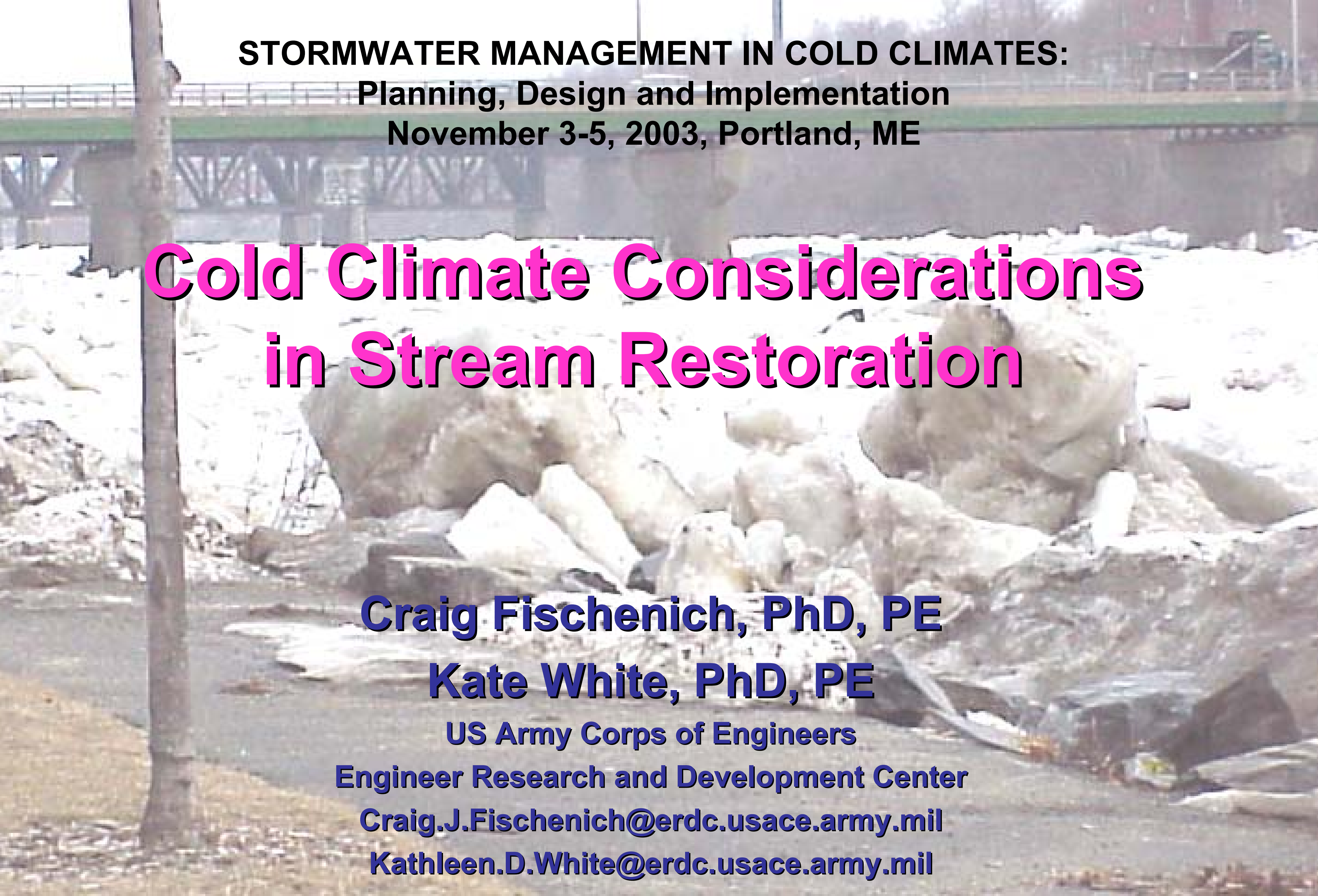

STORMWATER MANAGEMENT IN COLD CLIMATES:
Planning, Design and Implementation
November 3-5, 2003, Portland, ME

Cold Climate Considerations in Stream Restoration

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Engineer Research and Development Center

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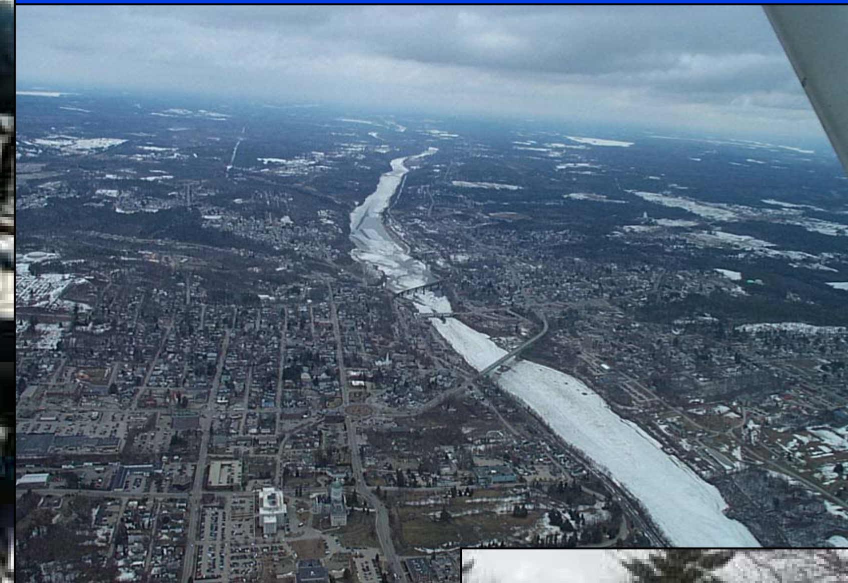
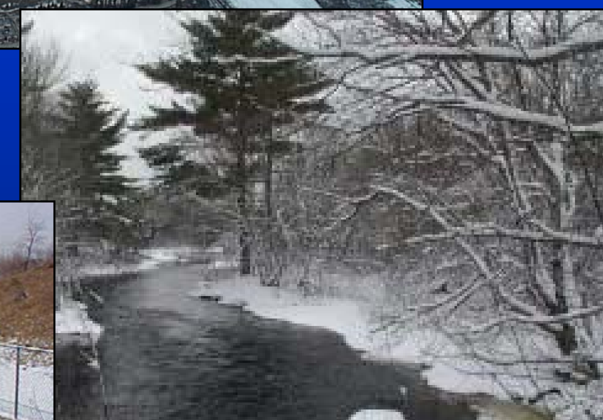
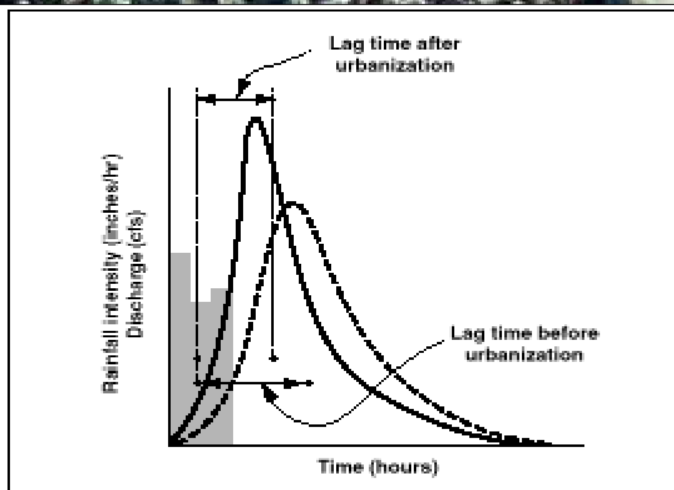
USACE Environmental Operating Principles

1. Strive to *achieve environmental sustainability*. An environment maintained in a healthy, diverse, and sustainable condition is necessary to support life.
2. Recognize the *interdependence of life and the physical environment*, and consider environmental consequences of Corps programs and activities in all appropriate circumstances.
3. Seek balance and synergy among human development activities and natural systems by designing *economic and environmental solutions* that support and reinforce one another.
4. Continue to *accept corporate responsibility and accountability* under the law for activities and decisions under our control that impact human health and welfare and the continued viability of natural systems.
5. Seek ways and means to assess and mitigate *cumulative impacts* to the environment; bring systems approaches to the full life cycle of our processes and work.
6. Build and share an integrated scientific, economic & social *knowledge base* that supports a greater understanding of the environment and impacts of our work.
7. *Respect* the views of individuals and groups interested in Corps activities; listen to them actively and learn from their perspective in the search to find win-win solutions to the Nation's problems that also protect & enhance the environment.







Adapted from Leopold (1968)

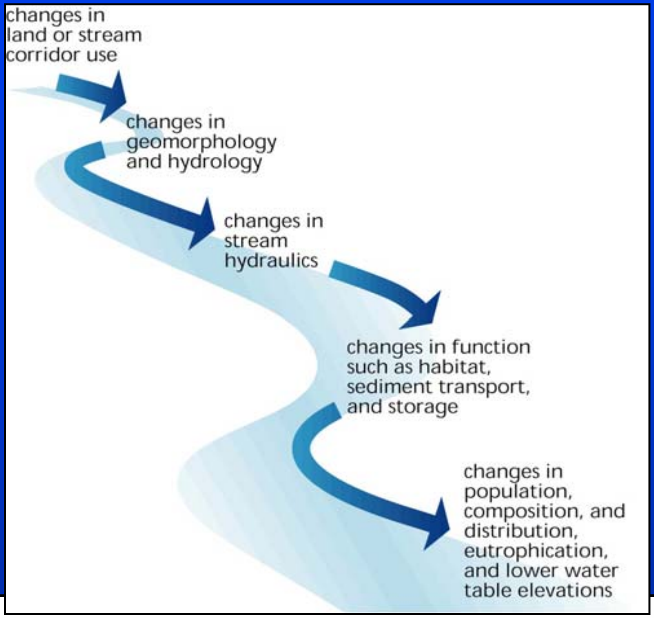
Sustainable Urban Flood Damage Reduction

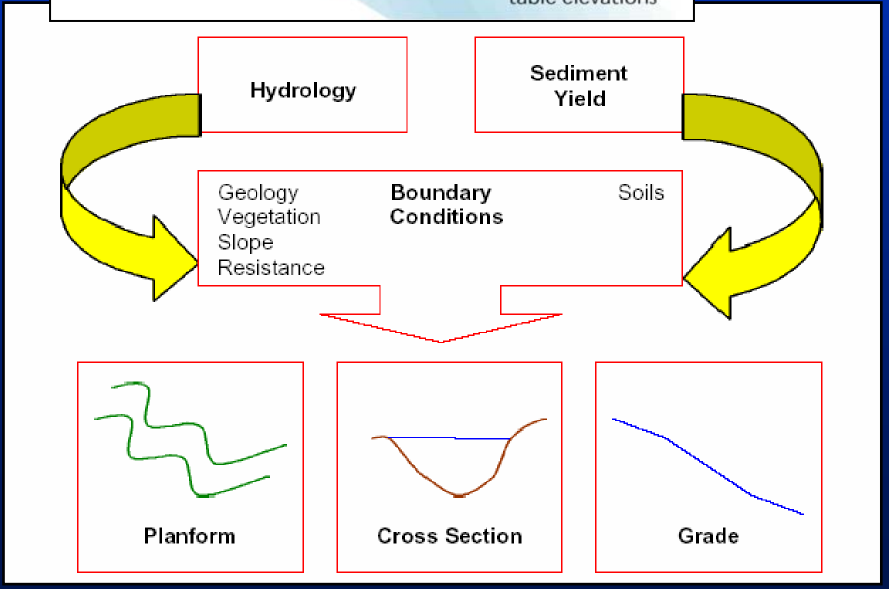
Sustainable Urban FDR

- The impacts of urbanization and the engineering efforts to control urban flooding are not simply local impacts, but are part of system-wide cumulative impacts and may affect the entire watershed
- There is little published guidance for accomplishing restoration of urban channels within a systems context that considers the entire watershed
  - Direct impacts of natural events and human activities
    - urbanization
    - construction of dams, levees, and diversion structures
    - straightening, widening, deepening, clearing of channel systems
  - Indirect impacts through pathways
    - hydrological
    - ecological
  - Cumulative impacts at the system scale

Stormwater Management Issues

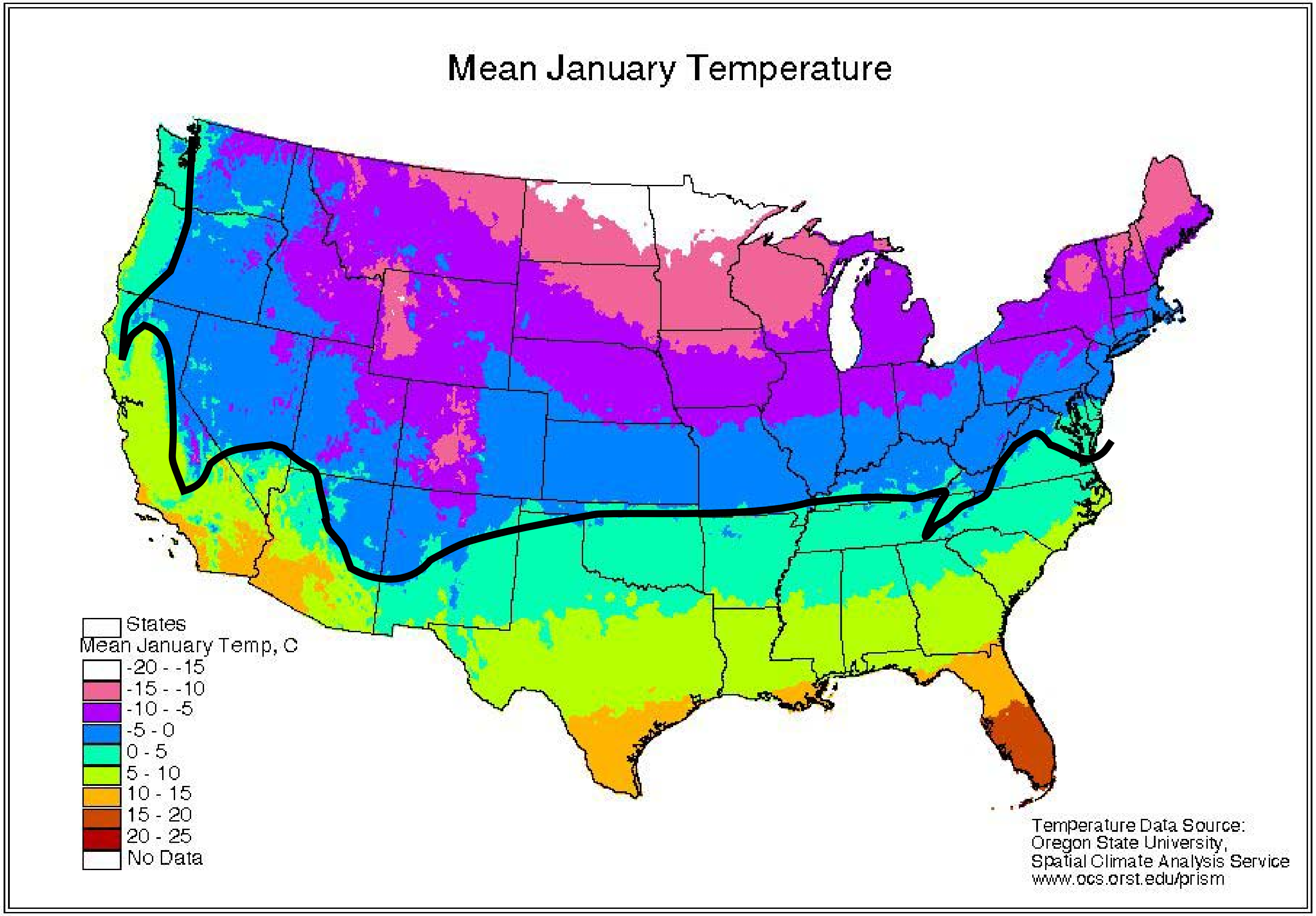
- Existing regulations tend to neglect system considerations
- Volume/duration/stability relations poorly understood
- Techniques for multiple benefits needed
- Guidelines for designs related to watershed position needed
- New outlet controls needed
- Efficient stormwater management often includes retention and detention basins to reduce the impacts of development upon runoff characteristics
  - Potential adverse impacts on receiving streams by extending the duration of flows with sufficient energy to induce erosion of the channel's bed and banks
  - Solutions that involve modification to the design of stormwater basins can reduce this impact
  - Methods to enhance or restore the stream and riparian environment are needed as well



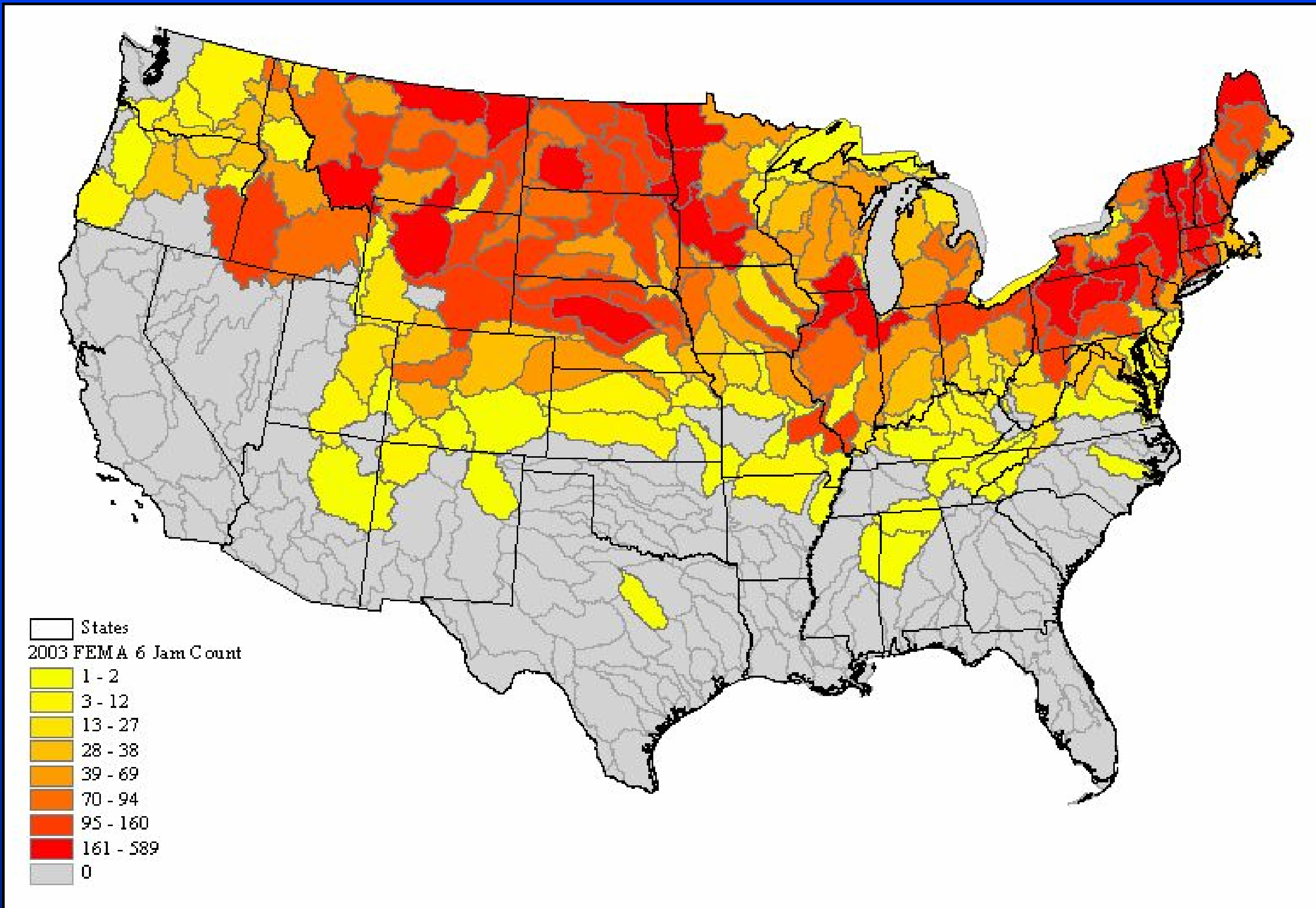


Cold Climate Issues

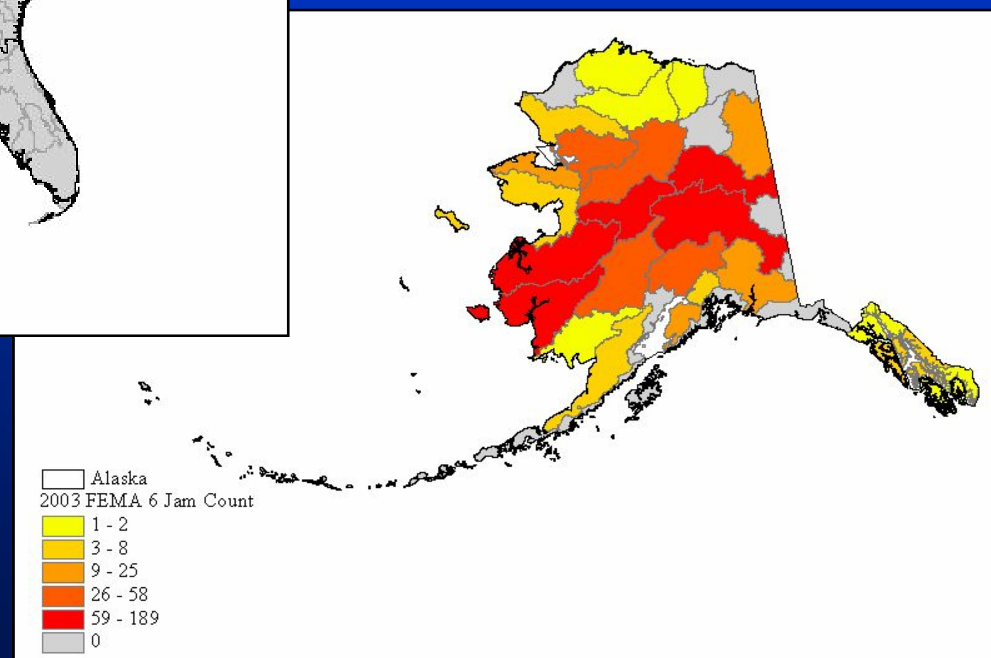
- Snowmelt ⇒ pollutant loads (numerous)
- Snow management, deicing techniques ⇒ pollutant loads (numerous)
- Stormwater facilities ⇒ freezing, pollutant loads, ice covers (e.g., Gary Oberts, MN BMP, Center for Watershed Protection)
- Stream restoration ⇒ effective design guidelines
- Impacts of ice on stream restoration design has not been adequately addressed
  - Design of a stable channel slope and channel stabilization measures
  - Ice-affected stage-frequency
- As a result, stream restoration projects in cold climates may not operate as designed
- This presentation will discuss planning and design considerations for stream restoration in cold climates



Mean January Temperature
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

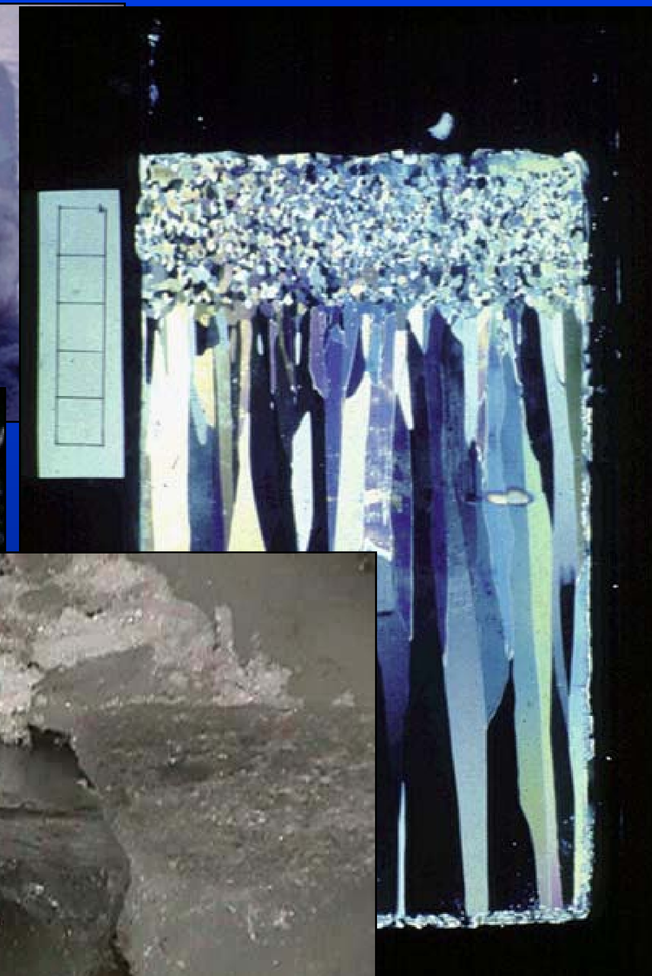


CRREL Ice Jam Database
>13,500 ice events
Currently updating Wisconsin, Pennsylvania, upstate New York

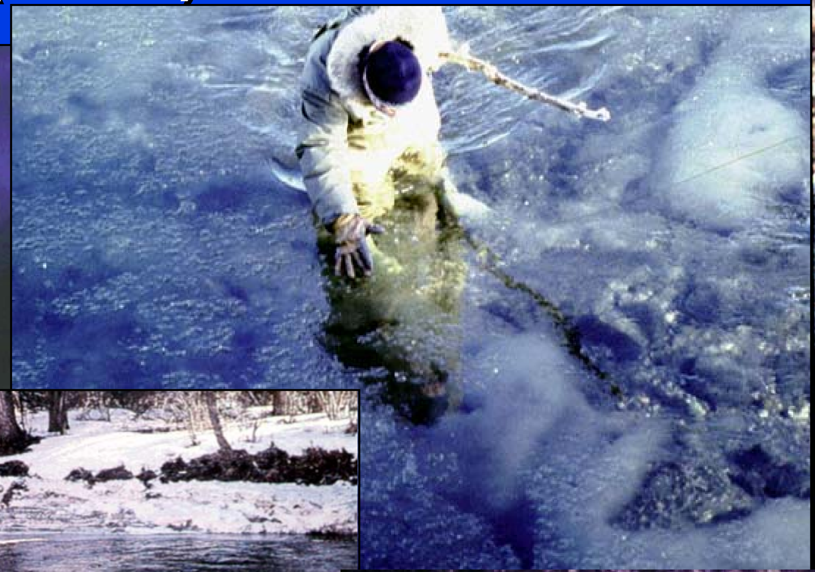


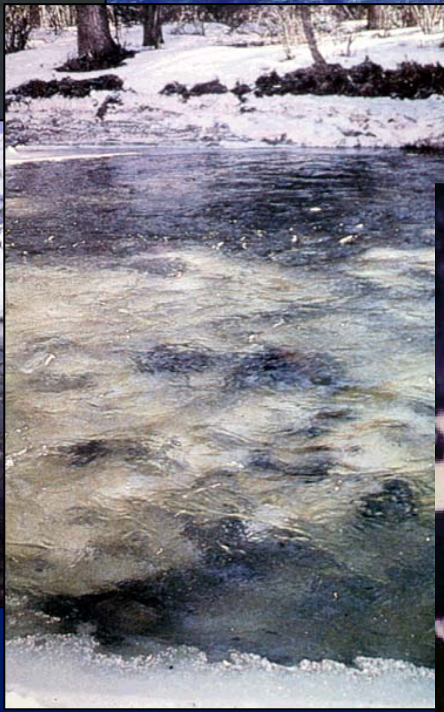
http://www.crrel.usace.army.mil/ierd/ijdb/

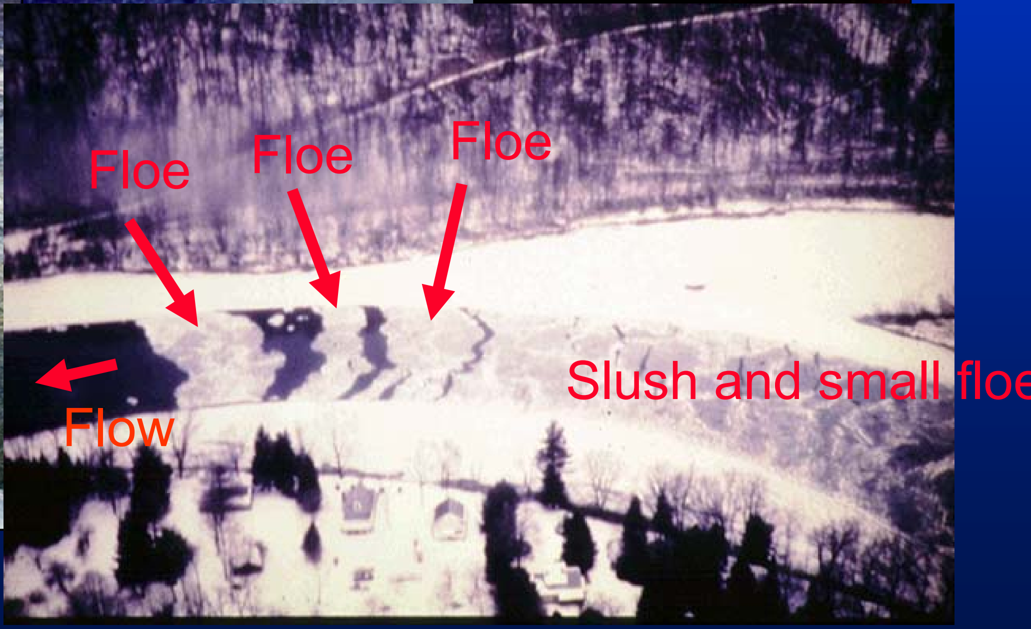
Thermally-grown ice



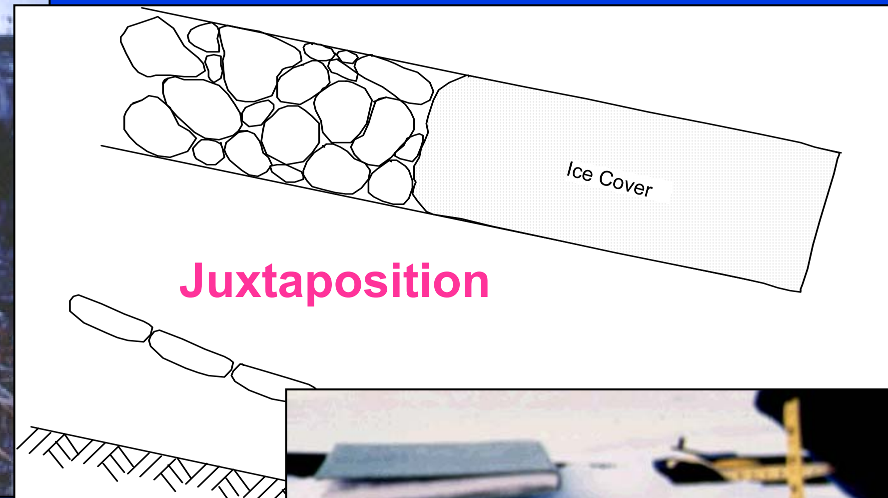
Dynamically formed (frazil) ice

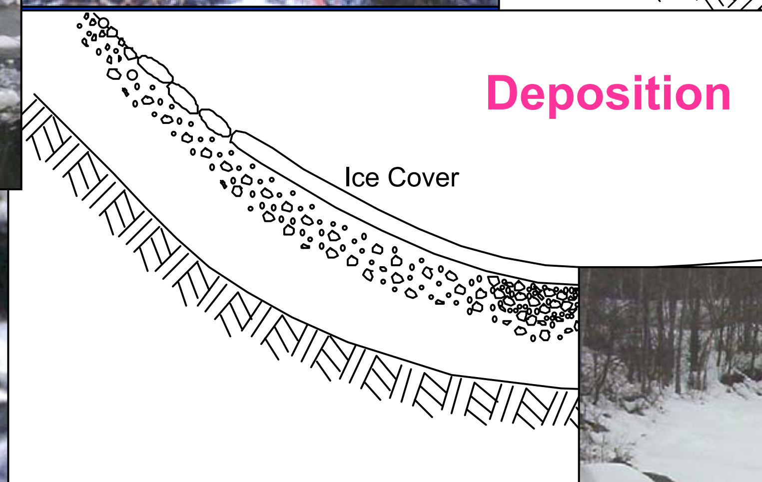






Dynamic Ice Cover Formation





Ice Cover Growth

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.

http://www.crrel.usace.army.mil/ierd/tectran/ieieb.htm

US Army Corps of Engineers® Cold Regions Research & Engineering Laboratory

Ice Enginee

U.S. Army Engineer Research and Development Center, Hanover, N

Method to Estimate River Ice Thicknes Based on Meteorological Data

River ice can damage riverine structures such as bridges, locks, dams, dikes, groins, levees, ri forms of bank protection, and can block hydropower and water supply intakes. Ice jams affect stoppages, or damage to tows, barges, and mooring/fleeting areas. Ice-induced scour may cause t banks, with adverse affects on fish and wildlife habitat, as well as the exposure of utilities buried presence of river ice can result in wintertime oxygen deficits that impair water quality.

Removal of dams in ice-affected rivers can result in changes to the riverine ice regime that r or more severe ice jamming. Emergency and medical relief to flooded areas may be limited by fl and erosion of roads resulting in road closures, or by the closure of bridges weakened or destr exists for death or serious injury during ice-related flooding, evacuations, and other ice mitigation

The planning, engineering, and design of ice jam mitigation measures designed to decreas described above generally require some estimate of ice cover thickness. Ice covers can result f cesses. This Ice Engineering Technical Note discusses a method of estimating ice thickness r processes based on meteorological data.

Figure 1. Hydraulic modeling of ice jams requires some estimate of ice thick

ERDC/CRREL Technical Note 03-4

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

CECW-EH

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

Manual
No. 1110-2-1612

Engineering and Design
ICE ENGINEERING

1. Purpose. This manual, composed of three parts, presents in Part I the planning, design, construction, and operation and maintenance of ice contr measures for Corps of Engineers projects; provides in Part II the current g jams and the resultant flooding, including preventive measures; and gives for engineering and operational solutions to ice problems on rivers used fo

2. Applicability. This manual is applicable to all USACE commands ha works design, construction, operations, and maintenance.

3. Distribution statement. Approved for public release, distribution is

4. References. Bibliographic material is included at the end of each cha

5. Discussion. All Corps projects subjected to freezing temperatures ha buildup on lock walls, hydropower intakes, and lock approaches; ice accum channels; ice passage over spillways that scours the downstream channels; structures and shorelines, etc. Therefore, ice control measures should be co existing projects to improve operations and safety in cold regions. In Part I discussion of ice formation processes, physical properties, and potential so Part II considers the problem of ice jams and ice jam flooding, and discuss measures. Part III of this manual addresses the considerations that arise fro waterways, including the conduct of river ice management studies and the management plans.

FOR THE COMMANDER:

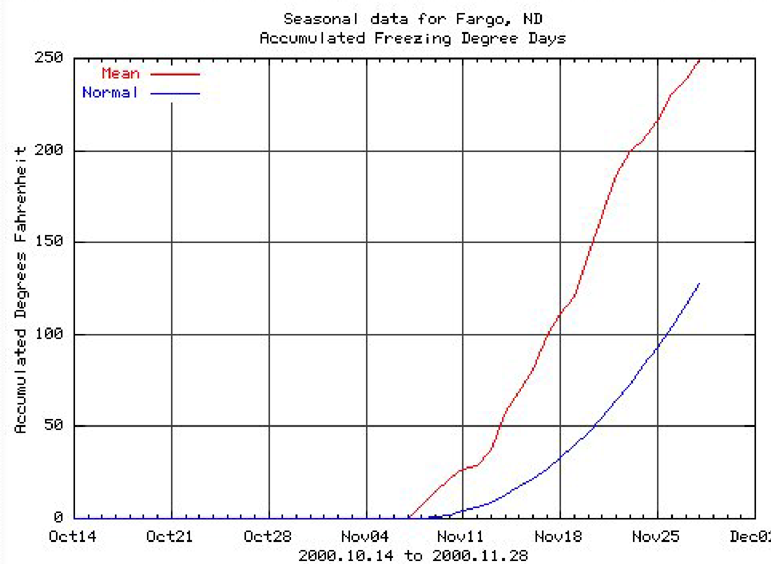
3 Appendices
(See Table of Contents)

JOSEPH SCHROEDE
Colonel, Corps of Engi
Chief of Staff

This manual supersedes EM 1110-2-1612, dated 30 April 1999.

EM 1110-2-1612

Seasonal AFDD Query Results



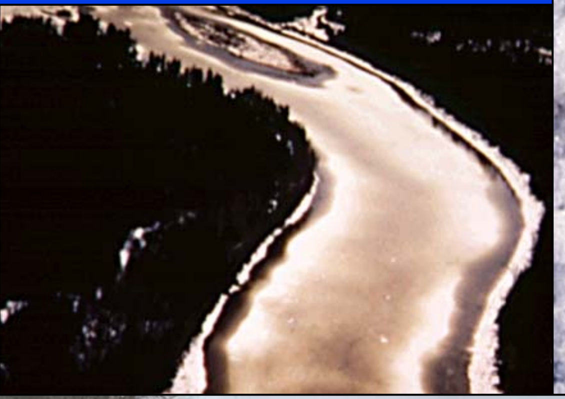
Seasonal AFDD: 249 Fahrenheit Normal AFDD: 128 Fahrenheit
Ice thicknesses for various conditions using the Stefan Formula:

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.mvp-wc.usace.army.mil/ice/

Ice Cover Breakup

- Continuum from thermal to mechanical
- Thermal Breakup: Ice cover melts in place
  - 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
- Mechanical Breakup: Hydrodynamic forces acting on cover exceed cover strength
  - Results from an increase in discharge
  - Precipitation event
  - Snowmelt event
  - Dam operation (large, sudden increase)



Ice Cover Breakup

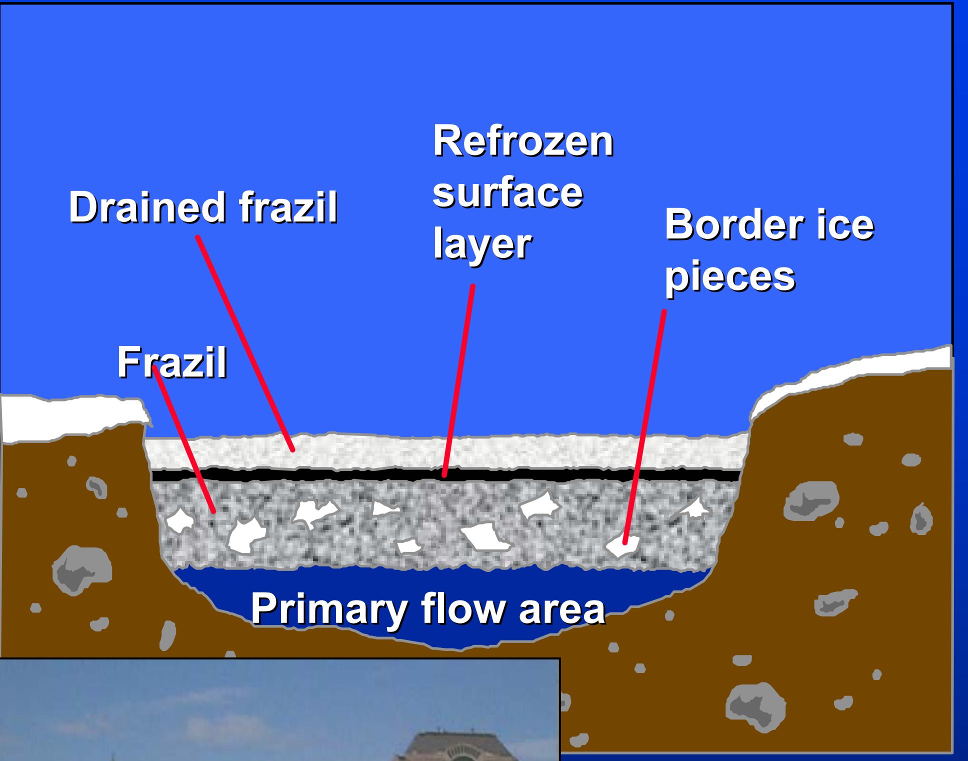
- Rule-of-thumb: stage increase of between 1.5 and 3 times the ice thickness needed to lift, break, and transport ice cover
- Often occurs later in impoundments due to damped hydrograph and thicker ice

Ice cover transport and jamming

- Broken pieces move downstream until transport capacity is exceeded
  - Decrease in slope
  - Constriction
  - Obstruction (e.g., solid ice cover)
  - Bend, island
- Jam forms quickly
- Underside is very rough, leading to erosion and scour
- Jam failure associated with surges that cause erosion

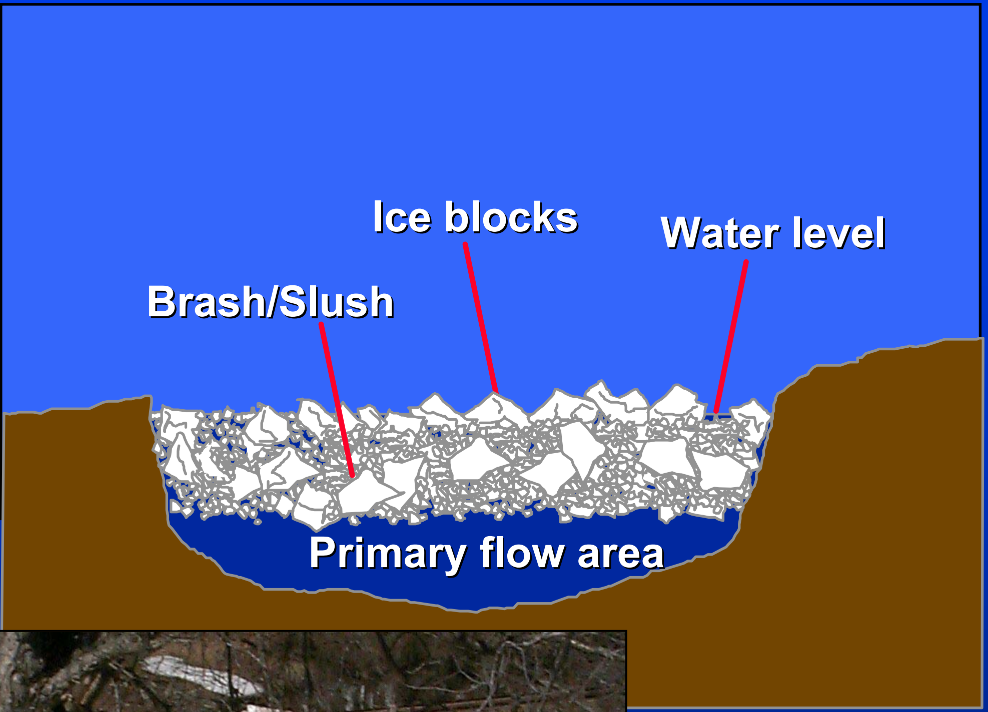
Freezeup Jams

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



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
- Highly unstable, with sudden failures
- Unsteady water flow (surges)
- Moderate to extreme surface roughness
- Midwinter jams may freeze in place, causing additional problems later in the season



Manning's Equation with Ice

$$Q = \frac{1.486}{n_c} A_i R_i^{2/3} S_o^{1/2}$$

½ when B>>d

$$Q = \frac{1.486}{n_c} Bd \left[\frac{Bd}{2B + 2d} \right]_i^{2/3} S_o^{1/2}$$

$$H = \frac{\rho'}{\rho} \eta + 1.32 \left[\frac{Q n_c}{1.486 B S_o^{1/2}} \right]_i^{3/5}$$

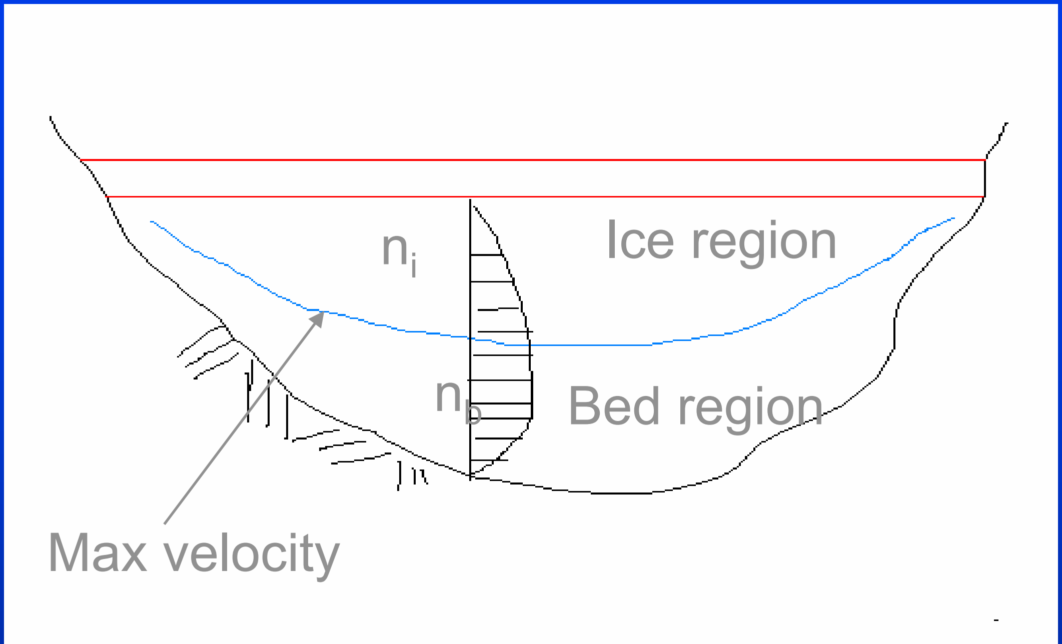
At least 32% increase in total depth due to ice cover at uniform flow

A = cross sectional flow area

P = wetted perimeter

Δx = distance between cross sections

R = *A/P* (hydraulic radius)



Velocity profile under steady flow conditions

- assume average flow velocity in the ice region and the bed region are equal
- assume Manning's equation applies to each
- assume the energy grade line is the same in both

$$V_i = \frac{1}{n_i} R_i^{2/3} S^{1/2}$$

$$V_b = \frac{1}{n_b} R_b^{2/3} S^{1/2}$$

$$V_o = \frac{1}{n_c} R_o^{2/3} S^{1/2}$$

$$n_c = \left[\frac{n_i^{3/2} + n_b^{3/2}}{2} \right]^{2/3}$$

Belokon-Sabaneev Formula

Table 1. Values of ice roughness coefficient (n_i) and composite roughness coefficient (n_c) calculated from discharge measurements.

(n_i)	(n_c)	*Comment*	*Reference*
	0.010–0.012	Sheet ice, early winter*	Nezhikhovskiy (1964)
	0.008–0.010	Sheet ice, late winter	Nezhikhovskiy (1964)
0.010–0.06†		Ice cover formed from loose frazil*	Nezhikhovskiy (1964)
0.013–0.09†		Ice cover formed from dense frazil*	Nezhikhovskiy (1964)
0.015–0.10†		Ice cover formed from sheet ice*	Nezhikhovskiy (1964)
0.010–0.028**	0.018–0.027	Sheet ice	Carey (1966)
0.004–0.013**	0.015–0.022	Sheet ice	Carey (1967)
0.10	0.090–0.109	Breakup jams	Beltaos (1978)
0.057–0.065, $\bar{n}_i = 0.060$	0.041–0.046	Breakup jam	Andres (1980)
0.010–0.015		Breakup jam	Knowles and Hodgins (1980)
	0.053–0.142	Breakup jams	Michel (1980)
0.013–0.040		Freezeup jam*	Beltaos (1981)
0.033–0.041††		Freezeup jam*	Beltaos (1983)
0.072		Breakup jams	Andres and Doyle (1984)
0.020-0.15		Freezeup jam, frazil deposits	Majewski and Grzes (1986)

*Within three days of formation.
†Higher values for thicker accumulations.
**Lower values earlier in the winter.
††Higher values for thinner accumulations.

White 1999 http://www.crrel.usace.army.mil/techpub/CRREL_Reports/reports/CR99_11.pdf

Table 4. Stability of Channel Linings for Given Velocity Ranges

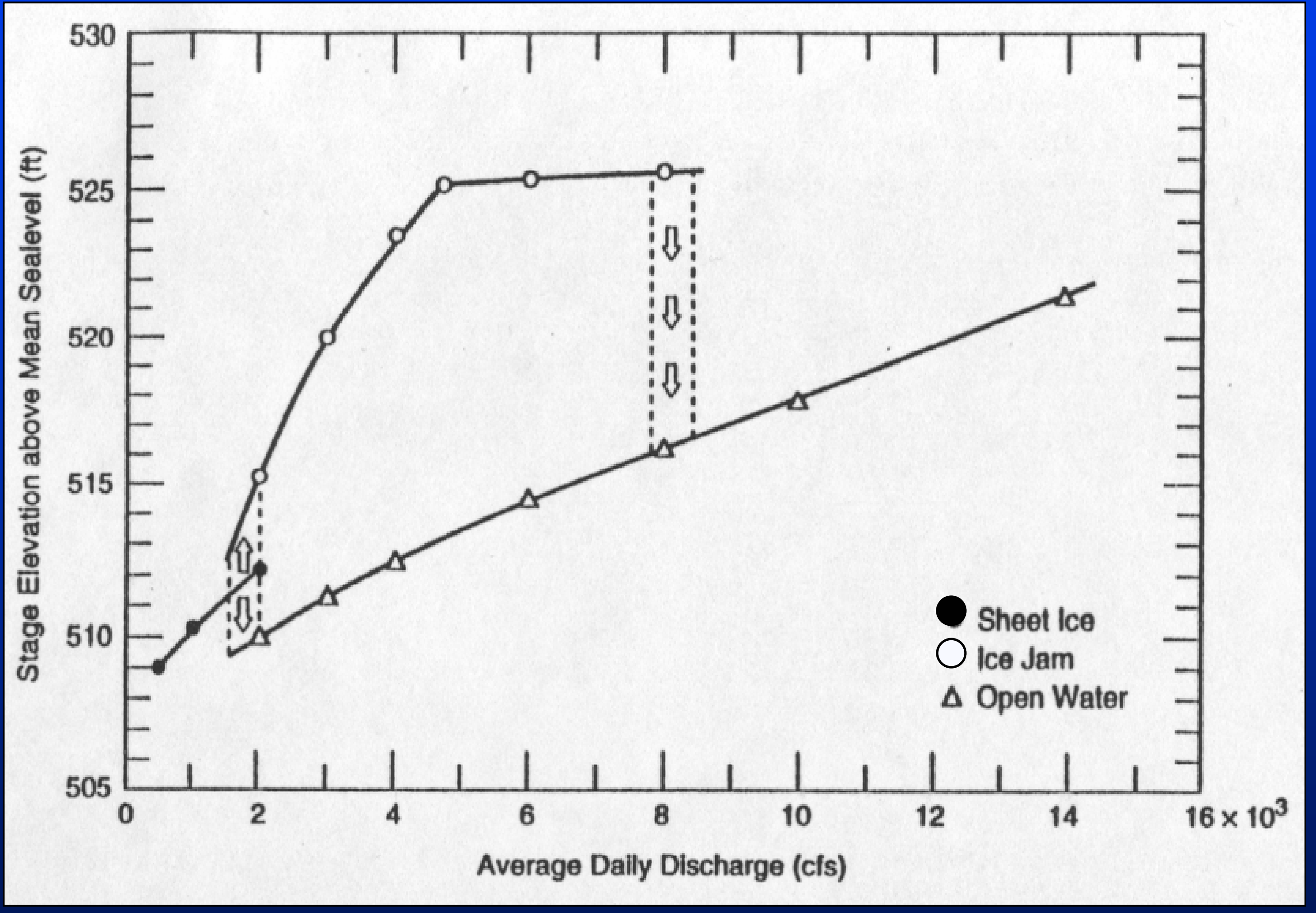
Lining	0 – 2 fps	2 – 4 fps	4 – 6 fps	6 – 8 fps	> 8 fps
Sandy Soils	Use Caution	Not Appropriate	Not Appropriate	Not Appropriate	Not Appropriate
Firm Loam	Use Caution	Use Caution	Not Appropriate	Not Appropriate	Not Appropriate
Mixed Gravel and Cobbles	Appropriate	Use Caution	Use Caution	Not Appropriate	Not Appropriate
Average Turf	Appropriate	Use Caution	Use Caution	Not Appropriate	Not Appropriate
Degradable RECPs	Appropriate	Use Caution	Use Caution	Use Caution	Not Appropriate
Stabilizing Bioengineering	Appropriate	Use Caution	Use Caution	Use Caution	Not Appropriate
Good Turf	Appropriate	Appropriate	Use Caution	Use Caution	Use Caution
Permanent RECPs	Appropriate	Appropriate	Appropriate	Appropriate	Use Caution
Armoring Bioengineering	Appropriate	Appropriate	Appropriate	Appropriate	Use Caution
CCMs & Gabions	Appropriate	Appropriate	Appropriate	Appropriate	Use Caution
Riprap	Appropriate	Appropriate	Appropriate	Appropriate	Appropriate
Concrete	Appropriate	Appropriate	Appropriate	Appropriate	Appropriate

Key:

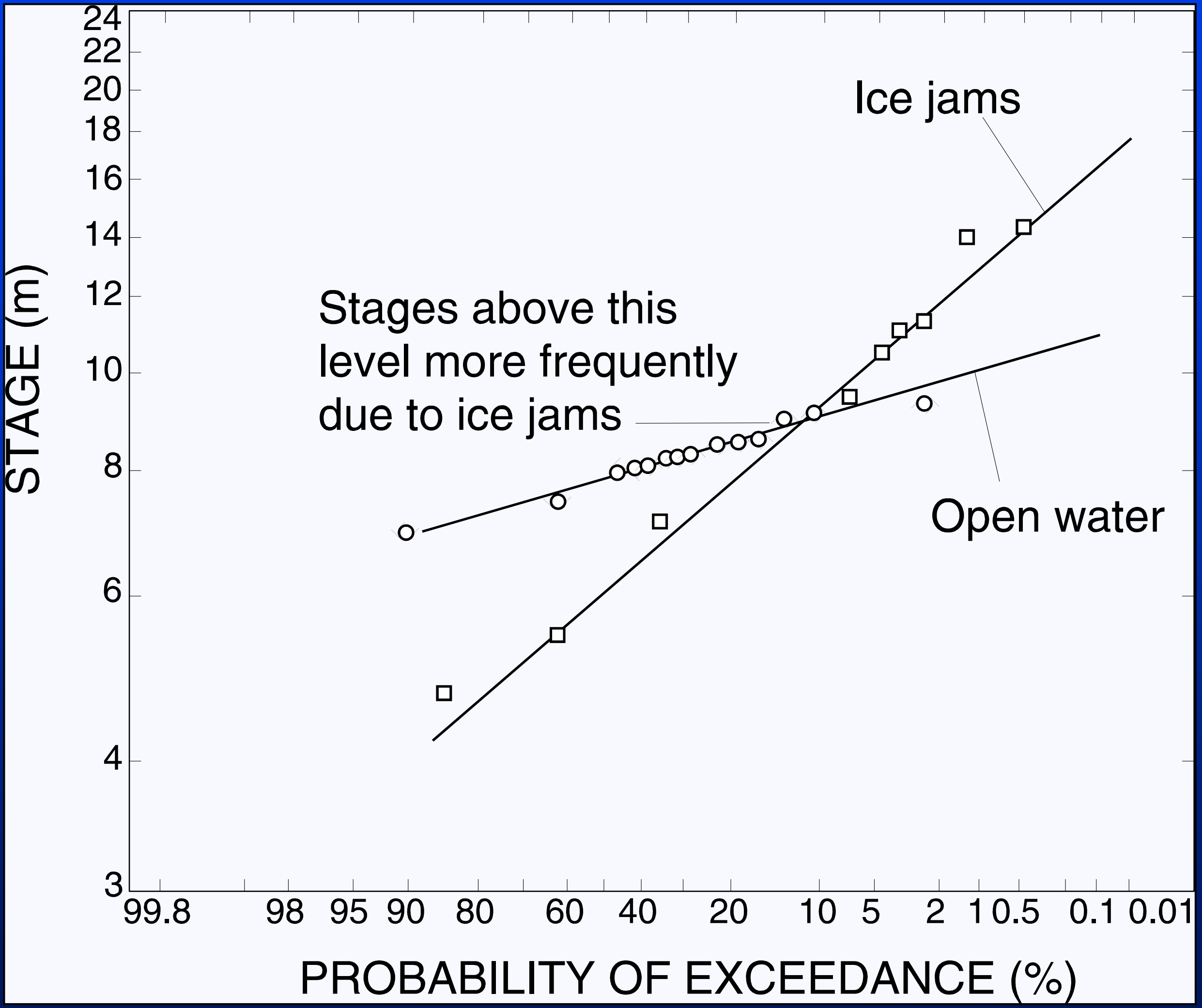
(green)	Appropriate
(yellow)	Use Caution
(red)	Not Appropriate

Increased velocity and shear due to ice cover has implications on material selection

Ice-Affected Stage-Frequency

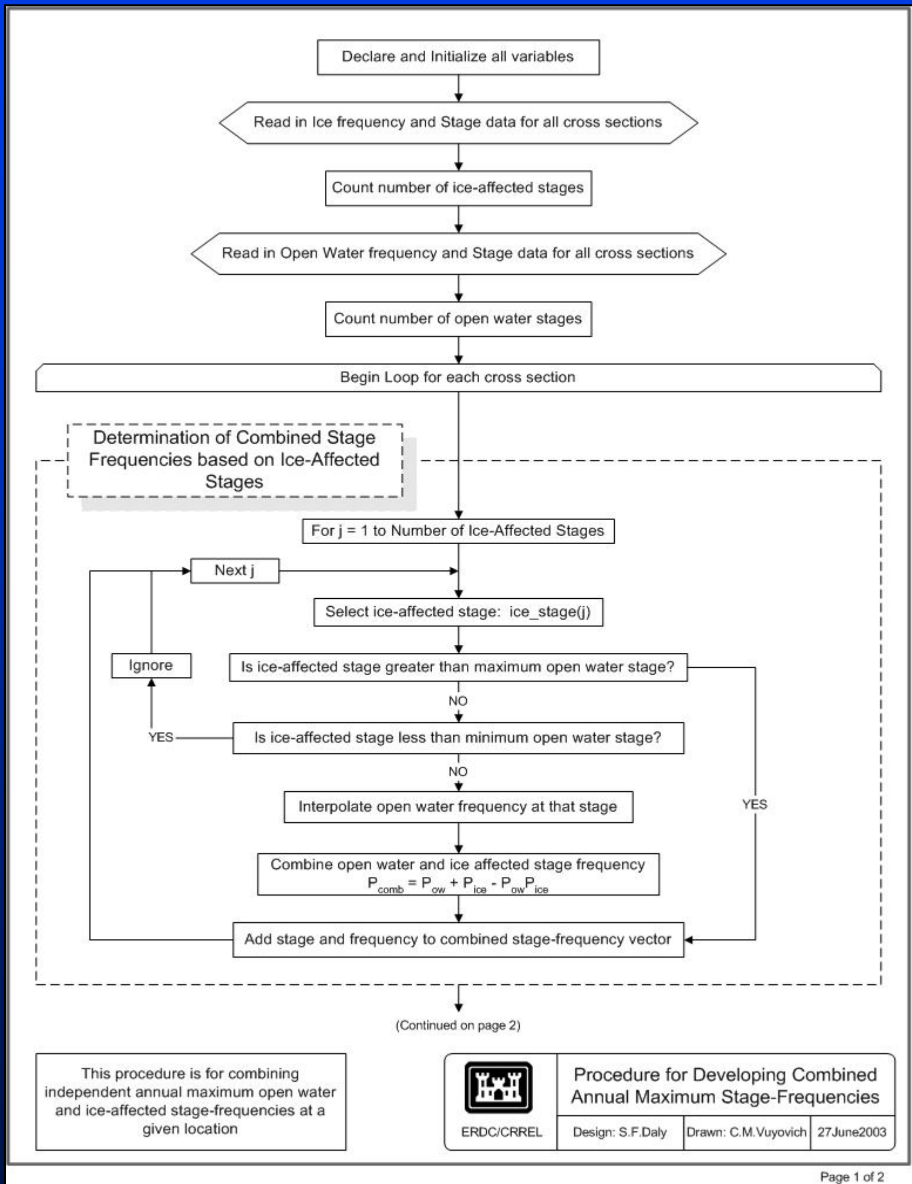


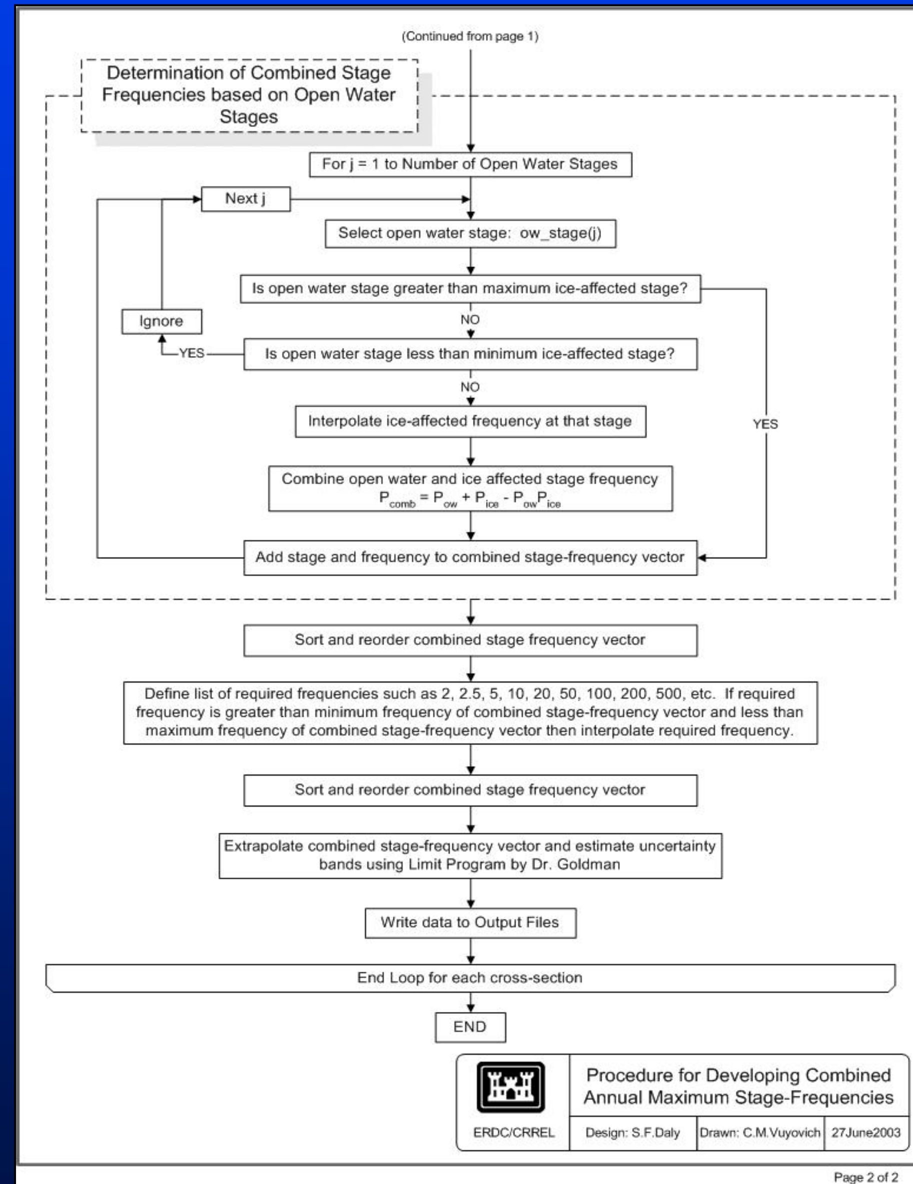
Ice-Affected Stage-Frequency



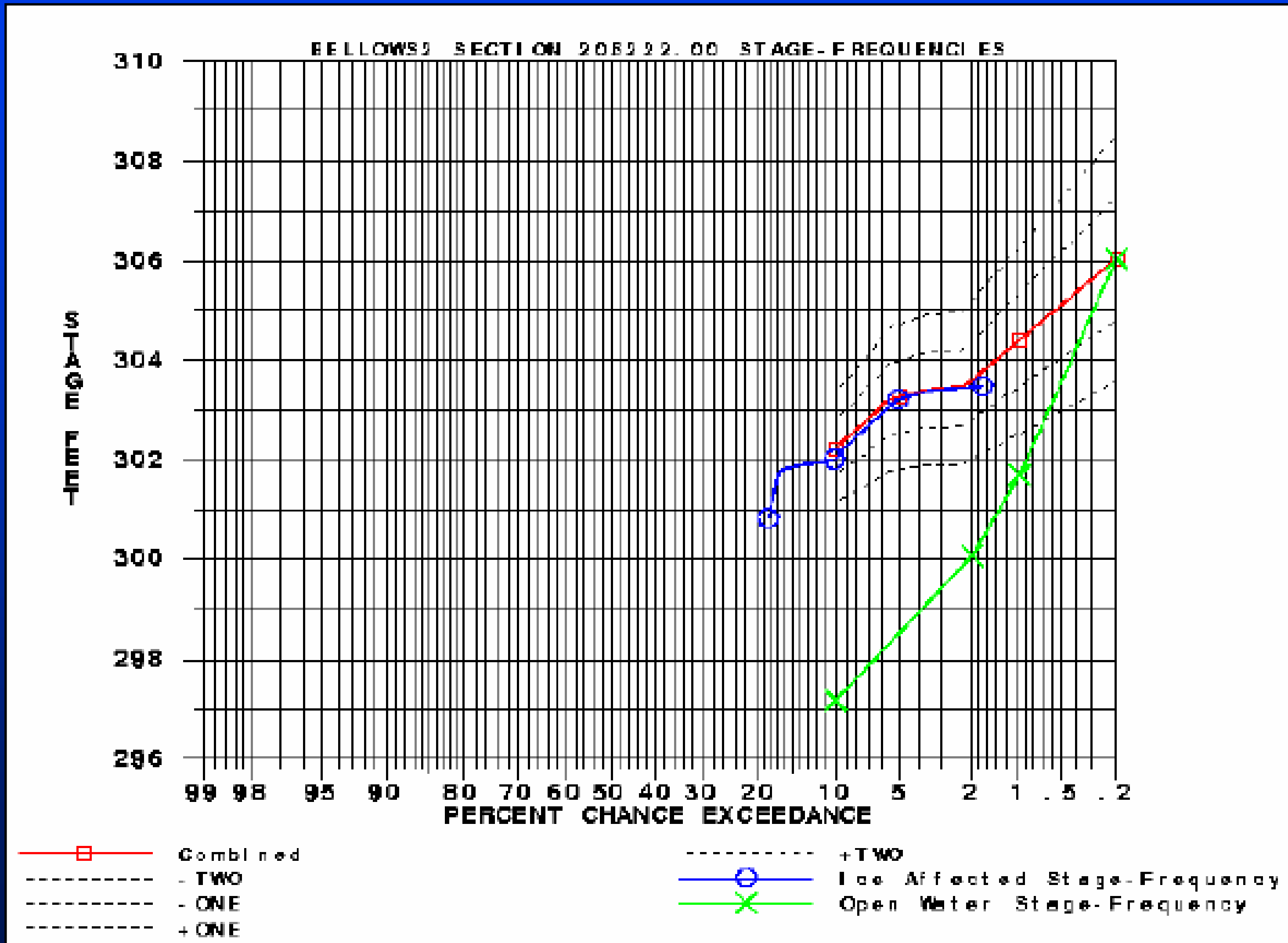
Gerard and Karpuck 1979

Combined Stage Frequency Method





Ice-Affected Stage-Frequency



Summary of river ice regime

- Frazil ice is dominant form of ice in northern rivers
- Ice often forms more quickly in impounded areas than in more turbulent river reaches
- Frazil deposits tend to form at upstream end of impoundments and tributary confluences
- Ice cover thickens due to thermal, deposition, shoving processes
- Thinner ice covers break up sooner than thicker ice covers with implications on jam location/timing
- Jams or rough ice covers increase scour and erosion
- Ice covers, deposits, and jams increase stage >30%

US Army Corps
of Engineers

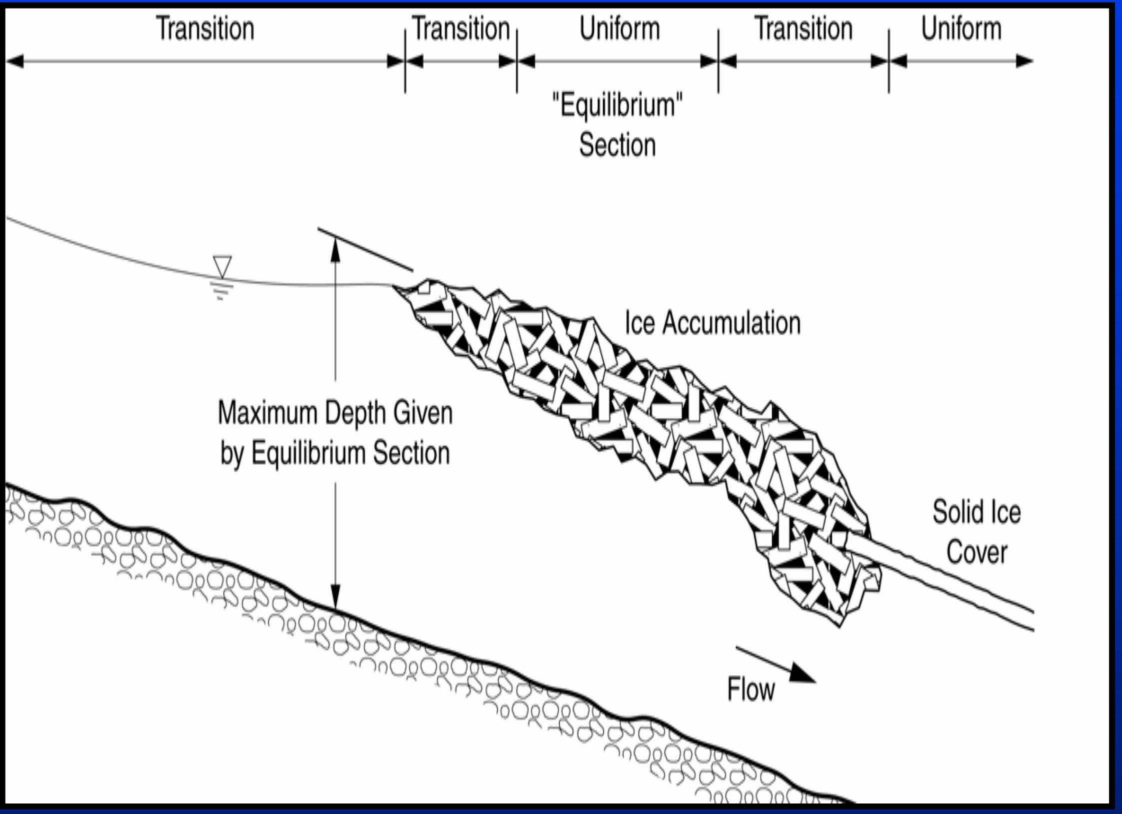
Replacement bridge: ice-affected stage-frequency not included in design

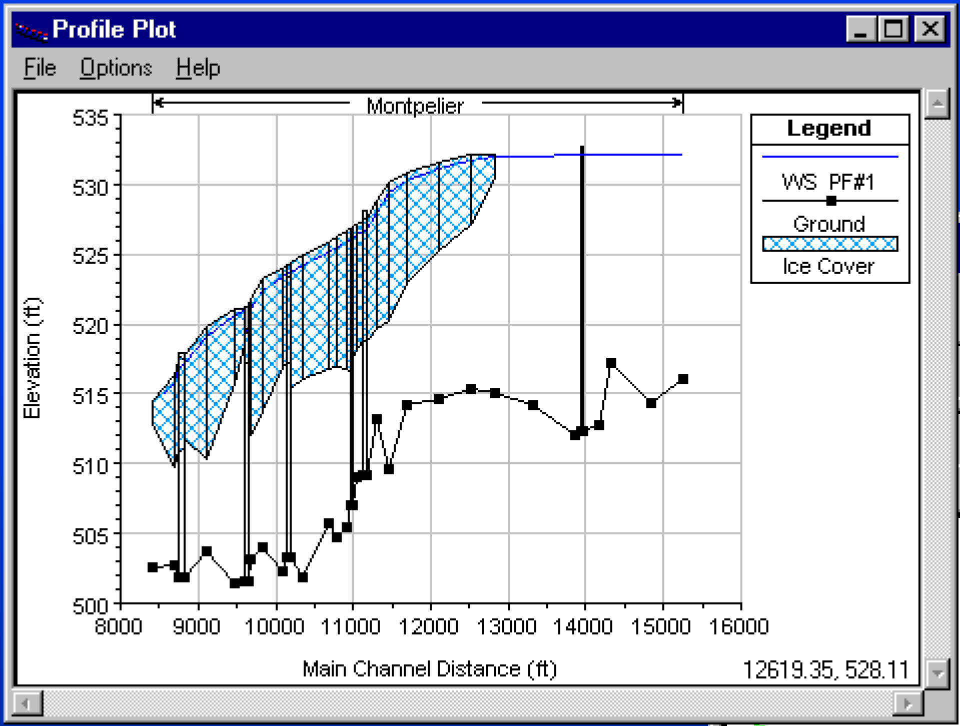
1999

2001

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




Profile Plot
File Options Help
Montpelier
Legend
WS PF#1
Ground
Ice Cover
Elevation (ft)
535
530
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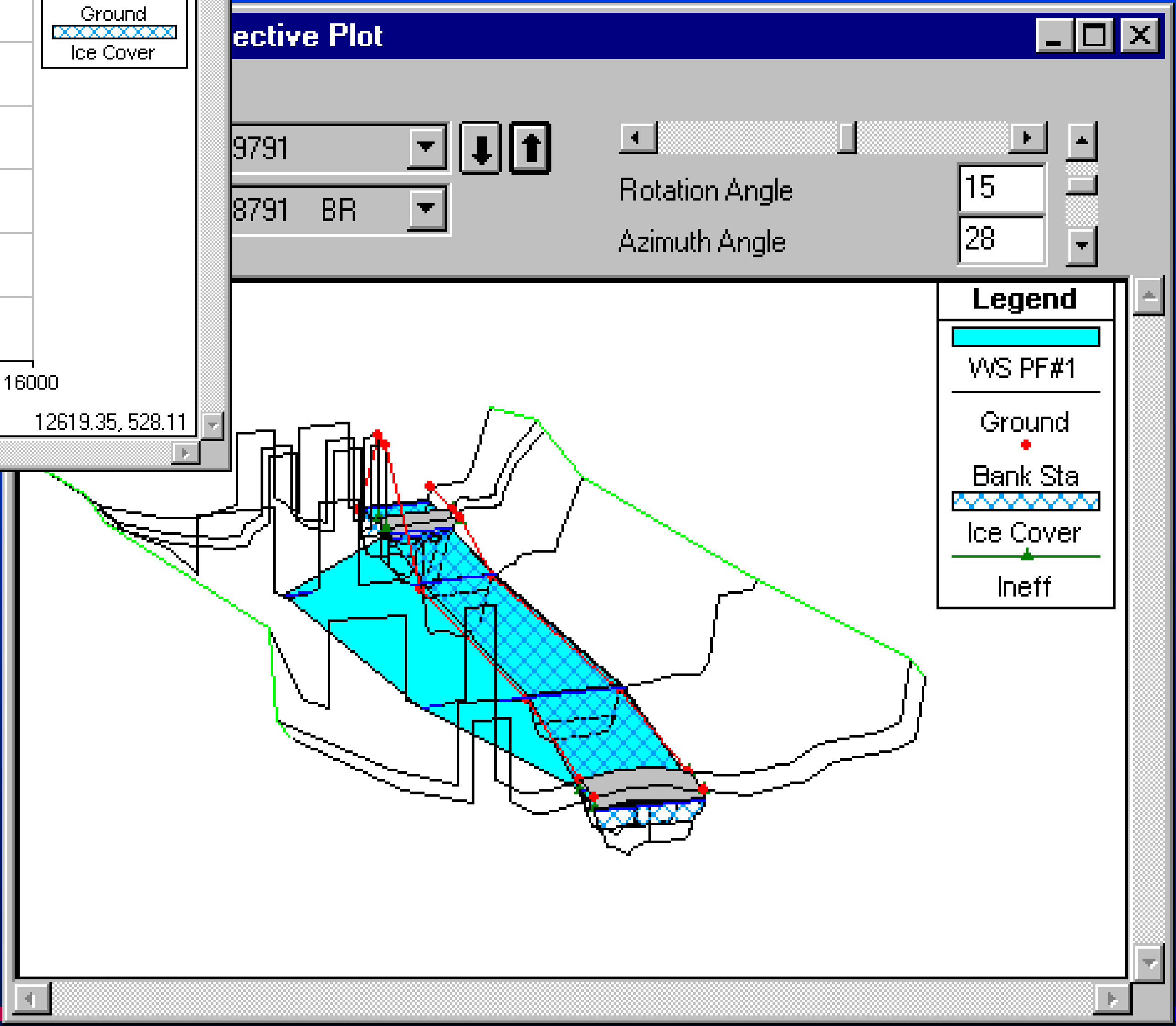
12619.35, 528.11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8791 BR
Rotation Angle
15
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28
Legend
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Ice Cover
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Recommendations

1. **Characterize existing ice regime**
   - Ice formation, growth, breakup, transport, jamming
   - Sources of information:
     - USGS gage records
     - NWS meteorological records
     - CRREL Ice Jam Clearinghouse, Ice Jam Database
     - Other historic documents (e.g., town histories, newspapers)
     - Anecdotal evidence

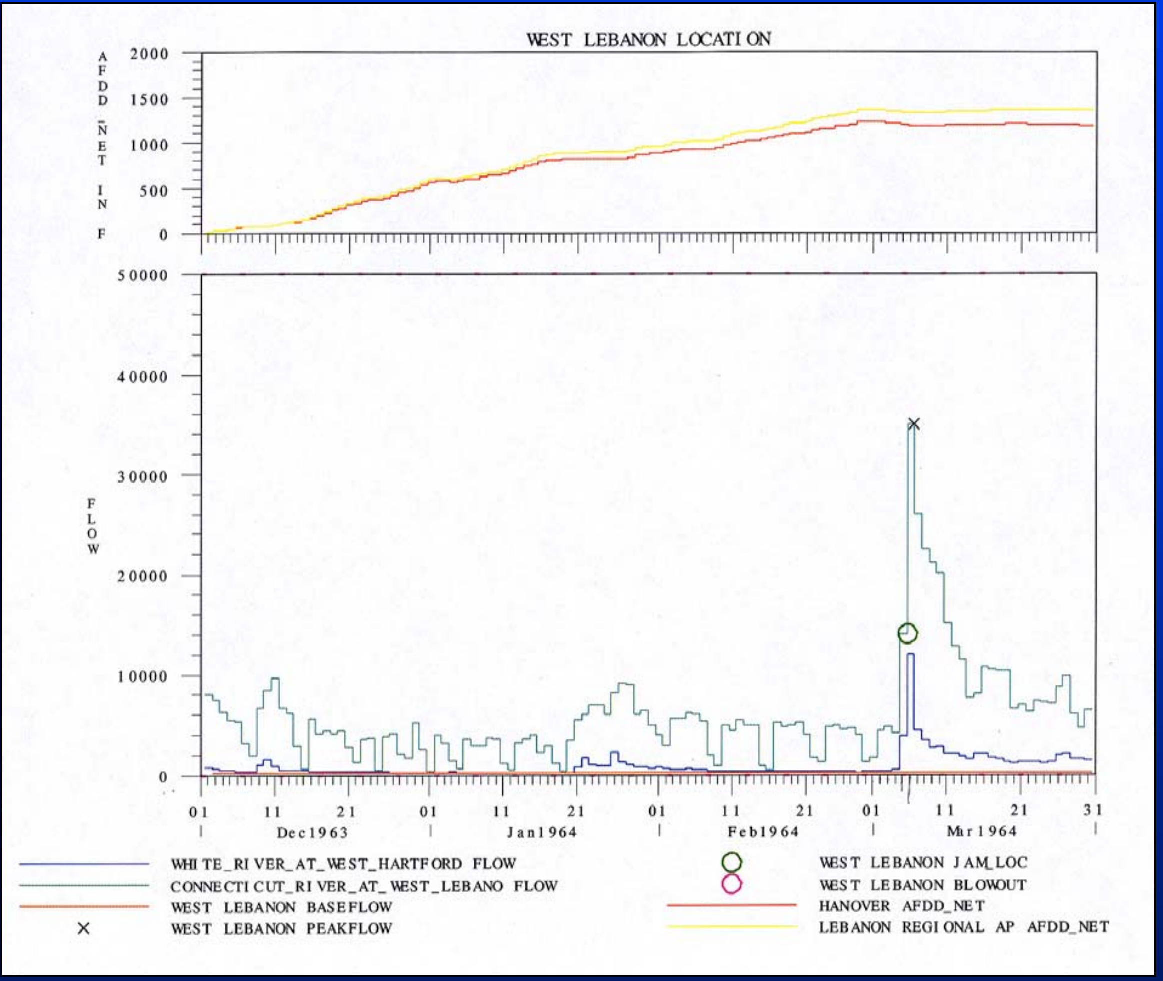
http://www.crrel.usace.army.mil/icejams/index.htm

Recommendations

2. Review hydrometeorological conditions
   - ID those associated with open-water, ice cover, ice jams
   - Estimate ice cover thickness
   - Estimate ice jam thickness and length

3. Perform hydraulic modeling of ice conditions to estimate stages
   - Ice cover
   - Ice jam
   - Numerous conference papers and technical reports available

4. Combine frequencies



US Army Corps of Engineers

Recommendations

5. **Determine ice impacts expected in channel restoration area (velocity, scour, stage)**