Cold Climate Considerations in Stream Restoration

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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.
Sustainable Urban Flood Damage Reduction

Adapted from Leopold (1968)
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 $\Rightarrow$ pollutant loads (numerous)
- Snow management, deicing techniques $\Rightarrow$ pollutant loads (numerous)
- Stormwater facilities $\Rightarrow$ freezing, pollutant loads, ice covers (e.g., Gary Oberts, MN BMP, Center for Watershed Protection)
- Stream restoration $\Rightarrow$ 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
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
Ice bridging or arching

Dynamic Ice Cover Formation

Shoving

Juxtaposition

Deposition

Underturning

No Ice Cover Possible
Ice Cover Growth

Estimate thermal ice growth from modified Stefan equation

\[ t(in) = \alpha \sqrt{AFDD(°F)} \]

<table>
<thead>
<tr>
<th>Ice Cover Condition</th>
<th>(\alpha^*)</th>
<th>(\alpha^\dagger)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windy lake w/no snow</td>
<td>2.7</td>
<td>0.80</td>
</tr>
<tr>
<td>Average lake with snow</td>
<td>1.7-2.4</td>
<td>0.50-0.70</td>
</tr>
<tr>
<td>Average river with snow</td>
<td>0.4-0.5</td>
<td>0.12-0.15</td>
</tr>
<tr>
<td>Sheltered small river</td>
<td>0.7-1.4</td>
<td>0.21-0.41</td>
</tr>
</tbody>
</table>

* AFDD calculated using degrees Celsius. The ice thickness is in centimeters.
† AFDD calculated using degrees Fahrenheit. The ice thickness is in inches.
Method to Estimate River Ice Thickness Based on Meteorological Data

This manual presents methods for computing river ice thickness based on meteorological data. It includes a discussion of the factors affecting ice thickness and the equations used for its calculation. The manual provides examples and case studies to illustrate the application of these methods.

1. Purpose. This manual is intended for use by engineers, hydrologists, and other professionals involved in the planning, design, construction, and operation of waterways and related structures. It is also useful for educational purposes in teaching courses related to water resources management.

2. Applicability. The methods presented in this manual are applicable to all USACE commands and projects, except where otherwise noted.

3. Distribution statement. This manual is approved for public release. Distribution of the hardcopy version is limited to authorized personnel and organizations.

4. References. The manual cites a number of references for further reading and reference. These references are listed in the bibliography section.

5. Discussion. The manual includes a discussion of the assumptions and limitations of the methods presented. It also provides guidelines for the interpretation of the results.

FOR THE COMMANDER:

J. W. SCHEIDER
Chief of Staff

EM 1110-2-1612

Seasonal AFDD Query Results

Seasonal data for Fargo, ND

Theoretical value: 16.2 inches or 41.2 cm (K = 3.5)
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)
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

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

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

\[ H = \frac{\rho'}{\rho} \eta + 1.32 \left[ \frac{Qn_c}{1.486 BS_o^{1/2}} \right]^{3/5} \]

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

\[ A = \text{cross sectional flow area} \]

\[ P = \text{wetted perimeter} \]

\[ \Delta x = \text{distance between cross sections} \]

\[ R = A/P \text{ (hydraulic radius)} \]
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 regions.

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

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

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

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

Belokon-Sabaneev Formula
Table 1. Values of ice roughness coefficient \( (n_i) \) and composite roughness coefficient \( (n_c) \) calculated from discharge measurements.

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

*Within three days of formation.
†Higher values for thicker accumulations.
**Lower values earlier in the winter.
††Higher values for thinner accumulations.
Increased velocity and shear due to ice cover has implications on material selection.

<table>
<thead>
<tr>
<th>Lining</th>
<th>0 - 2 fps</th>
<th>2 - 4 fps</th>
<th>4 - 6 fps</th>
<th>6 - 8 fps</th>
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<td>Firm Loam</td>
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<td>Mixed Gravel and Cobble</td>
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<td>Average Turf</td>
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<td>Degradable RECPs</td>
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<td>Bioengineering</td>
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<td>Good Turf</td>
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<td>Permanent RECPs</td>
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<tr>
<td>Concrete</td>
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</tbody>
</table>

**Key:**
- **Appropriate**
- **Use Caution**
- **Not Appropriate**
Ice-Affected Stage-Frequency
Ice-Affected Stage-Frequency

Gerard and Karpuck 1979
Combined Stage Frequency Method

1. Declare and Initialize all variables.
2. Read in Ice frequency and Stage data for all cross sections.
3. Count number of ice-affected stages.
4. Read in Open Water frequency and Stage data for all cross sections.
5. Count number of open water stages.
6. Begin Loop for each cross section.

**Determination of Combined Stage Frequencies based on Ice-Affected Stages**

For j = 1 to Number of Ice-Affected Stages

7. Select ice-affected stage: ice_stages(j).
8. Is ice-affected stage greater than maximum open water stage? 
   - Yes: Next j
   - No: Interpolate open water frequency at that stage
9. Is ice-affected stage less than minimum open water stage? 
   - Yes: Next j
   - No: Combine open water and ice affected stage frequency
10. Add stage and frequency to combined stage-frequency vector

**Determination of Combined Stage Frequencies based on Open Water Stages**

For j = 1 to Number of Open Water Stages

11. Select open water stage: ow_stages(j).
12. Is open water stage greater than maximum ice-affected stage? 
   - Yes: Interpolate ice-affected frequency at that stage
   - No: Next j
13. Is open water stage less than minimum ice-affected stage? 
   - Yes: Next j
   - No: Combine open water and ice affected stage frequency
14. Add stage and frequency to combined stage-frequency vector

15. Sort and reorder combined stage frequency vector
16. Define list of required frequencies such as 2, 2.5, 5, 10, 20, 50, 100, 200, 500, etc. If required frequency is greater than minimum frequency of combined stage-frequency vector and less than maximum frequency of combined stage-frequency vector then interpolate required frequency.
17. Sort and reorder combined stage frequency vector
18. Extrapolate combined stage-frequency vector and estimate uncertainty bands using Lind Program by Dr. Goldman
19. Write data to output files

End Loop for each cross-section

This procedure is for combining independent annual maximum open water and ice-affected stage-frequencies at a given location.

**Procedure for Developing Combined Annual Maximum Stage-Frequencies**

[EPICORREL]
Design: S.P. Elly
Drawn: C.M. Voyvodic
27 June 2003
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%
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
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

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