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

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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.

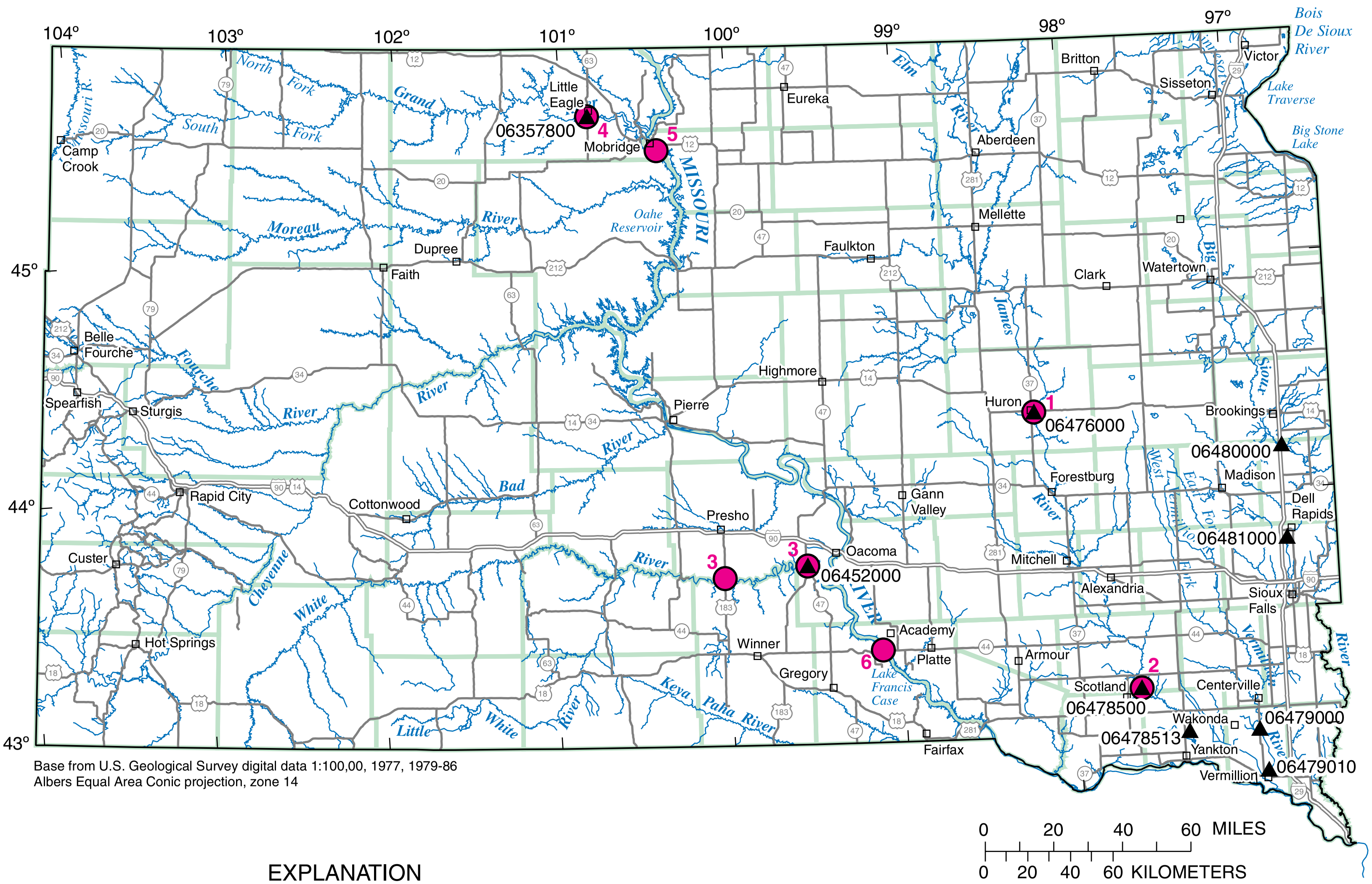
Site 3 (White River near Oacoma/Presho) is at two separate locations—at the U.S. Highway 183 bridge south of Presho and at the State Highway 47 bridge near Oacoma. The Oacoma site is within a few miles of the intersection of the White River with Lake Francis Case. Most of the ice data were collected 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	--	--



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

EXPLANATION

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

06452000 STREAMFLOW-GAGING STATION—Number is station number in table 1

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

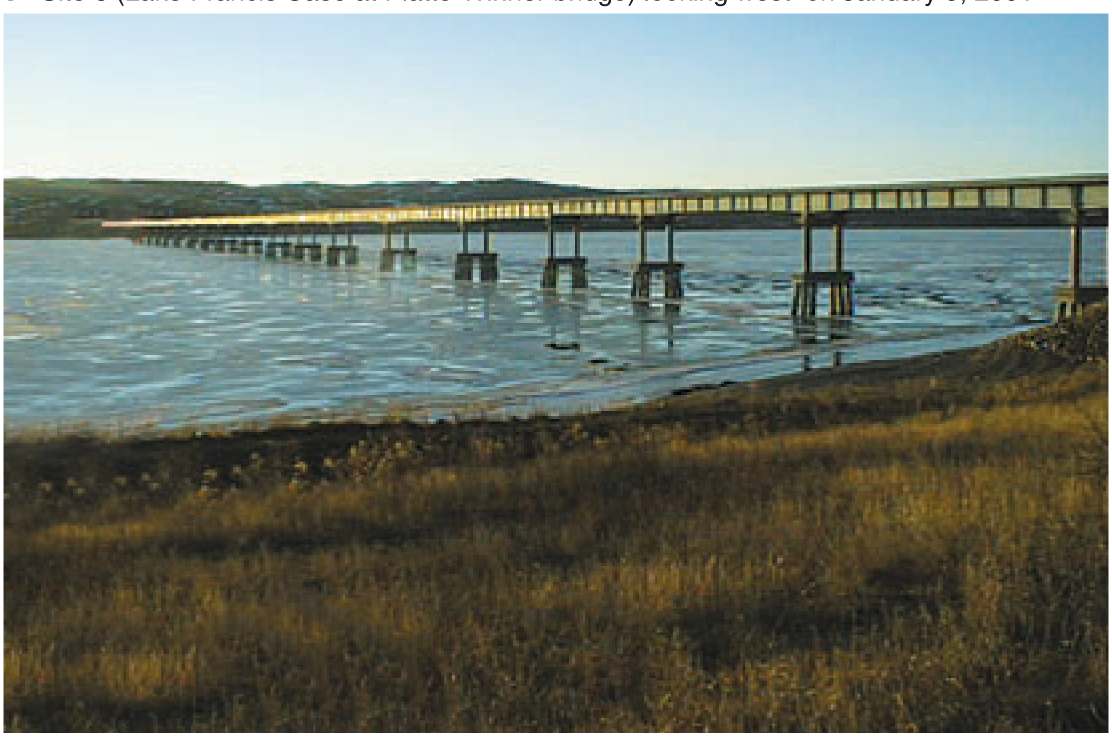


Figure 2. Photographs of the ice-data collection sites in South Dakota.—Continued

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)

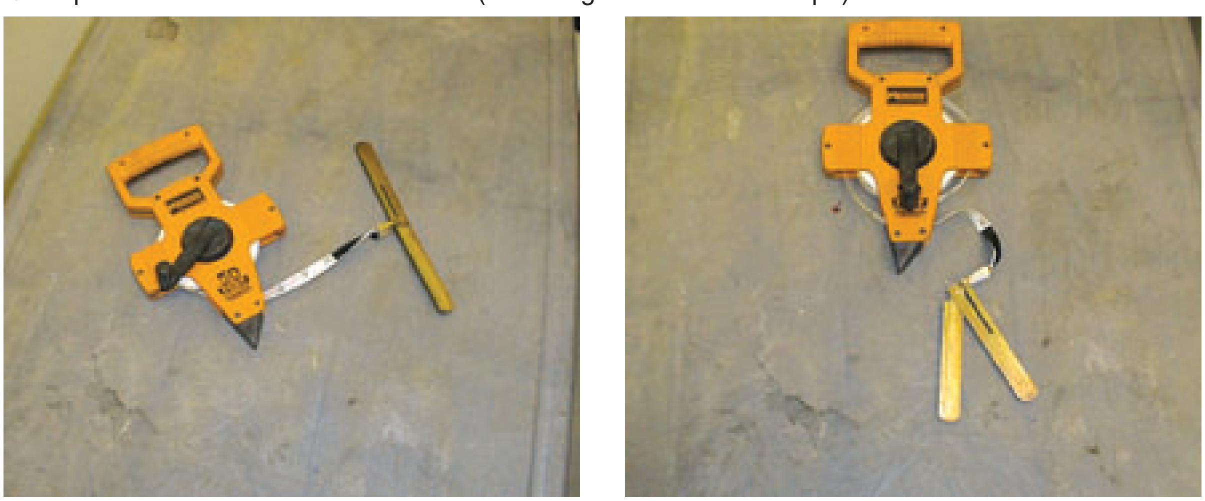


Figure 3. Photographs of equipment used to collect ice-thickness data for the study.

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

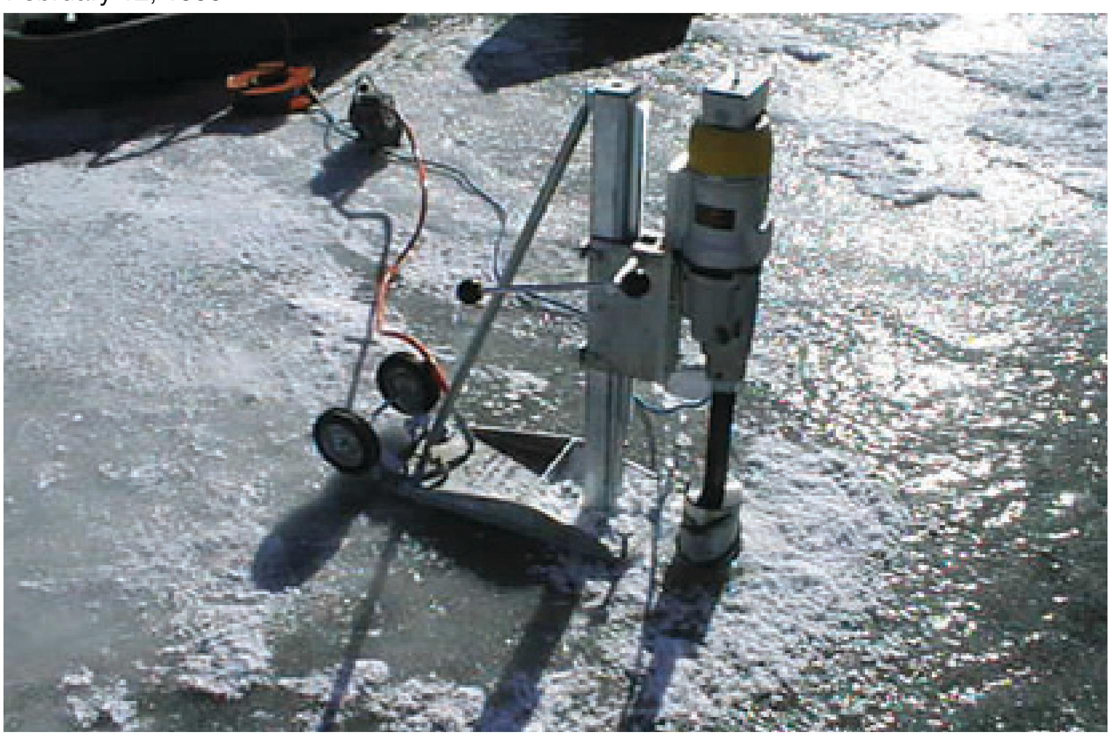


Figure 4. Photographs of equipment used to collect samples and measure ice-crushing strength for the study.

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

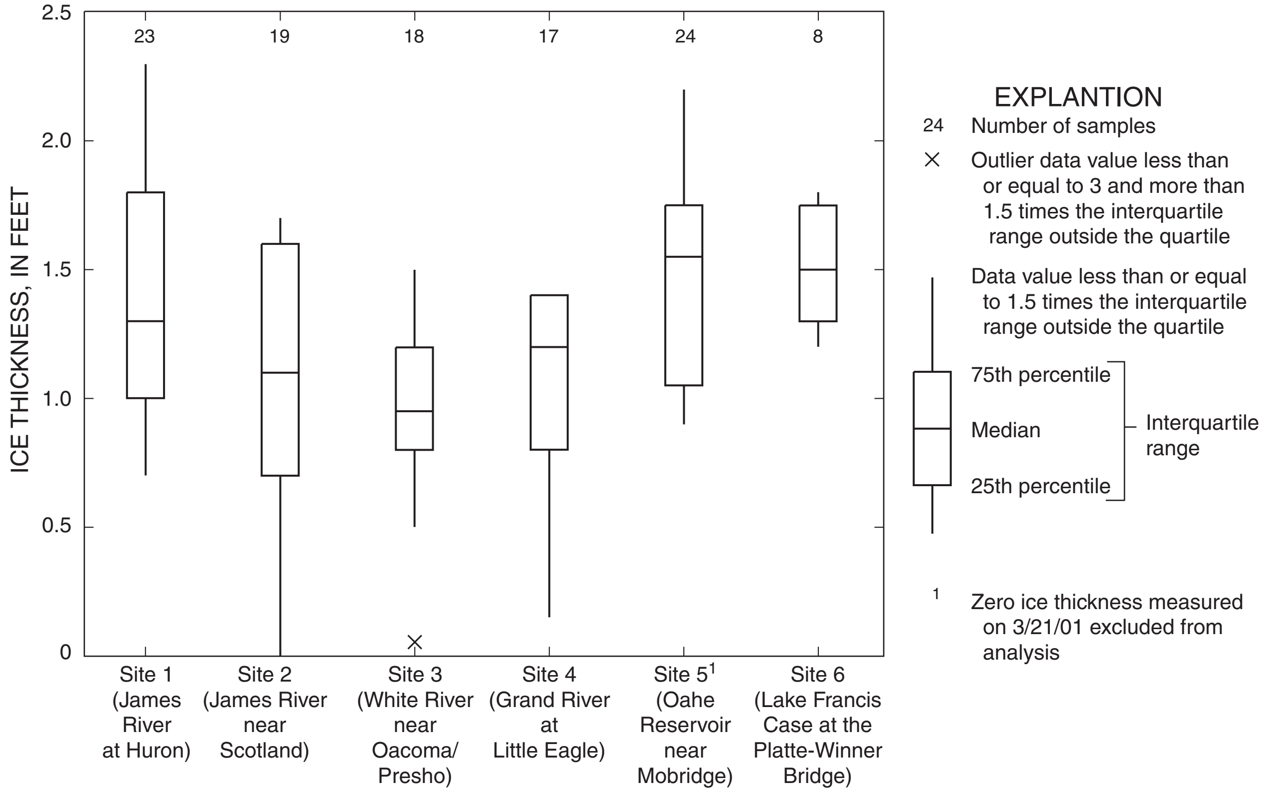


Figure 5. Boxplots of measured ice thickness at ice-data collection sites for the study, 1999-2001.

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).

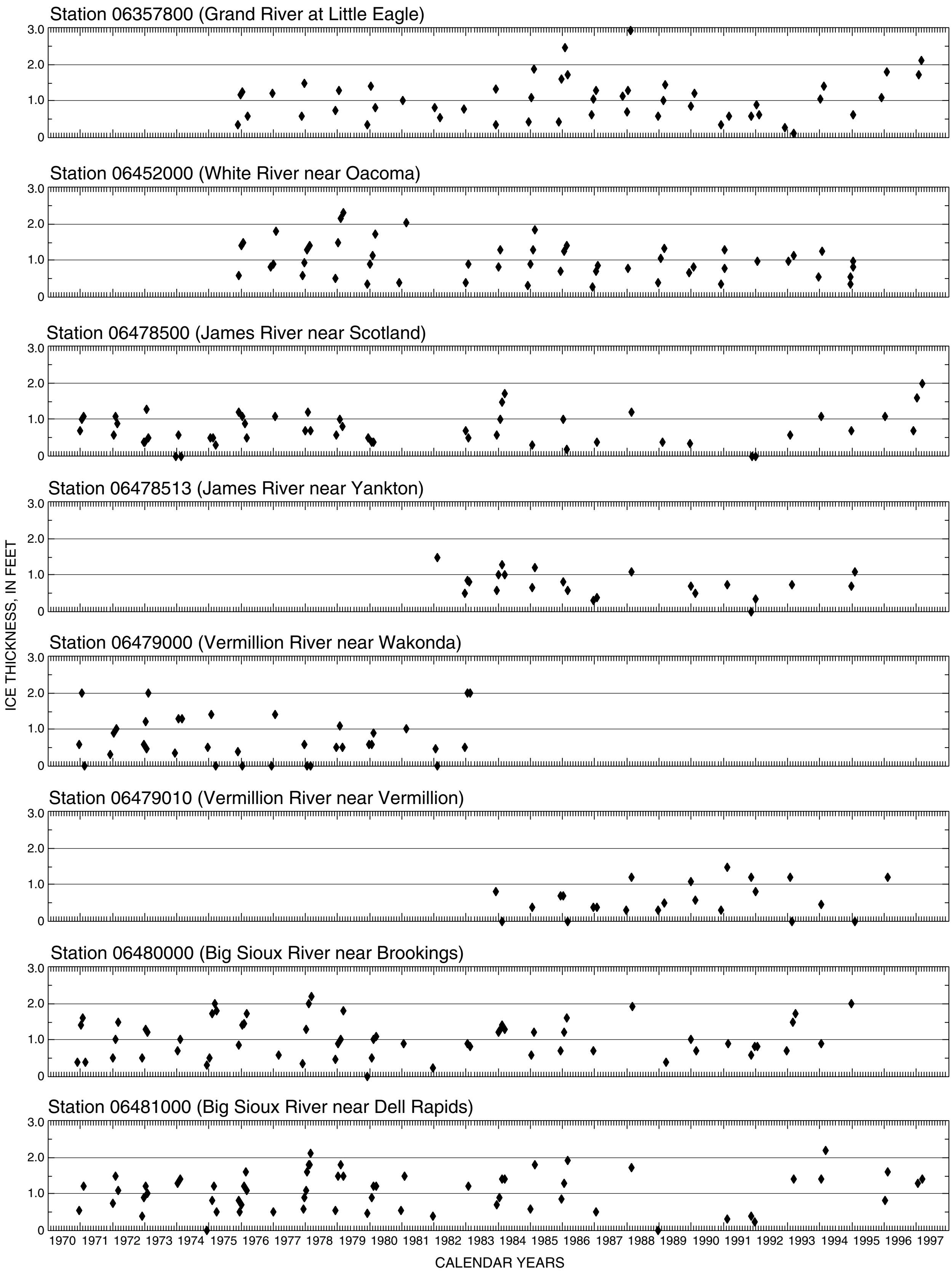


Figure 7. Maximum measured historical ice thickness at selected U.S. Geological Survey streamflow-gaging stations in South Dakota, 1970-97.

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.

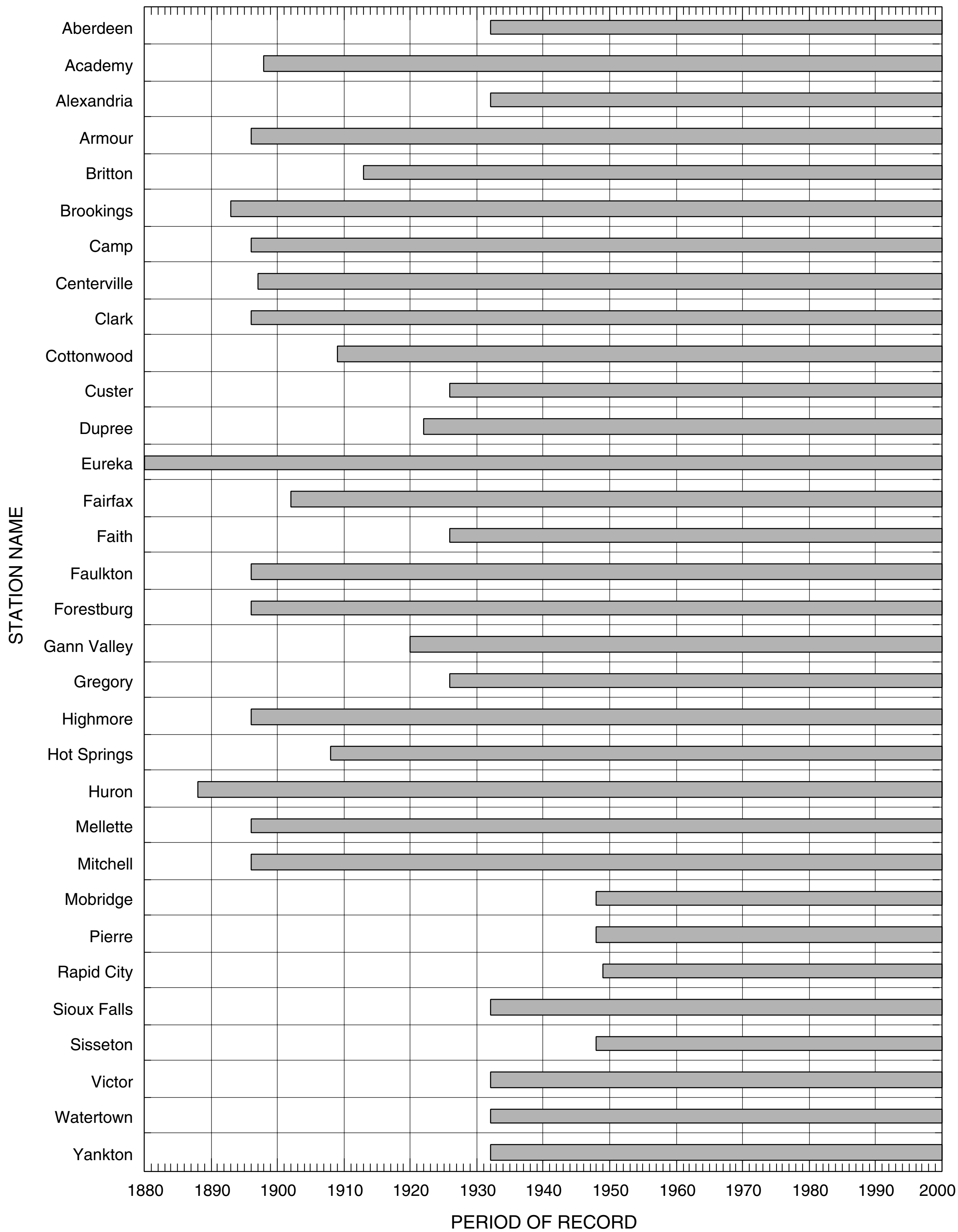


Figure 8. Period of record for selected National Weather Service stations in South Dakota.

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.

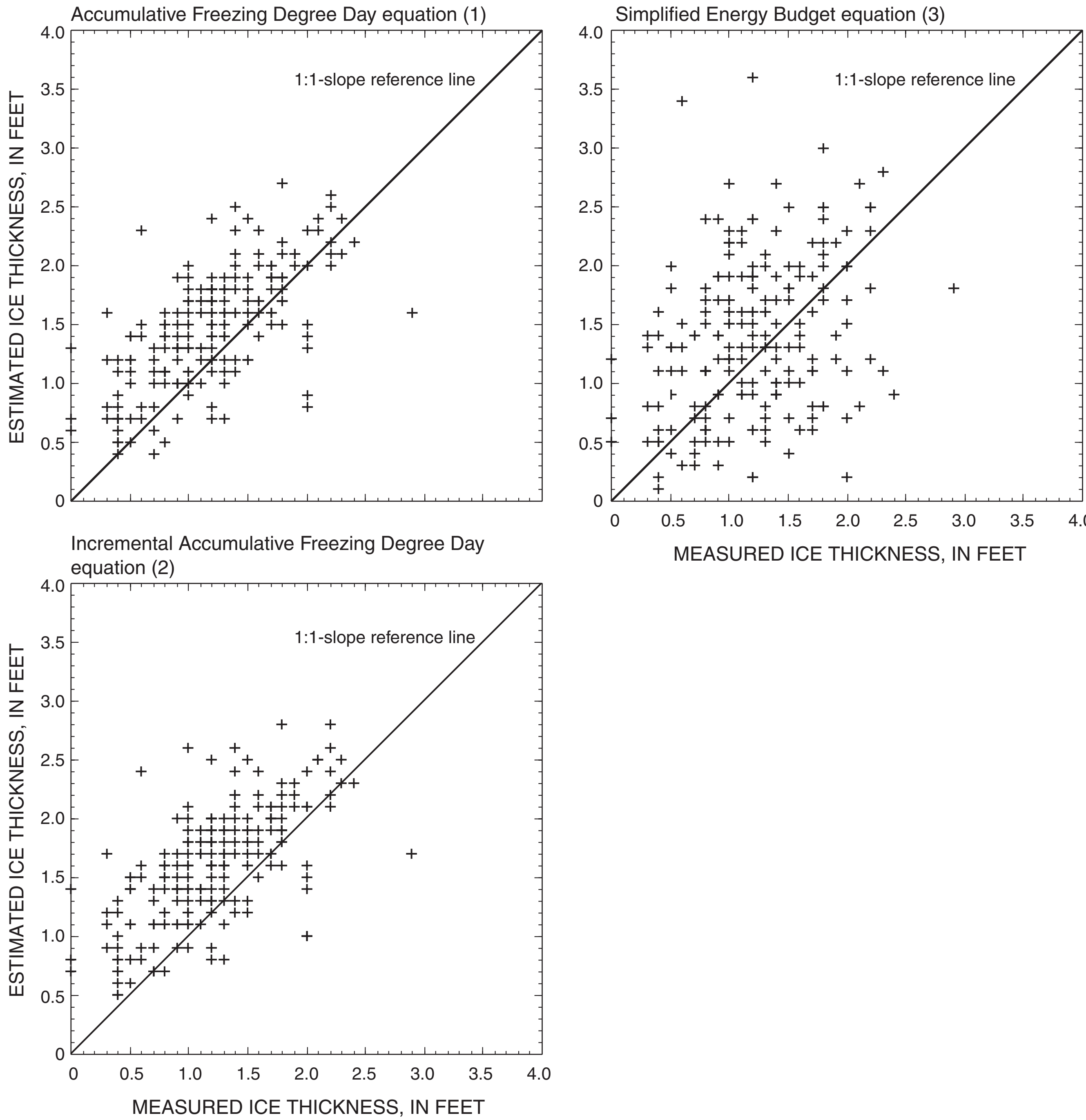


Figure 9. Equation-estimated versus measured ice thickness using both historical and study-collected ice-thickness data at selected sites in South Dakota (see table 6).

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.

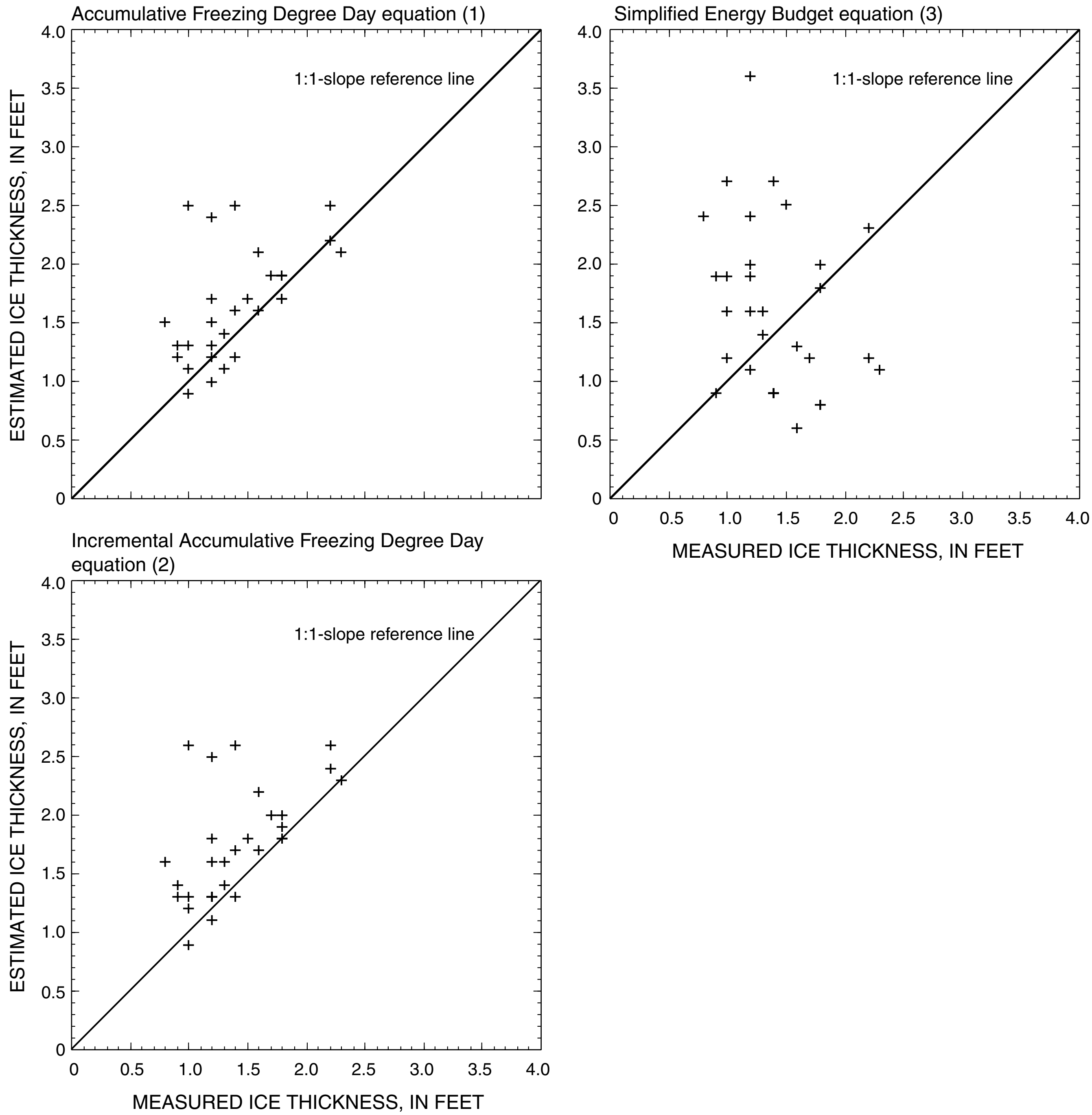


Figure 10. Equation-estimated versus measured ice thickness using only study-collected ice-thickness data at selected sites in South Dakota (see table 7).

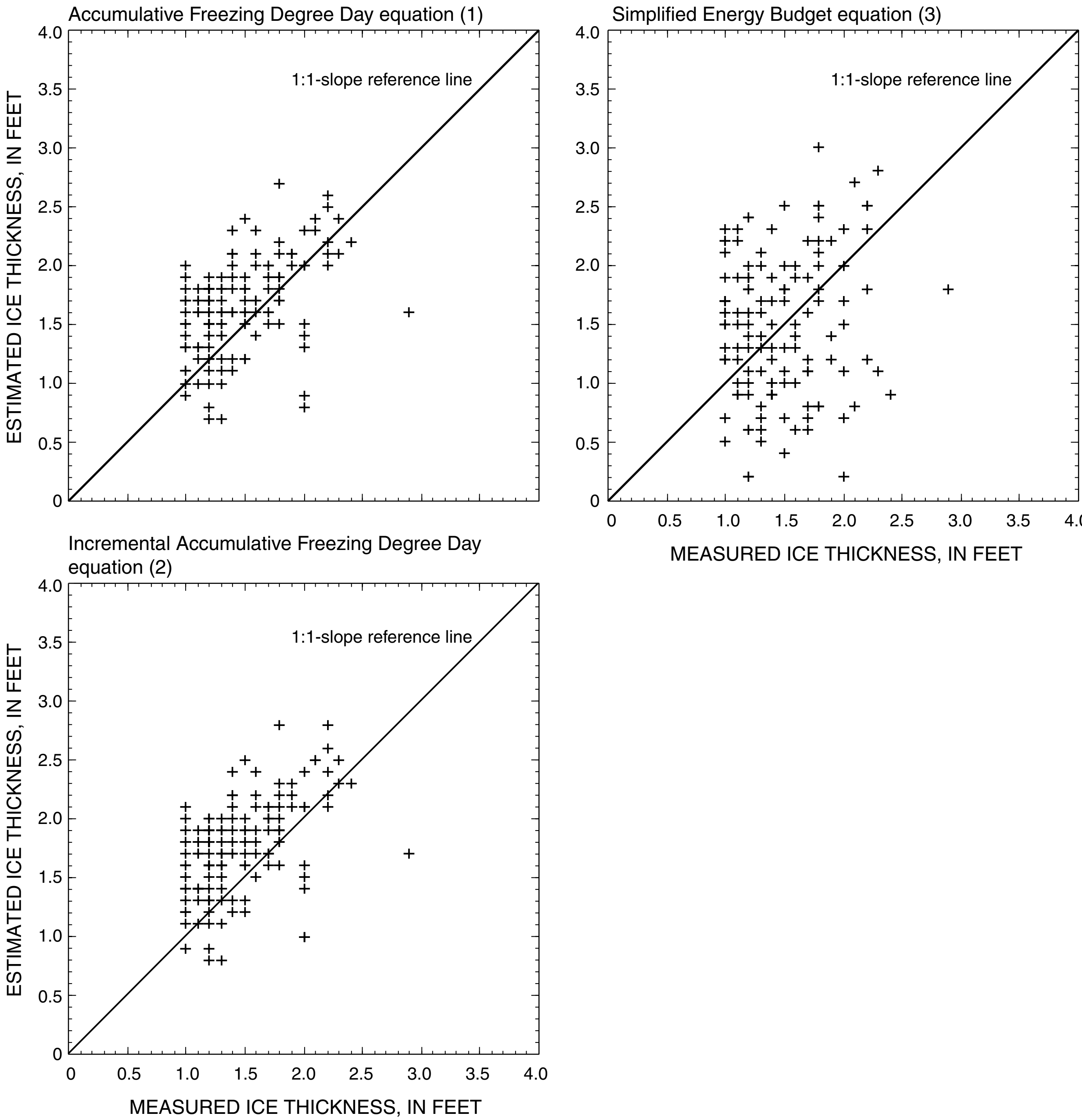


Figure 11. Equation-estimated versus equal or greater-than-1-foot measured ice thickness using both historical and study-collected ice-thickness data at selected sites in South Dakota (see table 8).

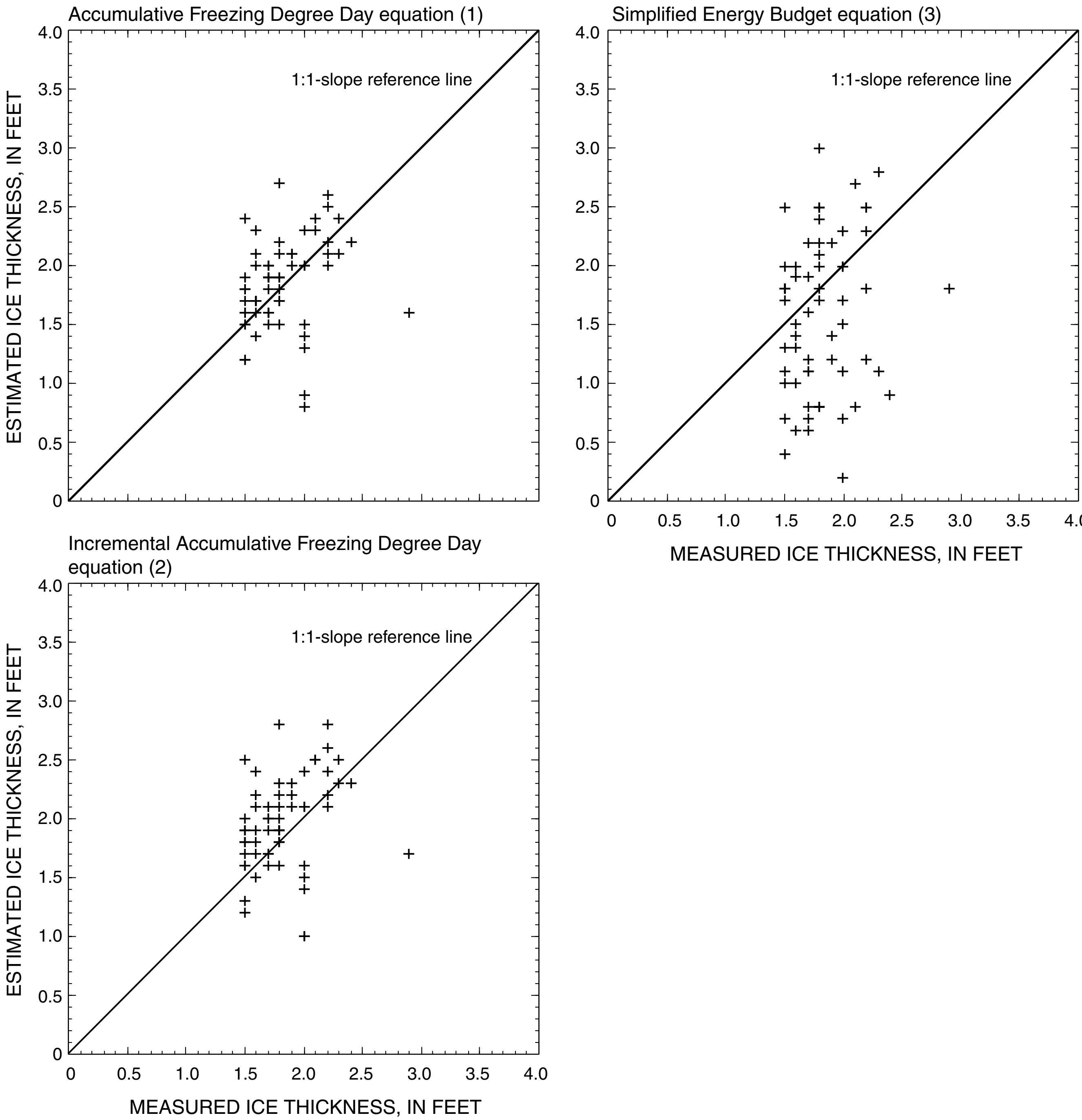


Figure 12. Equation-estimated versus equal or greater-than-1.5-foot measured ice thickness using both historical and study-collected ice thickness data at selected sites in South Dakota (see table 9).

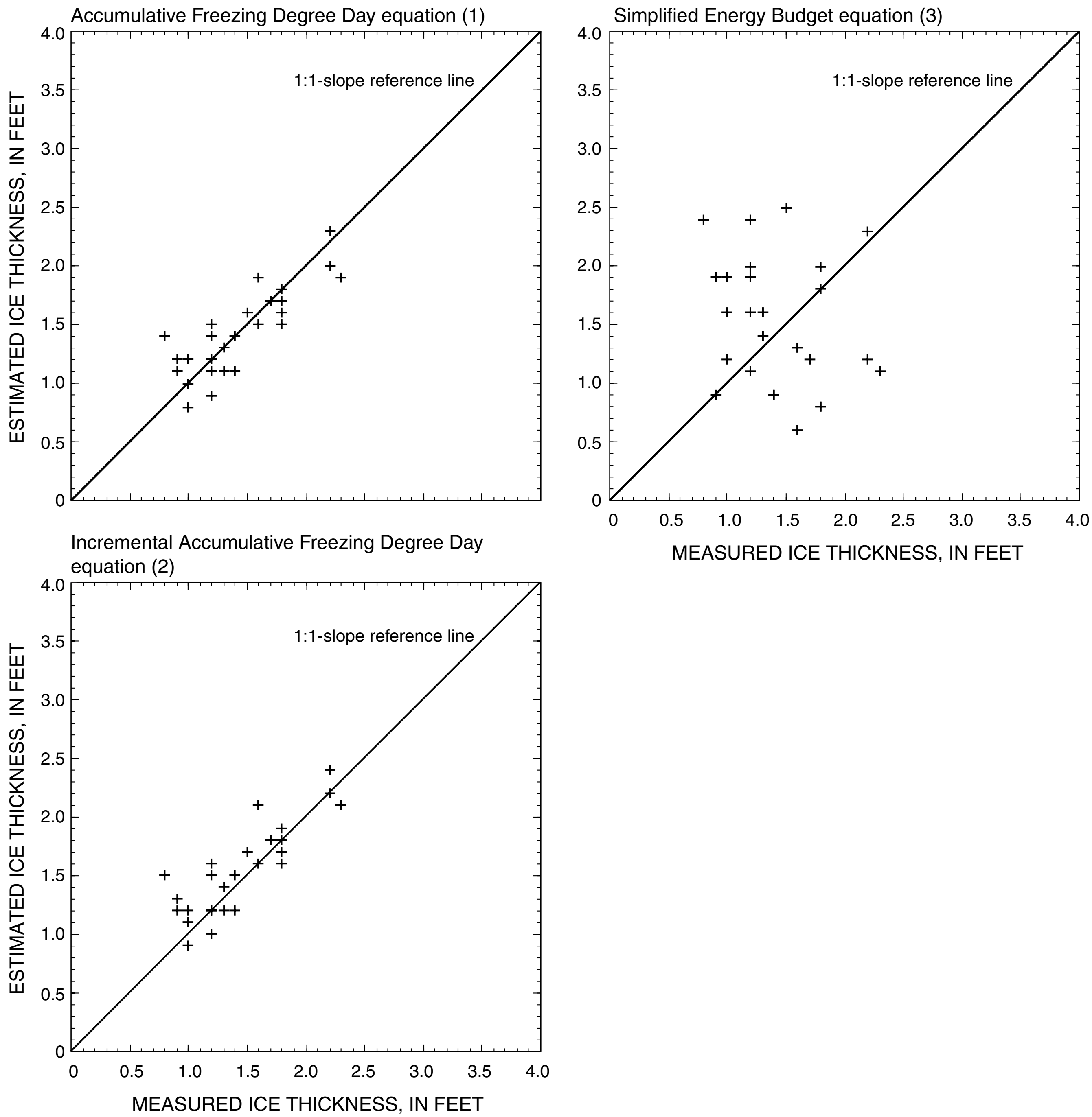


Figure 13. Equation-estimated versus measured ice thickness using only study-collected ice-thickness data with an α coefficient of 0.55 at selected sites in South Dakota (see table 10).

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.

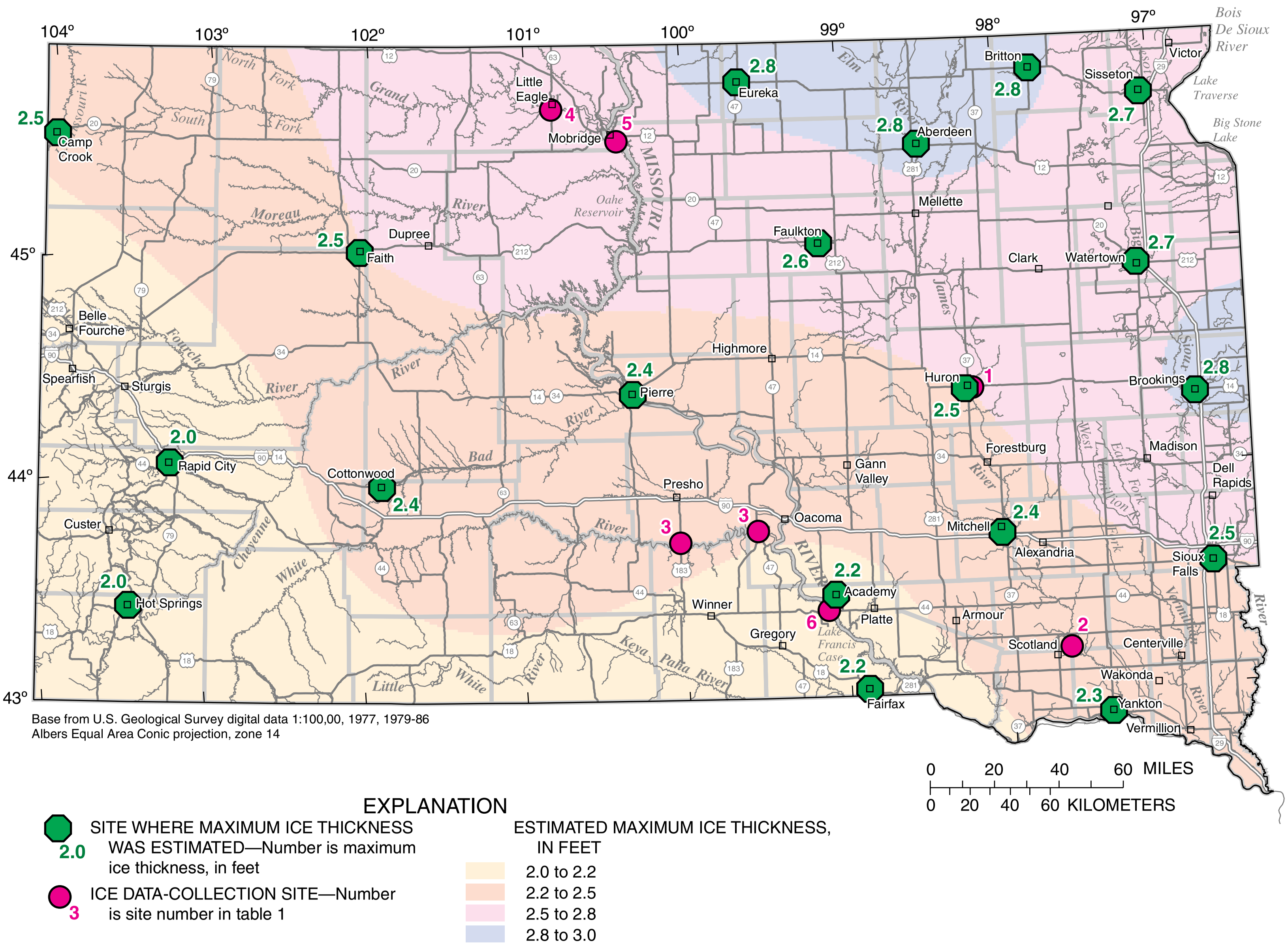


Figure 14. Estimated maximum potential ice thickness on rivers and lakes or reservoirs in South Dakota.