Ice Jams in the United States

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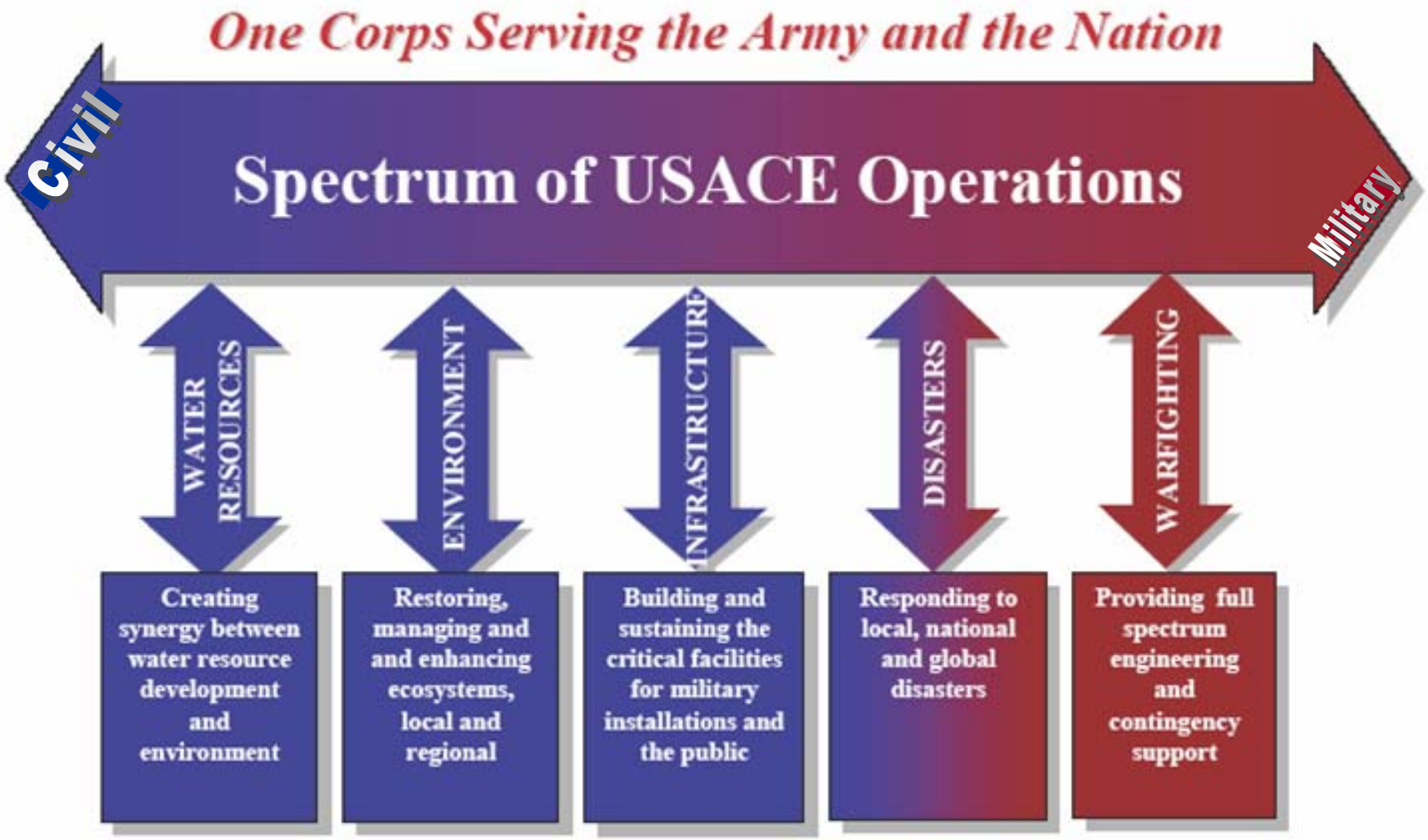


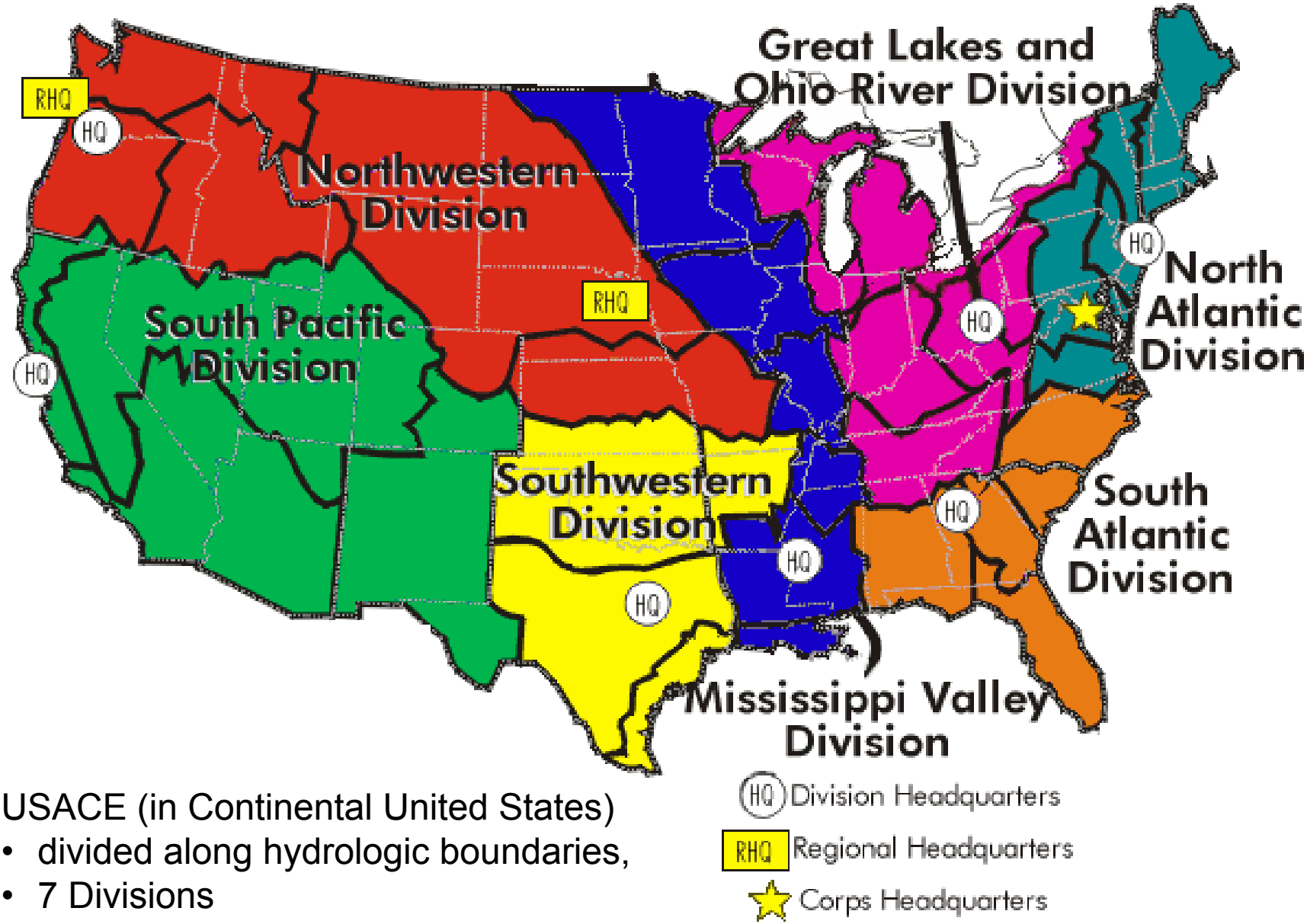
Focus on USACE Civil Works Mission:

Navigation, Flood and Coastal Storm Damage Reduction, Environmental Protection and Restoration, Regulatory, Hydropower, Recreation, Water Supply, Emergency Management, Support for Others

Support to the Army and Nation

Civil Works Value to the Nation

- US Ports & Waterways convey > 2B Tons Commerce
- Foreign Trade alone creates > $160 B Tax Revenues



USACE (in Continental United States)

- divided along hydrologic boundaries,
- 7 Divisions
- 39 Districts

Outline

Introduction to Ice Processes

Summary of Ice Jam Flooding in the United States

- **Chronic Flooding**
- **Flash Floods**

Ice Jam Impacts

Ice Jam Mitigation

Current Research

Summary

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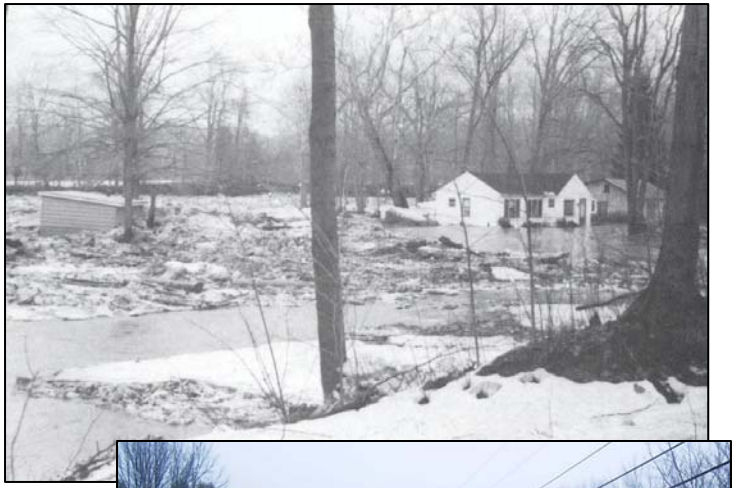
Ice Jams in the United States

- *Ice Jams in the United States result in three types of situations*
  - No flood threat, but environmental and geomorphological impacts possible
  - Freezeup jams or freezing of mid-season breakup jams that causes chronic flooding problems for the remainder of the winter season (e.g., Michigan 2005)
  - Breakup ice jams that cause sudden or flash floods (numerous)



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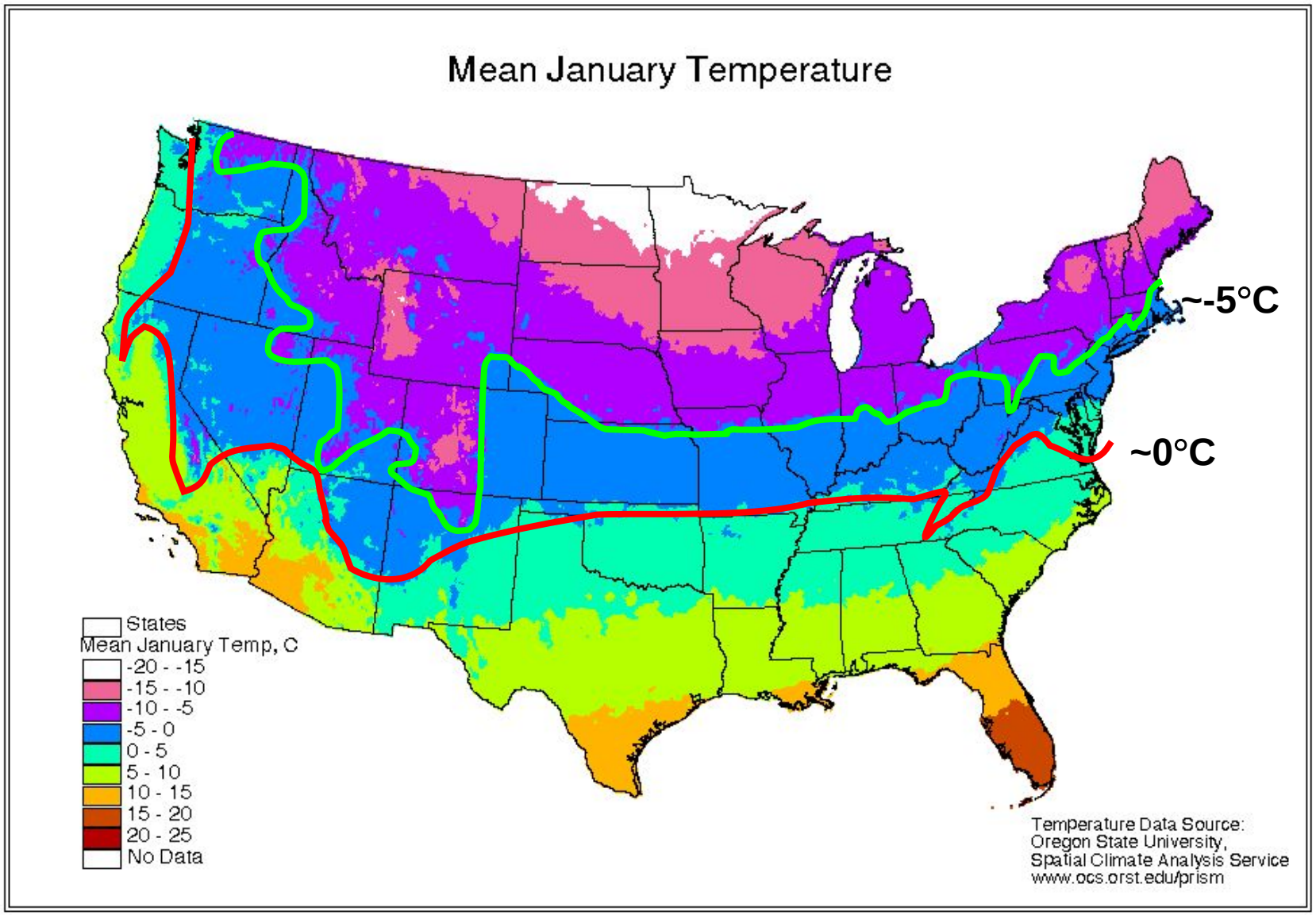
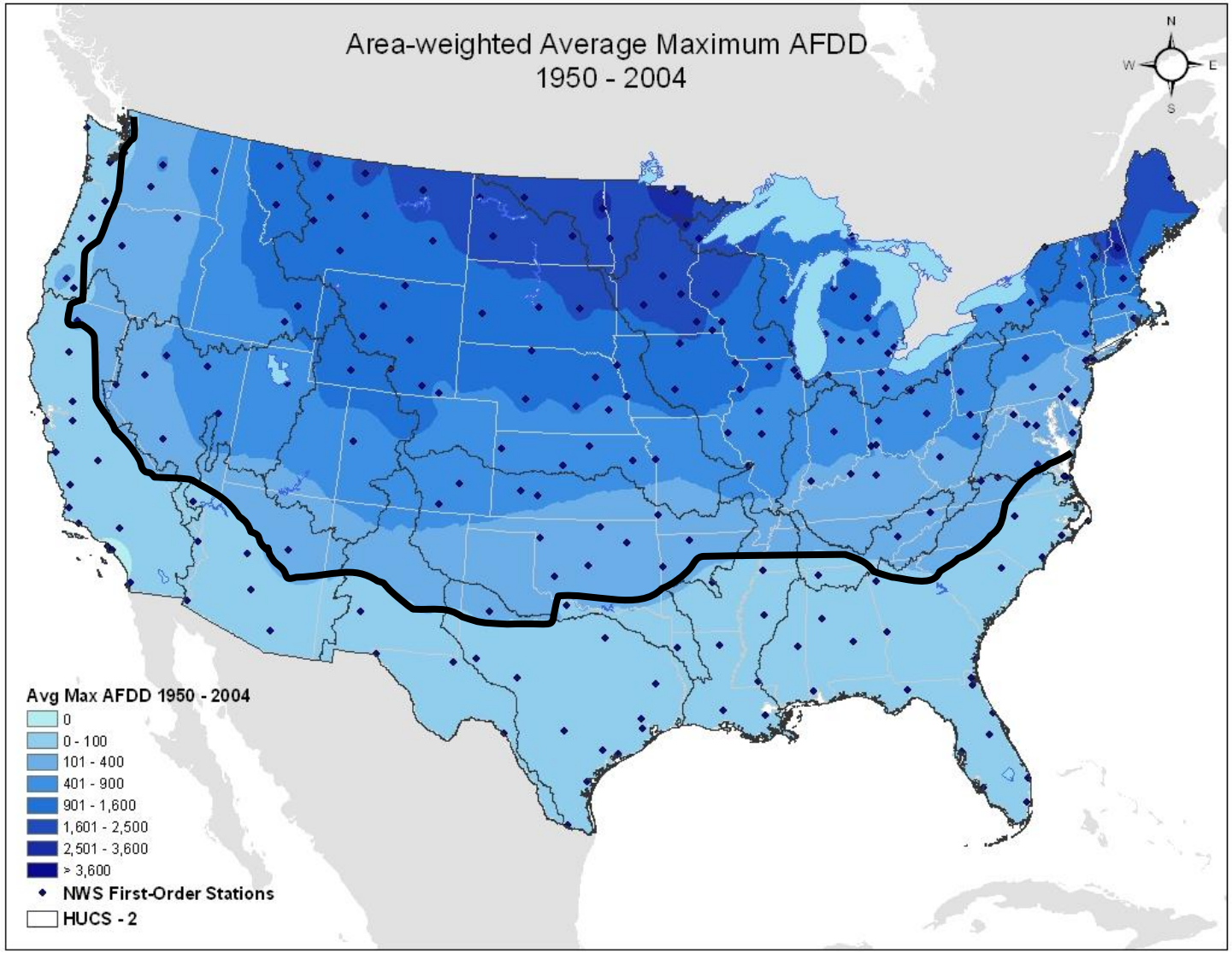

Mean January Temperature
~-5°C
~0°C
States
Mean January Temp, C
-20 - -15
-15 - -10
-10 - -5
-5 - 0
0 - 5
5 - 10
10 - 15
15 - 20
20 - 25
No Data
Temperature Data Source:
Oregon State University,
Spatial Climate Analysis Service
www.ocs.orst.edu/prism

Average Maximum AFDD (1950-2004)



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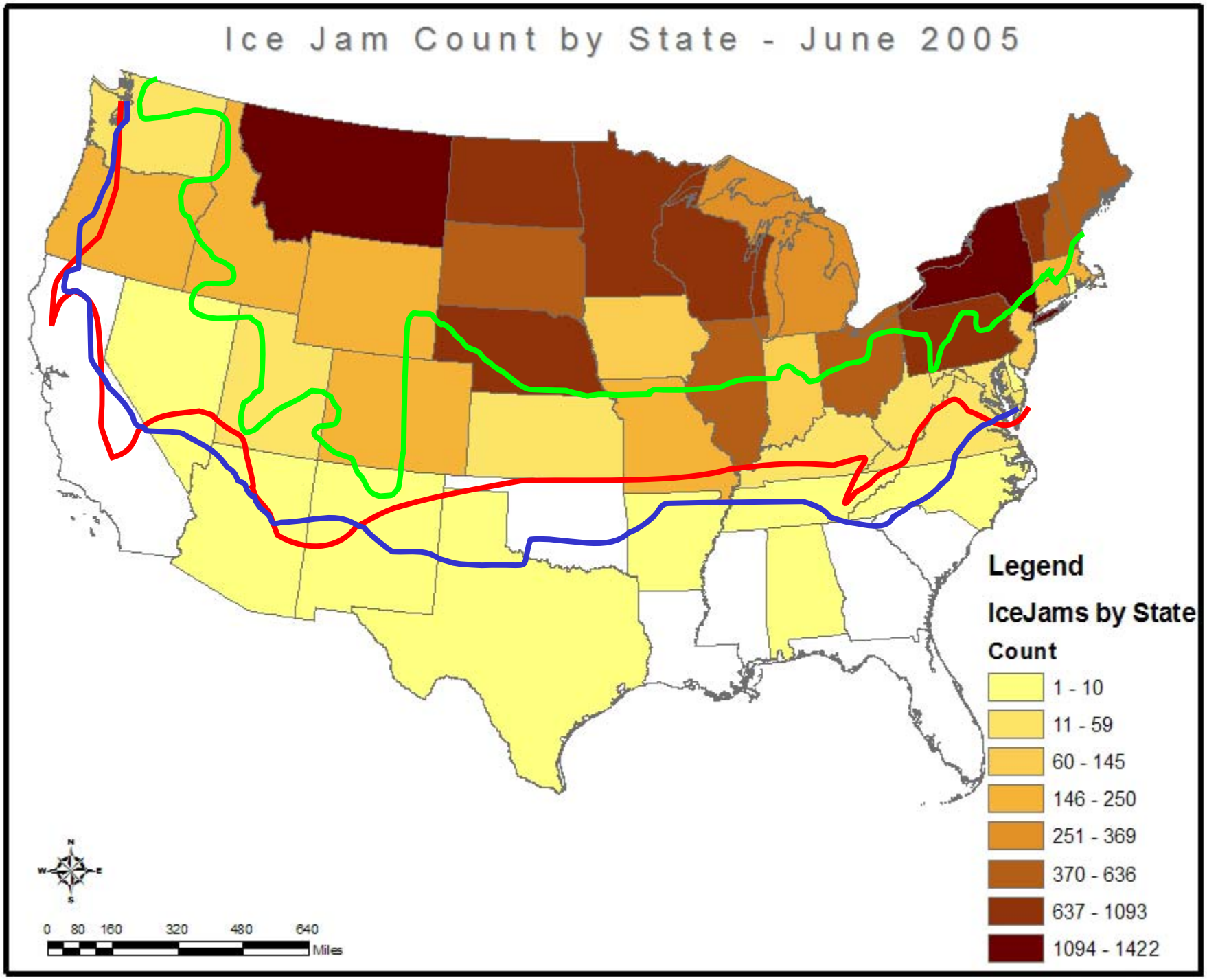
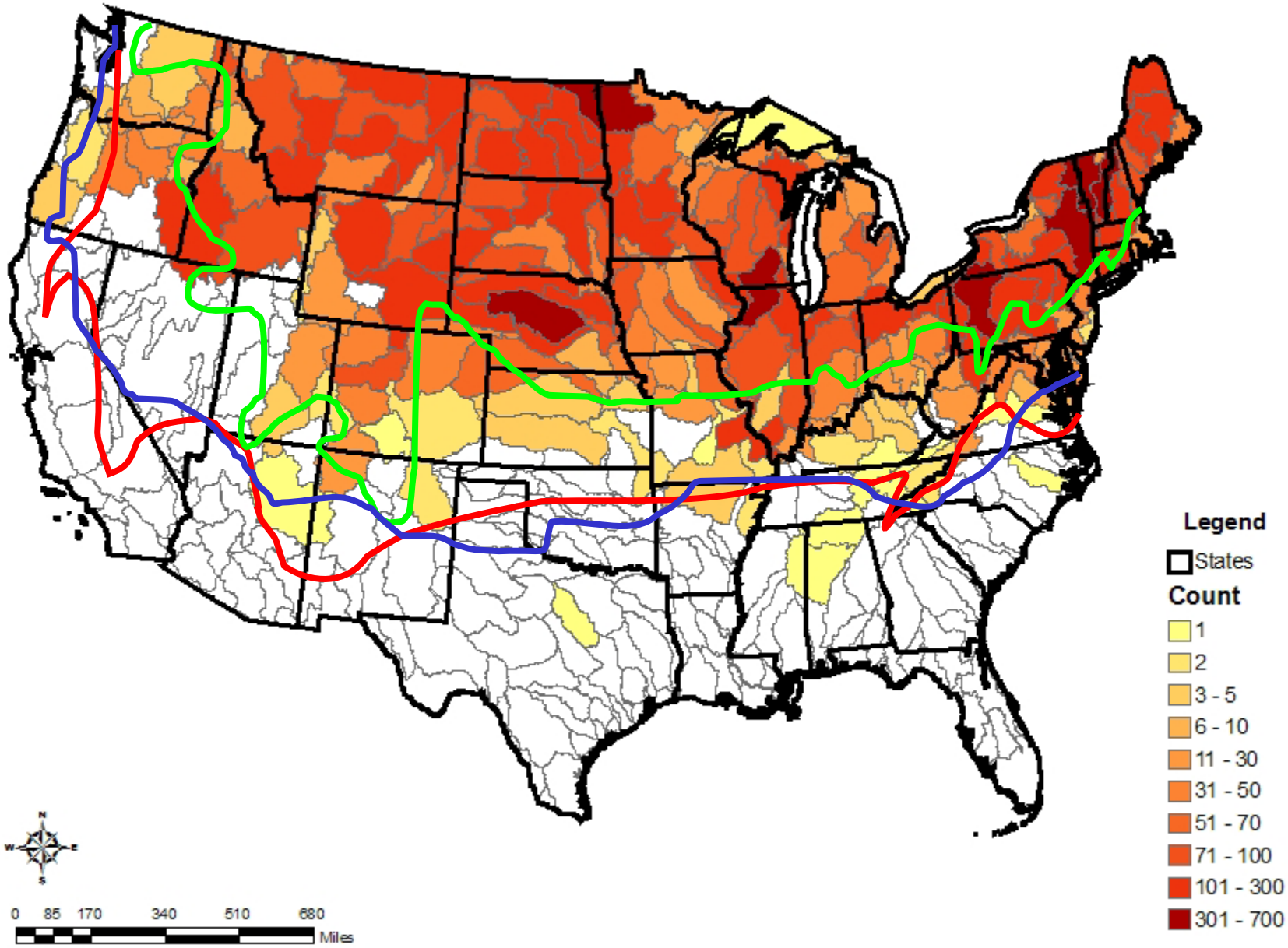
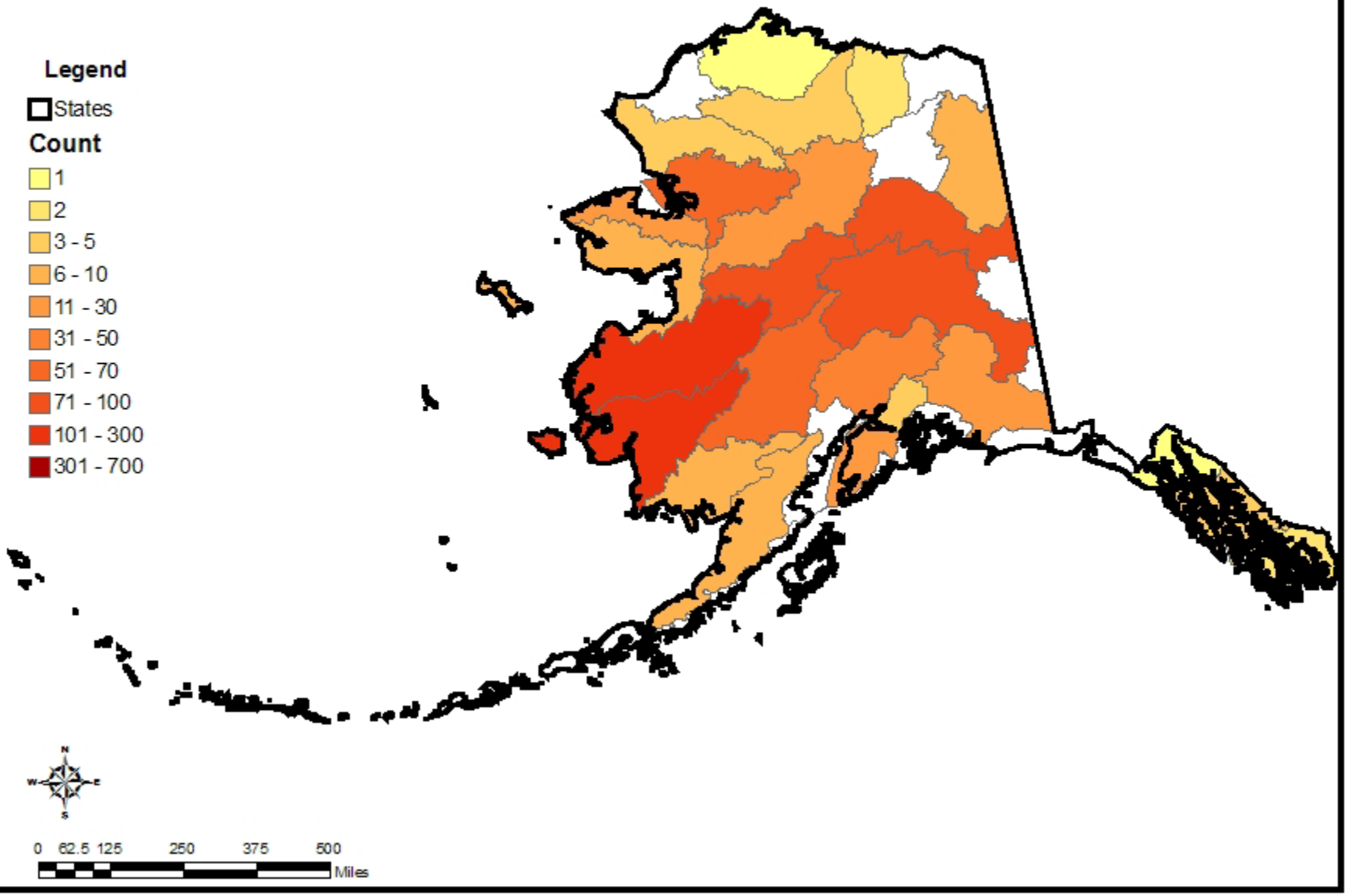

Ice Jam Count by State - June 2005
Legend
IceJams by State
Count
1 - 10
11 - 59
60 - 145
146 - 250
251 - 369
370 - 636
637 - 1093
1094 - 1422
N
W
E
S
0 80 160 320 480 640
Miles

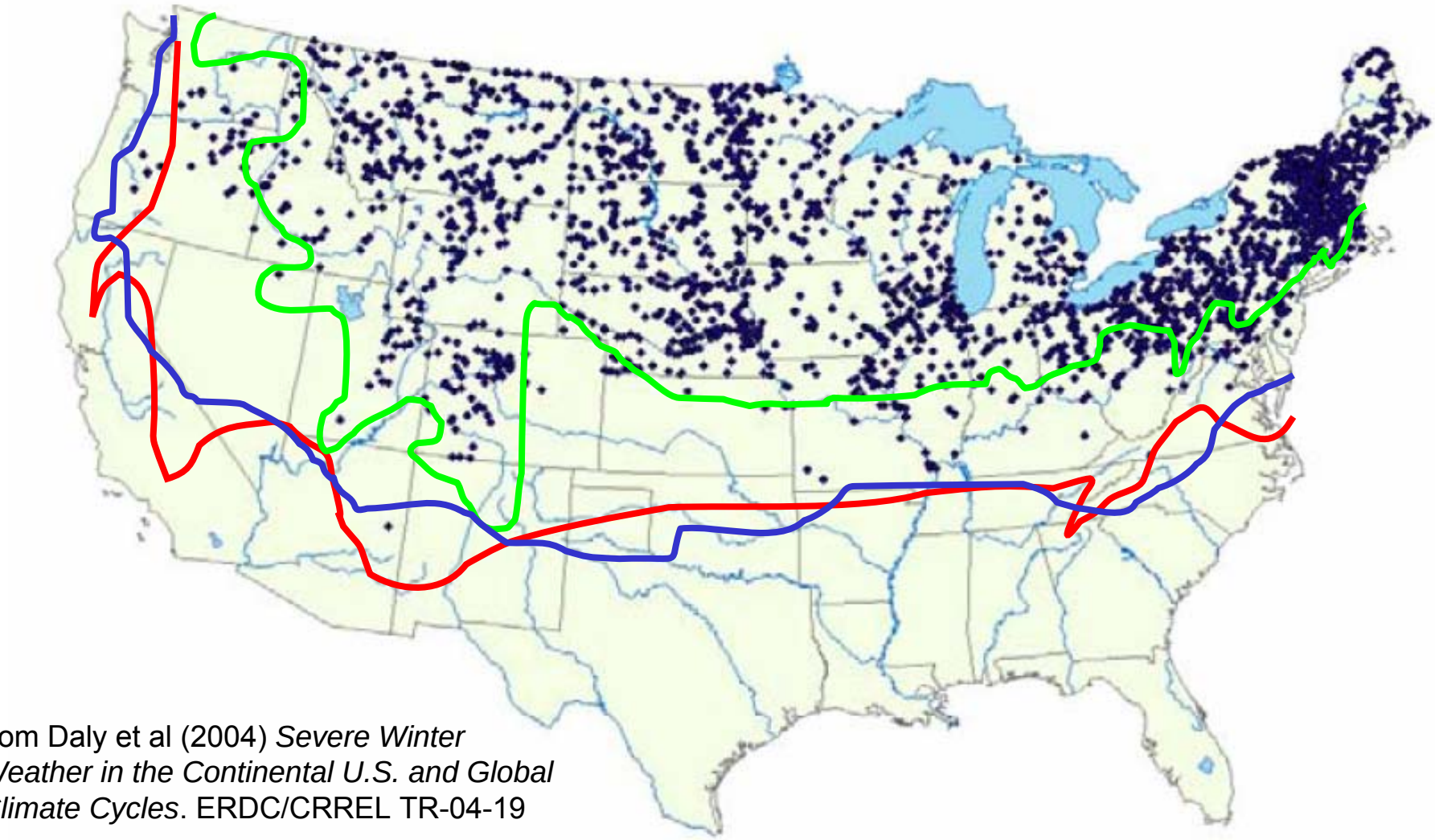
Ice Jam Count by Hydrologic Unit Code - June 2005



Ice Jam Count by Hydrologic Unit Code - June 2005



Ice Jams & Ice Covers (1950-2001)



from Daly et al (2004) *Severe Winter Weather in the Continental U.S. and Global Climate Cycles*. ERDC/CRREL TR-04-19

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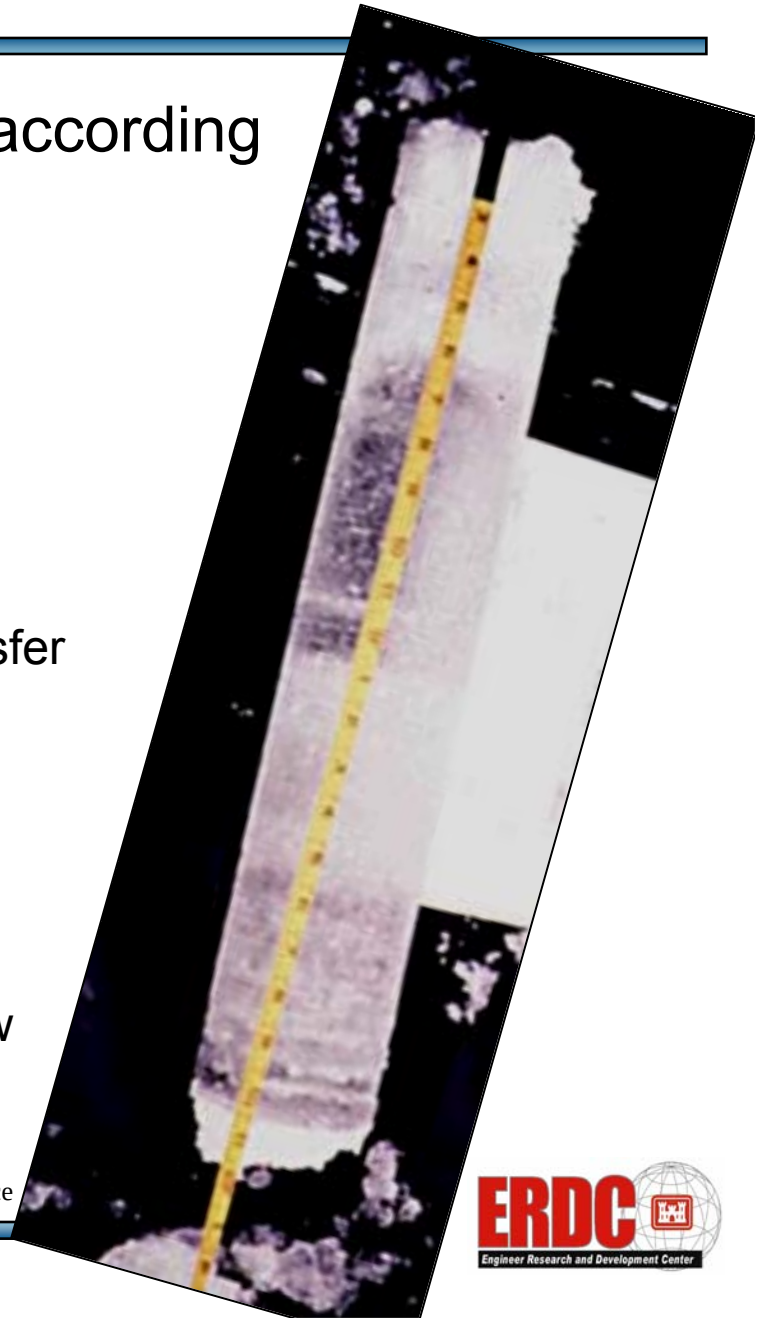
Basic Ice Processes: Formation

- The 2 basic ice types are classified according to their ice crystal structures
  - Columnar ice: Thermally-grown ice
    - Thermally grown
    - “Black” ice
    - Transparent, allows solar penetration, becoming "candled” as it decays
    - Tends to occur in more quiescent flow
    - Can estimate thickening using heat transfer theory
  - Fine grained ice: Frazil ice
    - Small ice particles or snow
    - “White” ice
    - Resists solar penetration
    - Tends to occur in dynamic, turbulent flow
    - Found in virtually all ice-affected rivers
    - Predominant ice type in northern rivers



Core from Israel River, Lancaster, NH, showing both thermal and frazil ice

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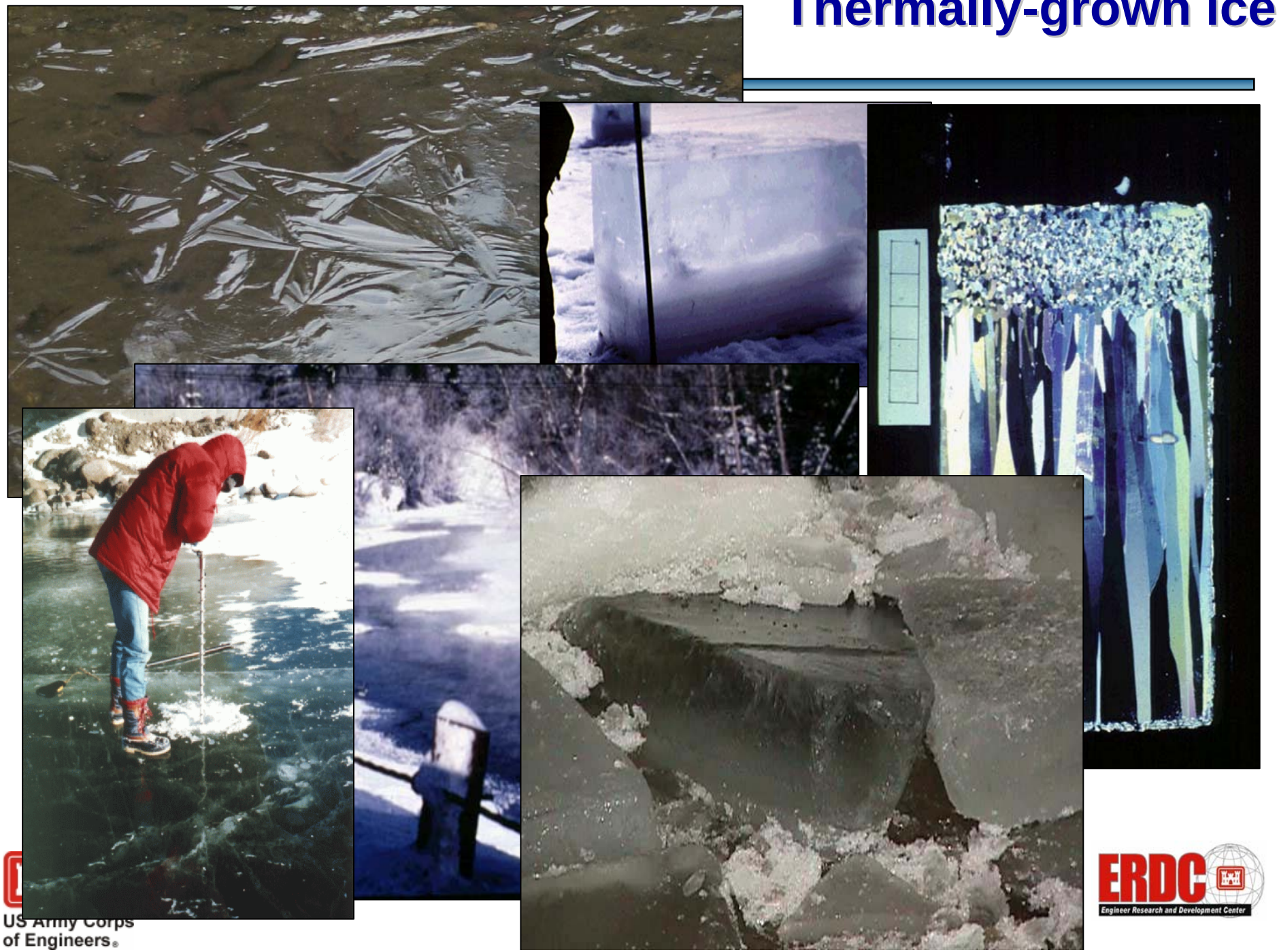
Thermally-grown ice



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Ice Cover Growth

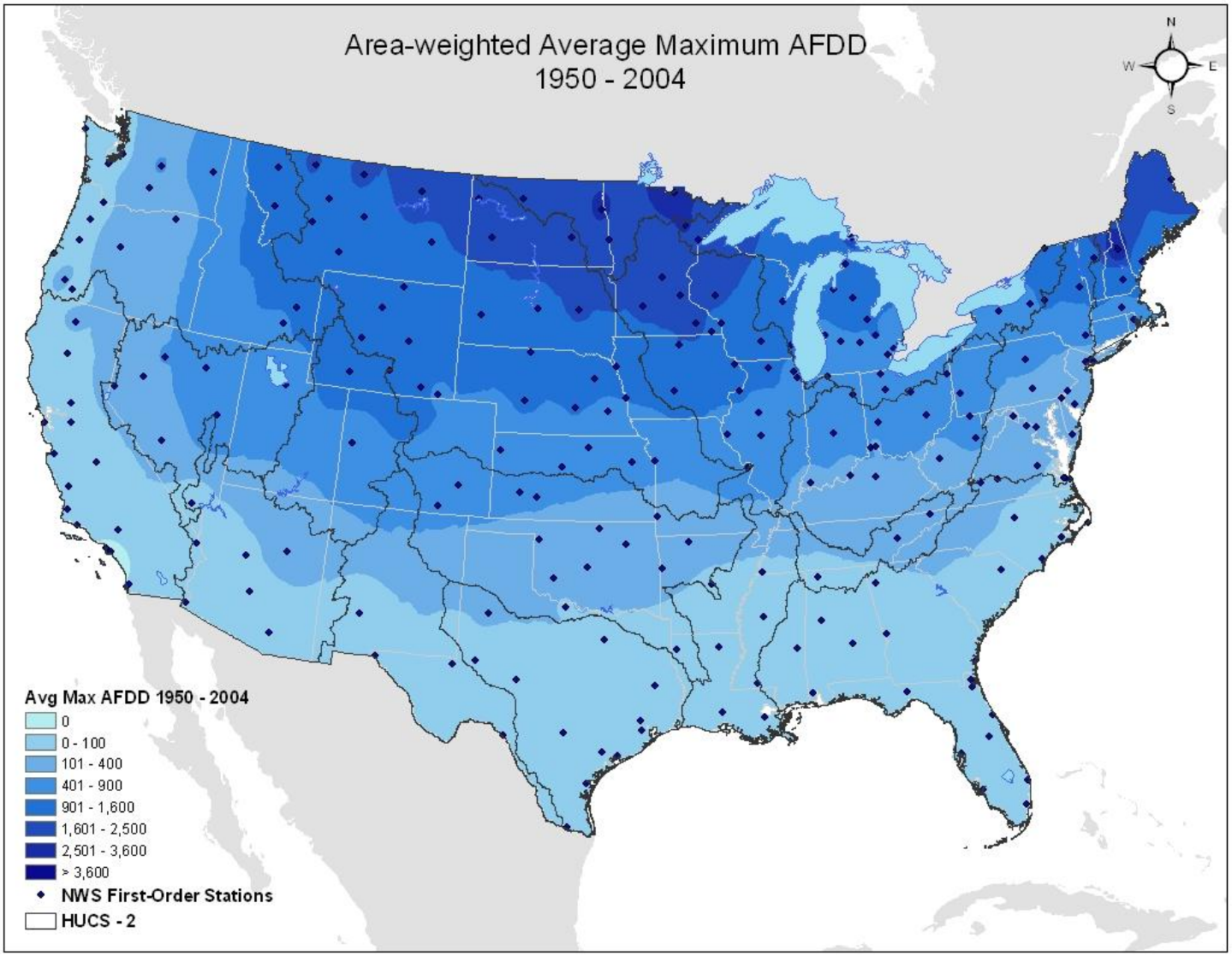
We can estimate thermal ice growth from modified Stefan equation

$$t(in) = \alpha\sqrt{AFDD(\circ F)}$$

Ice Cover Condition	α*	α †
Windy lake w/no snow	2.7	0.80
Average lake with snow	1.7-2.4	0.50-0.70
Average river with snow	0.4-0.5	0.12-0.15
Sheltered small river	0.7-1.4	0.21-0.41

* AFDD calculated using degrees Celsius. The ice thickness is in centimeters.
† AFDD calculated using degrees Fahrenheit. The ice thickness is in inches.

Average Maximum AFDD (1950-2004)



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http://www.usace.army.mil/inet/usace-docs/eng-manuals/cecw.htm

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Ice Engineering

U.S. Army Engineer Research and Development Center, Hanover, New Hampshire

Method to Estimate River Ice Thickness Based on Meteorological Data

Some knowledge of ice thickness is required for the design of structures—such as bridges, dams, weirs, locks, piers, intakes, channel stabilization measures, and coastal shoreline protection—in ice-affected rivers. One recent case illustrating the need for considering ice in the design of riverine structures is the failure of the McKeesport (Pennsylvania) Marina on the Youghiogheny River in January 2001 (Fig. 1 [Silver and Fuoco 2001] and 2). The marina was constructed in 1997 at a cost of more than $2 million. According to the ERDC-CRREL Ice Jam Database sources (National Weather Service 2001a, b; Veltri 2001), ice jam breakup, jamming, and failure resulted in the complete destruction of the marina by chunks of ice measuring up to one foot thick. Contemporary reports estimated that the damage began around 6:30 p.m. on 31 January, and by 8:37 p.m., the marina was torn away. Reconstruction costs for the marina have been estimated at more than $1 million.

Figure 1. Twisted docks at McKees Point Marina on the Youghiogheny River, Pennsylvania. Photo by Darrell Sapp, Post-Gazette.

Ice covers and ice jams can cause rapid increases in stage that can cause flooding and damage (Fig. 3). Numerical models of rivers to develop stage-frequency information required for modeling ice jams for flood damage reduction measures, flood insurance studies, and changes to the ice regime that occur from development in the floodplain or dam removal also require that ice thickness be estimated. Analyses of ice-induced scour and erosion in ice-affected rivers must include knowledge of ice thickness.

Unlike discharge or stage measurements, observations of ice thickness can be challenging to locate. The USGS does record ice thickness as part of its winter discharge measurements, but these records are often archived in paper form and can be difficult to access. Some local flood warning systems measure ice thickness. A good example is the Nebraska Ice Warning System (http://dnrdata.dnr.state.ne.us/Icejam/index.asp), which contains seasonal ice thickness measurements.

Given the lack of existing data, ice thickness must often be estimated. Because ice covers result from complex physical processes, there is not yet a method to account for all factors affecting thickness. This technical note presents a method to estimate ice thickness that results from heat transfer processes based on meteorological data.

Figure 2. Debris from the McKeesport Marina trapped above Emsworth Locks and Dam on the Ohio River about six miles downstream from Pittsburgh. Photo by Andy Tuthill, ERDC-CRREL.

ERDC/CRREL Technical Note 04-3 June 2004

EM 1110-2-1612

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

EM 1110-2-1612

30 October 2002

Engineering and Design
ICE ENGINEERING

ose. This manual, composed of three parts, pre
design, construction, and operation and mainten
for Corps of Engineers projects; provides in Par
the resultant flooding, including preventive mea
eering and operational solutions to ice problems

icability. This manual is applicable to all USA
sign, construction, operations, and maintenance.

ibution statement. Approved for public relea

rences. Bibliographic material is included at th

ussion. All Corps projects subjected to freezing
n lock walls, hydropower intakes, and lock appr
ice passage over spillways that scours the down
and shorelines, etc. Therefore, ice control meas
projects to improve operations and safety in cold
n of ice formation processes, physical properties,
nsiders the problem of ice jams and ice jam flood
Part III of this manual addresses the considerati
s, including the conduct of river ice management
ent plans.

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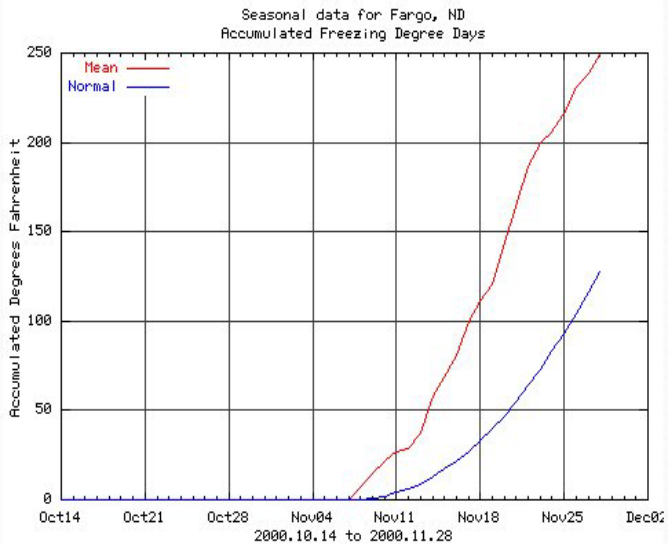
JOSEP
Colone
Chief

ual supersedes EM 1110-2-1612, dated 30 April

Seasonal AFDD Query Results



Seasonal AFDD: 249 Fahrenheit Normal AFDD: 128 Fahrenheit

Ice thicknesses for various conditions using the Stefan Formula:

Theoretical value:	16.2 inches or 41.2 cm	($K = 35$)
Windy lakes with no snow:	12.5 inches or 31.8 cm	($K = 27$)
Average lake with snow:	9.5 inches or 24.1 cm	($K = 20.5$)
Average river with snow:	6.7 inches or 17.1 cm	($K = 14.5$)
Sheltered small river with rapid flow:	4.9 inches or 12.3 cm	($K = 10.5$)

http://www.crrel.usace.army.mil/techpub/CRREL_Reports/reports/TN04-3.pdf

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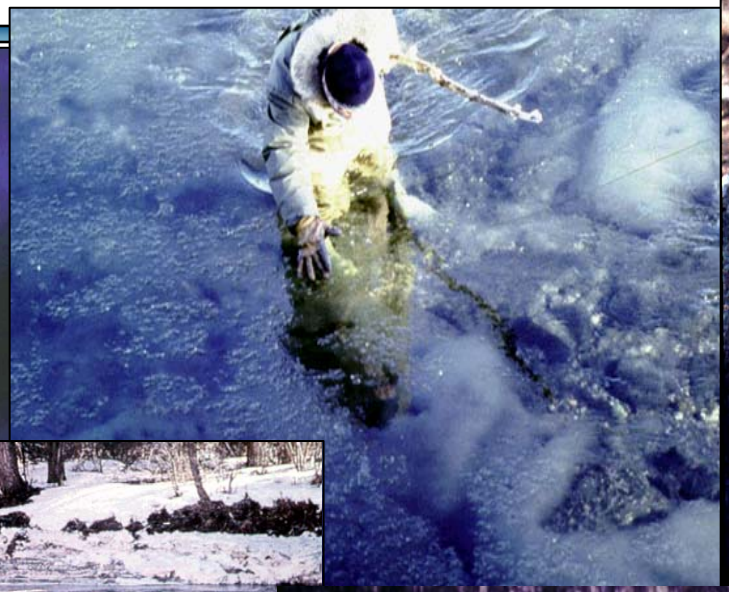
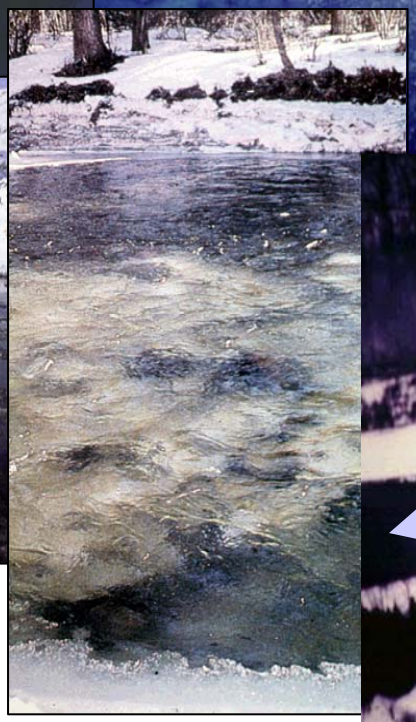
http://www.mvp-wc.usace.army.mil/ice

Frazil Ice





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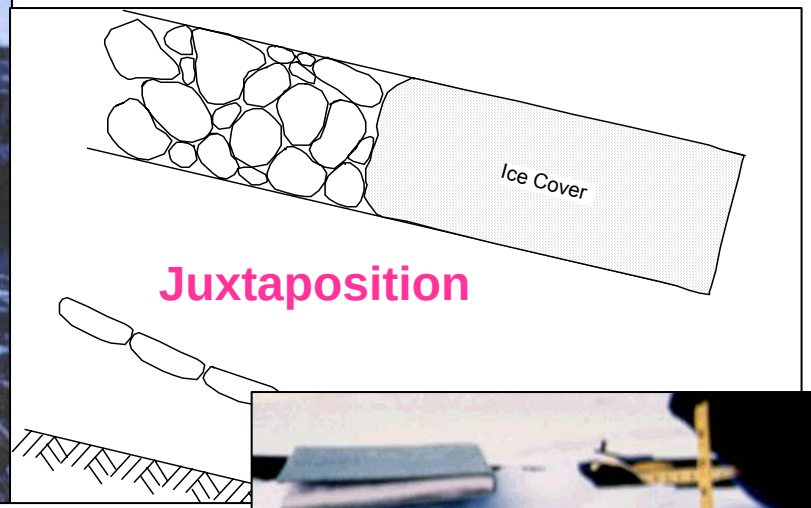
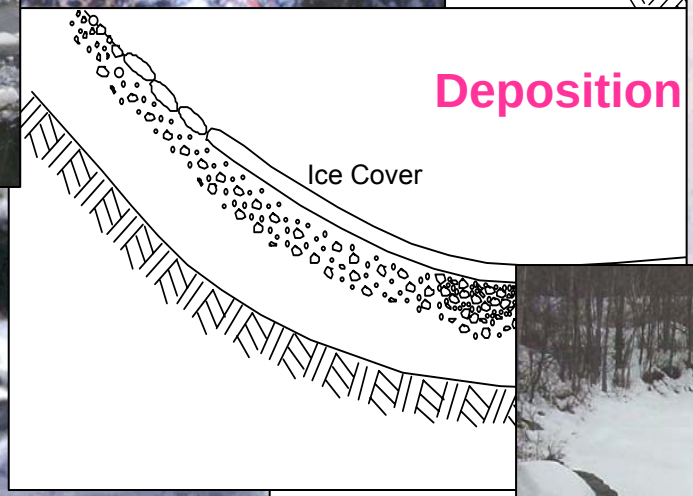
Dynamic Ice Cover Formation





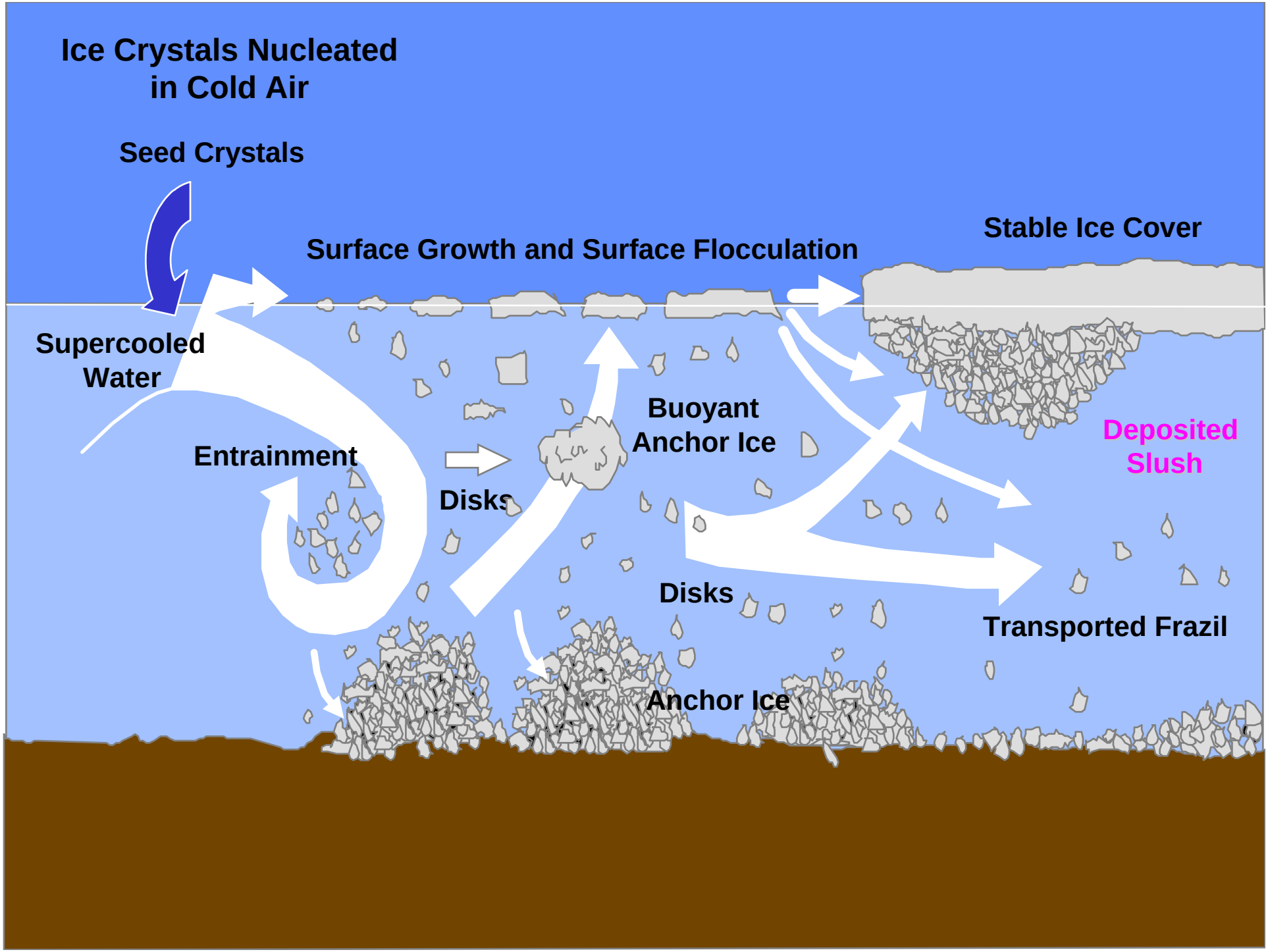
Dynamic Ice Cover Formation

- Bridging
- Juxtaposition of Floes
- Shoving of ice cover
- Underturning of floes
- Under-ice transport and deposition
- No ice-cover progression (unstable)

Increasing Flow Velocity

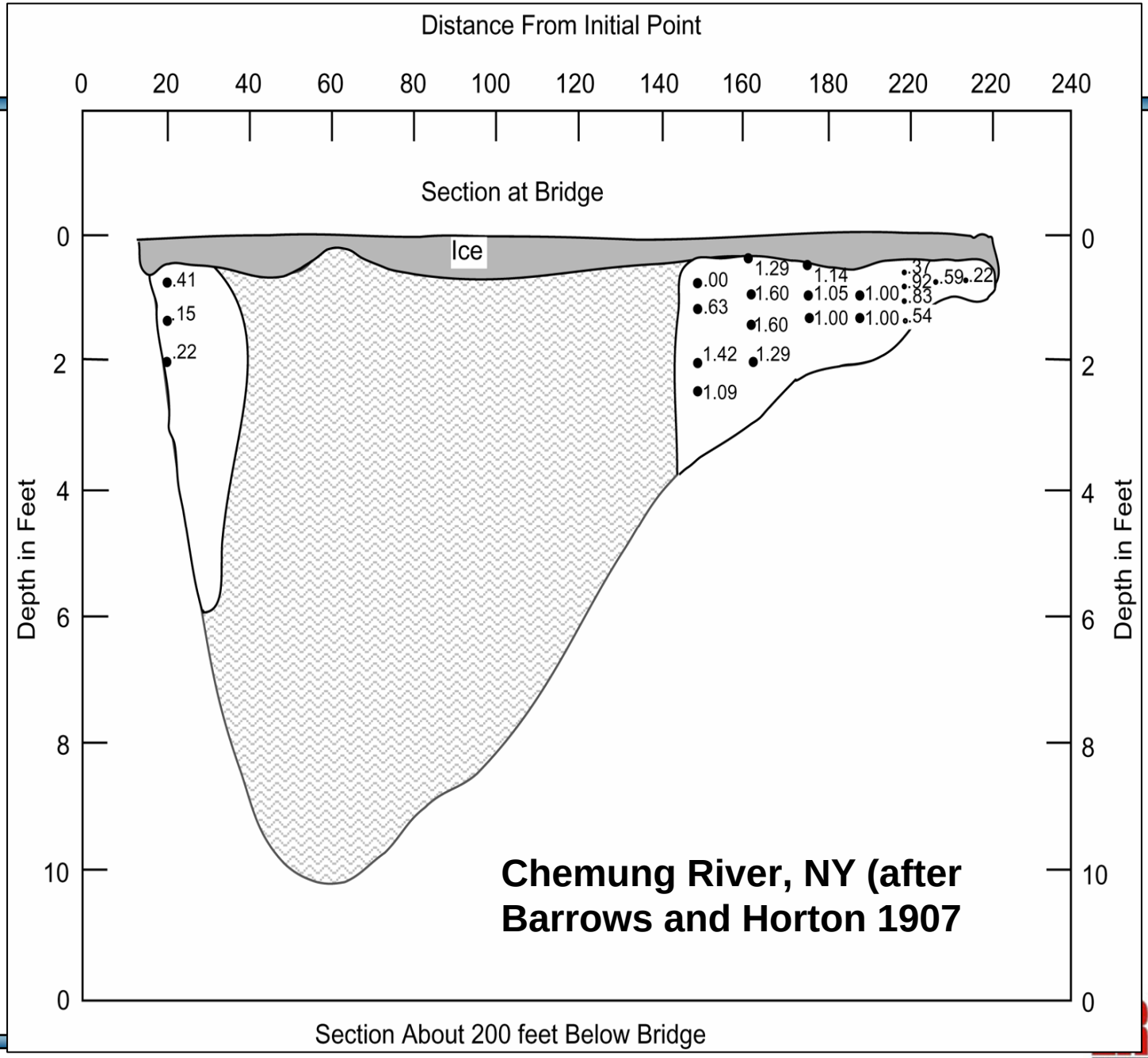
Froude Number $F = \frac{v}{\sqrt{gd}}$

Increasing Flow Depth


Ice Crystals Nucleated
in Cold Air
Seed Crystals
Surface Growth and Surface Flocculation
Stable Ice Cover
Supercooled
Water
Entrainment
Disks
Buoyant
Anchor Ice
Deposited
Slush
Disks
Transported Frazil
Anchor Ice

Frazil Ice Deposition

- Where to look for it:
  - Change in slope from steep to mild
    - Upstream end of impoundments
    - Confluence of smaller and larger tributary
  - Downstream from locations that are turbulent enough to remain open most of the winter (e.g., tailrace, rapids)
- What are the physical implications?
  - Thicker ice takes longer to break up than thinner ice
  - Potential jam location
  - Increases ice volume compared to no deposition
- When to be concerned about thicker than normal frazil deposition:
  - Sudden period of intense cold when there is little to no ice cover to insulate water surface



Chemung River, NY (after Barrows and Horton 1907

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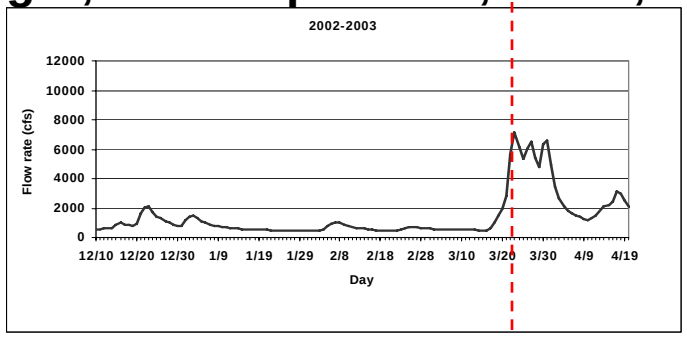
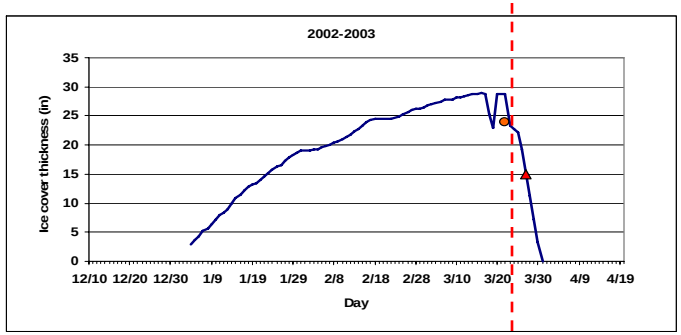
Ice Transport and Jamming

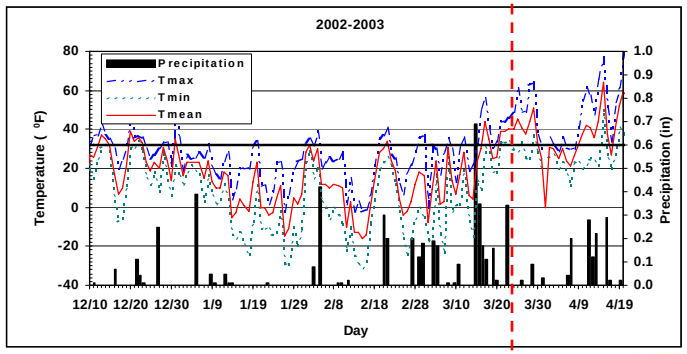
- Frazil floes or broken ice pieces move downstream until river's transport capacity is exceeded
  - Decrease in slope
  - Constriction
  - Obstruction (e.g., solid ice cover)
  - Bend, island
- Jam forms quickly
- Freezeup: underside is rough but smooths over time, increasing conveyance
- Breakup: underside is very rough, leading to erosion and scour; can smooth over time due to melt or deposition

Factors Affecting Ice Cover Breakup

Hydrograph, Ice Thickness (AFDD), Ice Strength, Air Temperature, Snow, Rainfall







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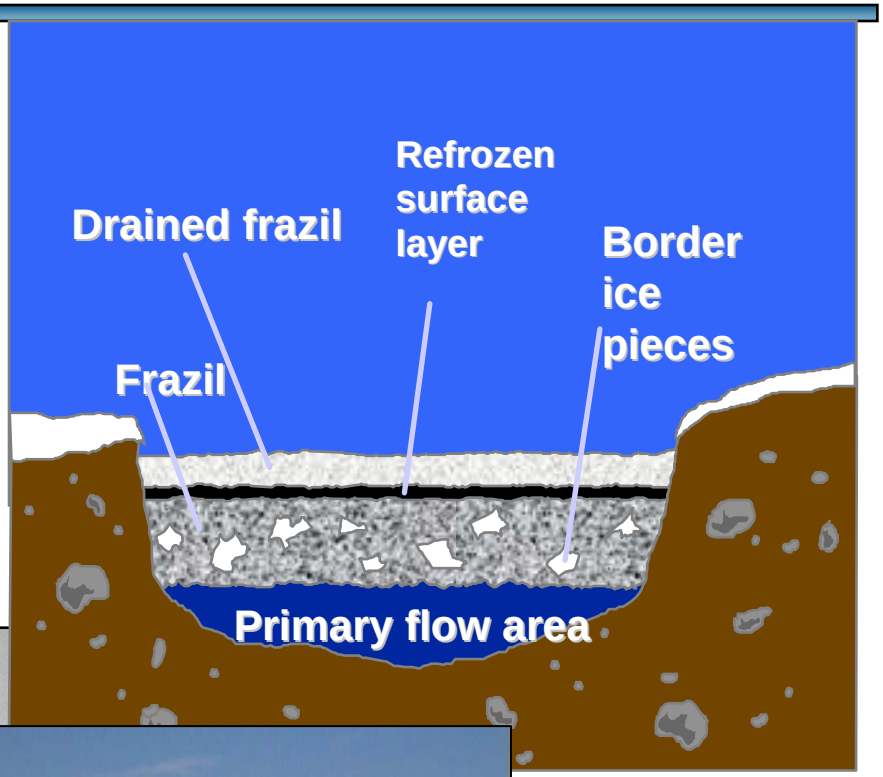
Freezeup Jams

- Early to midwinter formation
- Subfreezing air temperatures
- Fairly steady discharge
- Frazil and broken border ice
- Unlikely to release suddenly
- Smooth to moderate surface roughness



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Ice Cover Breakup

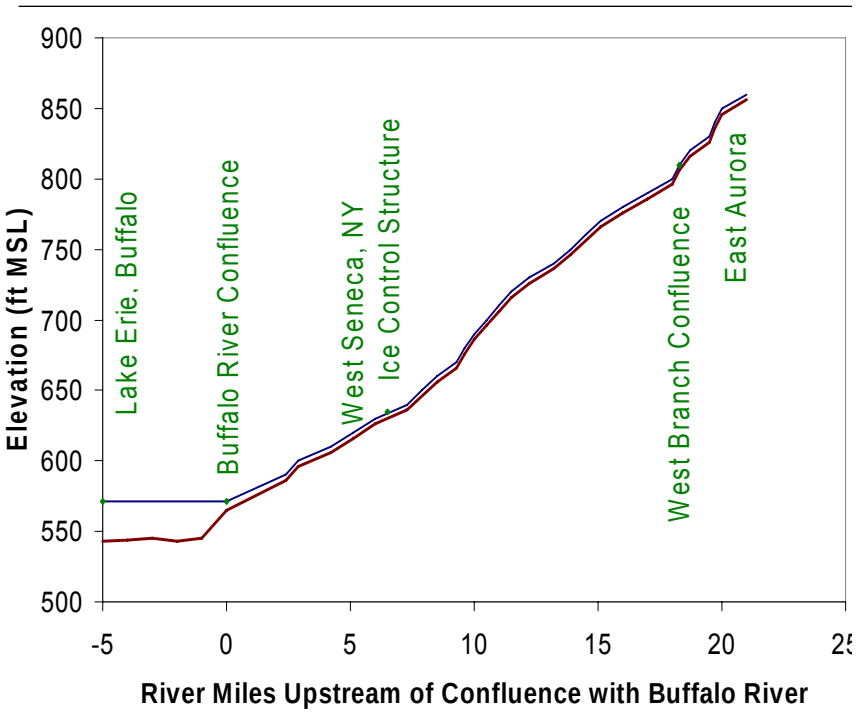
- Continuum from thermal to mechanical
- Thermal Breakup: Ice cover melts in place, **no flash floods**
  - Direct sunlight plays a large role
  - Surface color influences absorption of sunlight:
  - Dusting ice promotes melting
  - Water on ice decreases reflection, may promote melting
  - Open water areas absorb sunlight

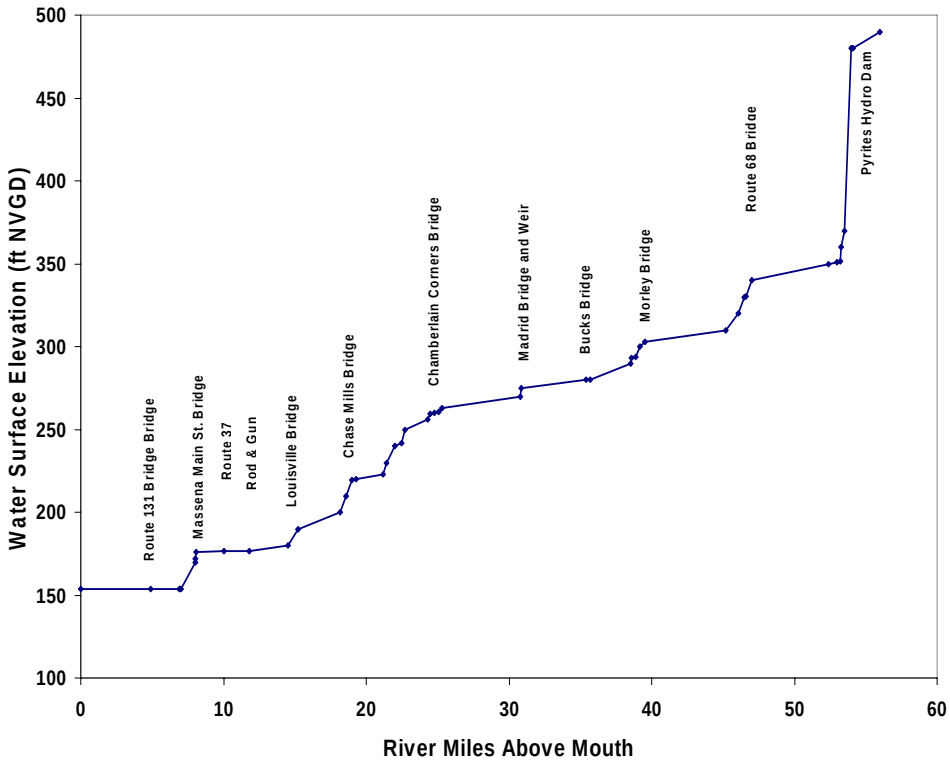
Ice Cover Breakup: Mechanical

- Mechanical breakup occurs when hydrodynamic forces acting on ice cover exceed ice cover strength
  - Results from an increase in discharge (=energy to system)
  - Precipitation event
  - Snowmelt event
  - Rarely, dam operation (large, sudden increase)
- Mechanical breakup tied to freezeup level:
  - Generally, ***lower freezeup level*** results in ***breakup at lower*** ΔQ $\Rightarrow$ breakup occurs unexpectedly
  - Lower discharges can mean decreased transport capacity $\Rightarrow$ jams in unexpected places
  - Mechanical breakup can result in **flash floods**
- Decreased discharge following freezeup can provide storage

Hinge cracks

Nature of Breakup Also Depends on River Bed Profile





Continuously steep river grading into flat section near downstream end:

-All ice may run and jam near mouth

Stepped river profile (e.g., small dams):

-Numerous steep sections may break up earlier, forming jams in flatter reaches

Sediment – and ice – tend to deposit at transition points from steeper to milder slope, decreasing ice conveyance and increasing ice jam potential

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Ice Cover Breakup

- **Rule-of-thumb:** stage increase of between 1.5 and 3 times the ice thickness needed to lift, break, and transport ice cover
- Often occurs later in impoundments, frazil deposition areas, and freezeup accumulations due to damped hydrograph and thicker ice

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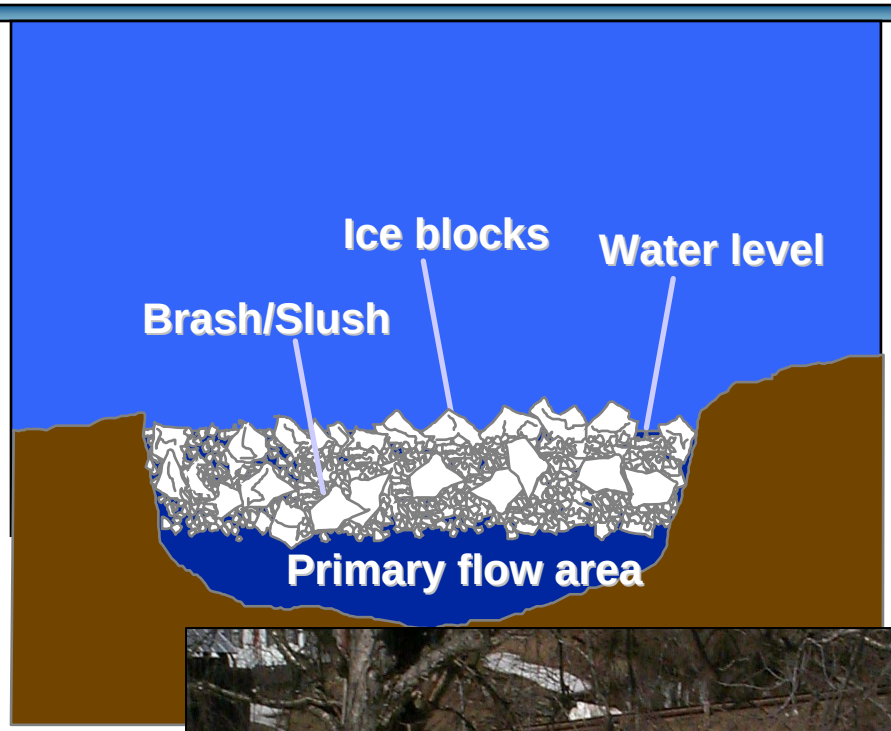
Breakup Jams

- Can occur any time after ice cover formation but generally mid to late winter
- Can form more than once per season
- Near-freezing air temperatures
- Form and progress quickly
- Highly unstable, with sudden failures ⇒ unsteady flow (surges)
- Moderate to extreme surface roughness
- Midwinter jams may freeze in place, causing additional problems later in the season



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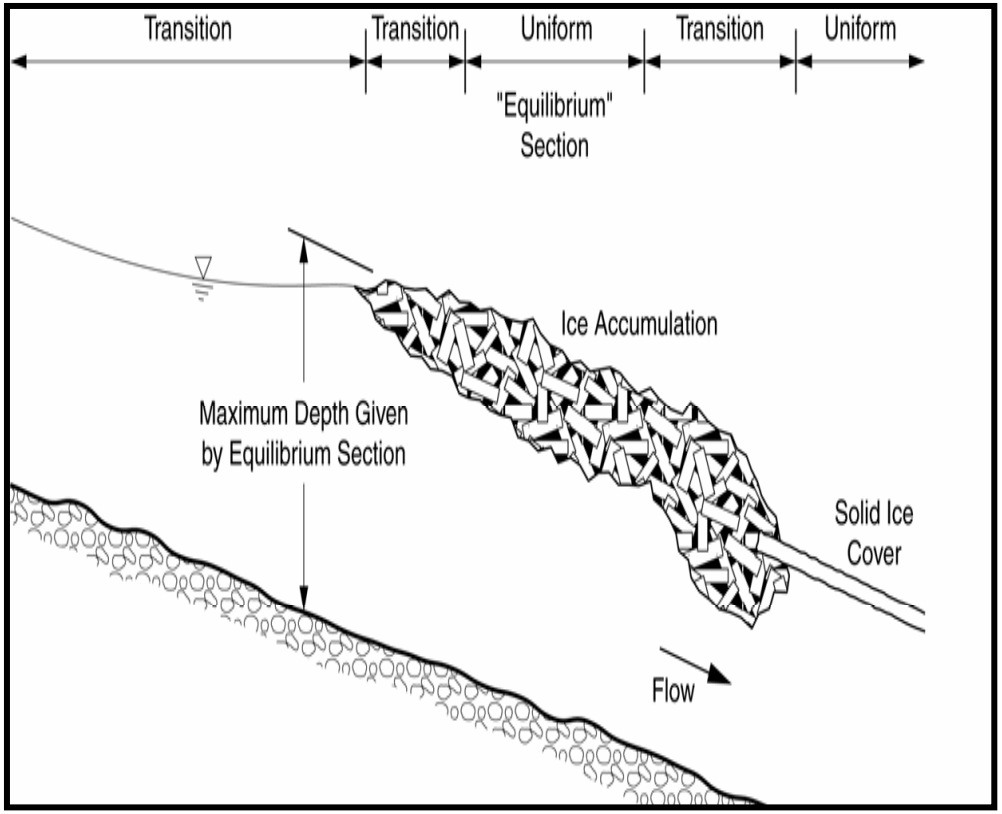
Modeling Ice-Covered Rivers

- Steady Flow
  - HEC-RAS (HEC-2 is obsolete!)
  - 1-D steady flow
  - Freezeup or breakup
  - Can model deposition using iterative process
- Unsteady Flow
  - UNET
  - Discrete Element Models
- Zufelt (1999) provides test to determine whether steady flow assumptions are violated to the point that unsteady flow is required
- 2 Dimensional Flow
  - Currently in development



Note: Flood insurance studies and re-studies at locations with frequent ice jams should include ice hydraulic modeling, or regulatory floodplain limits may not be conservative enough

Chronic Flooding

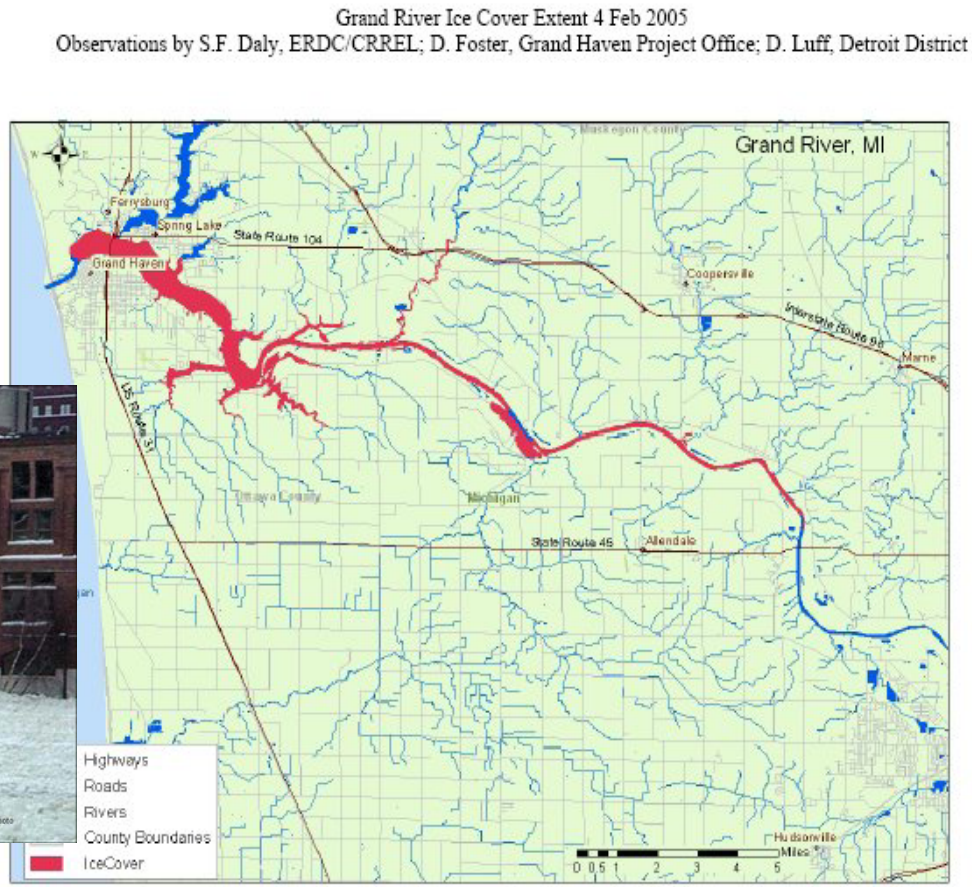
- Generally due to freezeup jamming or freezing of mid-season breakup ice jam
- Primary impacts can be predicted
  - Smoothing of bottom of ice cover over time increases conveyance
  - Ice profile
  - Ice strength, thickness
- Secondary impacts more difficult to predict

St. John River, US and Canada 2005

Chronic Flooding Example:

Grand River MI, January – February 2005

- Frigid temperatures, followed by mild temperatures and rainfall caused the existing river ice to break up and move, imitating jams in 5 different locations between Jan 18-22, 2005
- Sub zero temperatures resulted in freezing of the breakup jams and frazil ice production adding to the existing ice accumulations and causing freezeup jams
- The Grand River was above flood stage between January 18 and February 12
- 50 homes were evacuated (13 completely destroyed) and 4 businesses damaged



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Flash Flooding

- National Weather Service (NWS) definition:
  - A flash flood is a rapid rise in water levels associated with heavy rainfall or the failure of a dam or ice jam
- Theoretical process:
  - River ice cover forms
  - Increase in discharge supplies energy to system:
    - raising stage
    - breaking and moving ice
  - Transport capacity of river exceeded:
    - ice stops moving (jams) $\Rightarrow$ backwater
    - shoving and thickening due to incoming ice increase thickness at jam toe $\Rightarrow$ higher stages upstream (lower stages downstream)
    - jam progresses upstream, raising water levels

Flash Flood Example: Montpelier, VT

Wednesday, March 11, 1992

- **6:57 a.m.** A large ice jam on the Winooski River breaks loose about the Pioneer Street Bridge and travels through Montpelier. Ice jams just below the Bailey Avenue Bridge and blocks conveyance in the river.
- **7:05 a.m.** Filled with rain and snowmelt, the Winooski begins to overflow its banks along State Street and the North Branch Winooski River begins backing up onto Elm Street **(~ 3 m rise in <10 min)**.
- **7:15 a.m.** Water surges dramatically into low-lying areas behind Main and State Streets, floating propane tanks from moorings, flooding parked cars and inundating store basements.
- **7:56 a.m.** Two to three feet of water is reported in front of Days Inn on State Street where an estimated 100 people are stranded. Flood waters pour onto Main Street, stalling cars and making the road impassable. Backed-up water from the swollen North Branch flows upstream on Elm Street **(~4-5 m rise in an hour)**.
- **8:09 a.m.** Evacuations begin of hundreds of stranded residents, workers and state employees on Main, State and Elm Street. Some wade to safety, while others are taken out by boat or by fire engines and dump trucks.

excerpted from: Ice & Water: The Flood of 1992 - Montpelier, Vermont, Copyright © 1992 "Ice and Water" Committee

Jim Cole, Associated Press
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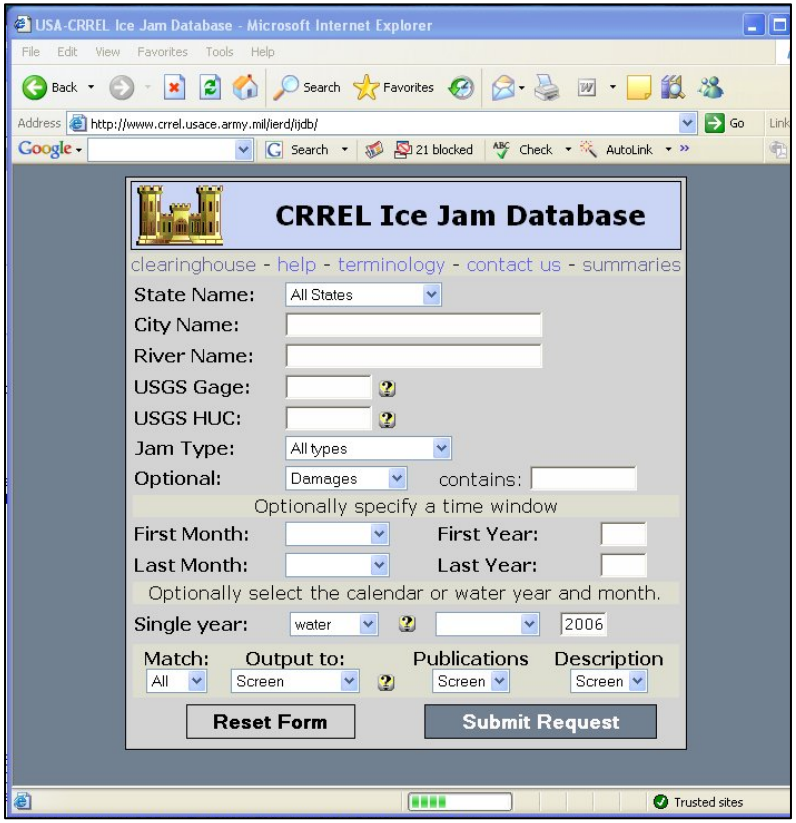
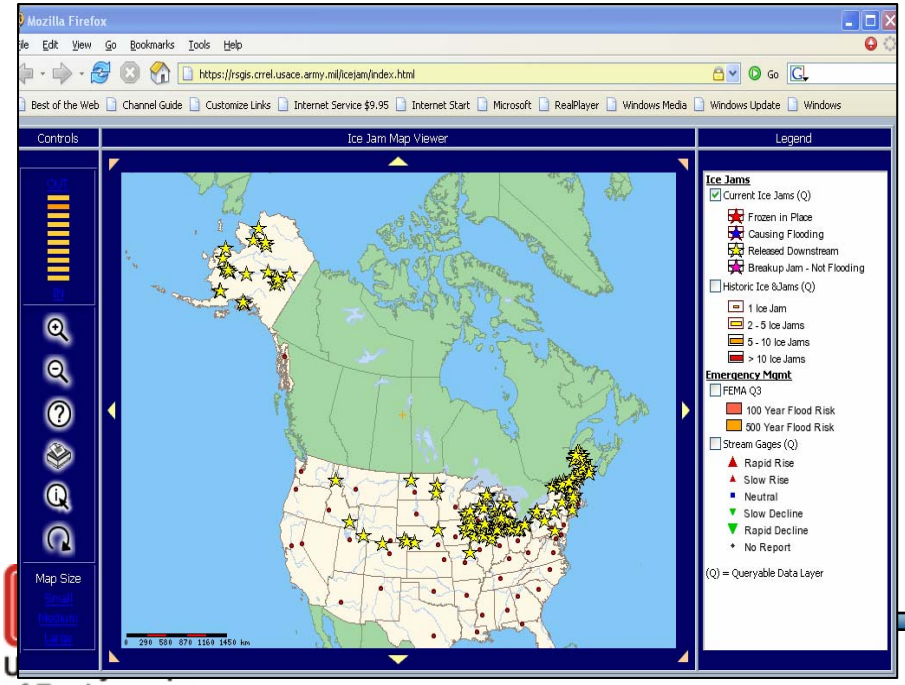
CRREL Ice Jam Database

Major source of data: CRREL Ice Jam Database

- Database begun 1990
- Now >14,900 events
- 1785-2006
- Ice information available from text-based database or rapid mapping tool
- Emergency management, design and engineering studies



http://www.crrel.usace.army.mil/ierd/ijdb/



Select “Current ice jams” from http://www.crrel.usace.army.mil/icejams/index.htm

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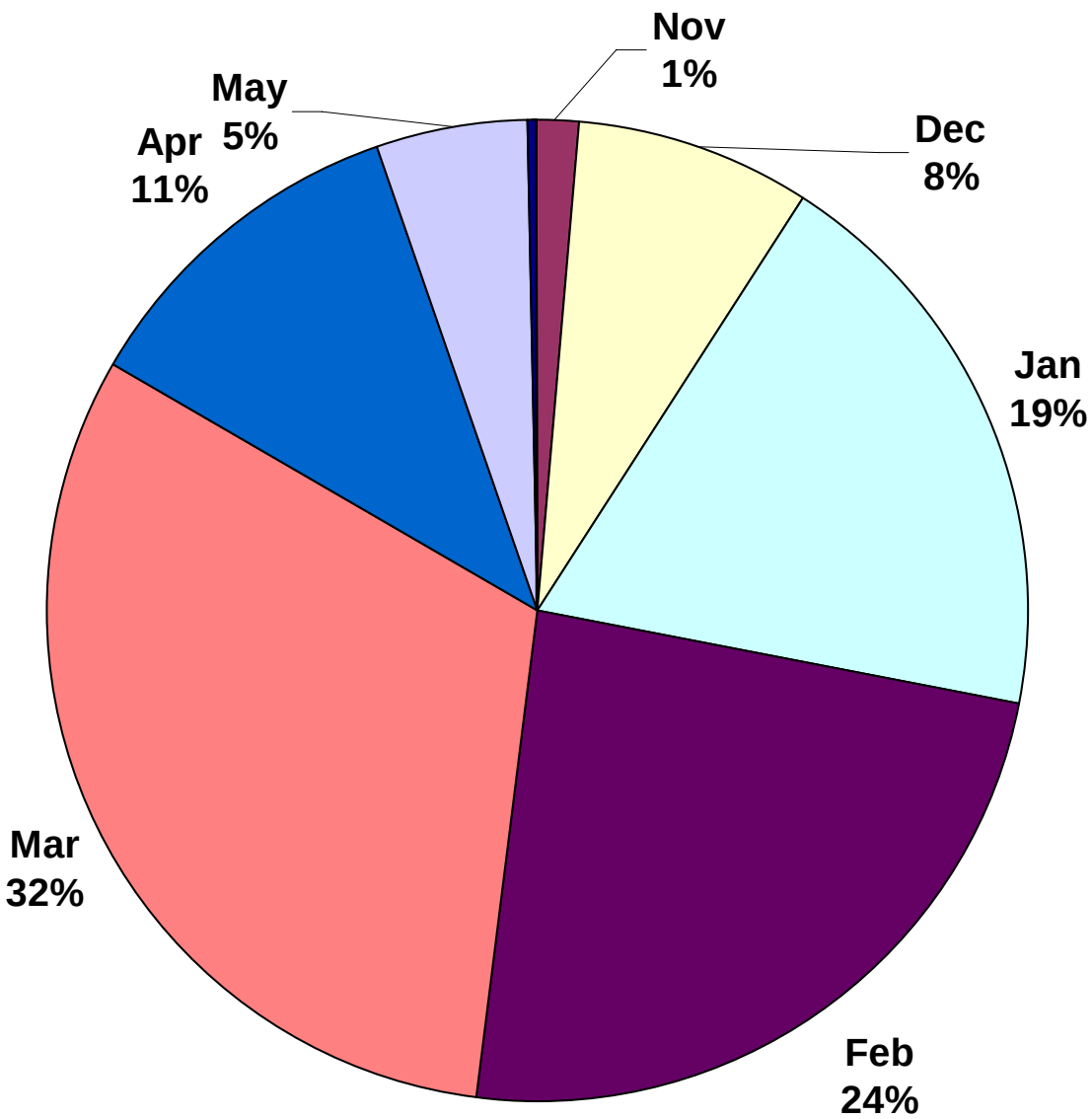
% of US Ice Events By Month



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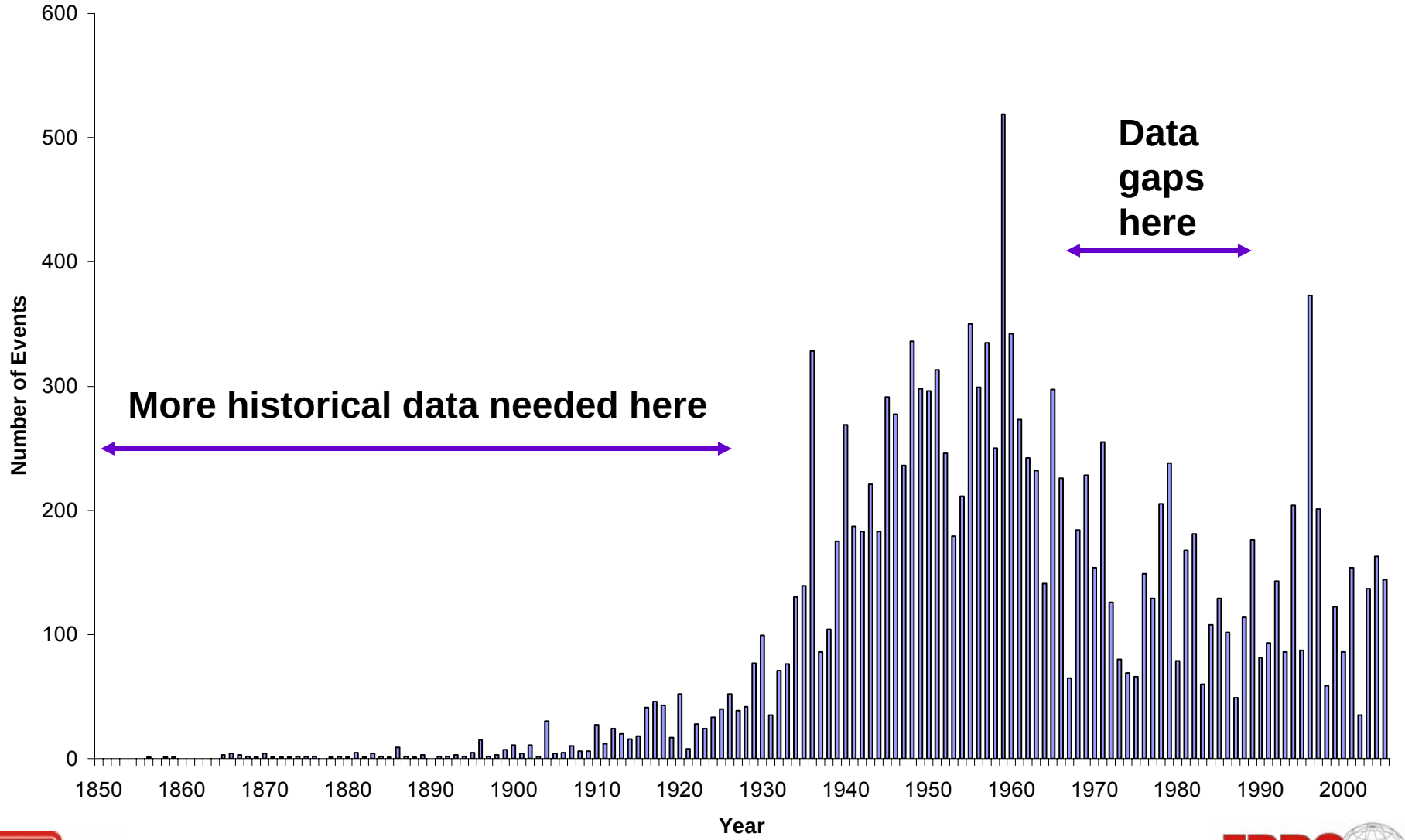
Number of US Ice Events Since 1850



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Ice Jam Impacts

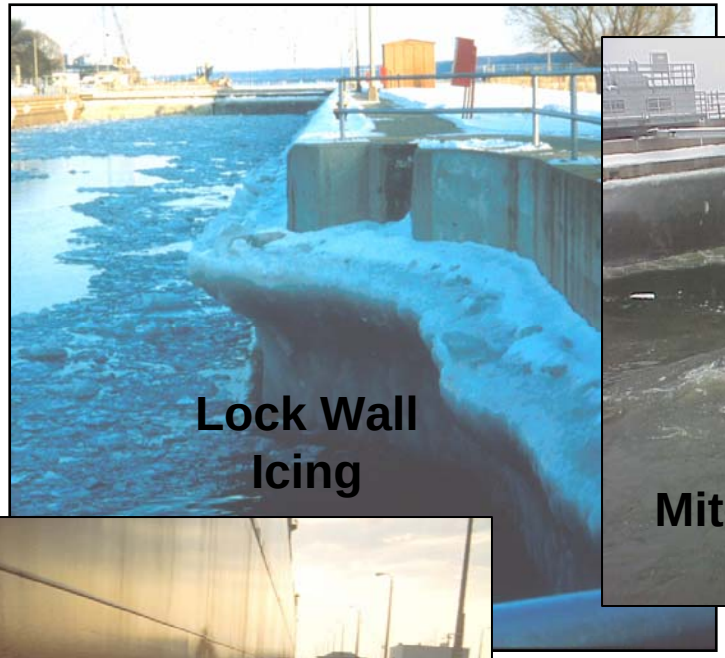
- Structural damage
  - Intake blockage — Can predict reasonably well from air, water T
  - Ice forces — Improving risk & uncertainty, need methods
  - Scour under ice — Just beginning
- Reduced conveyance
  - Flooding upstream from jam — Some improvements
  - Intake daylighting downstream — Can predict reasonably well
  - Ice jam prediction — Need to reduce error
- Geomorphology
  - Bank failure — Just beginning
  - Erosion and scour — Just beginning
  - Channel shifting — Just beginning
- Habitat
  - Fish overwintering/spawning areas — Just beginning
  - Microbial communities — Just beginning
  - Riverine margins/estuaries — Just beginning

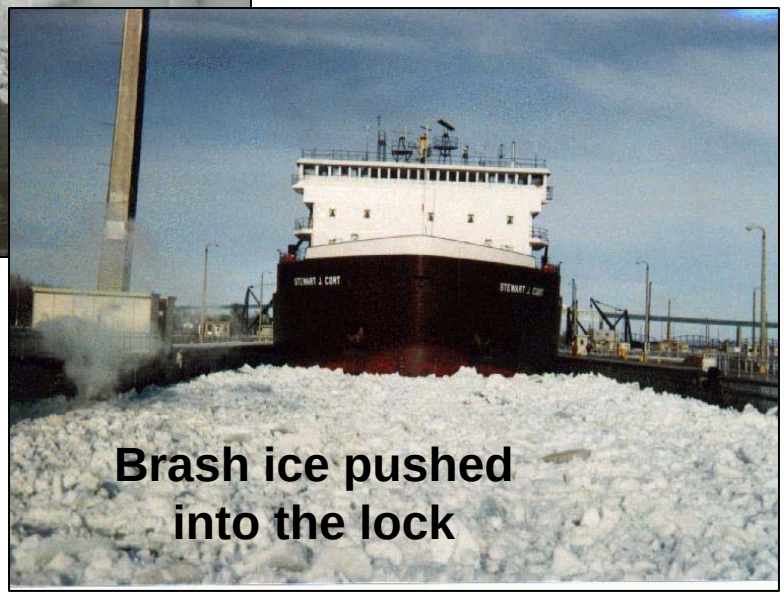
R&D: Ice Jam Prediction

- Simple method for wide area:
  - Joint CRREL-NWS NCRFC: Development of Empirical Threshold Models for Ice Jam Forecasting
  - Collect and develop ice jam data for selected sites nationwide
  - Develop empirical threshold indicators based on information that is readily available to the RFC's or could be easily derived from existing data sources
    - river ice formation
    - ice cover breakup
    - Ice jam formation
    - ice jam flooding
  - Assess science and software implications of including indicators in the operational river forecast processing stream

- Site-specific:
  - New/improved multivariate statistical methods (e.g., spatial correlation, multidimensional scaling)
  - Artificial intelligence (ANN, genetic algorithms)
  - Dynamic analysis (further exploration of analytical expressions)

R&D: Persisting Ice Problems at Locks





Normal lockage time = 45 minutes
Lockage time in heavy ice = 2 to 30 hours

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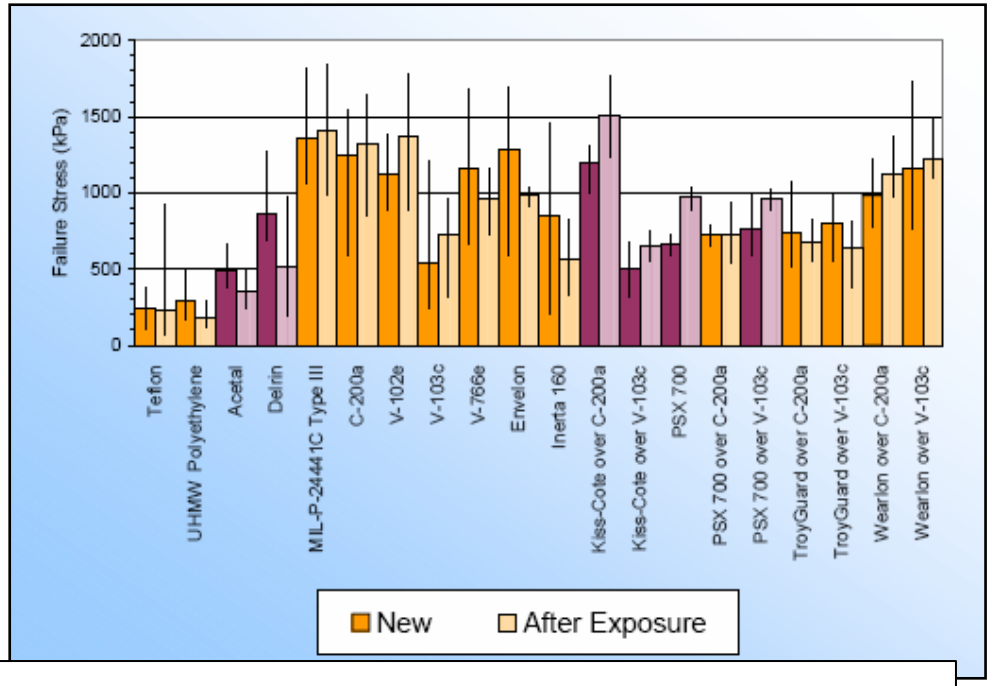
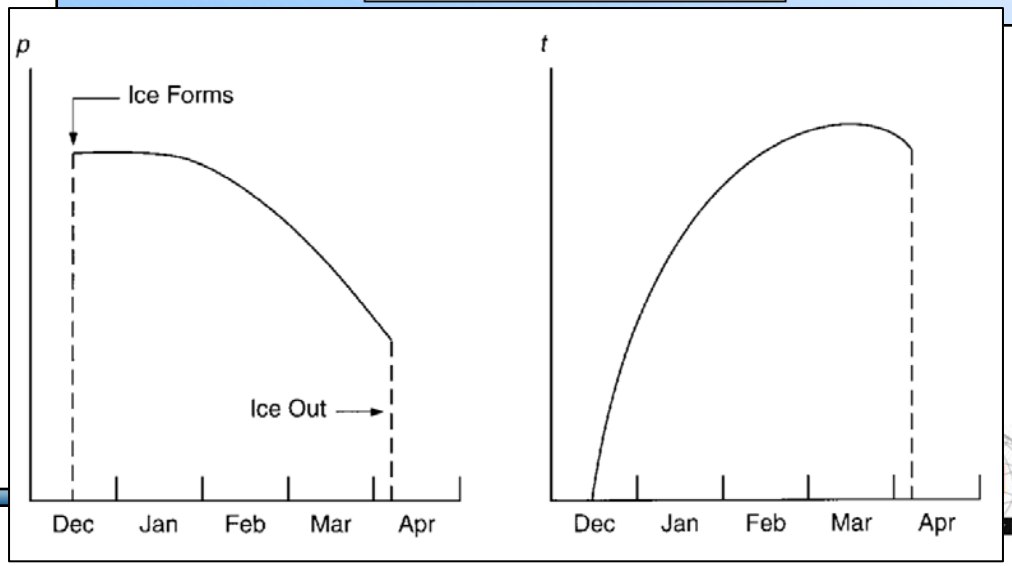
R&D: Ice Forces on Structures

- Persisting ice problems at locks
  - Bubbler designs improved
  - Require full lock wall/gate solution for deicing
- Ice forces on bridges
  - Update methods to account for risk and uncertainty
  - Include trends of ice strength, *p*, and thickness, *t*, throughout a typical winter season
- Discrete element modeling of ice and debris for engineering design





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Figures from R Haehnel

Ice Impacts on Bridge Piers

All 2005 Events

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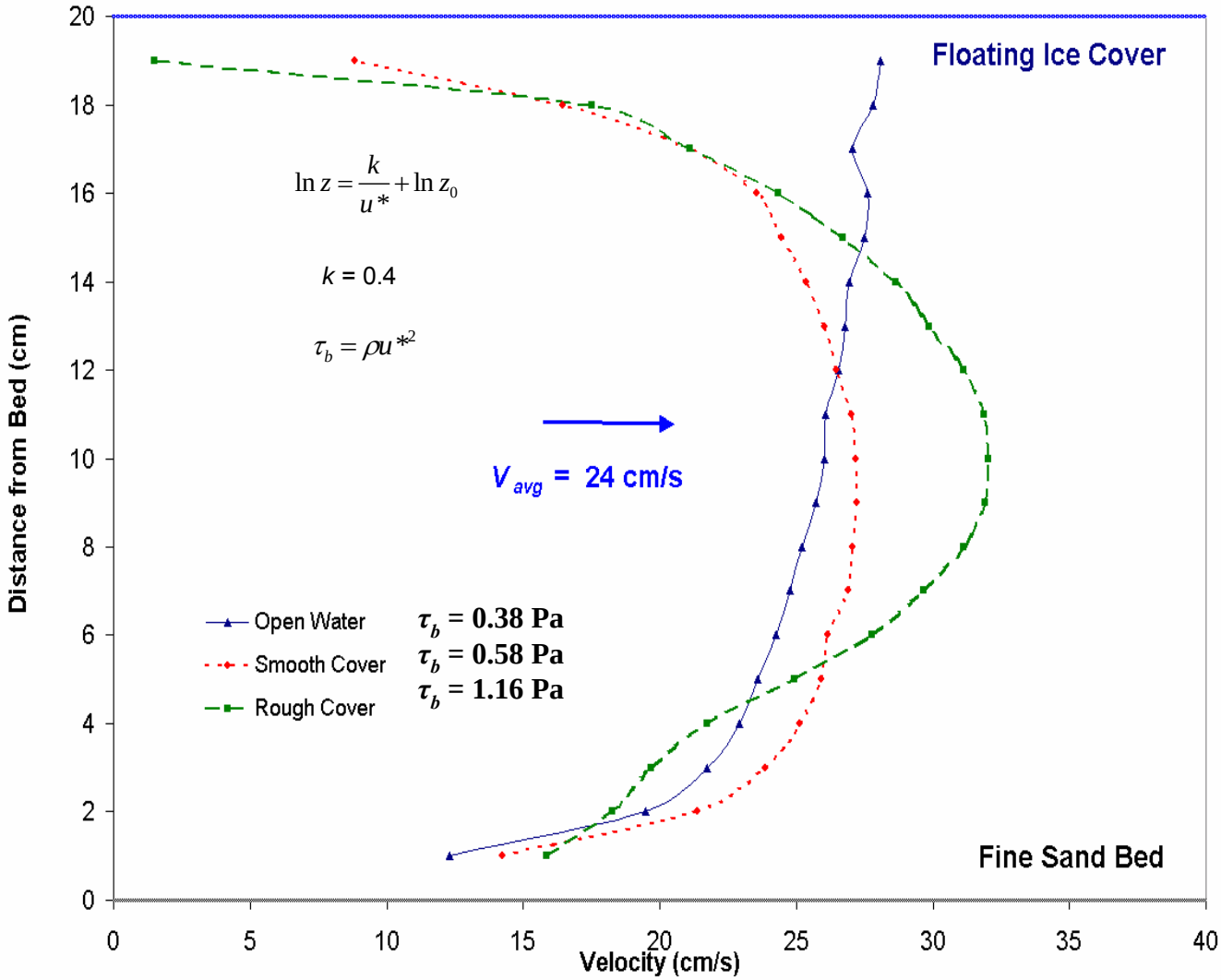
R&D: Scour Under Ice Covers

Effect of Ice Cover on Velocity Profile and Bed Shear



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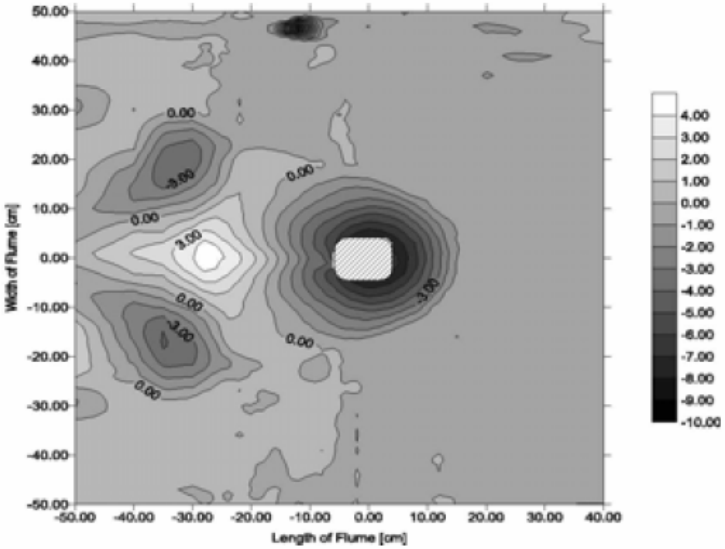
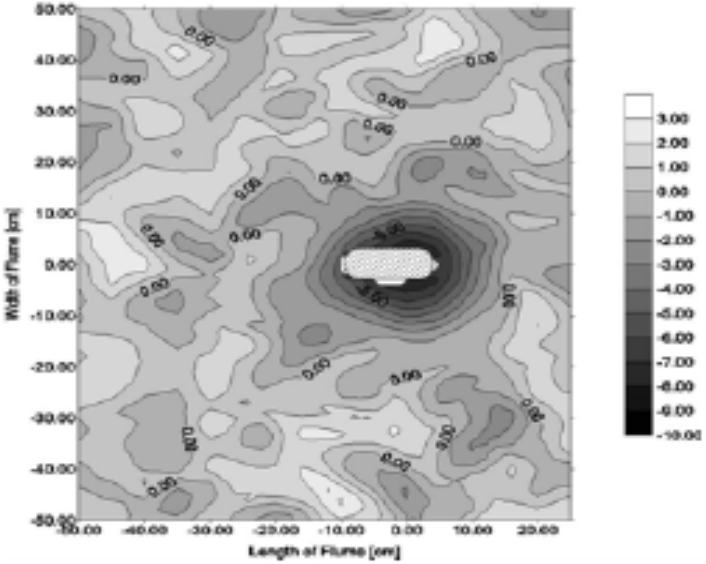
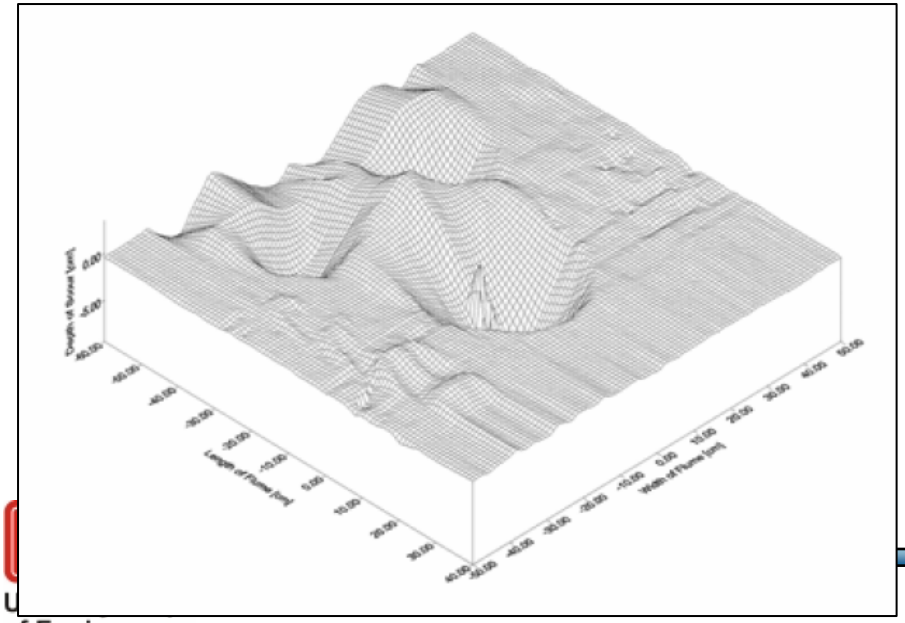
from flume experiments of Hains and Zabilansky (2004)

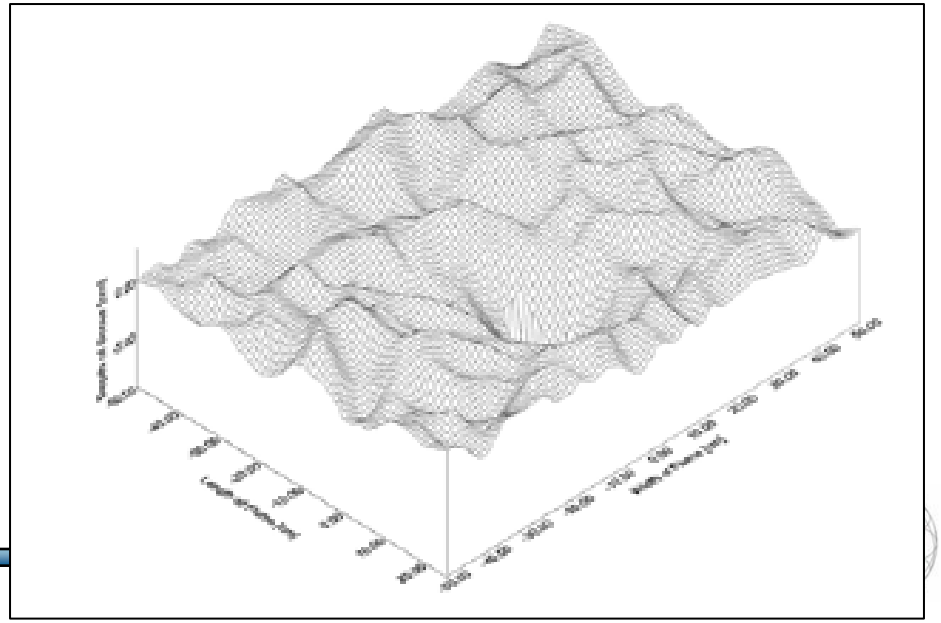
Smooth Ice Cover

Rough Ice Cover

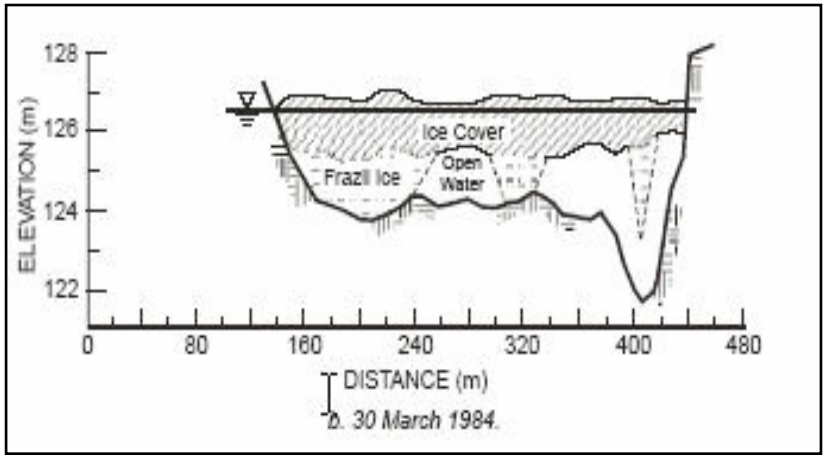




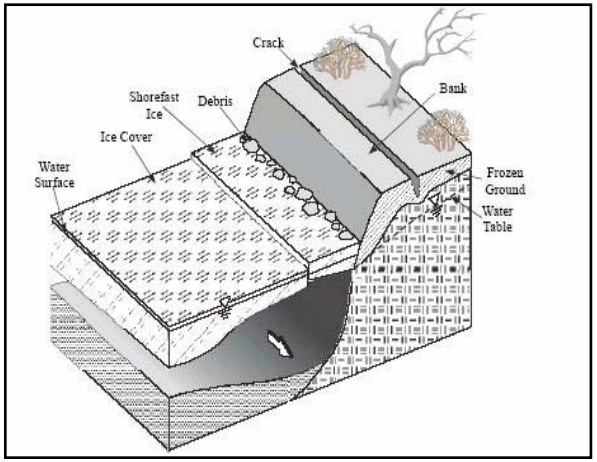




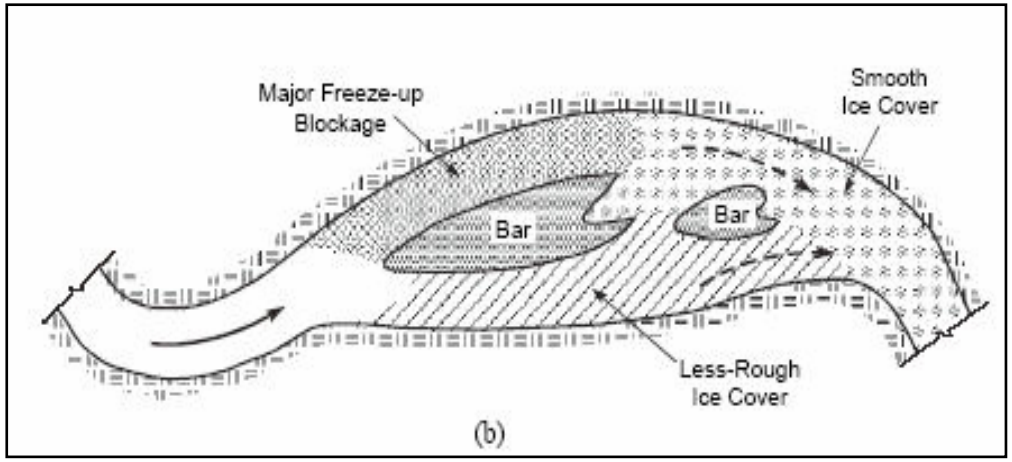
Ice-Sediment Processes During Ice Cover Formation



Frazil ice blocks portions of cross section concentrating flow along bed or channel sides.



High velocity flow forced against channel side by ice cover. Combined with freeze-thaw, may contribute to bank failure.



Ice cover resists flow in one channel shifting flow into another, eroding a new thalweg.

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Figures from Ettema and Daly (2004) "Sediment Transport Under Ice" CRREL TR-04-20.

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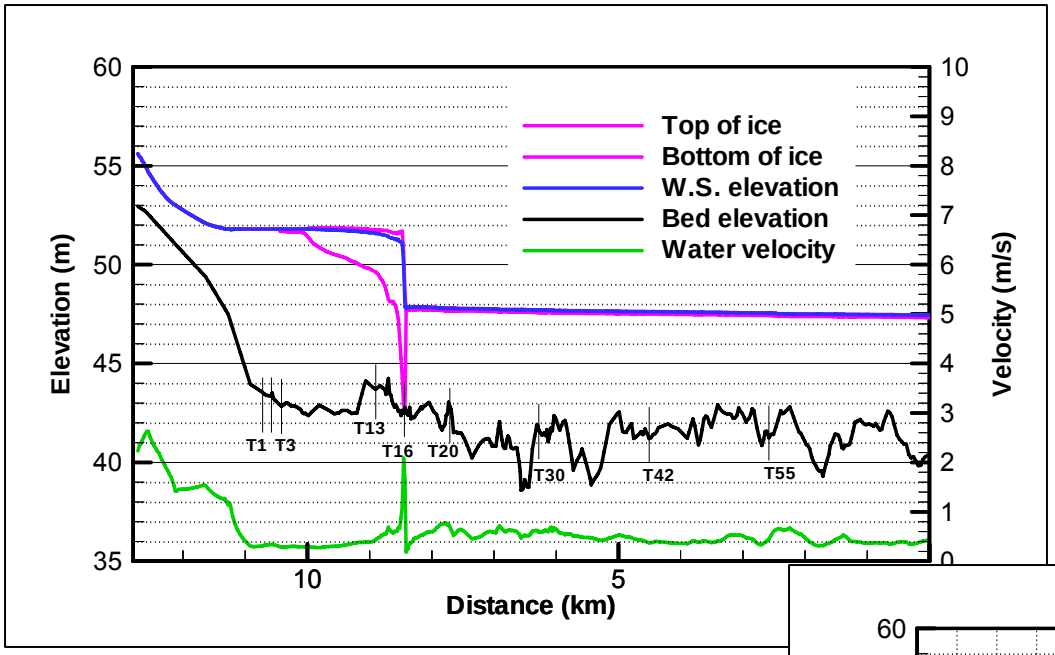
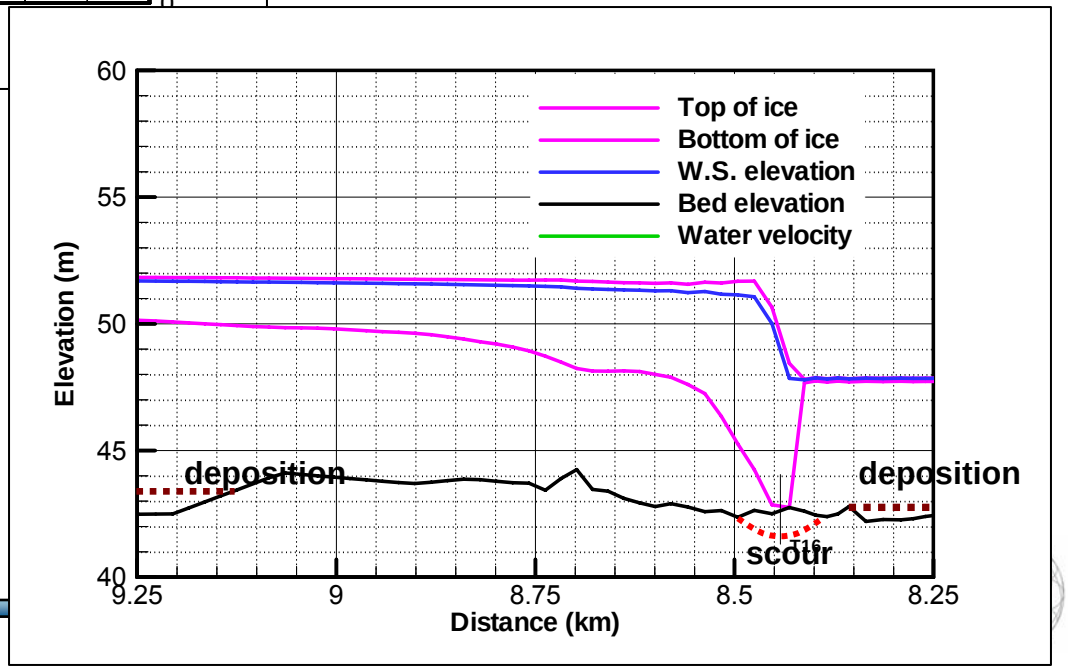
Ice Jam Related Sediment Transport



Jam may thicken to the point of grounding and the moving ice may mechanically scour the river bed

Ice jam can result in high water velocities near the bed

Scour may occur beneath the toe with deposition possible upstream and downstream of the jamming location



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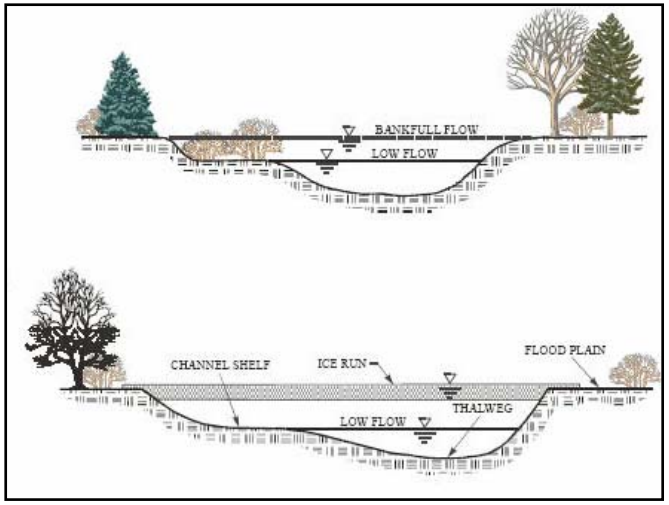
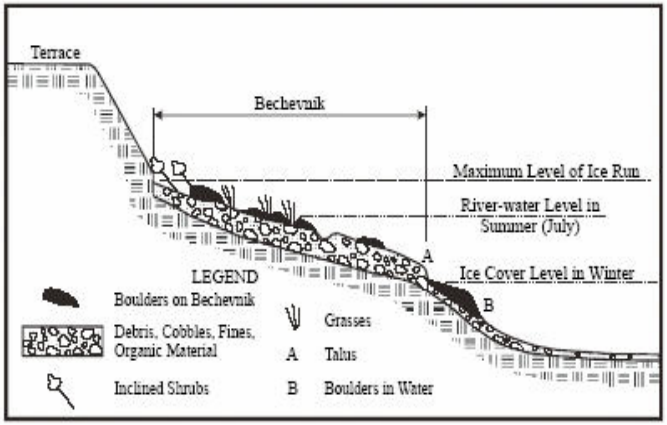
Figures from AM Tuthill

Ice Effects on River Banks and Riparian Vegetation



Plants and trees on floodplain and banks may be absent due to ice



Characteristic ice-resistant species and bank materials found at various levels

Figures from Ettema and Daly (2004) "Sediment Transport Under Ice", CRREL TR-04-20.

Ice scarring to trees along banks

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Estimating Ice Jam Frequency & Severity from Tree Scar Data

Ice-scarred willow overhanging Lower Grasse River

Sawn willow section used to date past ice events

Foresters coring tool used to date ice tree scar events

Ash tree on upper Grasse river with scars from multiple ice events

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R&D: Bioengineered Channel Stabilization

To date, funding constraints have limited R&D to observations rather than detailed experiments

R&D: Bioengineered Channel Stabilization

All 2005 Events

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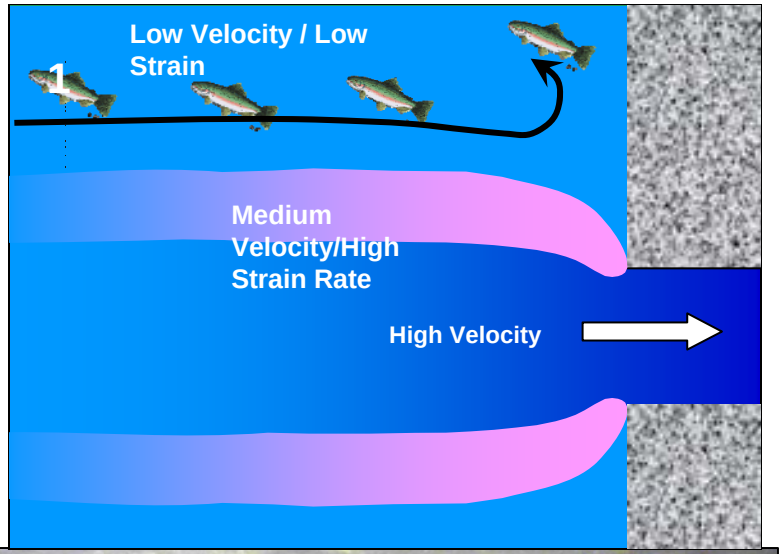
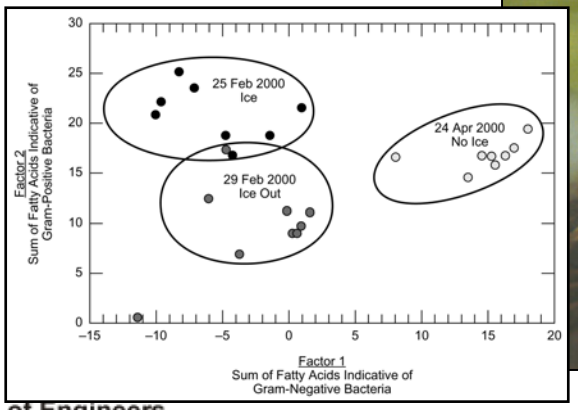
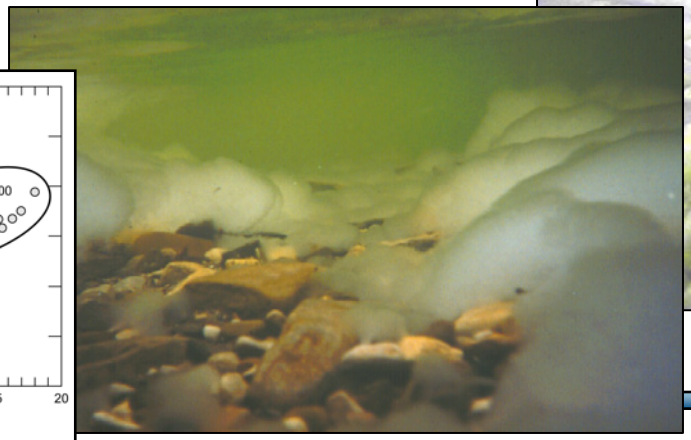
R&D: Habitat

- Some observations in field (mostly Canadian) and laboratory (CRREL)
- Fish Overwintering: Would be illuminating to include frazil ice in agent-based modeling (e.g., John Nestler and Andy Goodwin, ERDC)
- Fish Spawning: Geospatial analyses
- Riverine margins/ vegetation: Field and laboratory studies necessary
- Estuarine: Brian Morse (Lavalle University, Montreal)
- Microbial: frazil communities, scouring of benthic communities







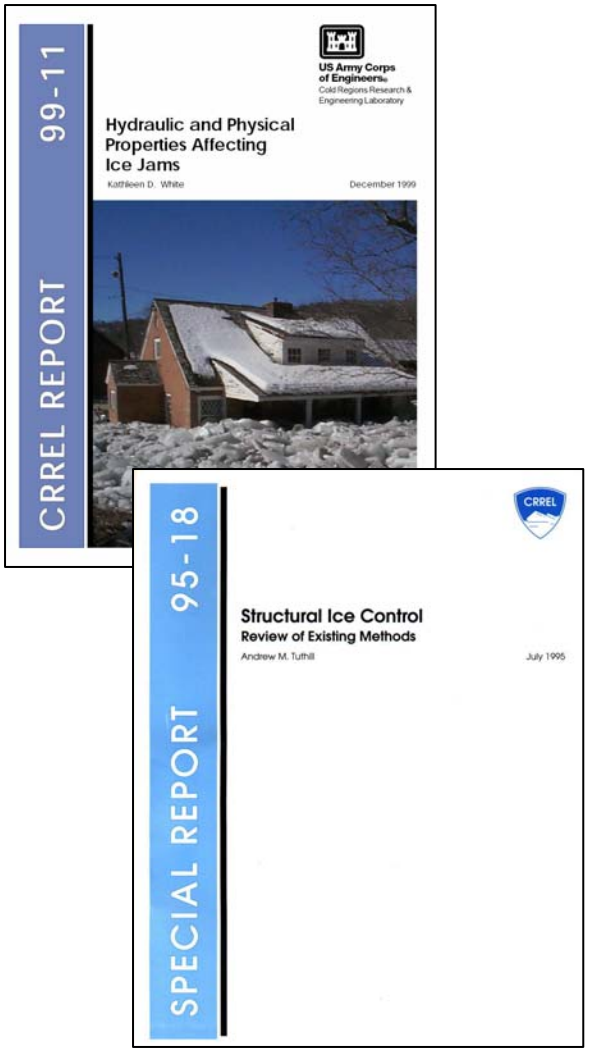
Figures from White (ERDC), Brown (PNL), Nestler (ERDC)

Summary

- Ice jams impact much of the US
- Ice Jam Database useful in emergency management, R&D, engineering and design studies, but additional data required
- ERDC-CRREL R&D continuing in ice jam prediction, ice forces on structures, ice hydraulic modeling, including discrete element models, application of risk and uncertainty to ice engineering, recent statistical/AI techniques
- R&D knowledge gaps in ice-related scour, geomorphology, sediment, habitat, ecosystems and ecosystem restoration must be addressed
- Partnering activity in national and international ice community will enhance research results and transfer of emergency management techniques

Resources

- CRREL Ice Jam Database
  - http://www.crrel.usace.army.mil/ierd/ijdb/
  - Reported jam locations/pictures/reports/other data
- CRREL Ice Jam Clearinghouse
  - http://www.crrel.usace.army.mil/icejams/index.htm
  - Rapid mapping of ice jam locations
  - Reaches Ice Jam Data Base text information
- Ice Engineering Information Exchange Bulletin
  - http://www.crrel.usace.army.mil/ierd/tectran/27InDesign.pdf
- Ice Engineering Manual
  - http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-1612/toc.htm
- CRREL Technical Reports:
  - http://www.crrel.usace.army.mil/techpub/CRREL_Reports/
    →River and Lake Ice
- ASCE J. Cold Regions Engineering
  - White, K.D. and J.N. Moore (2002) "Impacts of Dam Removal on Riverine Ice Regime." *ASCE J. Cold Regions Engineering*, Vol. 16, No. 1, p. 2-16.
- Assessing the Effectiveness of the Israel River Ice Control Structure
  - http://www.crrel.usace.army.mil/techpub/CRREL_Reports/reports/TR06-1.pdf



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