Energy Budget equations, respectively; NWS, National Weather Service; NE, Northeast; E, East; N, North; NW, Northwest]

NWS station name	NWS station number	For ice formation		Winter	NWS coldest winter rank	Ice thickness (feet)			Equation 1 estimated maximum potential ice thickness (feet)
		Begin date[1]	End date			Equation 1	Equation 2	Equation 3	
Aberdeen Regional Airport	390020	11-21-71	03-10-72	1972	12	2.4	2.5	1.5	2.8
Aberdeen Regional Airport	390020	11-09-77	03-20-78	1978	2	2.7	2.9	1.9	
Aberdeen Regional Airport	390020	11-10-78	03-31-79	1979	1	2.8	2.9	2.3	
Aberdeen Regional Airport	390020	10-30-96	03-20-97	1997	9	2.7	2.8	1.3	
Academy 2 NE	390043	11-28-71	03-05-72	1972	12	1.7	1.8	2.1	2.2
Academy 2 NE	390043	11-20-77	03-08-78	1978	2	2.2	2.4	1.9	
Academy 2 NE	390043	11-11-78	12-04-79	1979	1	2.2	2.3	2.5	
Academy 2 NE	390043	12-08-16	03-18-17	1917	3	2.1	2.2	2.5	
Britton	391047	10-31-35	03-07-36	1936	4	2.8	3.0	3.0	2.8
Britton	391047	11-18-71	03-10-72	1972	12	2.5	2.6	.9	
Britton	391047	11-10-77	03-19-78	1978	2	2.7	2.8	1.0	
Britton	391047	11-11-78	03-31-79	1979	1	2.8	3.0	1.9	
Brookings 2 NE	391076	11-18-71	03-13-72	1972	12	2.4	2.6	1.8	2.8
Brookings 2 NE	391076	11-11-77	03-18-78	1978	2	2.7	2.8	2.6	
Brookings 2 NE	391076	11-11-78	03-31-79	1979	1	2.8	2.9	3.1	
Brookings 2 NE	391076	11-09-96	03-20-97	1997	9	2.6	2.7	1.6	
Camp Crook	391294	11-20-71	03-05-72	1972	12	2.0	2.1	1.5	2.5
Camp Crook	391294	11-10-78	03-26-79	1979	1	2.5	2.7	1.7	

Table 11. Estimated maximum potential ice thickness using three equations at selected sites in South Dakota–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day equation; Incremental Accumulative Freezing Degree Day; and Simplified Energy Budget equations, respectively; NWS, National Weather Service; NE, Northeast; E, East; N, North; NW, Northwest]

NWS station name	NWS station number	For ice formation		Winter	NWS coldest winter rank	Ice thickness (feet)			Equation 1 estimated maximum potential ice thickness (feet)
		Begin date[1]	End date			Equation 1	Equation 2	Equation 3	
Cottonwood 2 E	391972	11-28-71	02-26-72	1972	12	1.7	1.8	1.8	2.4
Cottonwood 2 E	391972	11-20-77	03-09-78	1978	2	2.0	2.1	1.1	
Cottonwood 2 E	391972	11-11-78	03-11-79	1979	1	2.4	2.5	2.2	
Cottonwood 2 E	391972	12-07-16	03-20-17	1917	3	2.1	2.2	2.4	
Eureka	392797	10-31-35	03-06-36	1936	4	2.8	3.0	3.3	2.8
Eureka	392797	11-10-78	03-31-79	1979	1	2.8	3.0	2.7	
Eureka	392797	11-05-96	03-19-97	1997	9	2.7	2.8	.7	
Fairfax	392820	12-01-35	03-01-36	1936	4	2.3	2.4	2.1	2.3
Fairfax	392820	12-07-16	03-19-17	1917	3	2.2	2.3	2.5	
Faith	392852	11-19-77	03-17-78	1978	2	2.4	2.6	1.2	2.5
Faith	392852	11-10-78	03-10-79	1979	1	2.5	2.7	1.7	
Faith	392852	11-08-96	03-15-97	1997	9	2.2	2.3	1.0	
Faulkton 1 NW	392927	11-18-71	03-09-72	1972	12	2.3	2.4	1.3	2.6
Faulkton 1 NW	392927	11-09-77	03-19-78	1978	2	2.6	2.6	2.3	
Hot Springs	394007	12-14-35	02-21-36	1936	4	1.7	1.8	1.2	2.0
Hot Springs	394007	11-26-71	02-11-72	1972	12	1.3	1.4	1.5	
Hot Springs	394007	11-19-77	03-07-78	1978	2	1.8	2.0	1.9	
Hot Springs	394007	11-10-78	03-04-79	1979	1	2.0	2.1	2.2	

Table 11. Estimated maximum potential ice thickness using three equations at selected sites in South Dakota–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day equation; Incremental Accumulative Freezing Degree Day; and Simplified Energy Budget equations, respectively; NWS, National Weather Service; NE, Northeast; E, East; N, North; NW, Northwest]

NWS station name	NWS station number	For ice formation		Winter	NWS coldest winter rank	Ice thickness (feet)			Equation 1 estimated maximum potential ice thickness (feet)
		Begin date[1]	End date			Equation 1	Equation 2	Equation 3	
Huron Regional Airport	394127	12-01-35	03-01-36	1936	4	2.5	2.6	2.4	2.5
Huron Regional Airport	394127	11-29-71	03-09-72	1972	12	2.2	2.3	1.4	
Huron Regional Airport	394127	11-20-77	03-17-78	1978	2	2.5	2.7	3.1	
Huron Regional Airport	394127	11-10-78	03-11-79	1979	1	2.5	2.7	2.4	
Huron Regional Airport	394127	12-07-16	03-20-17	1917	3	2.4	2.5	2.7	
Mitchell 2 N	395671	12-01-35	03-01-36	1936	4	2.4	2.5	2.0	2.4
Mitchell 2 N	395671	11-27-71	03-05-72	1972	12	2.0	2.1	2.1	
Mitchell 2 N	395671	11-08-98	03-31-99	1899	7	2.3	2.1	3.2	
Pierre Municipal Airport	396597	11-28-71	03-08-72	1972	12	2.1	2.2	2.5	2.4
Pierre Municipal Airport	396597	11-18-77	03-17-78	1978	2	2.4	2.5	2.1	
Pierre Municipal Airport	396597	11-10-78	03-05-79	1979	1	2.4	2.5	3.5	
Pierre Municipal Airport	396597	11-09-96	03-15-97	1997	9	2.2	2.3	1.4	
Rapid City Regional Airport	396937	11-27-71	03-04-72	1972	12	1.6	1.7	2.2	2.1
Rapid City Regional Airport	396937	11-19-77	03-08-78	1978	2	2.1	2.2	2.3	
Rapid City Regional Airport	396937	11-10-78	03-04-79	1979	1	2.0	2.2	2.0	
Sioux Falls Foss Field	397667	11-25-71	03-09-72	1972	12	2.2	2.3	1.7	2.5
Sioux Falls Foss Field	397667	11-20-77	03-17-78	1978	2	2.4	2.6	2.8	
Sioux Falls Foss Field	397667	11-14-78	03-15-79	1979	1	2.5	2.6	2.4	
Sioux Falls Foss Field	397667	11-08-96	03-18-97	1997	9	2.4	2.5	1.5	

Table 11. Estimated maximum potential ice thickness using three equations at selected sites in South Dakota–Continued

[Equations 1, 2, and 3 are the Accumulative Freezing Degree Day equation; Incremental Accumulative Freezing Degree Day; and Simplified Energy Budget equations, respectively; NWS, National Weather Service; NE, Northeast; E, East; N, North; NW, Northwest]

NWS station name	NWS station number	For ice formation		Winter	NWS coldest winter rank	Ice thickness (feet)			Equation 1 estimated maximum potential ice thickness (feet)
		Begin date[1]	End date			Equation 1	Equation 2	Equation 3	
Sisseton	397742	11-18-71	03-10-72	1972	12	2.3	2.4	1.5	2.7
Sisseton	397742	11-09-77	03-17-78	1978	2	2.6	2.7	.9	
Sisseton	397742	11-11-78	03-31-79	1979	1	2.7	2.9	2.1	
Watertown Municipal Airport	398932	11-18-71	03-10-72	1972	12	2.4	2.6	2.0	2.7
Watertown Municipal Airport	398932	11-09-77	03-25-78	1978	2	2.7	2.9	1.6	
Watertown Municipal Airport	398932	11-12-78	03-31-79	1979	1	2.7	2.9	2.4	
Yankton 2 E	399502	12-11-35	03-01-36	1936	4	2.3	2.4	2.0	2.3
Yankton 2 E	399502	11-30-71	03-06-72	1972	12	1.9	2.0	2.0	
Yankton 2 E	399502	12-02-77	03-09-78	1978	2	2.3	2.4	2.0	
Yankton 2 E	399502	11-19-78	03-12-79	1979	1	2.3	2.5	2.7	

[1]Beginning of ice formation based on average daily temperatures as reported by the NWS.