Ice Formation Processes and Concerns in Hydraulic Engineering

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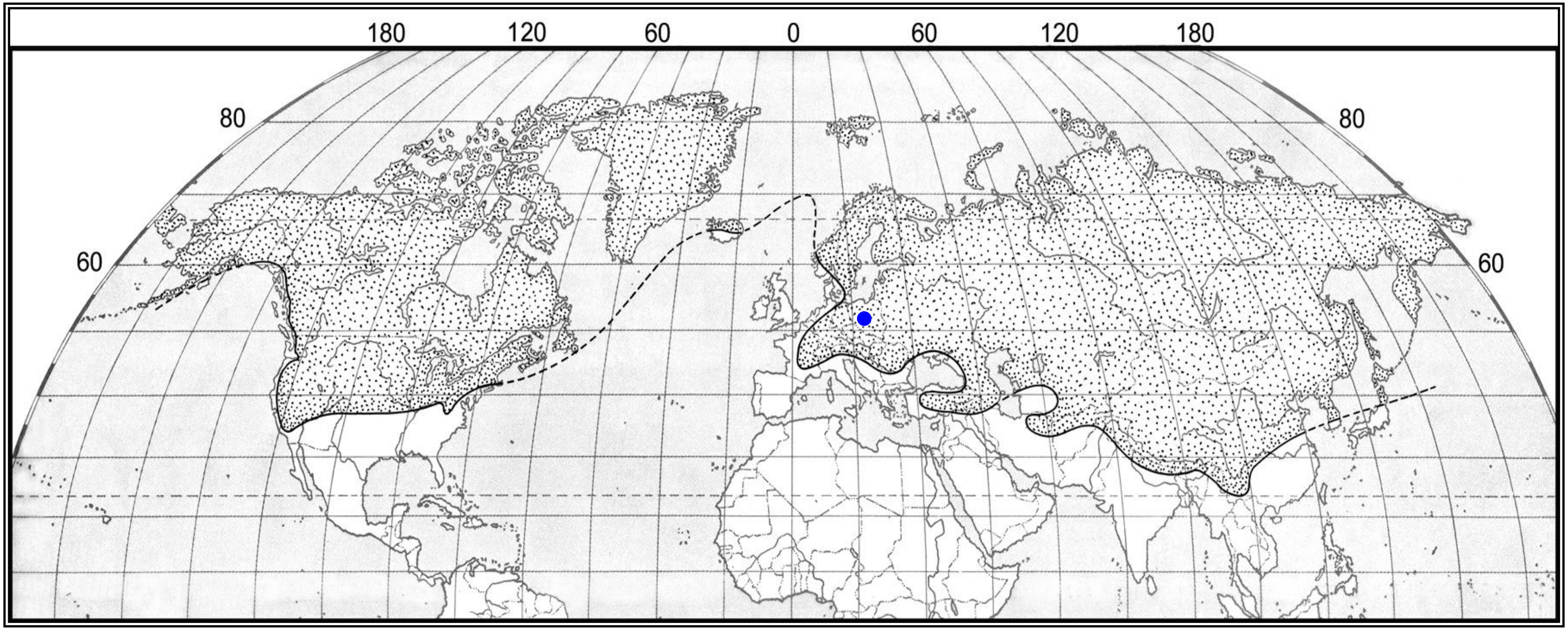
1. Introduction (Main Points)

- Water is a material
- Water’s material properties influence hydraulic engineering
- In many parts of the world, and times of the year, water turns into ice
- Ice adds complexity to hydraulic engineering
- **The purpose of this lecture is to inform you about ice in hydraulic engineering**

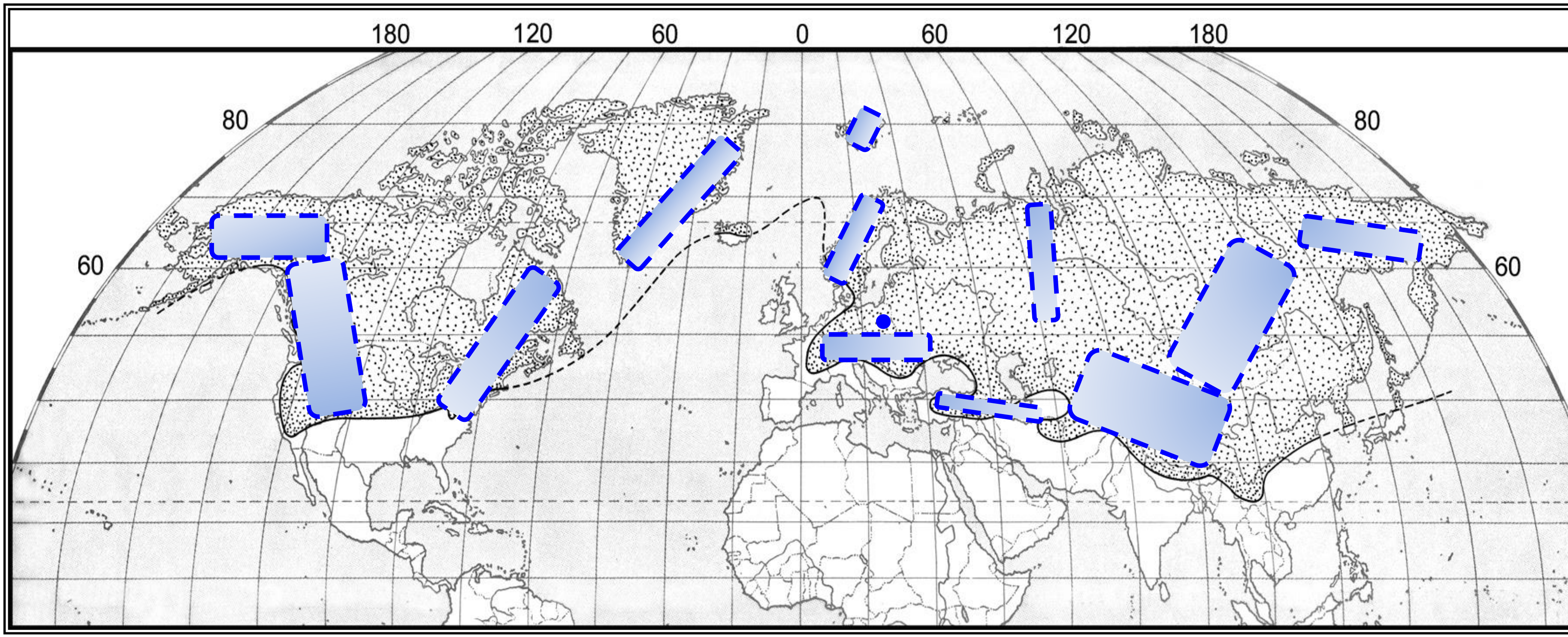
Extensive regions can be freezing cold



Parts of the Northern Hemisphere that experience at least one month of average air temperature below 0^{o}C

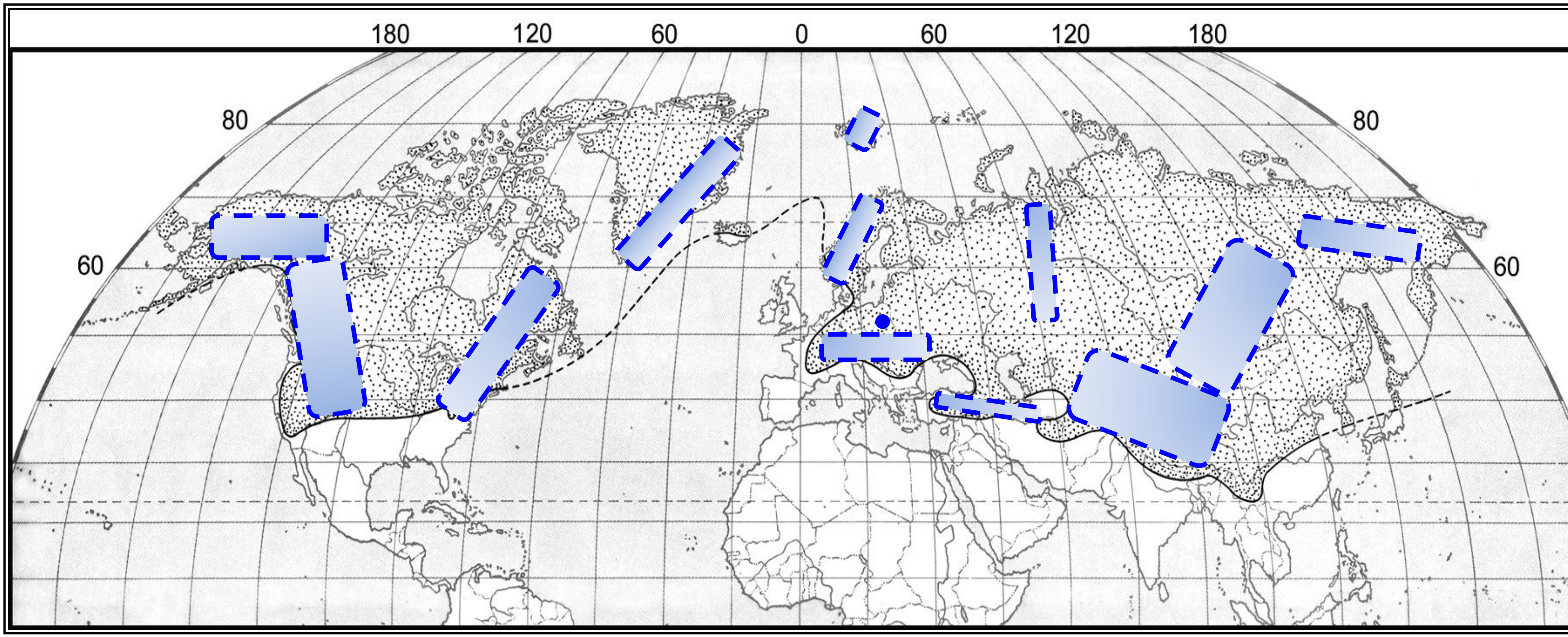
Some regions are cold and mountainous

(Major temperature, pressure and phase changes in hydraulics systems)



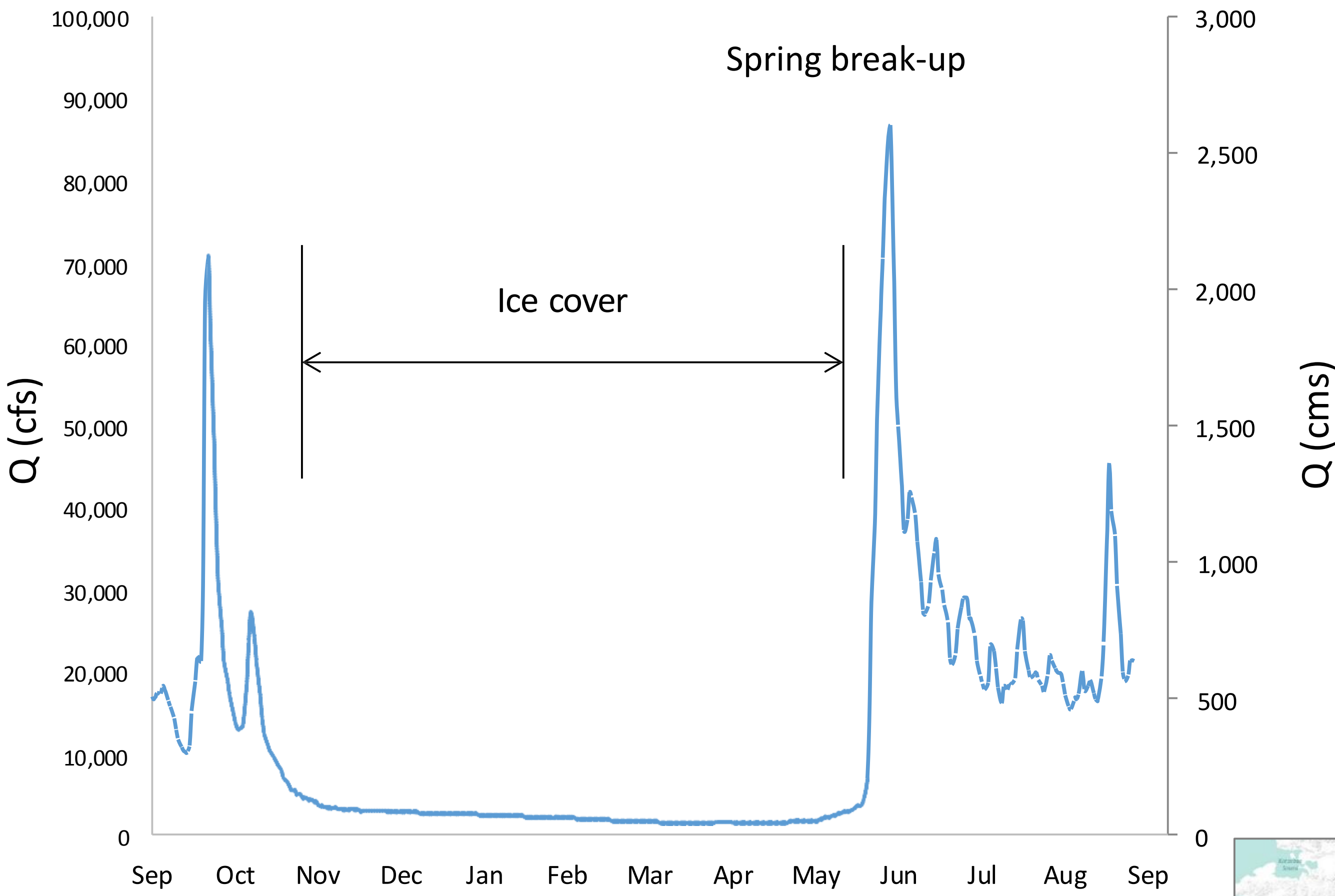
Some regions are cold and mountainous

(Temperature, pressure and phase variations in hydraulics systems)

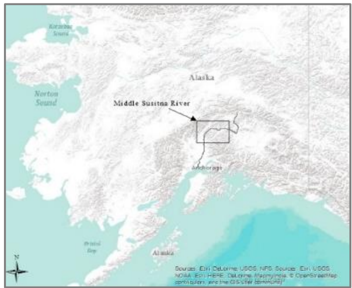


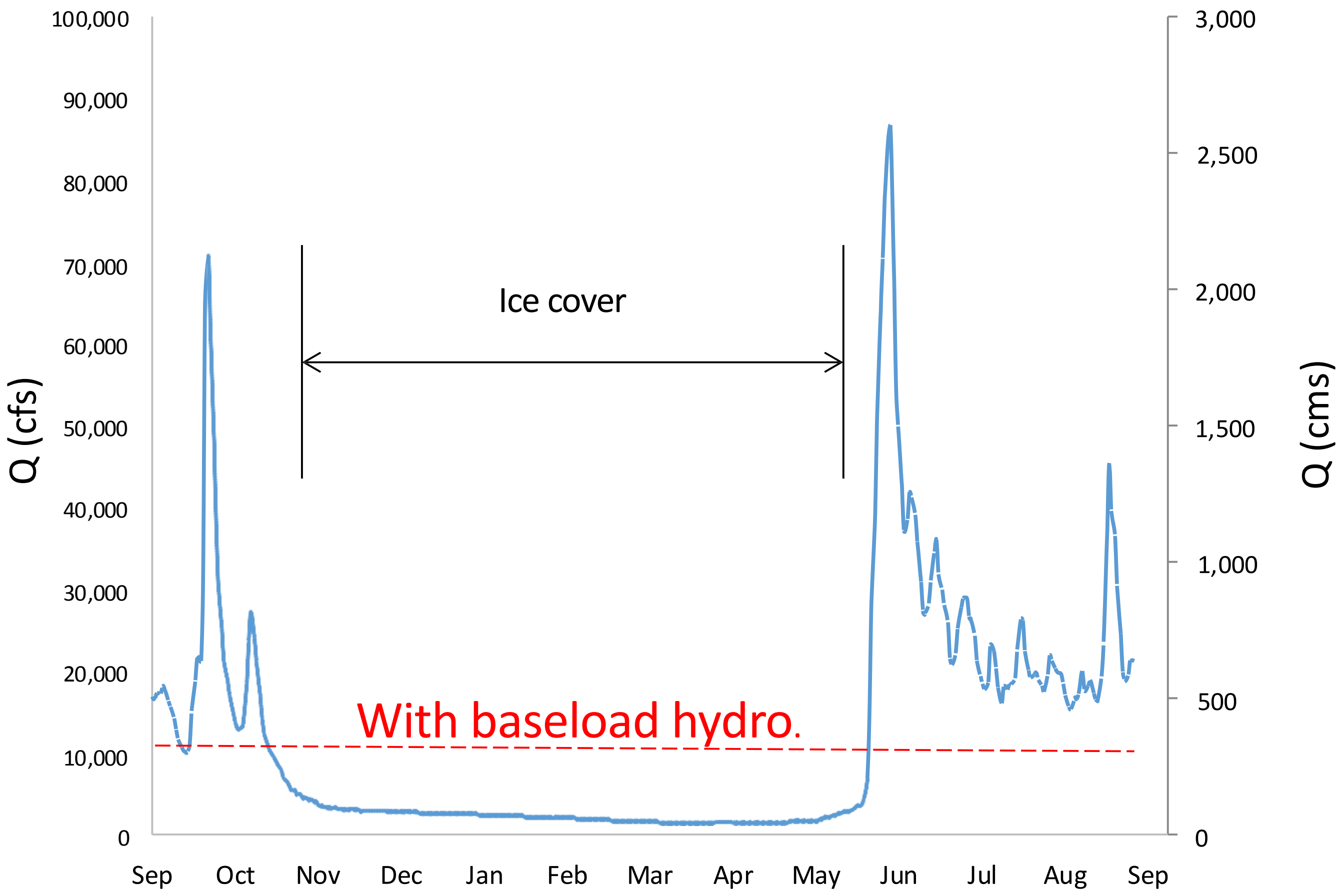
Hydraulic engineers often unprepared for “Jack Frost”

E.g., hydropower development



Monthly flows in the Middle Reach of the Susutna River, Alaska (2012-2013)





Susitna River, Alaska (2012-2013)

Ice (Jack Frost) overlooked quickly complicates things

Perplexed ranchers viewing wintertime, bank erosion along Missouri River, Eastern Montana (a reach d/s of Ft Peck Hydro Dam)

Lecture Outline

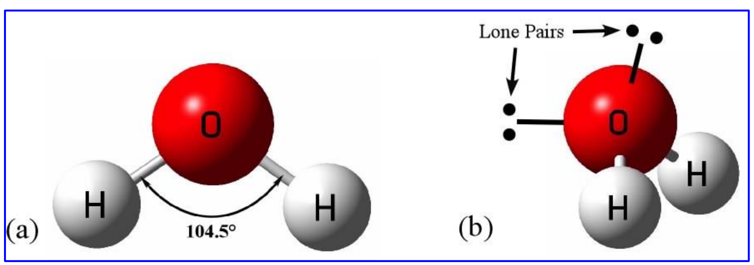
1. Introduction
2. Water's material properties
3. Ice formation processes
4. Ice break-up processes
5. Ice concerns for hydraulic systems
   a). Mountainous terrain
   b). Lower terrain
6. Ice and fluvial morphology
7. Hydraulics problem in a large lake

2. Water's Properties (Main Points)

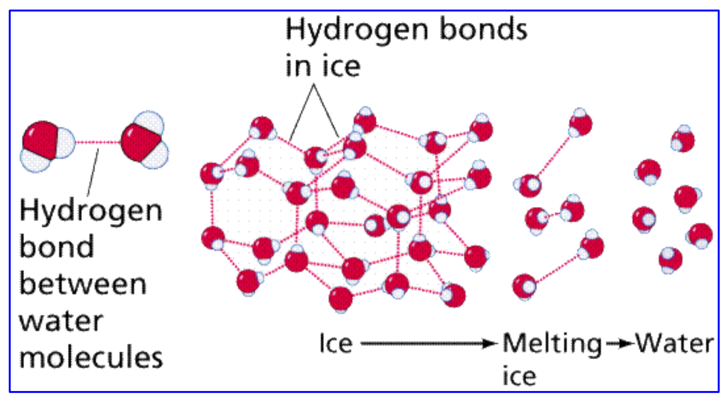
- Water has a simple, small molecule, whose behavior is complex
- Water's unique phase diagram
- Material property variations of greatest interest
    - density
    - freezing temperature (liquid $\leftrightarrow$ solid)
    - thermal conductivity
    - strength

We'll briefly consider

- Phases (and molecular structure)
- Freezing temperature of water
- Densities of water and ice
- Viscosity of water
- Ice's mechanical strengths

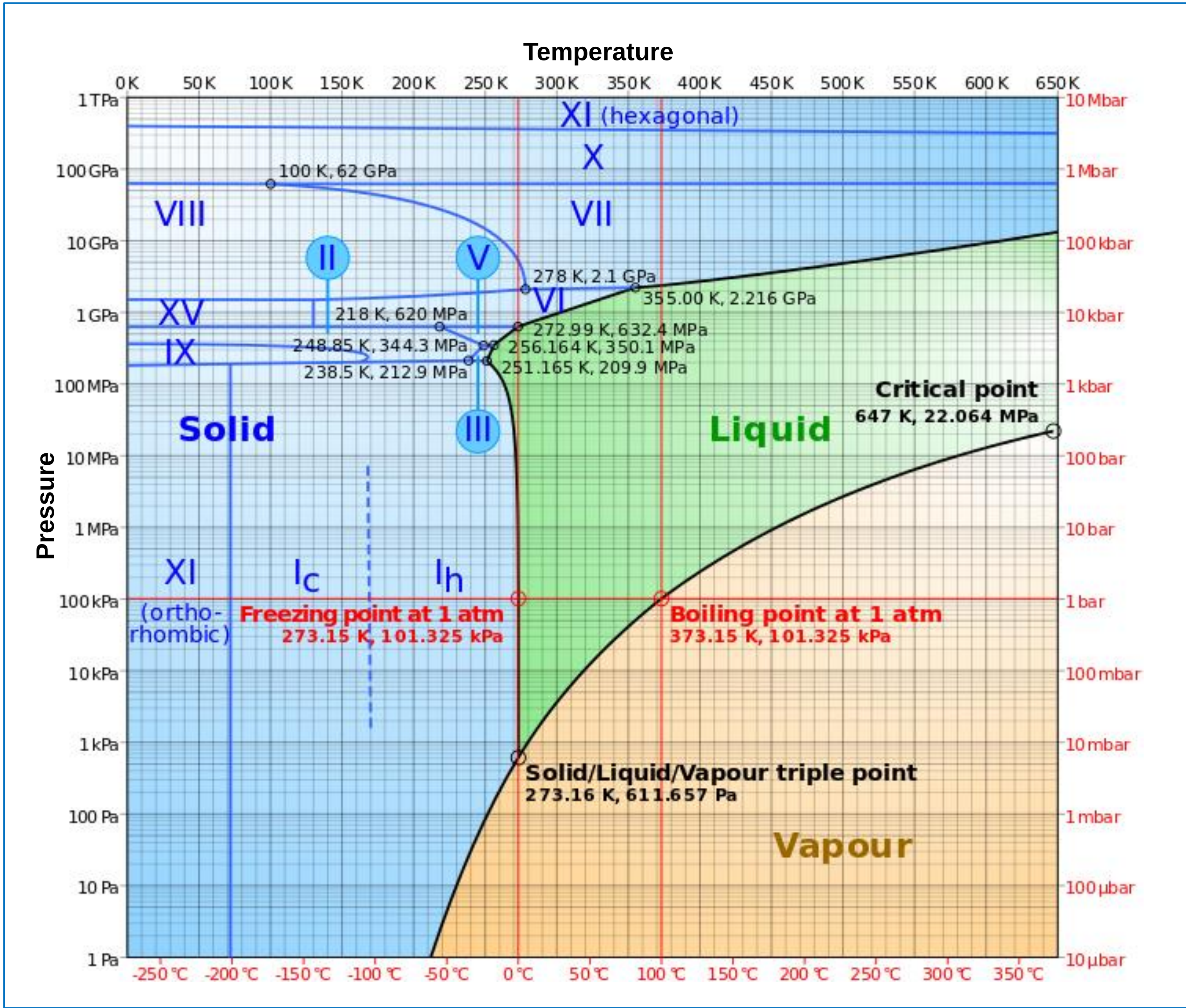


A small, polar molecule



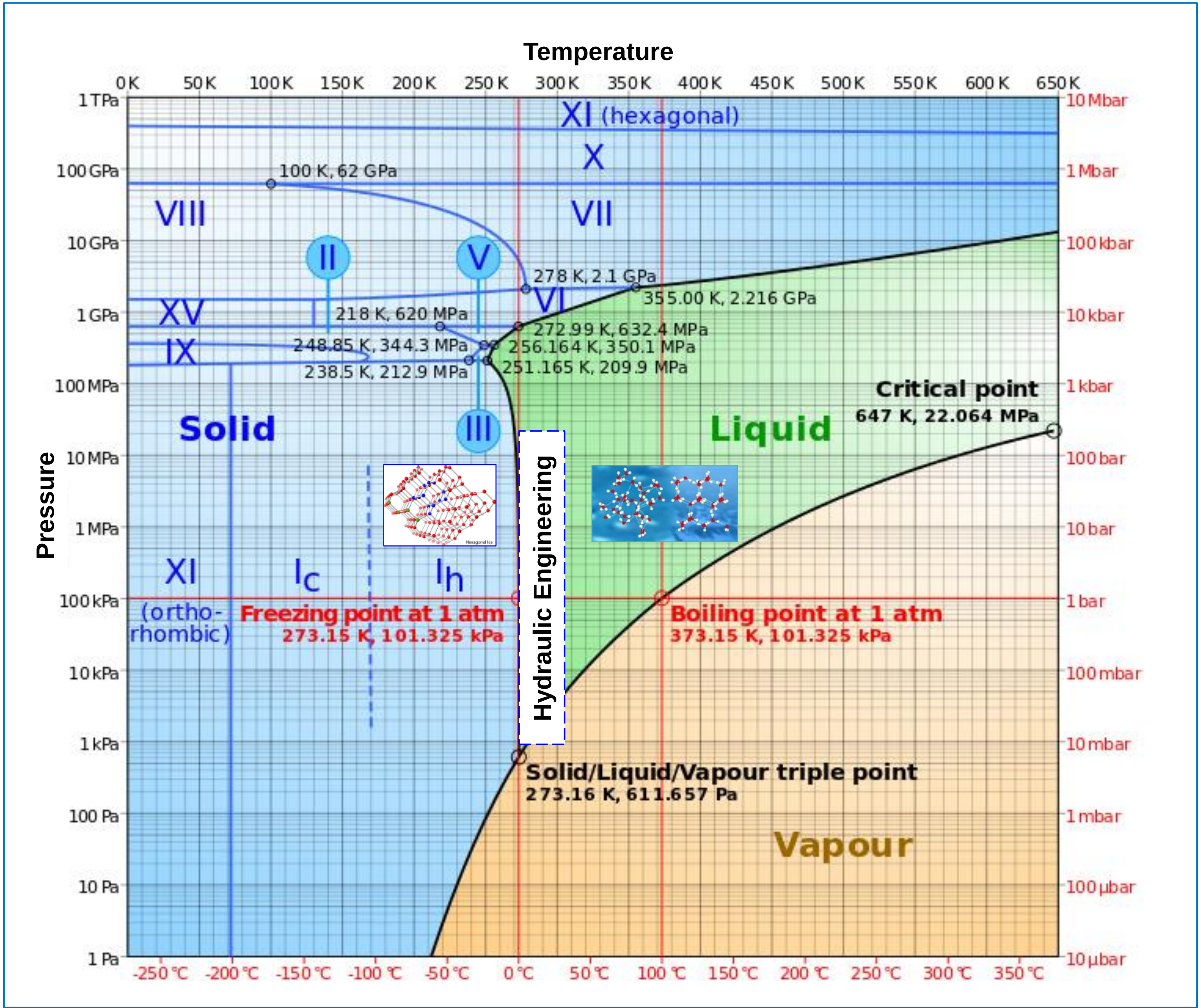
Water's Phases

Ice can assume a large number of different crystalline structures, more than any other known material!

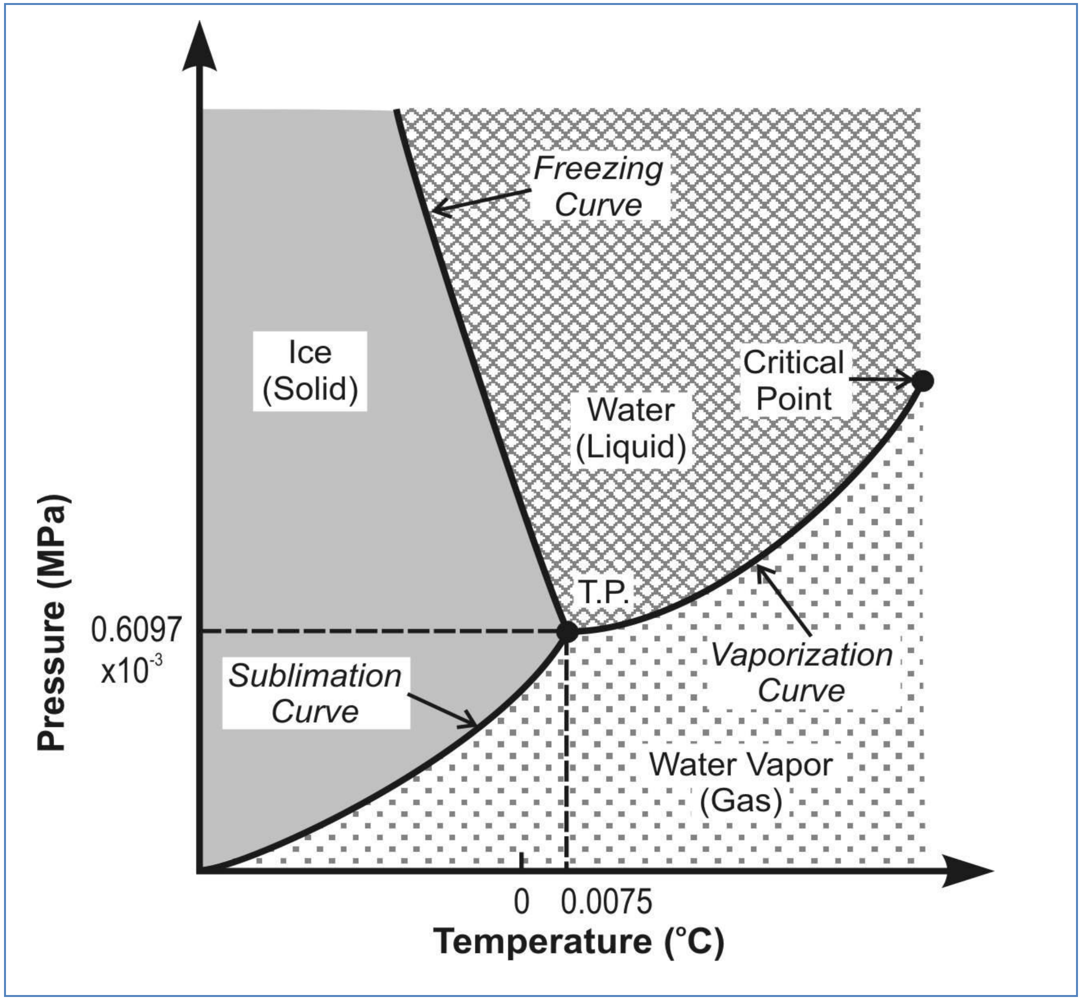


Water's Phases

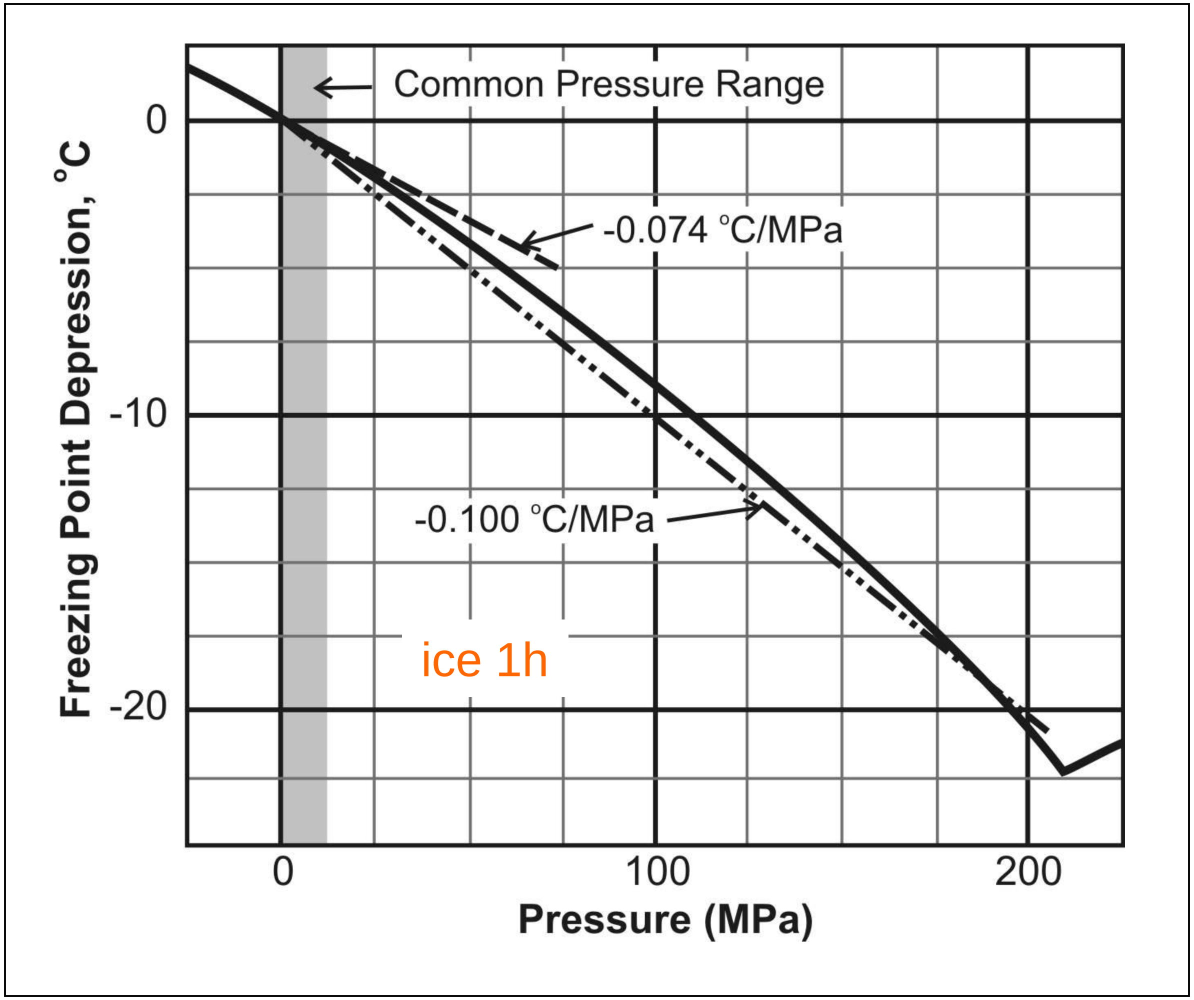
Hydraulic engineering deals with ice "1h", an open hexagonal crystal structure

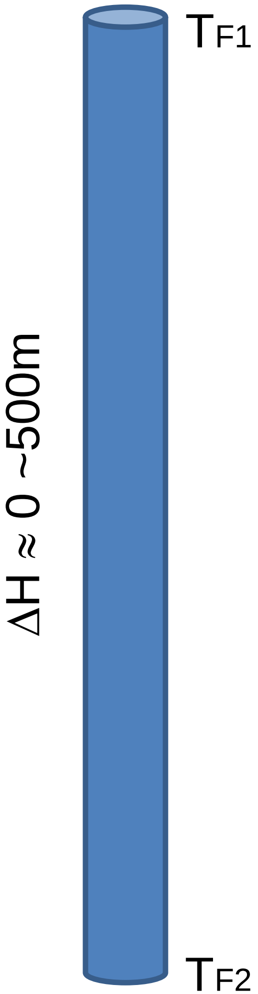


Water's freezing curve is unique



Variation of freezing temperature with pressure

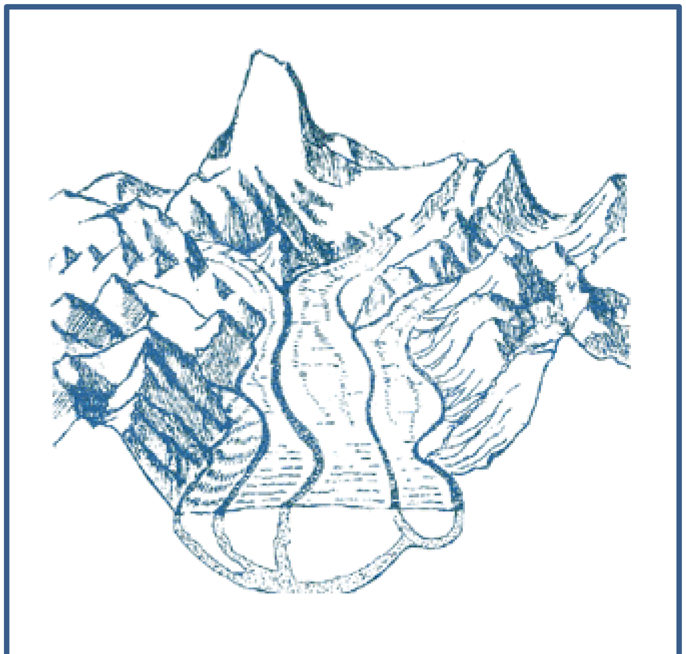


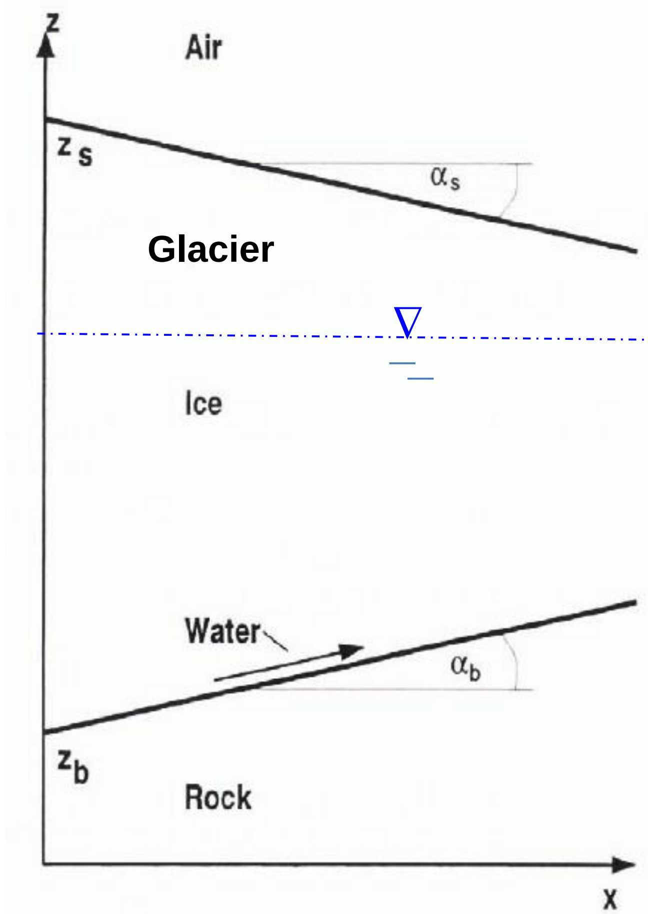


$$T_F = 273.16\left[1-\left(\frac{P}{395.2}\right)\right]^{1/9}$$

Does freezing temperature depression occur in natural flows?
<u>Yes</u>, e.g., for some over-deepened glaciers

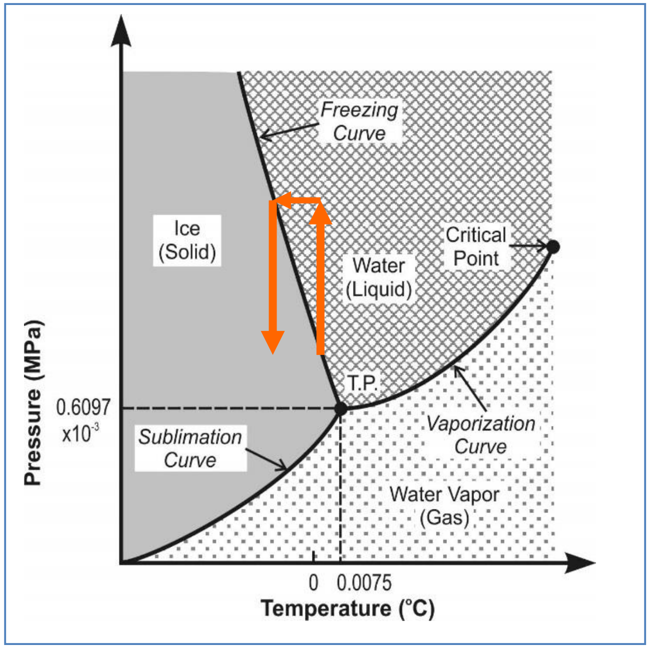
(e.g., Alley et al. (1998), "Glaciologic supercooling: a freeze-on mechanism to create stratified basal ice," JoG





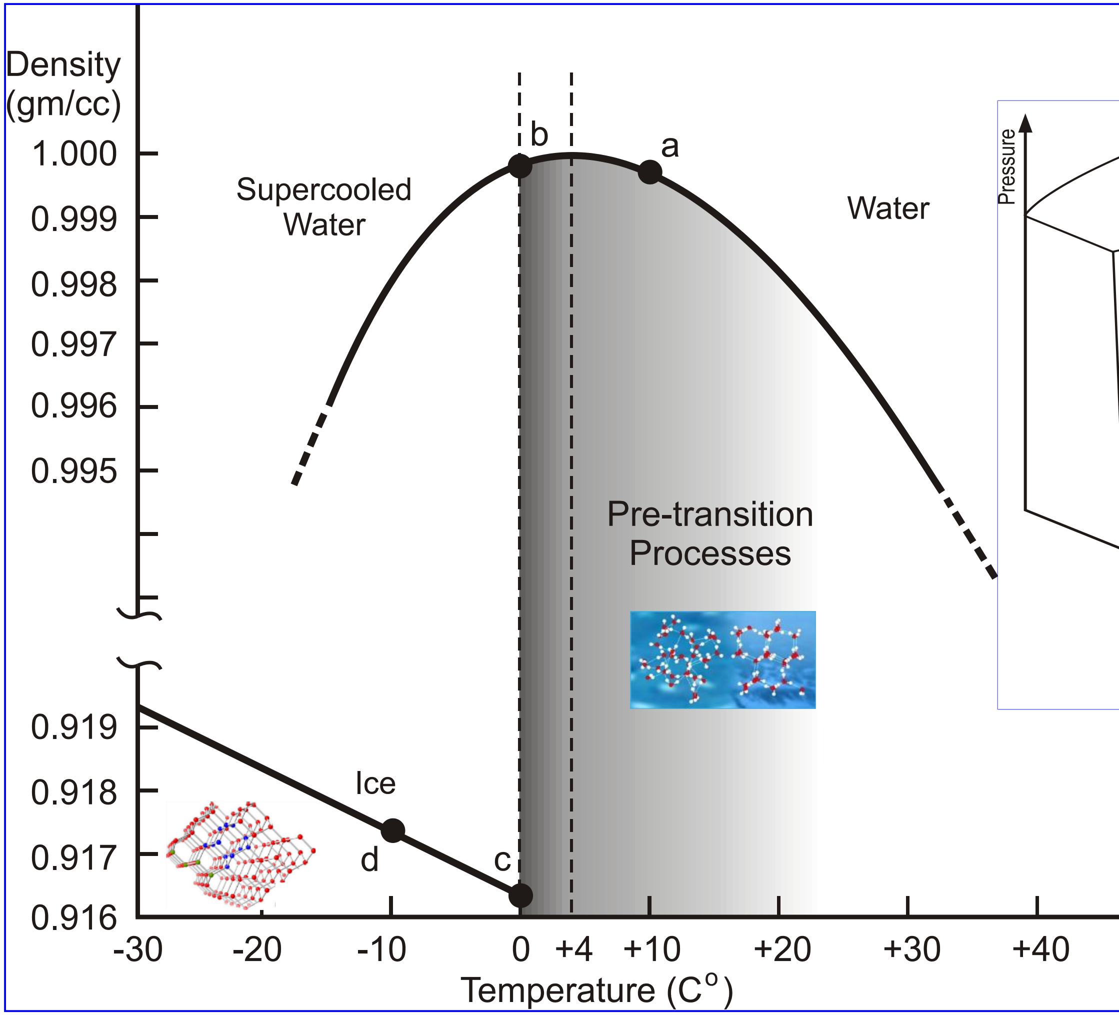
Does depression of freezing temperature occur in hydraulic engineering?

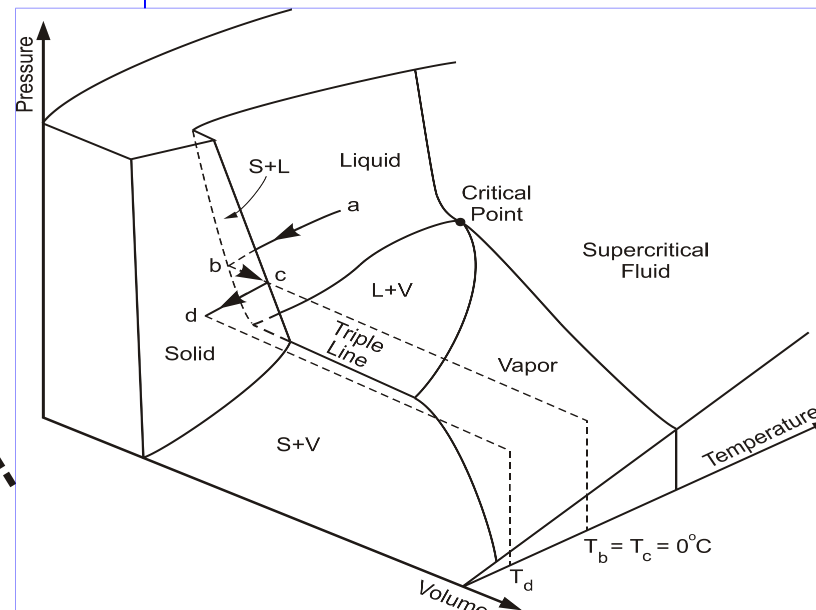
You bet! - For pressurized situations



Also, the reverse process may occur (see later)

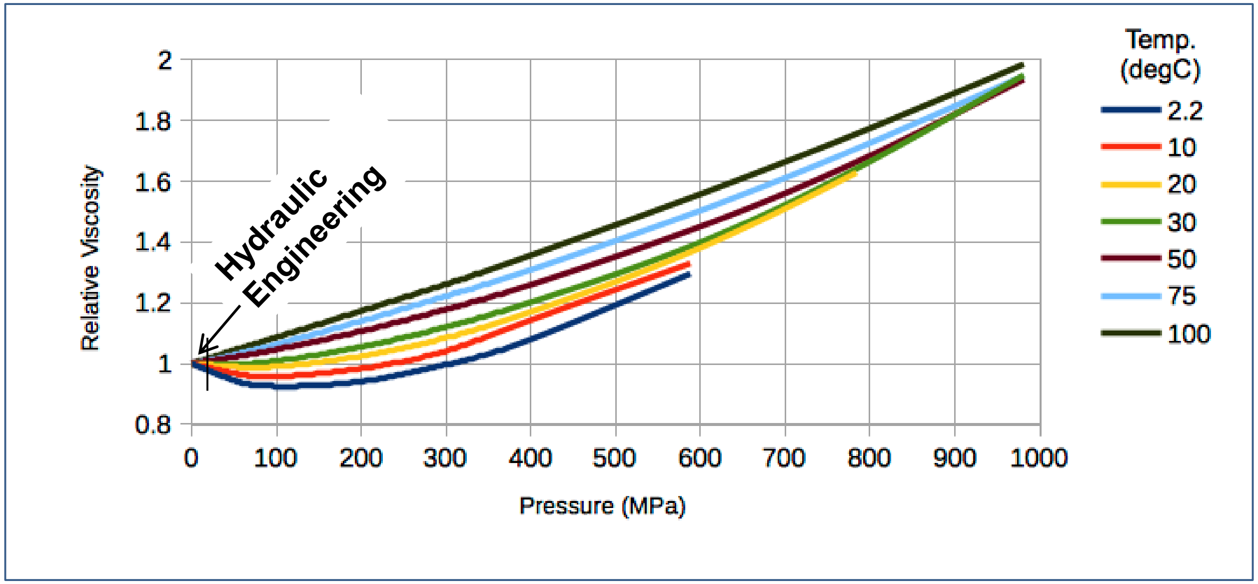
Variation of water density with freezing temperature





Water is unique, as its solid phase (1h) is lighter than liquid phase

Variation of viscosity with pressure and temperature



Significant, but value range narrow in hydraulic engineering

3. Ice Formation in Rivers and Lakes (Main Points)

- Need to consider thermal and phase-change processes
- Ice assumes different forms (same basic 1h crystal)

  frazil ice, anchor ice, border ice, “thermal” ice, aufeis (naled)

- Main types of ice cover

  accumulation (most rivers start this way; large lakes)

  → freeze-up jams (and possible flooding)

  thermal (lakes; eventually rivers; small lakes)

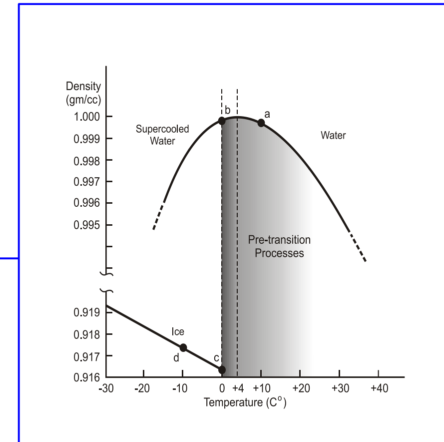
  accretion (very turbulent flows; steep rivers)

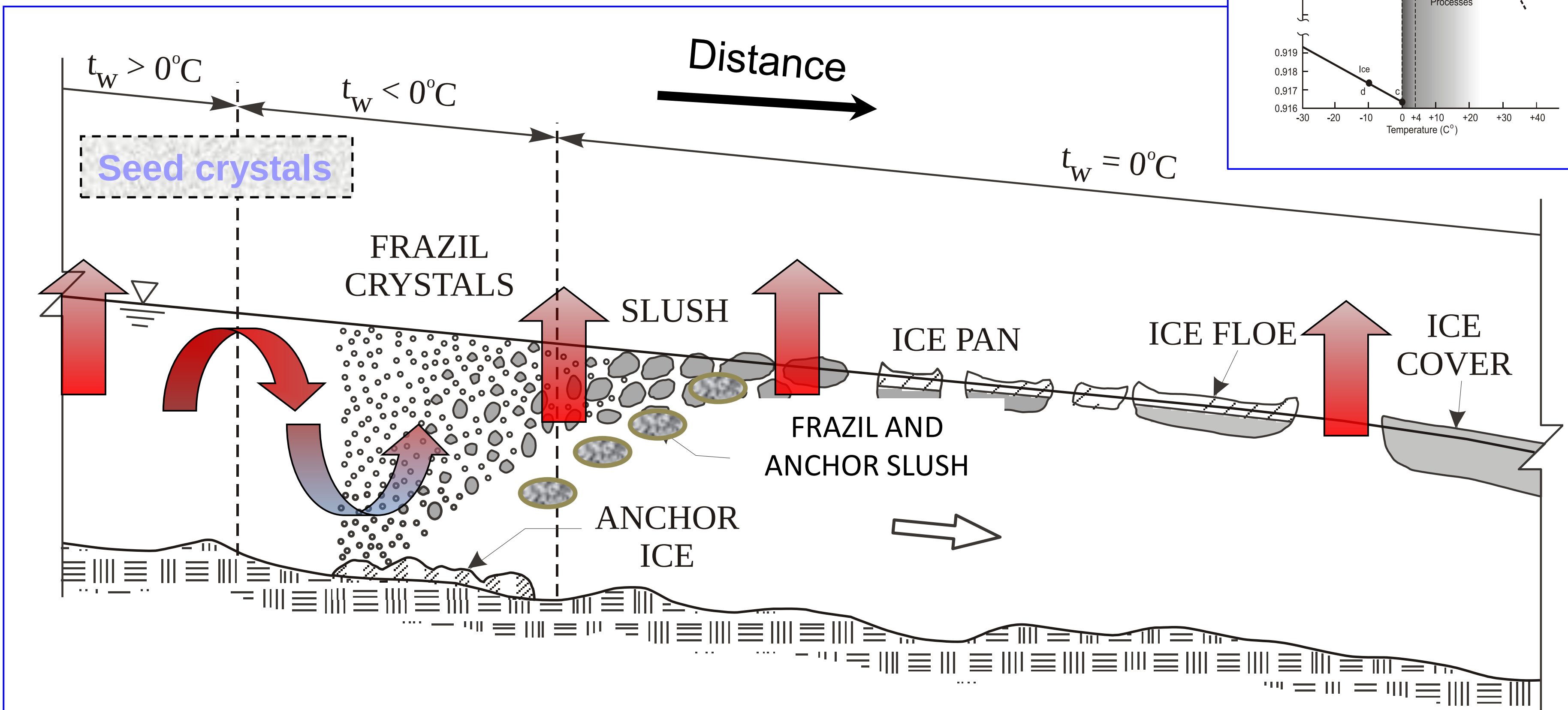
- Ice insulates (reduces convective heat loss to air), esp. when snow on cover
- Ice presence alters flow distribution (3D)
- Freeze-up flooding typically cause flooding along smaller rivers, streams, creeks … low order streams in watershed

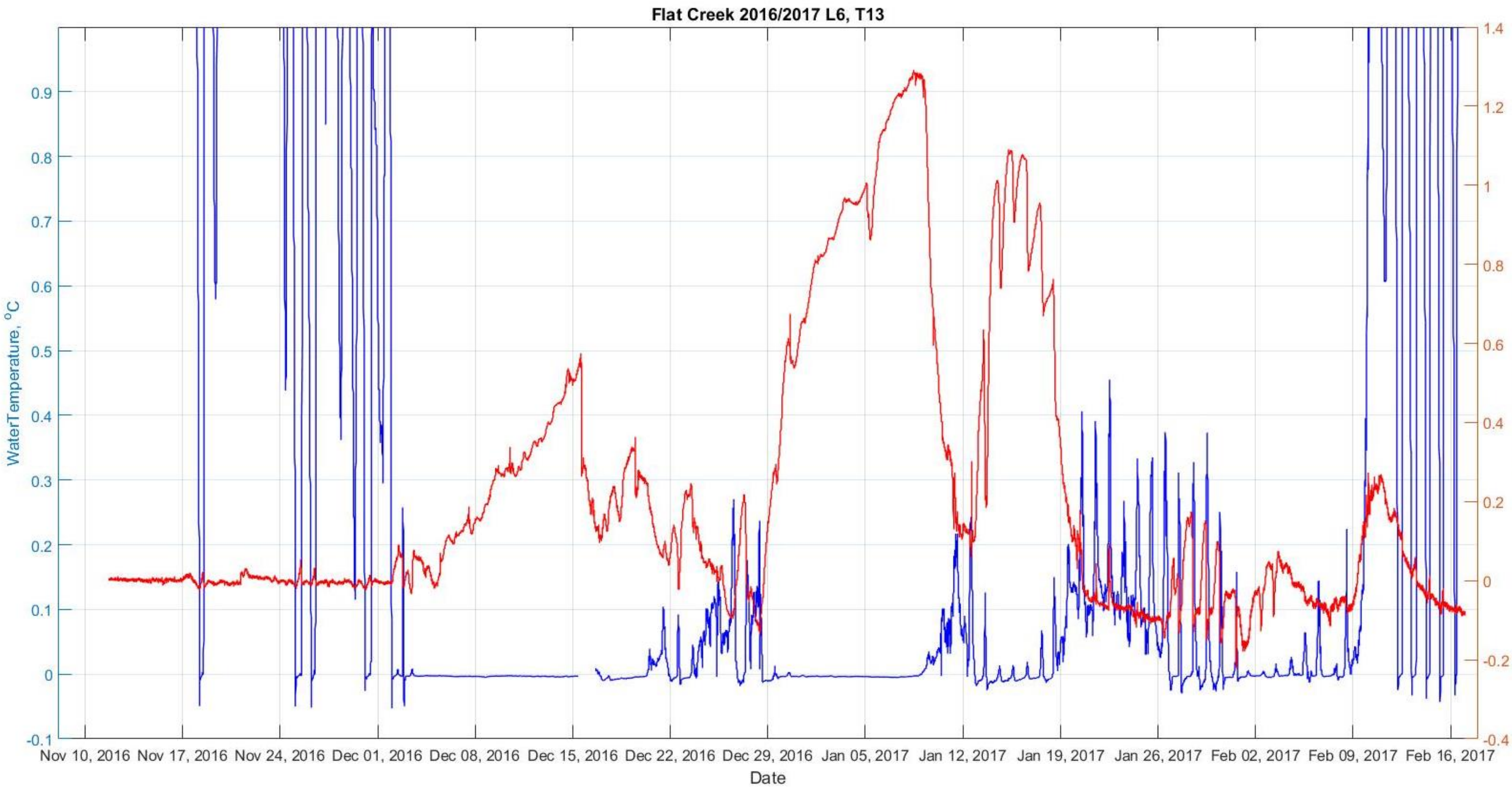
Thermal and Mixing Processes

Mixing of water faster than thermal fluxes in turbulent flows

(Monin-Obukhov Length important)





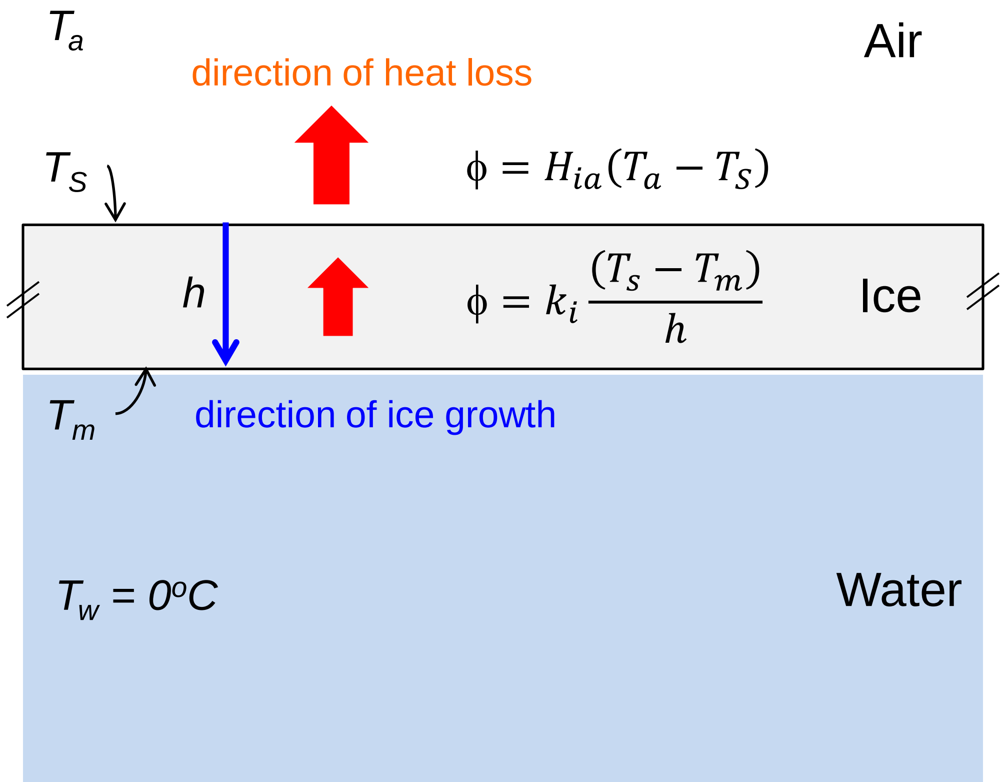


Water temperature and water level
at one location in Flat Creek, Jackson, Wyoming,

An accumulation ice cover becomes a “thermal” ice cover

Yellowstone River near Glendive MT

Thermal growth of ice cover – "thermal ice"

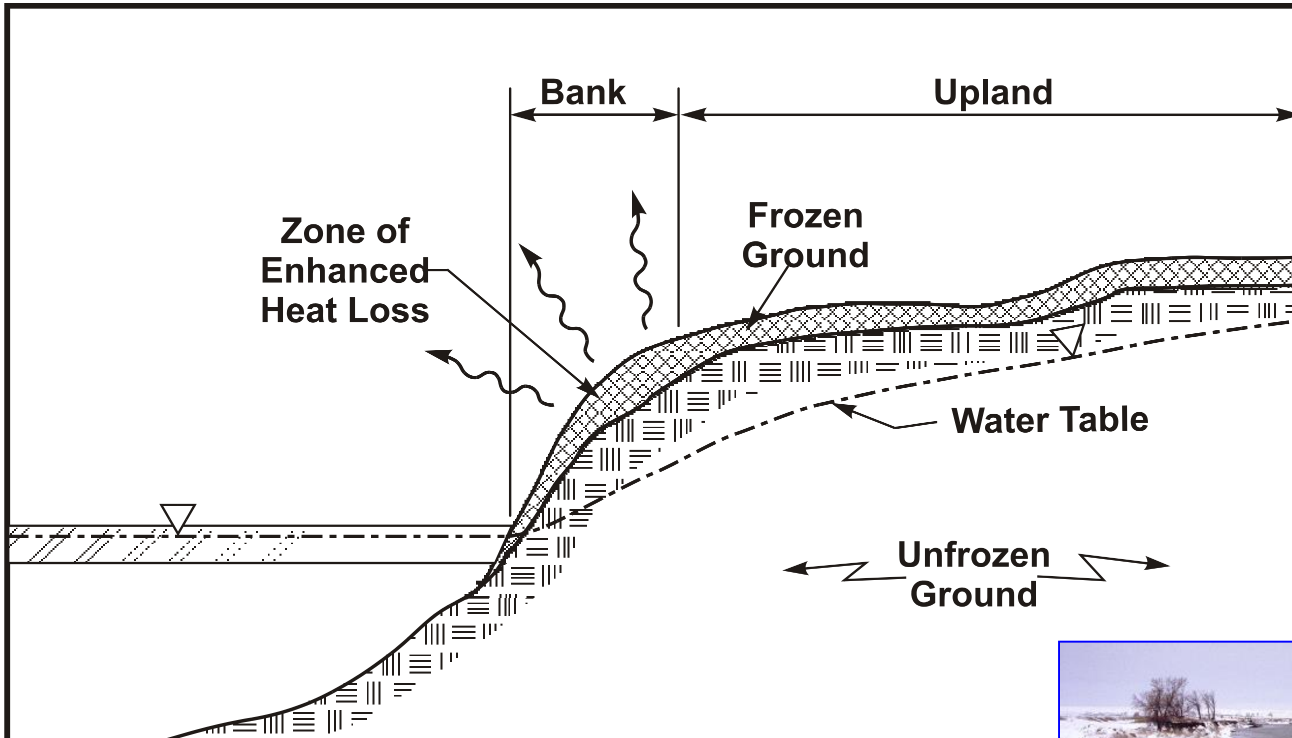


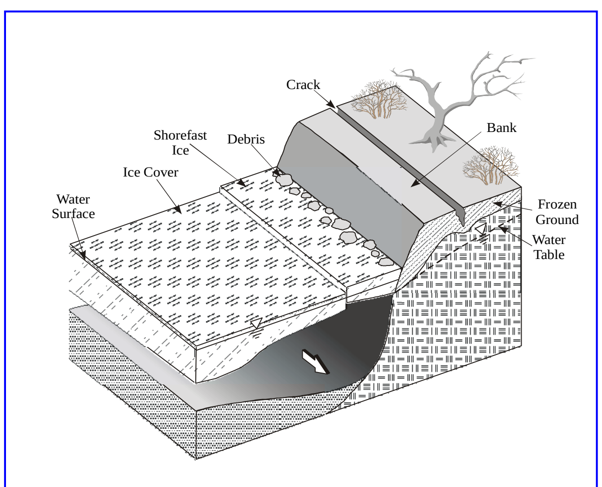
The heat loss coefficient, H_{ia}, takes into account heat fluxes due to – *net short wave; net long-wave; sensible heat; heats of evaporation, condensation & sublimation*

In simplified form, the Stefan equation gives

$h = \alpha(ADDF)^{0.5}$, with *ADDF* = accumulated degree-days freezing

Thermal processes also affect river banks





Several Forms of River Ice
(frazil and anchor ice; border ice; ice cover; aufeis/naled)

Frazil, anchor ice
and border ice

Frazil

Anchor Ice

Drifting slush may comprise frazil and anchor ice

Floating ice cover on Missouri River, MT

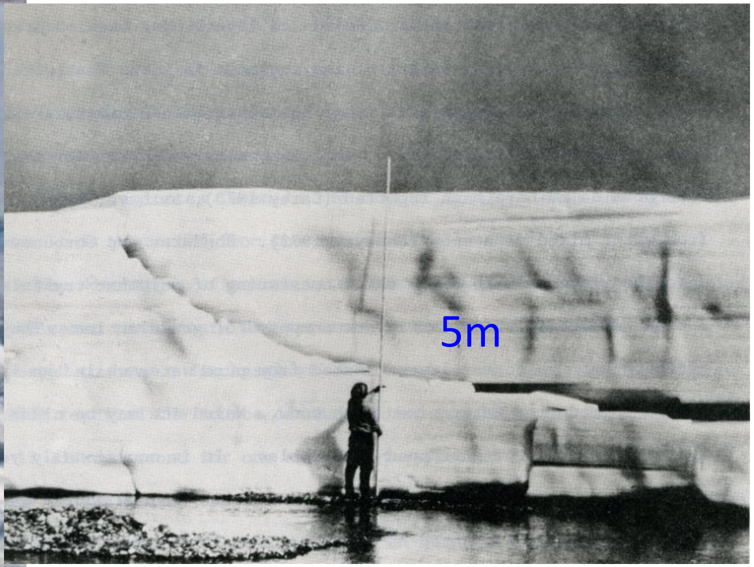
Fixed, irregular cover on Poudre River, CO

Grounded ice, aufeis (naled), in Siberian River

Layering of aufeis (naled)

Aufeis in gravel bed channels
(Runoff flow substantially redirected)

Melt flow cuts through aufeis on a gravel-bed river, AK

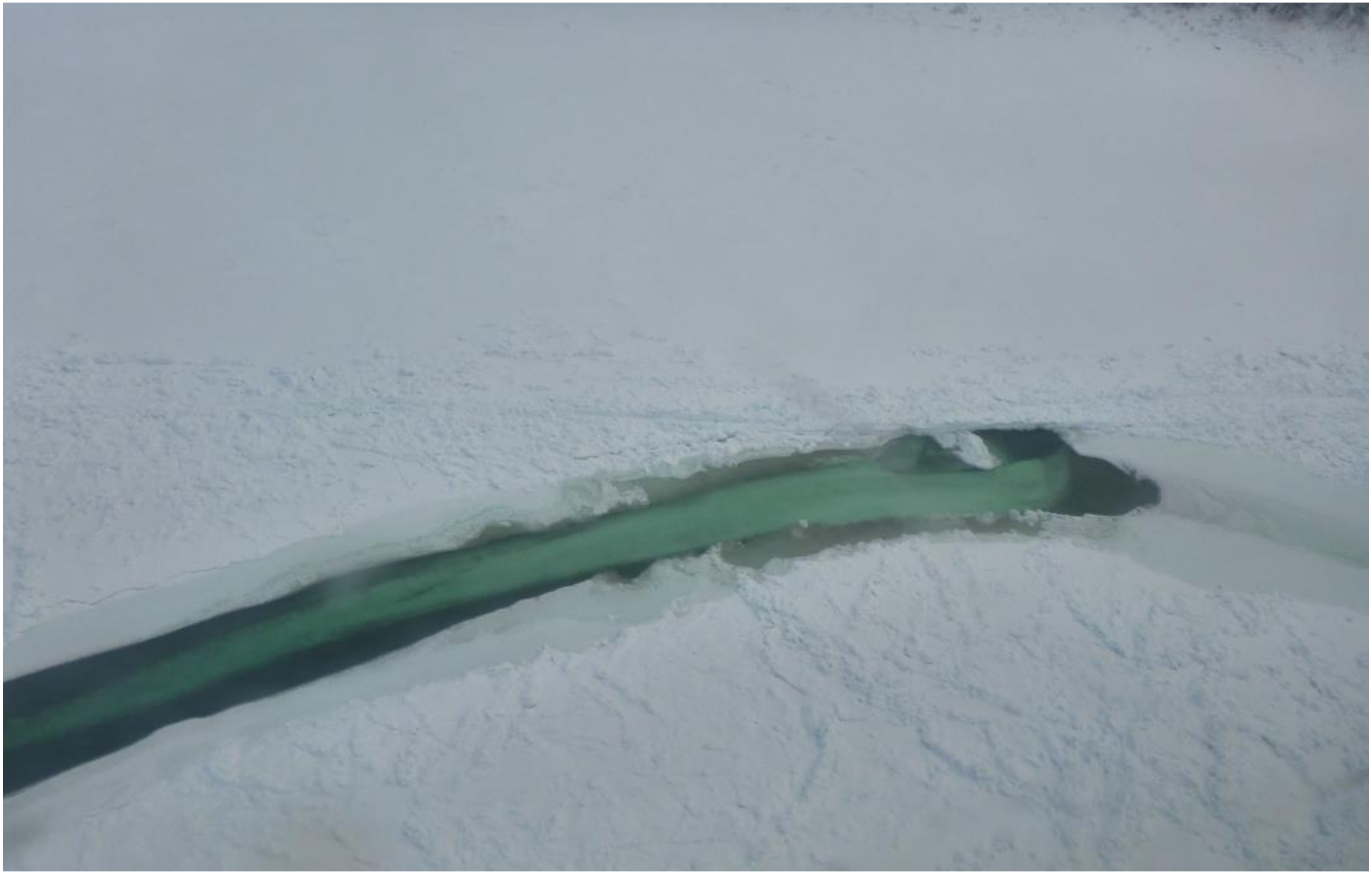


Aufeis formations can get very large, Echooka River, AK (Sloan et al. 1976)

In mountainous regions with substantial groundwater inflow, openwater thermal leads common

Middle Reach of Susitna River, AK

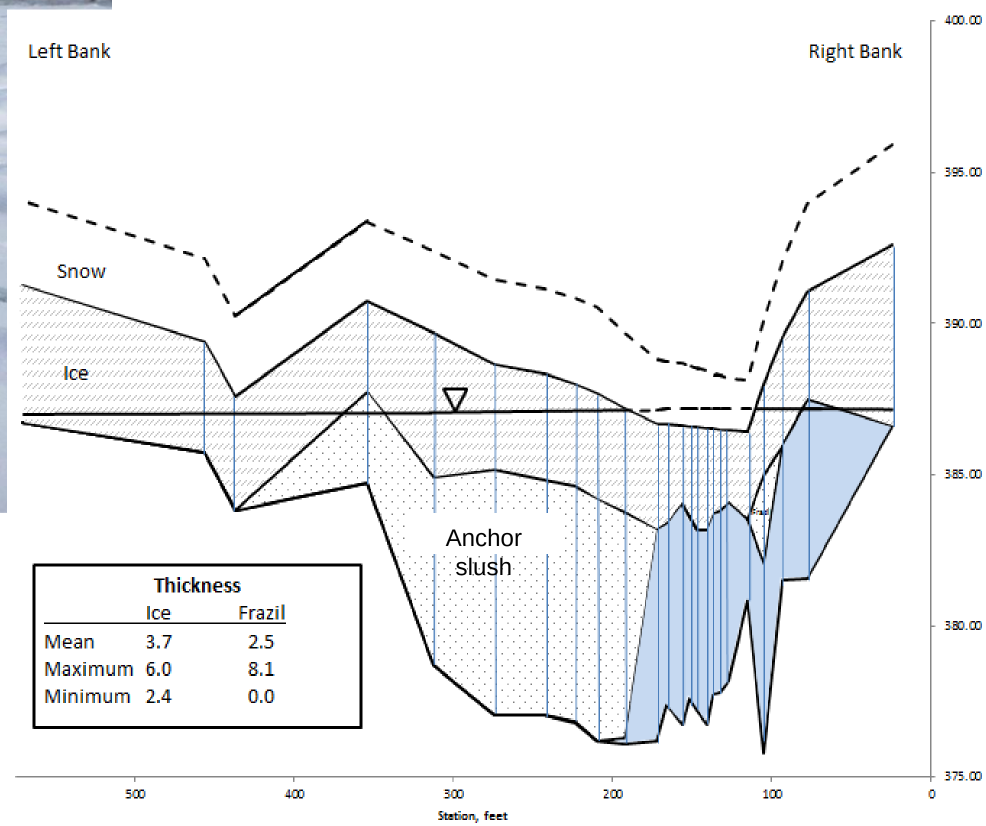
Anchor ice in hydraulic & thermal lead (Susitna River)



Why is anchor ice formation so robust?

Ice under ice, and lateral concentration of flow

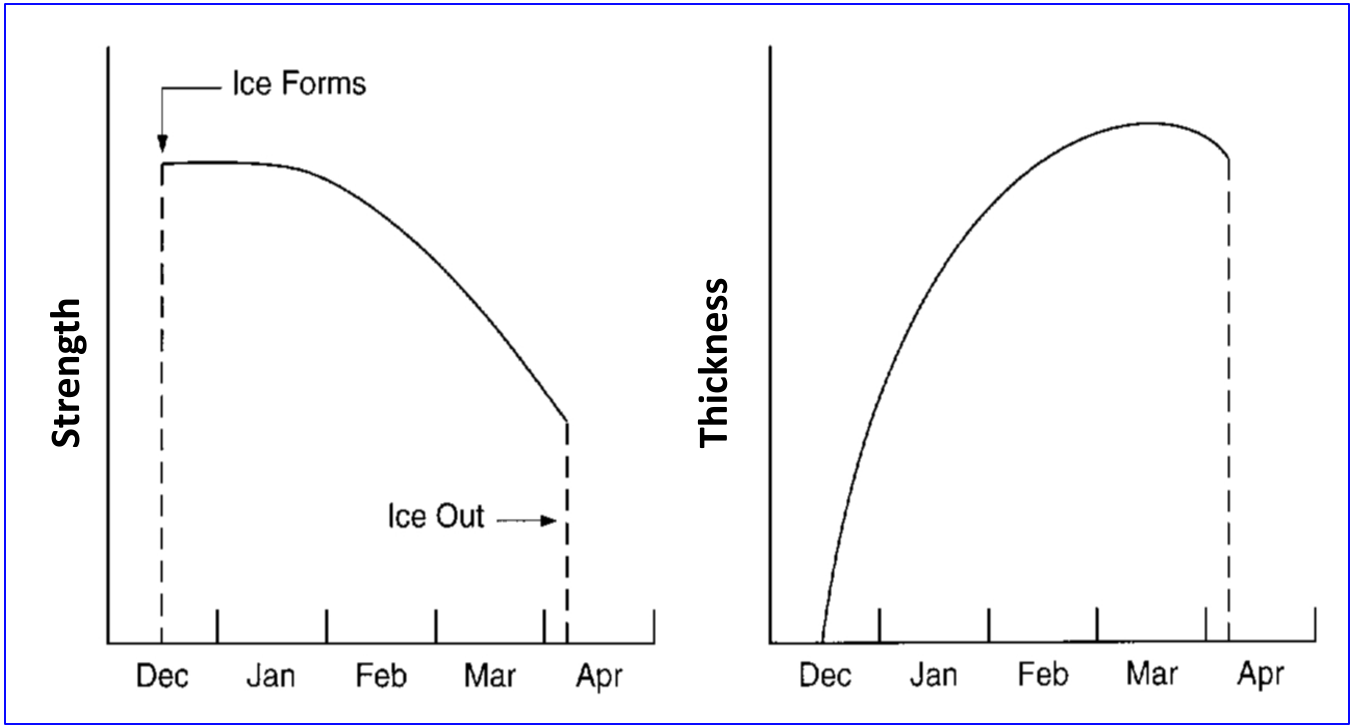
(Channel constriction; Susitna River)



4. Ice Cover Break-up (Main Points)

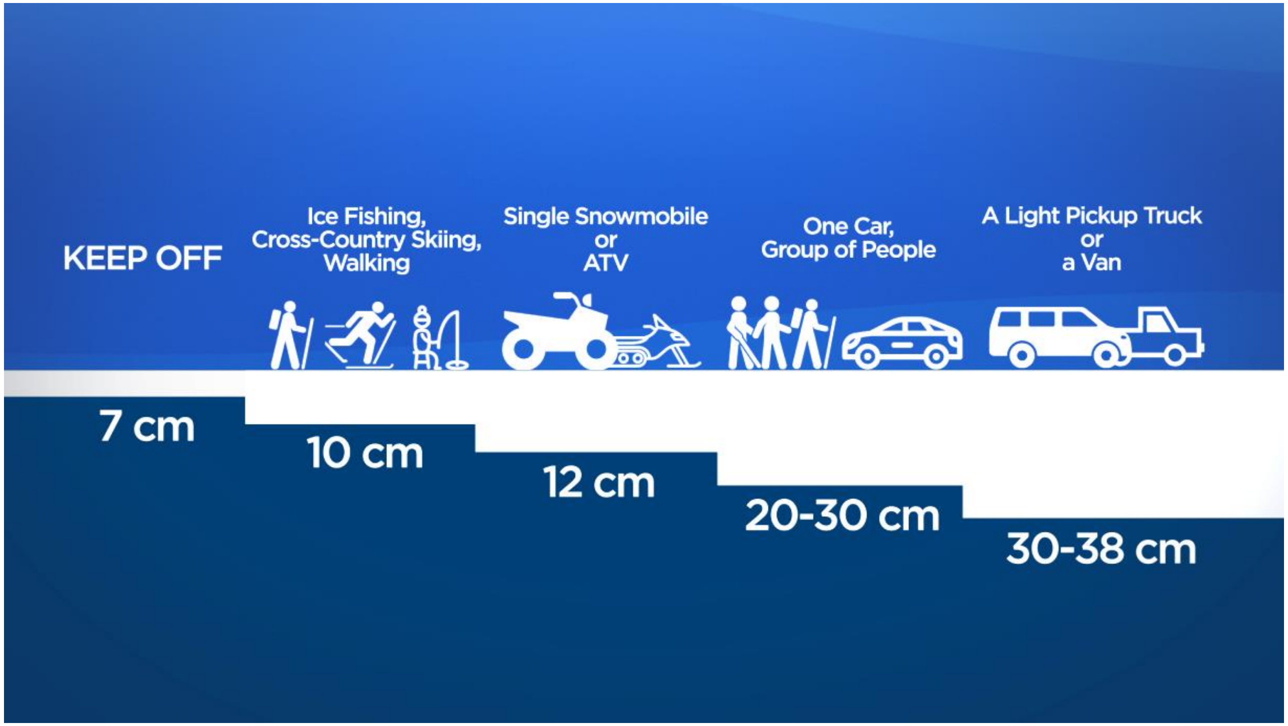
- Ice covers break-up two main ways
  - thermal decay
  - dynamic (mechanical failure)
- Thermal decay ice mainly “rots” in situ
- Dynamic break-up can be abrasive on channels
- Dynamic break-up most dynamic on north-flowing rivers
- Break-up jams typically cause flooding along larger rivers or higher order streams in a watershed

Need to Consider Ice Strength and Thickness



General trends in effective ice-cover strength over the course of winter
Break-up may occur when ice cover is weakened or thin.

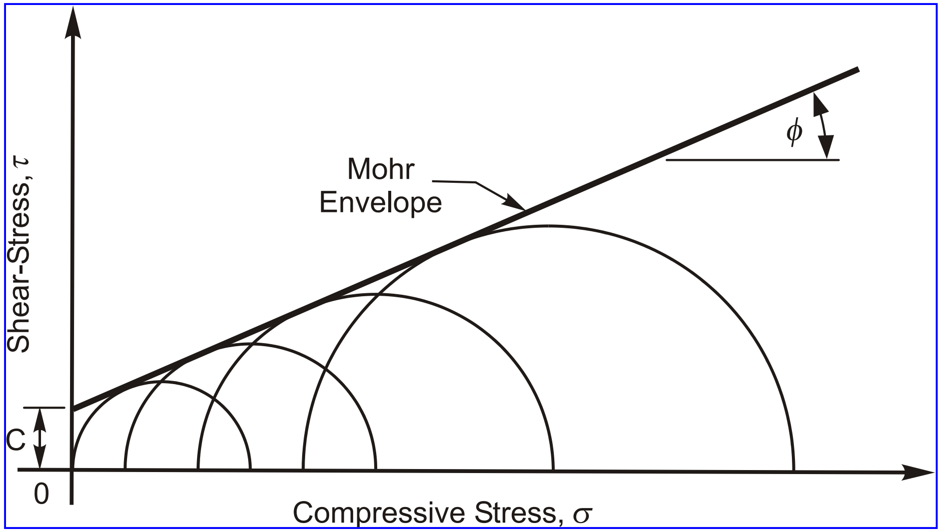
Ice sheet strength: weakest is flexure (upward)
(Ice acts a floating elastic plate on an elastic foundation)



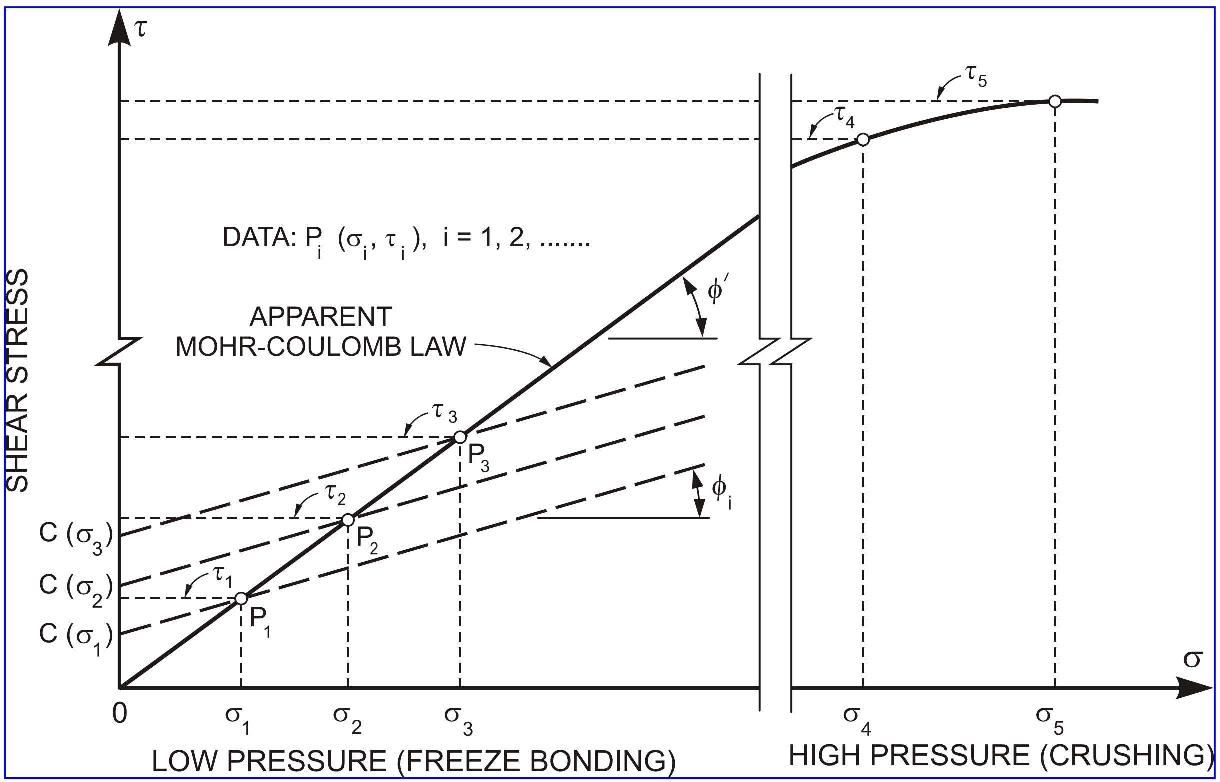
General guidelines

Flexural failure of ice impacting a levee

Ice on Union Dike, Platte River, NE

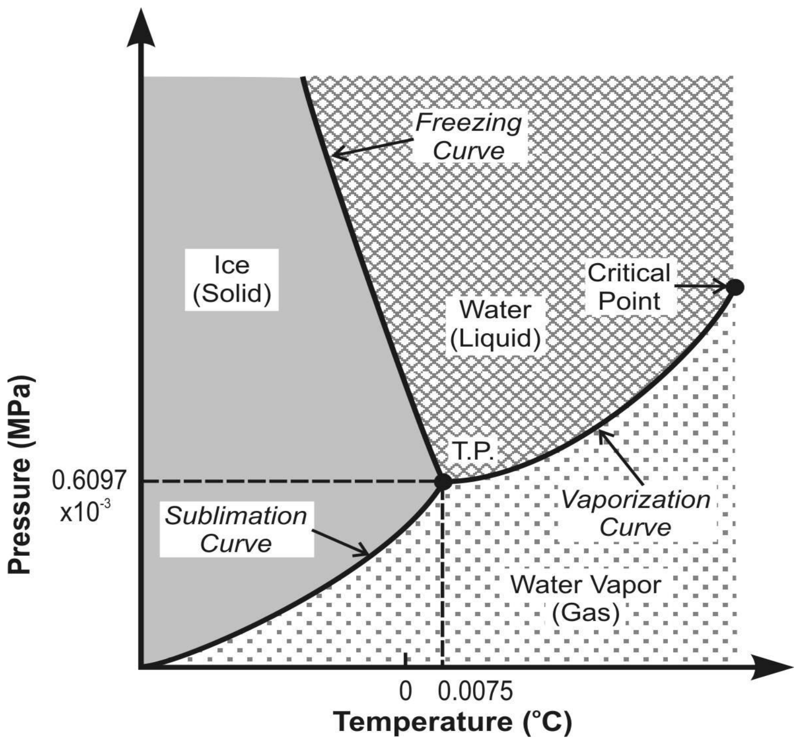


Ice rubble in water has high "apparent" angle of internal resistance, *ϕ′*, owing to "freeze-bonding" of ice pieces (*a pressure effect on freezing temp*.)



4. Ice Concerns in Hydraulic Systems

a). Mountainous Regions



Main Points

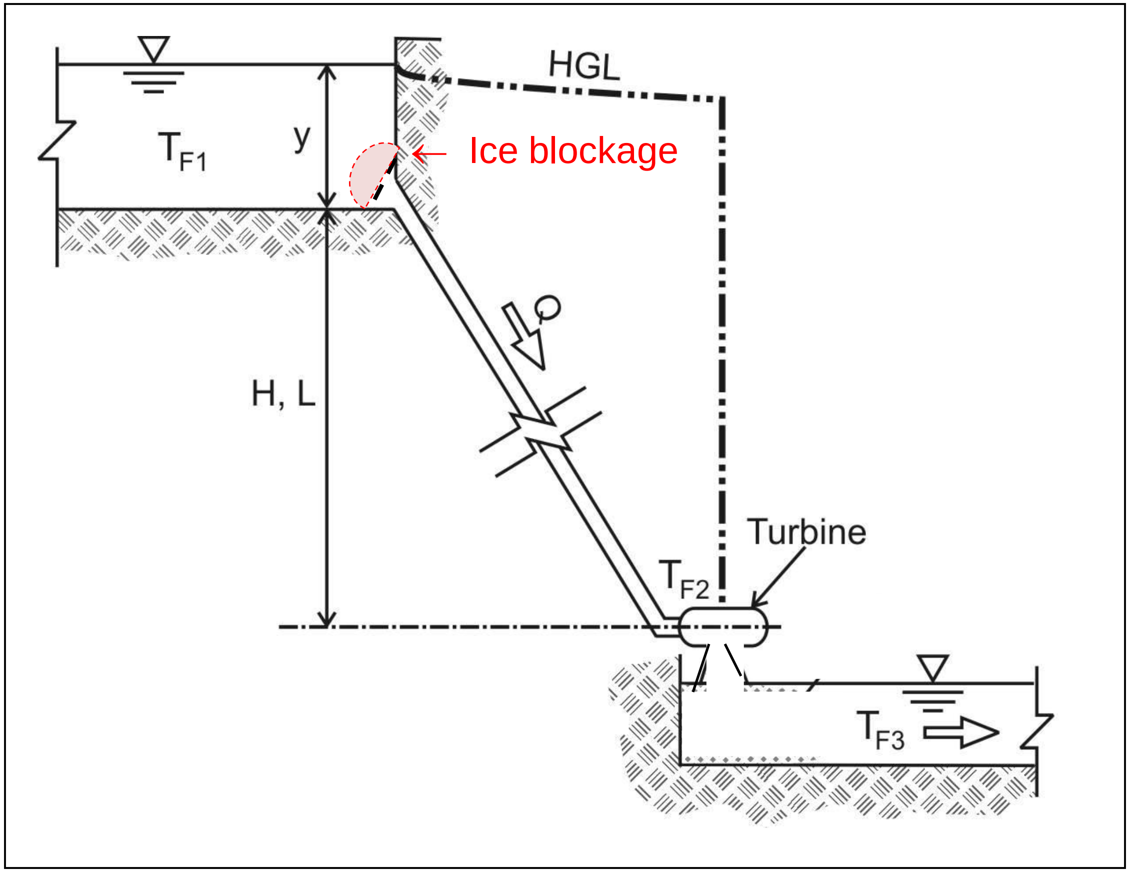
- Ice congests and blocks flow, adds a flow boundary
- Creates problems with various hydraulic systems
  - Hydropower plants
  - Pipelines
  - Channels
  - Tunnels
  - Water intakes
  - Spillways
  - Freeze-up flooding (developed mountain valleys)
- We'll consider other "problems" shortly (Part b, lower elns.)

Mountainous regions are important sources of water, but pose additional complications for the winter performance of flow conduits – colder, greater pressures, groundwater

In mountainous terrain, flow often conveyed in free-surface and pressurized conduits

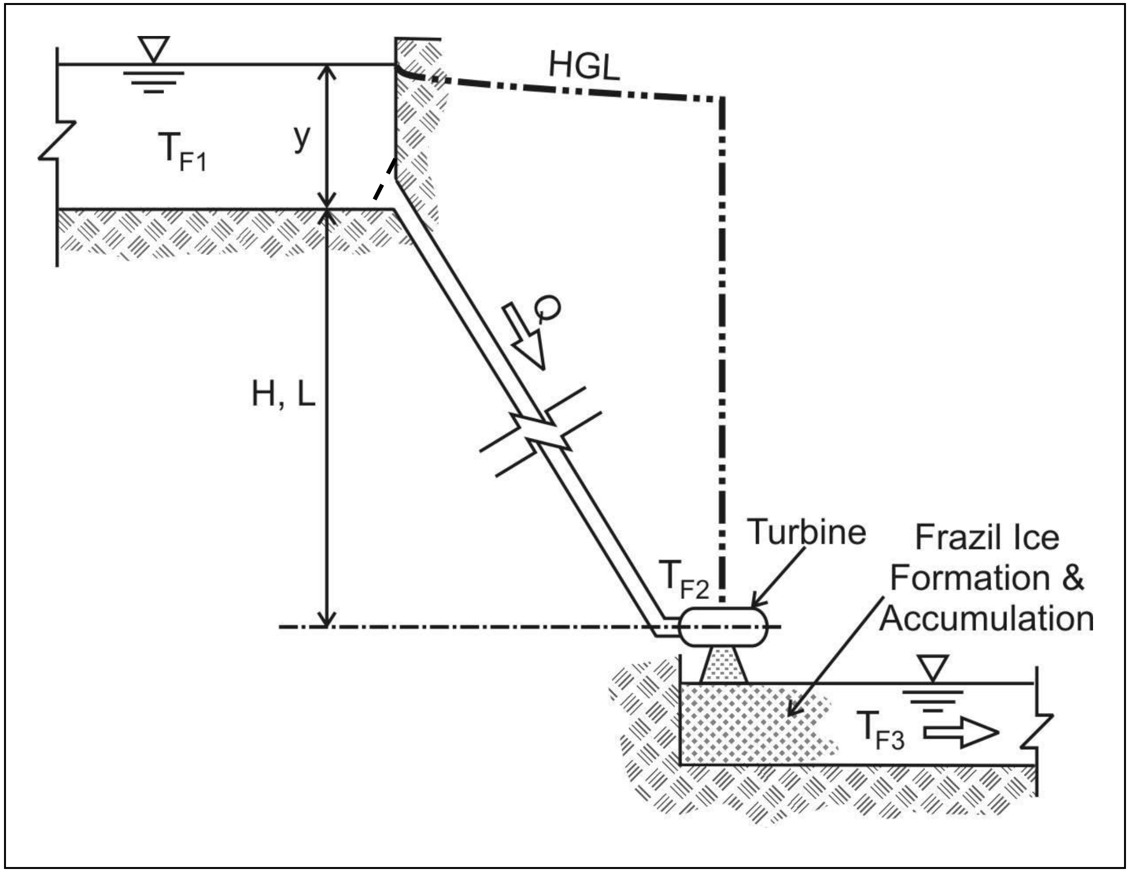
El Dorado Water Diversion System, Sierra Nevada Mountains, CA-NV

Water intakes



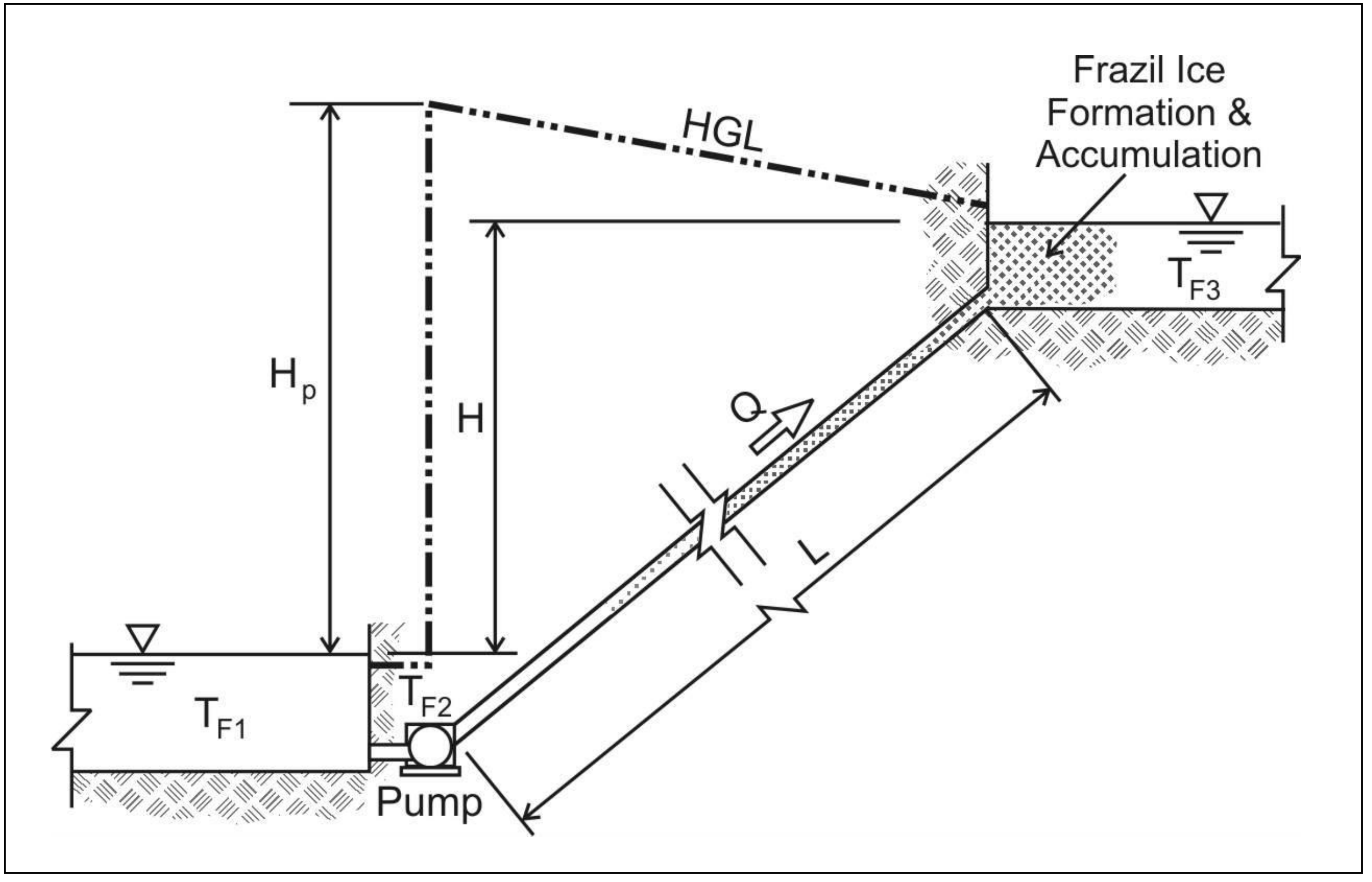
Frazil and anchor ice lockage of intake for hydropower plant

Hydropower penstock and turbine



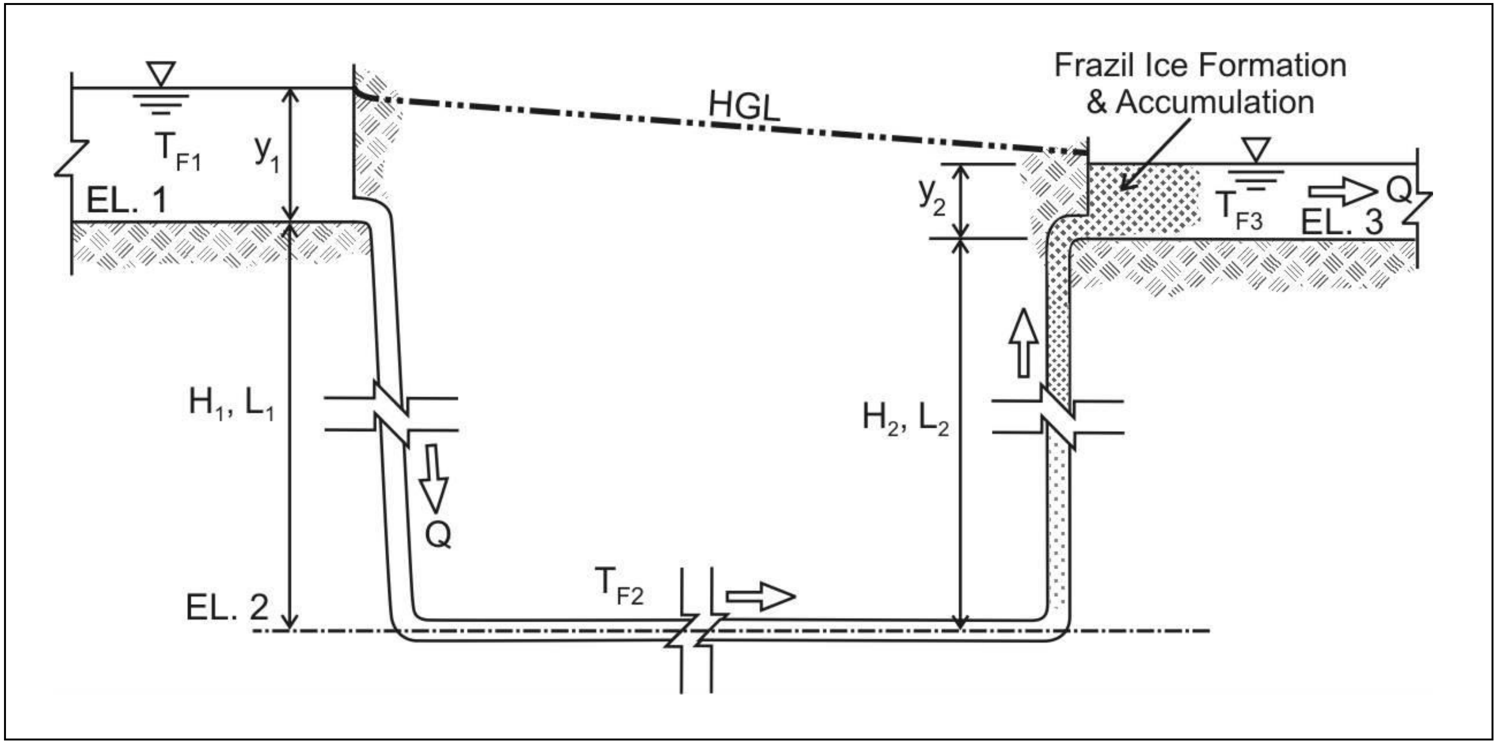
Water-freezing temperatures $T_{F1} = T_{F3} = 0.00^{o}C$; $T_{F2} < 0.00^{o}C$

Pump and pipeline



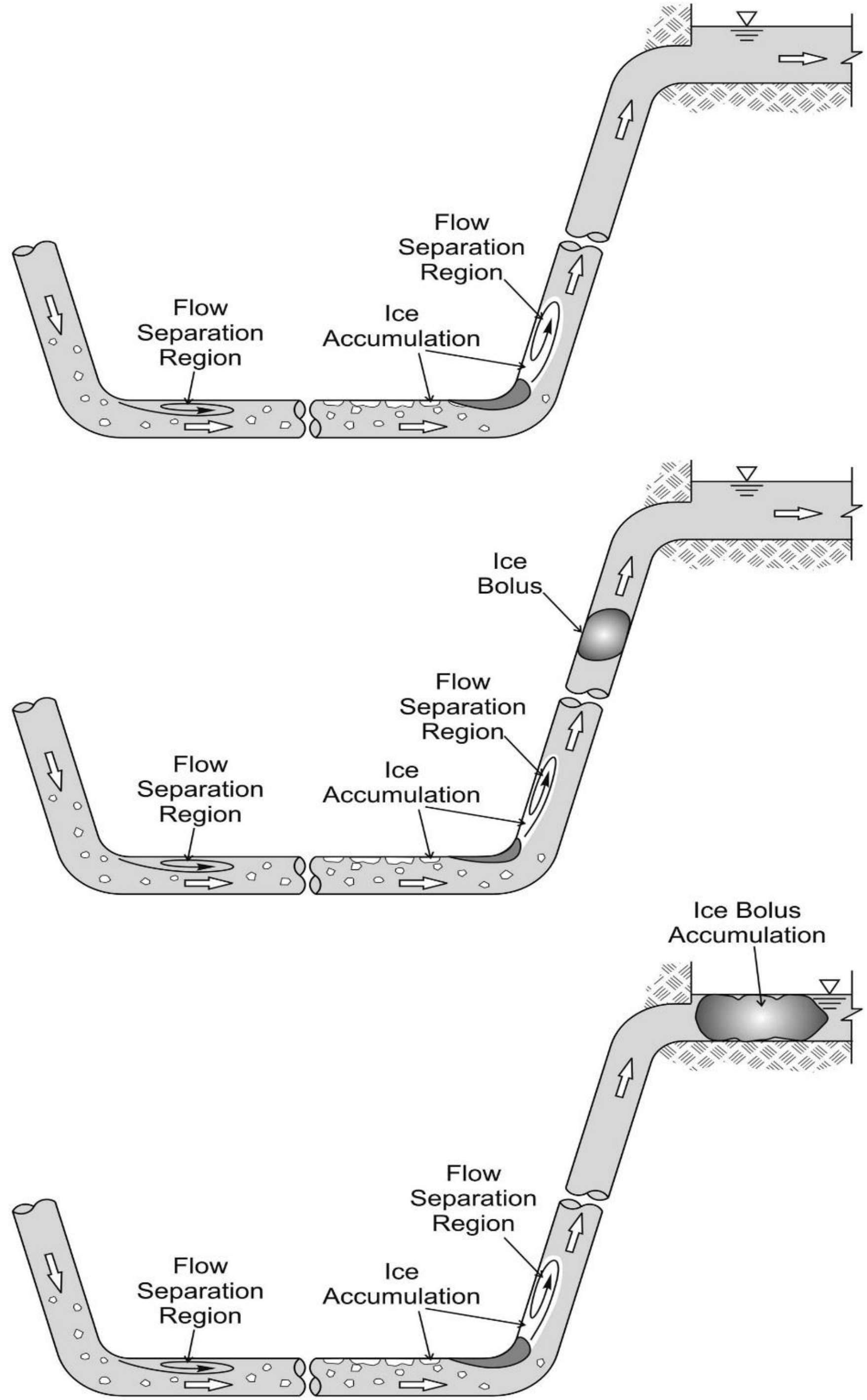
Water-freezing temperatures $T_{F1} = T_{F3} = 0.00^oC$; $T_{F2} < 0.00^oC$

Siphon (inverted)



Water-freezing temperatures $T_{F1} = T_{F3} = 0.00^oC$; $T_{F2} < 0.00^oC$

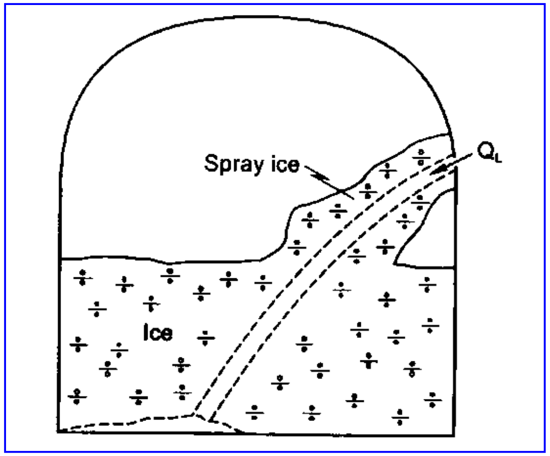
Ice bolus formation

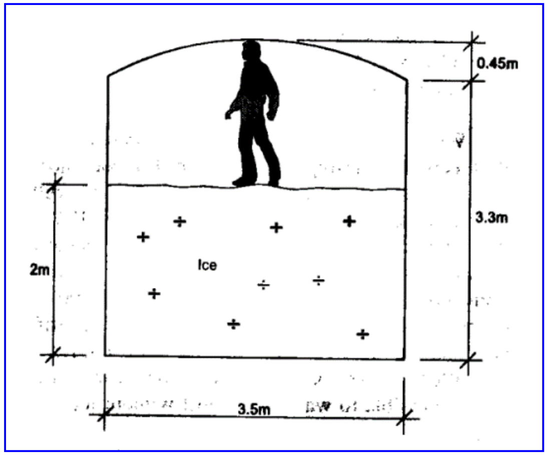


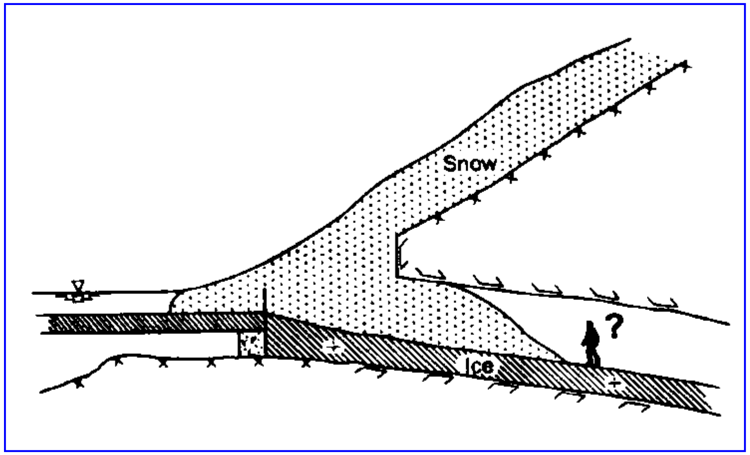
Tunnels

Ice concerns:

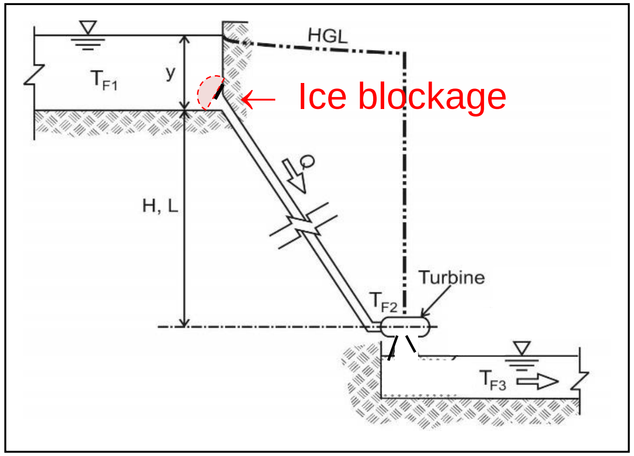
- Similar concerns as penstock and siphon bottom, though pressures less
- Ice accumulation
- Icing and aufeis from seepage
- Snow at entrance or exit



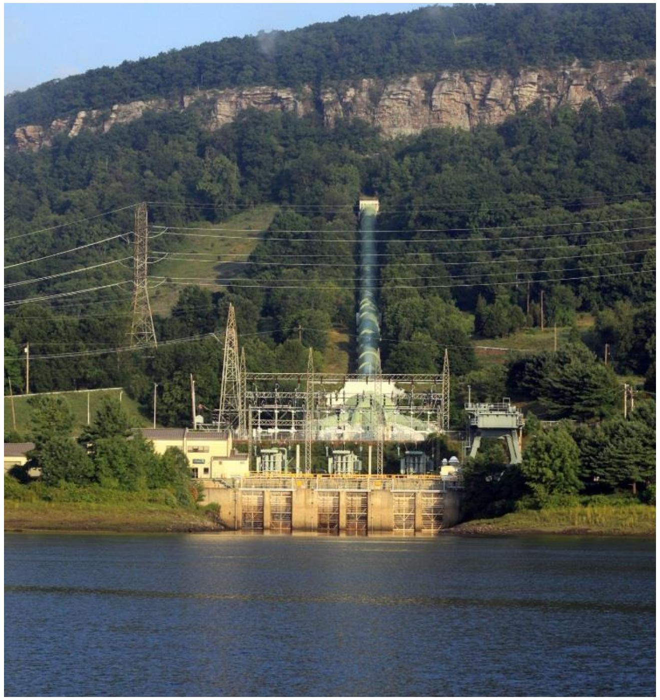




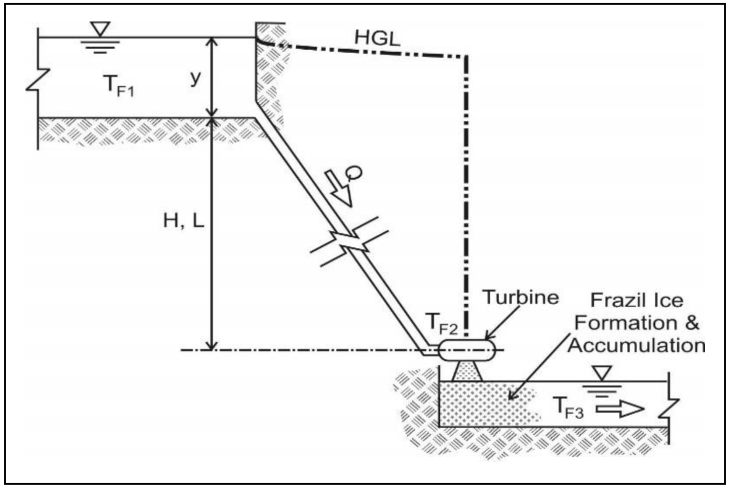
Example 1: Pump-Storage Hydropower Facility
(Yards Creek, New Jersey)



Net head ≈ 200m; Discharge ≈ 7m^3/s



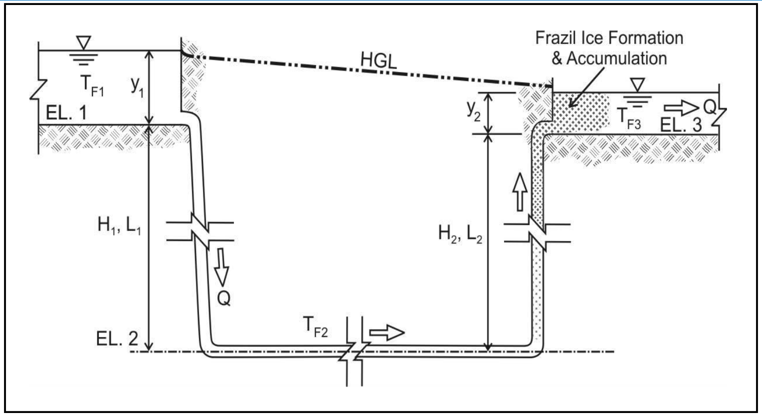
Example 2: Hydropower Facility
(King Cove, Aleutians, Alaska)



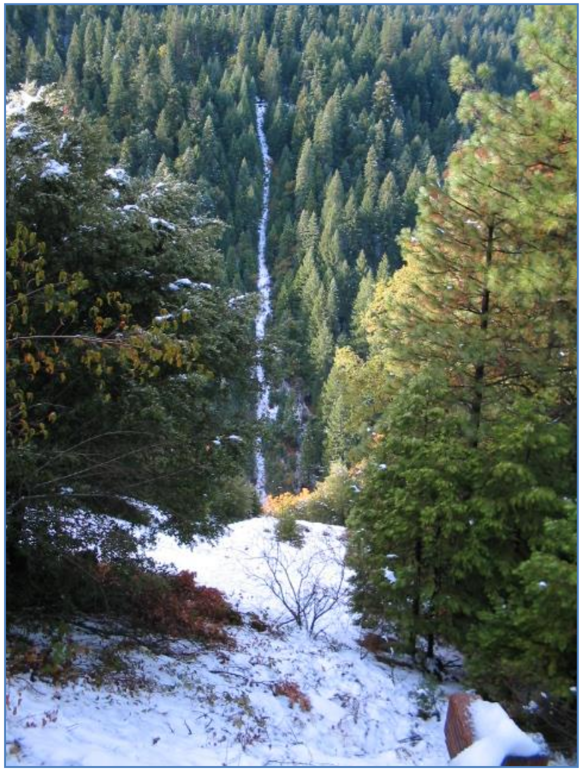
Net head ≈ 70m, Discharge ≈ $1\text{m}^3/s$

Example 3: Alder Creek and Plum Creek Siphons

(Sierra Nevada Mts., California-Nevada)

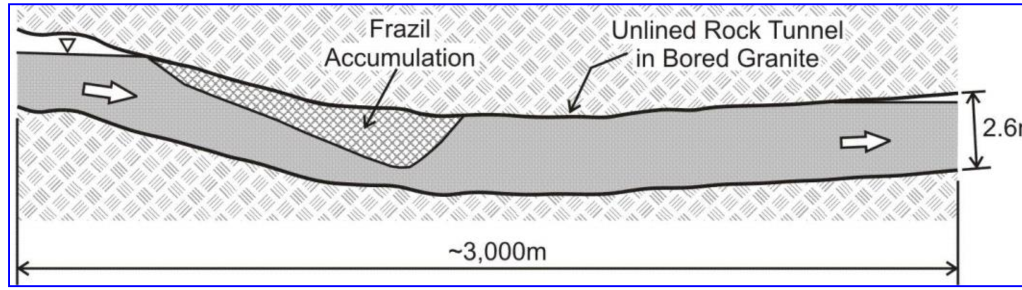


$H_1 \approx 100m$; $Q \approx 2m^3/s$

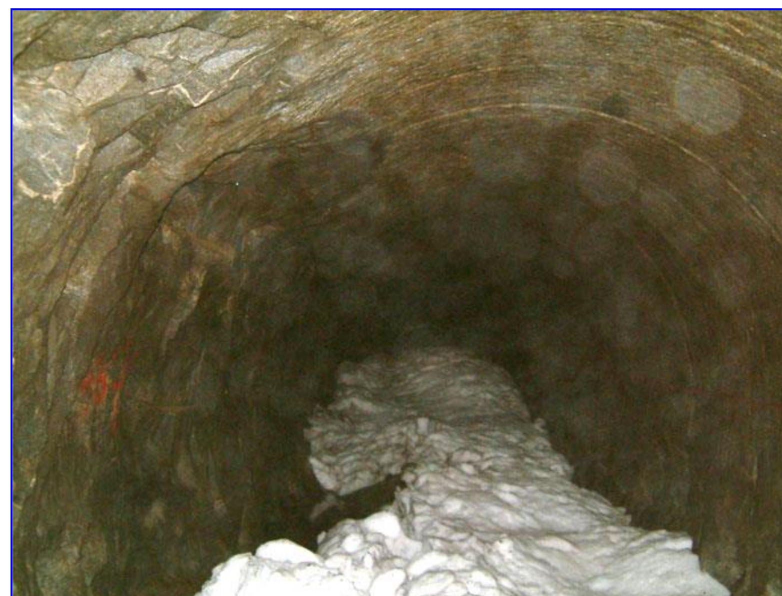


As ice boluses slow siphon flow; boluses enlarge, accelerating blockage of siphon outlet

Example 4: Tunnel Blockage
(Mill-Bull Tunnel, Sierra Nevada Mts., California-Nevada)

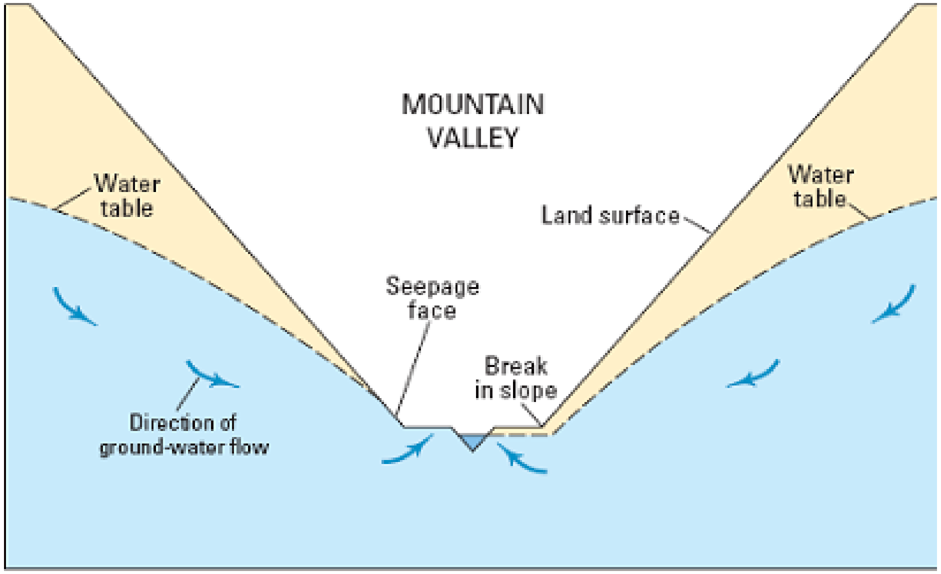


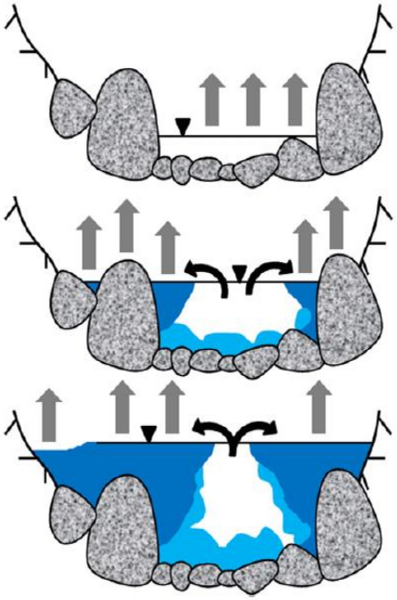
$L = 3000\text{m},\ \Delta H \approx 2.7\text{m},\ Q \approx 2\text{m}^3/\text{s}$



Example 6: Winter Flooding in Mountain Valley

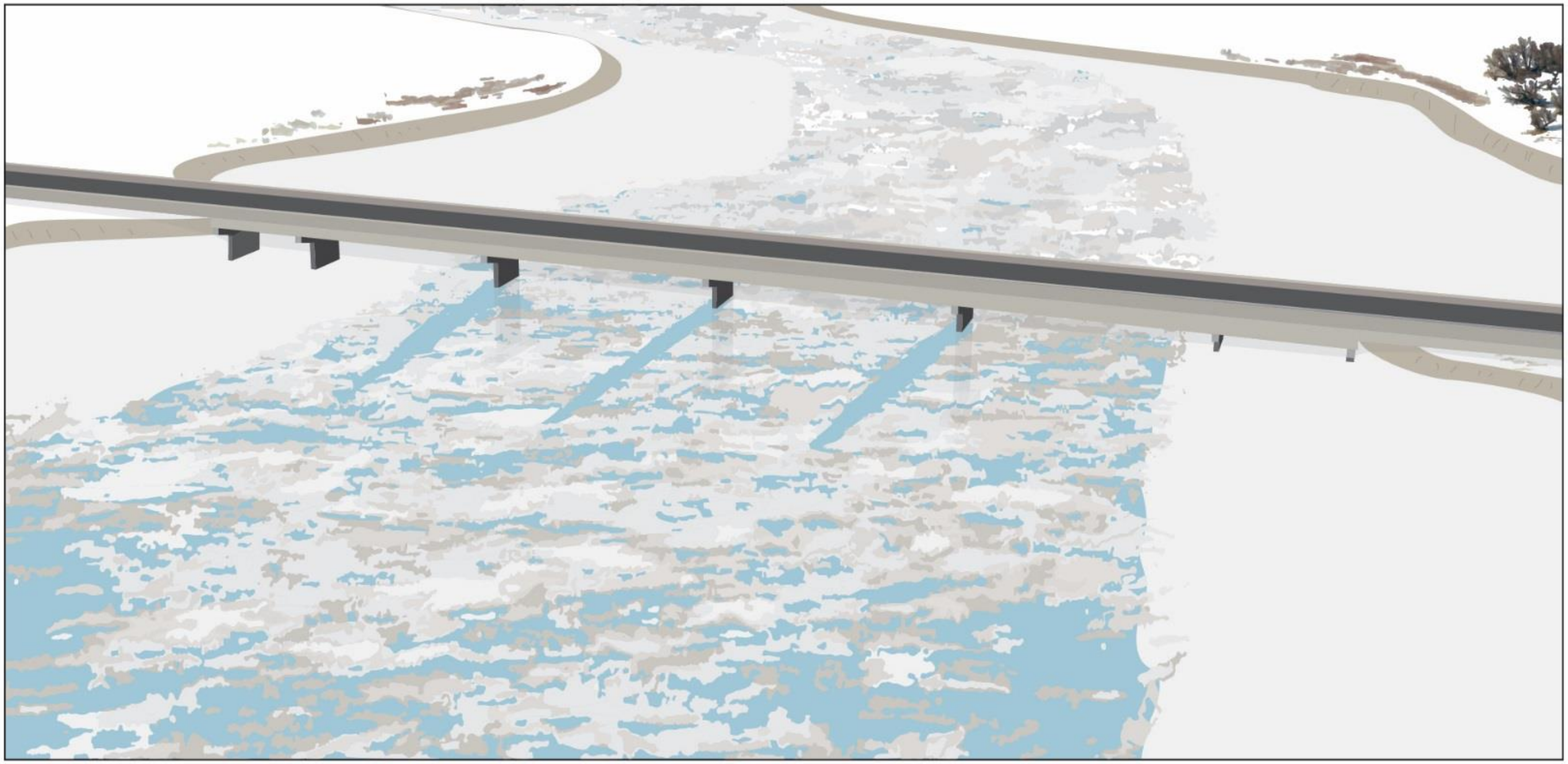
(Flat Creek, Jackson WY)





b). Hydraulics at lower elevations

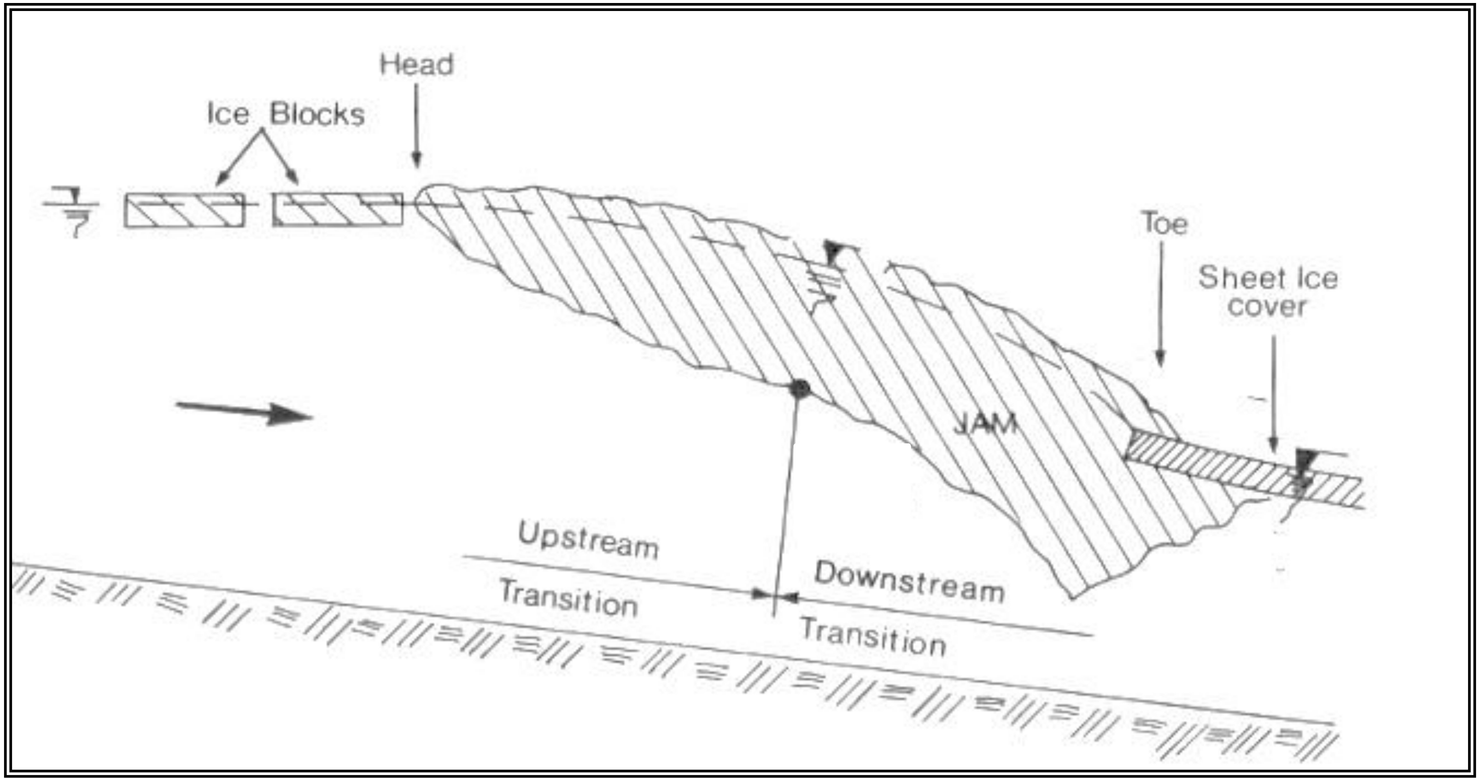
- Ice jams
- Loads on bridges
- Ice loads on riprap and embankments
- Ice problems for spillways and gates
- Navigation difficulties (locks, towboats)
- Fluvial channel shifting
- Effects on vegetation



Hydraulic Eng. Concern: Ice Jam Flooding
(Problem sites: bridges, bends, confluences, bars)

Ice blockage at a bridge forms jam on the Bighorn River, Wyoming

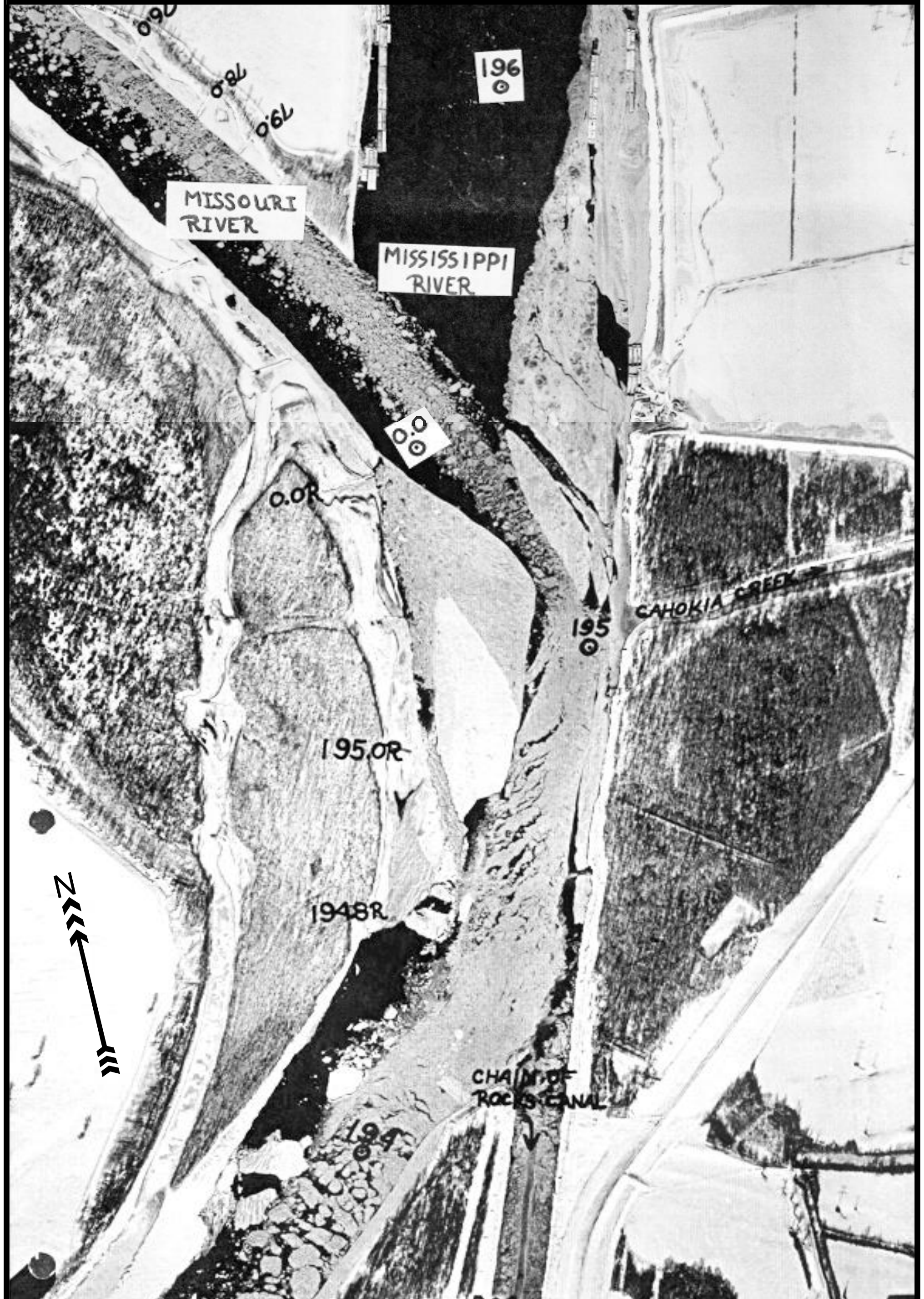
Ice jams



- Quite well formulated but estimation of water levels complicated by data lack
- Main lack: jam strength and roughness, and bed scour
- Need info. on rate of flow-rate increase as well as on flow rates (*rate of snow melt and/or rain intensity on frozen ground have major effects on ice runs jam flooding*)

Eng. Concern: Ice loading of bridges

Iowa River, Iowa



Ice congestion at confluence of the Missouri and Mississippi Rivers

Concerns

- stoppage of navigation along Mississippi River
- blockage of locks
- grounding of barges

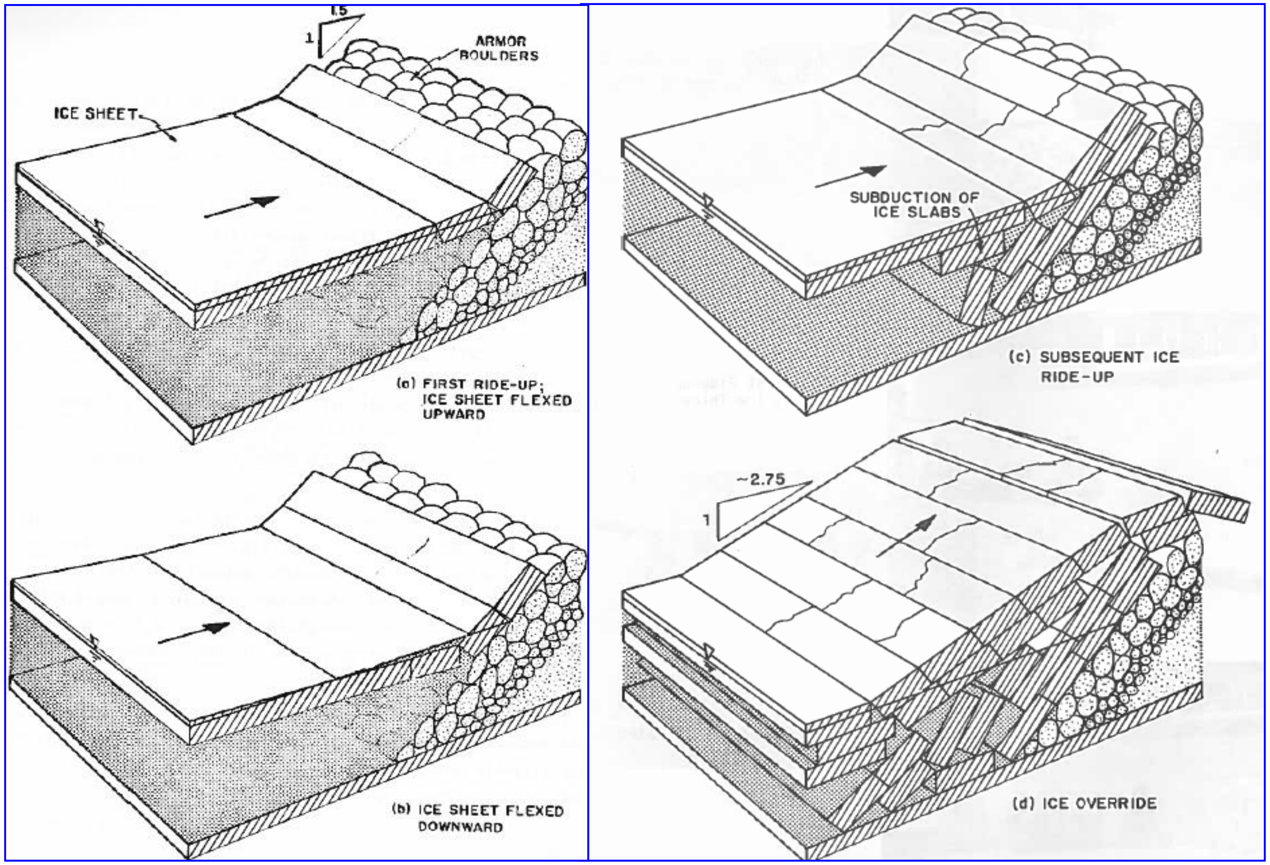
Aufeis on Spillway

Oldman Hydro Dam, Oldman River, Alberta

Icing of spillway gates

Gavins Point Dam, Missouri River, NE

Ice ride-up of dam or levee face



Concern for riprap dislodgment and o'topping

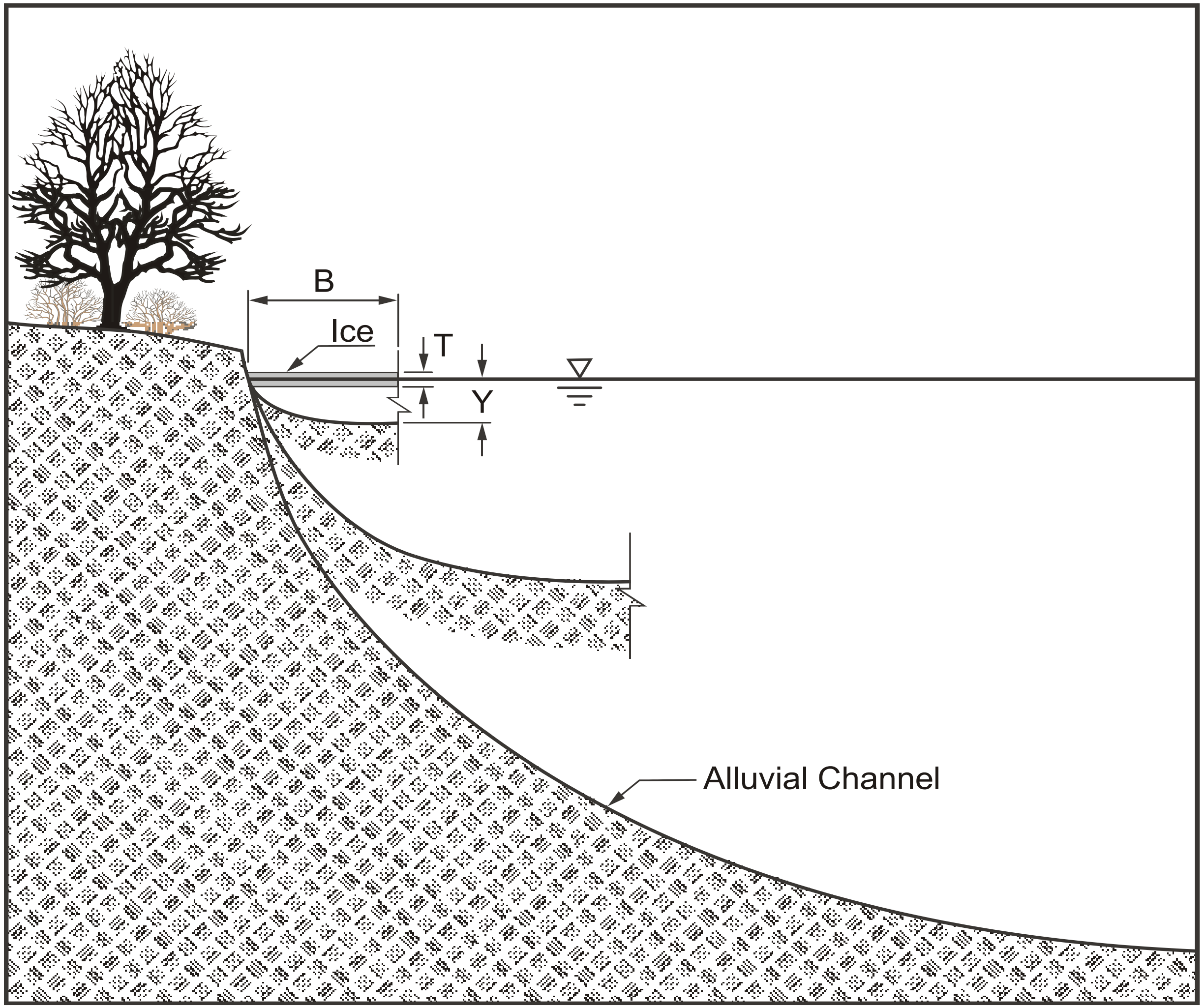
5. Ice, Sediment Transport and Fluvial Morphology (Main Points)

- Need to consider 2 ice conditions
  a) ice formation and presence
  b) break-up
- Spatial, temporal and thermal scales (also access) complicate perception of ice effects on bed-sediment transport and channel morphology
- Sediment transported by ice and by water flow *(frontier issue)*
- Ice responsible for transport of gravel, boulders *(frontier issue)*
- Ice creates channel instabilities but doesn't imprint channel morphology *(debate)*
- Major ice disturbances occur with major water discharges … dynamic break-up *(frontier issue)*
- Vegetation has a role, at times *(frontier issue)*
- Influence on river ecology is little known *(frontier issue)*

a). Effects on sediment transport and fluvial morphology

Impact of ice processes a matter of scales

Ice involves spatial, dynamic, thermal, temporal scales … also access an issue



Ice affects flow resistance and distribution

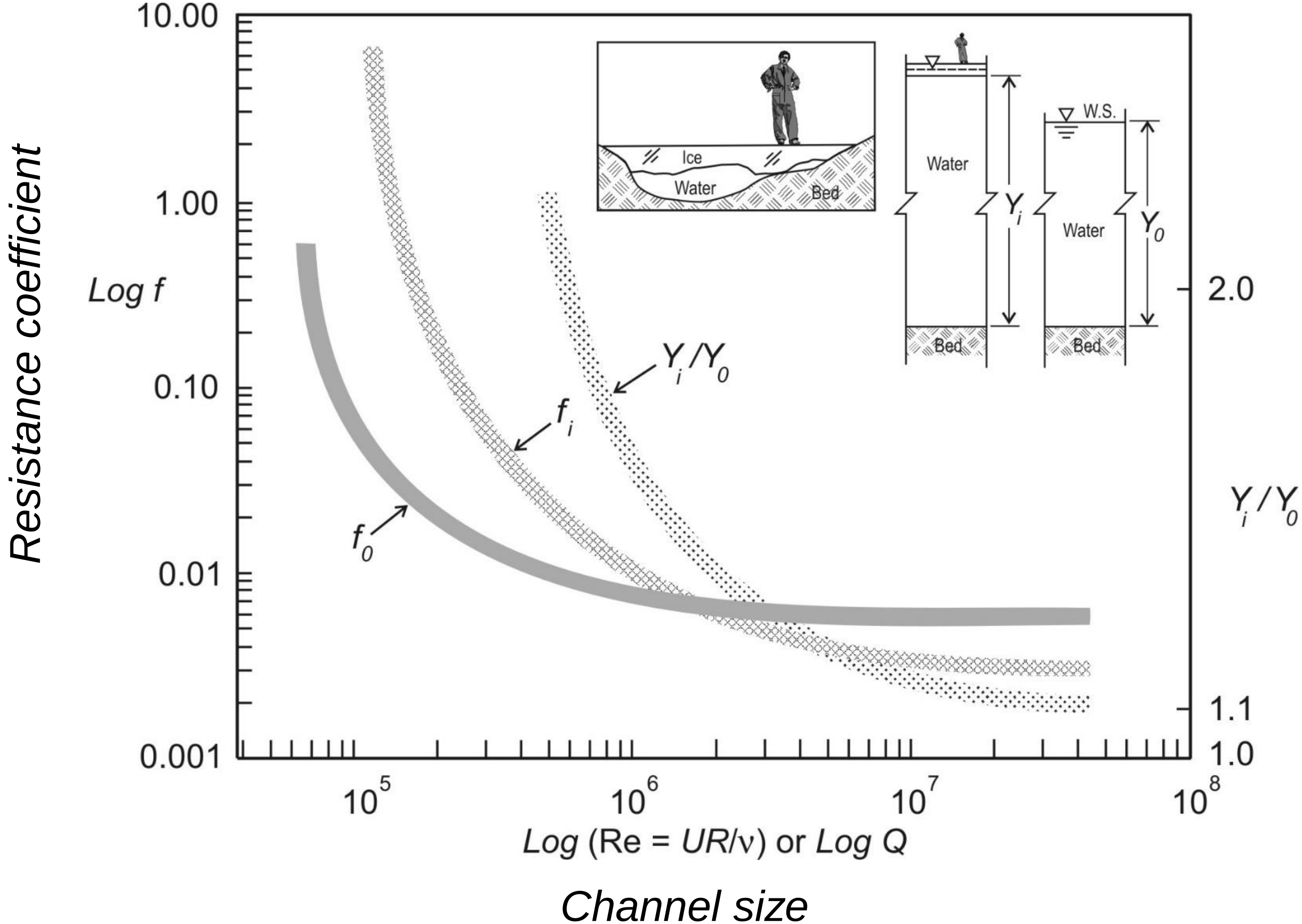
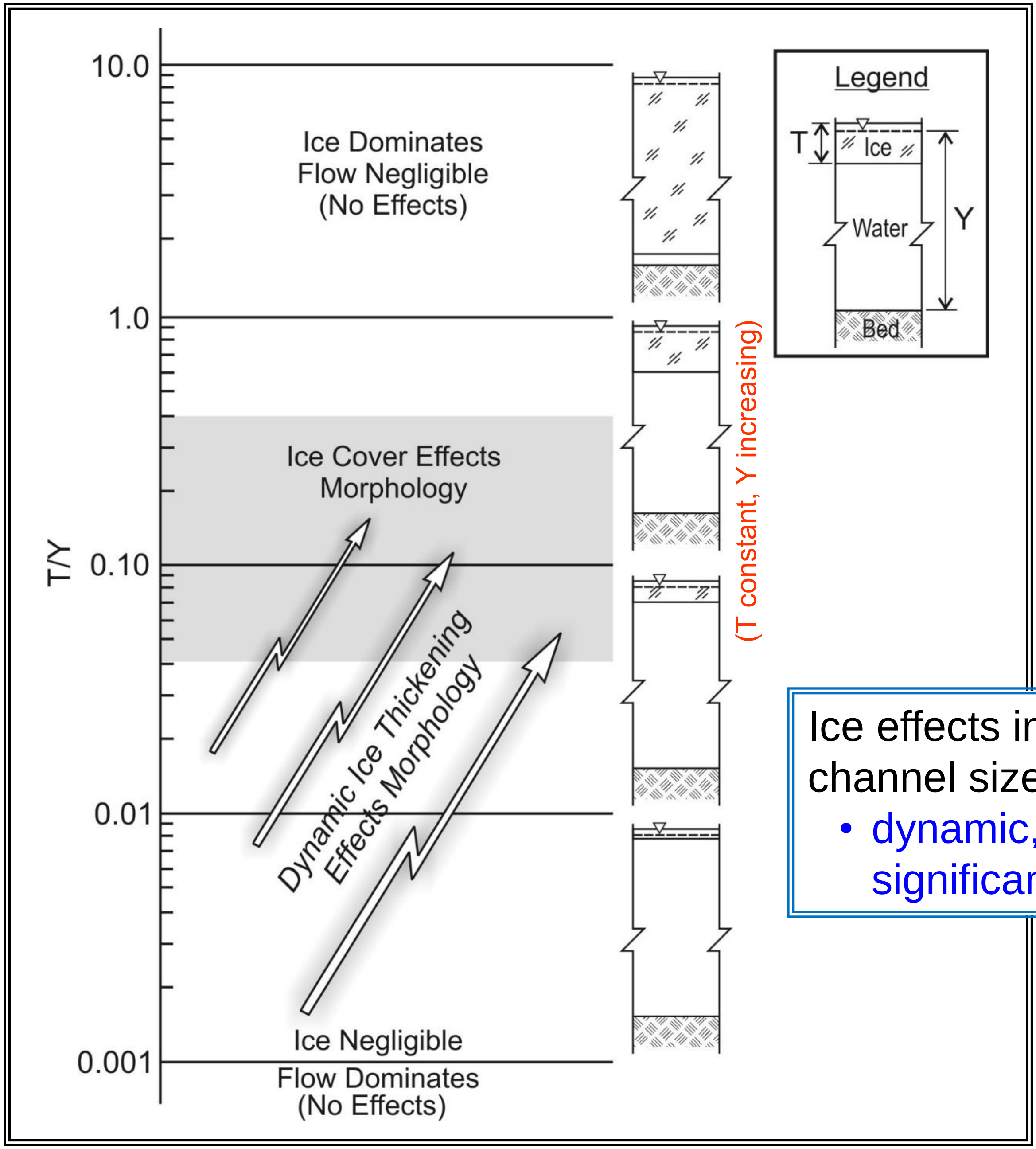
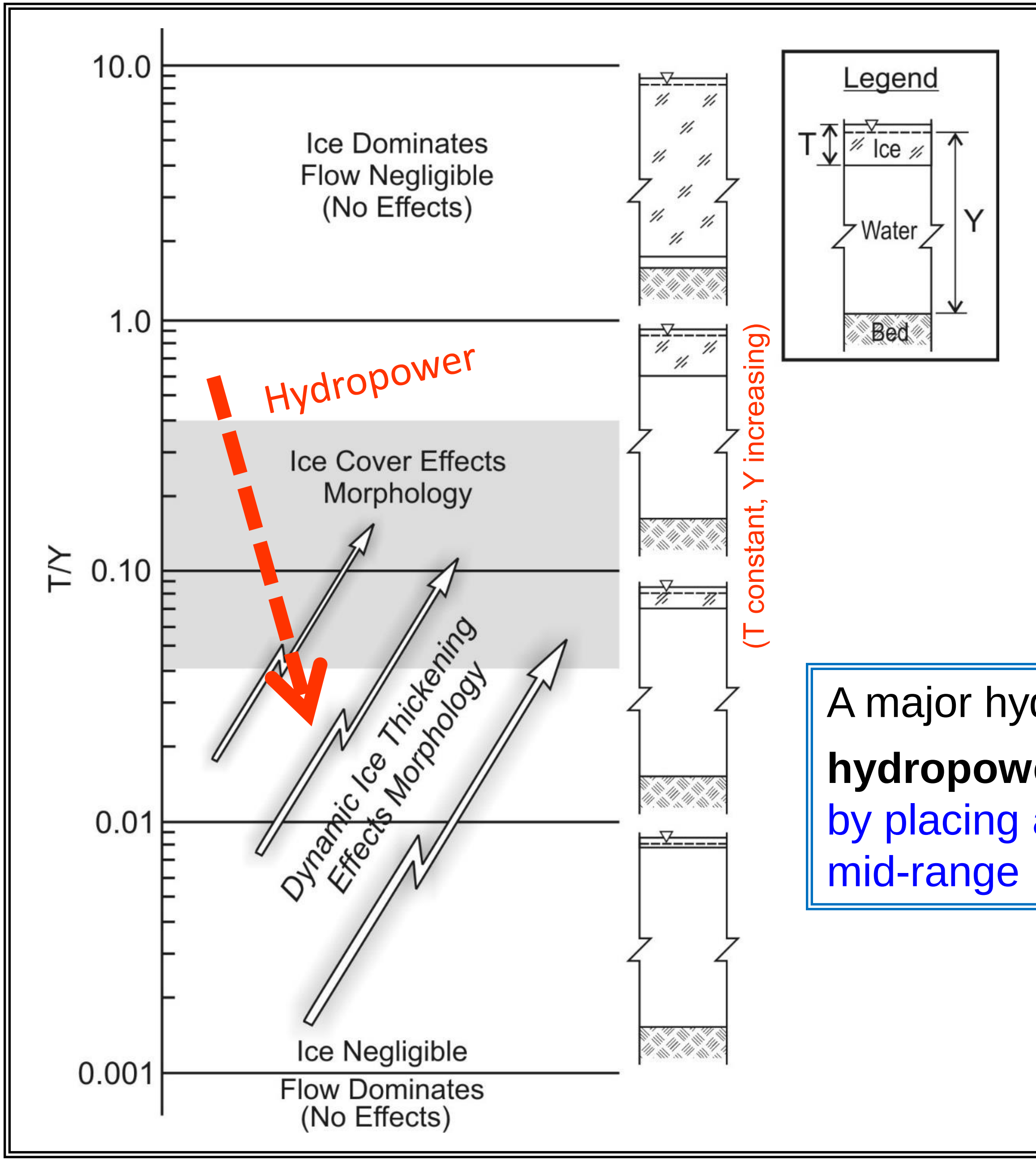


Figure still hypothetical



Ice effects important over a mid-range of channel sizes

- dynamic, spatial & thermal scales all significant!

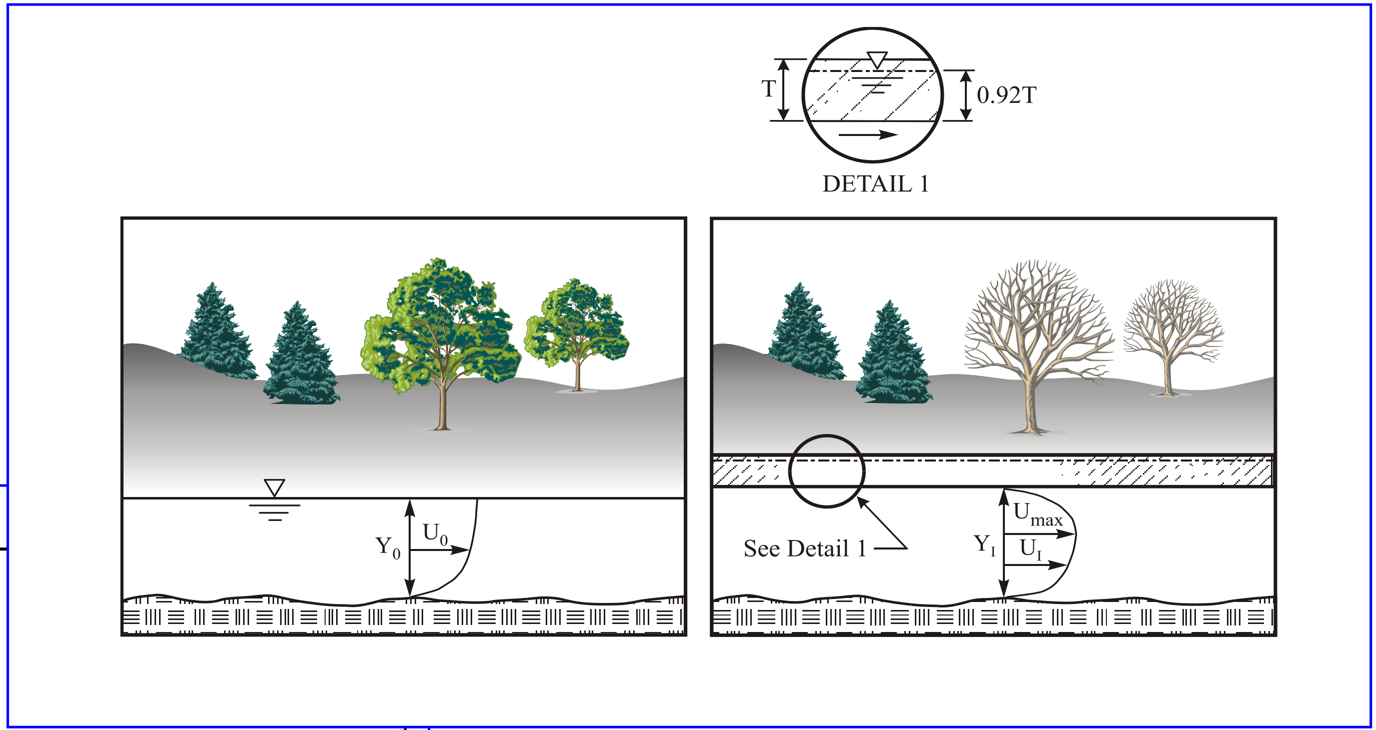


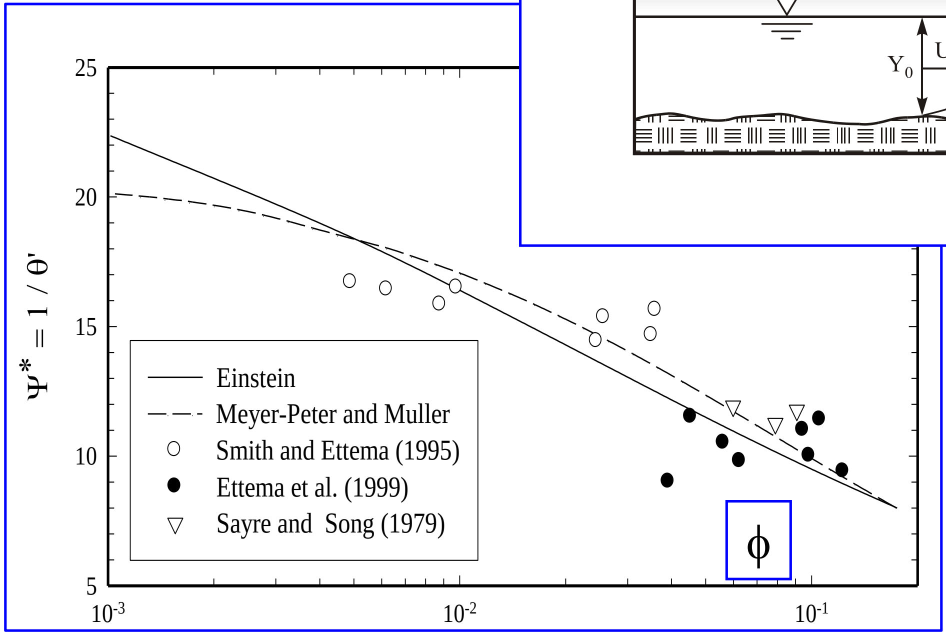
A major hydraulic engineering concern:

hydropower, increases importance of ice, by placing a channel in a more dynamic mid-range

Flow under level floating ice cover

(Cover deepens and redistributes flow vertically; bedload reduces)





Covered flow data on bedload conform with openwater relationships

Ice Rafting

Anchor ice morphology on bed (Laramie River, WY)

Ice Rafting

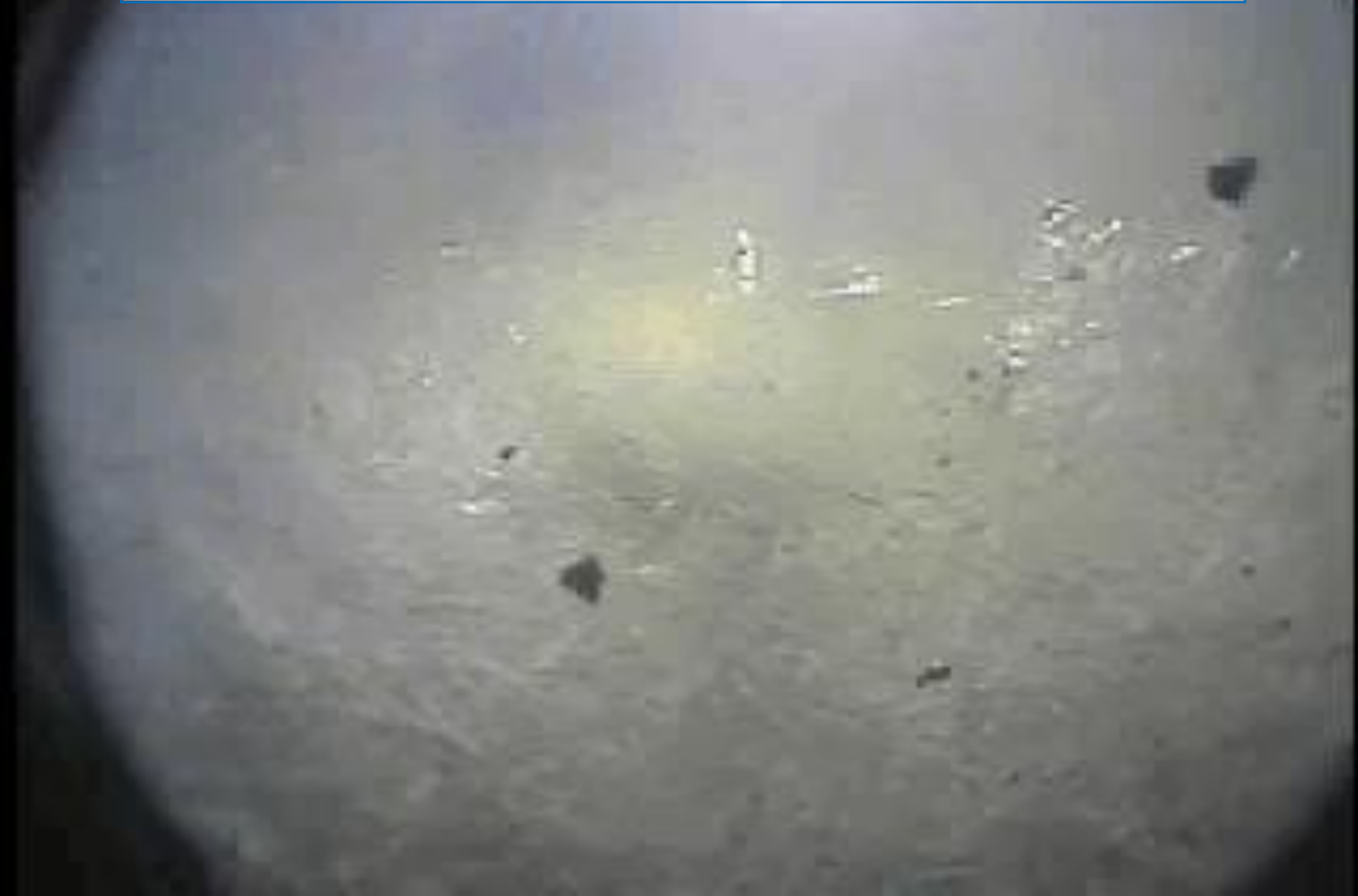
Anchor ice growth on gravel bed (Laramie River, WY)

Ice Rafting

Anchor ice detaching from gravel bed

Ice Rafting

Anchor ice detaching from gravel bed



Ice Rafting

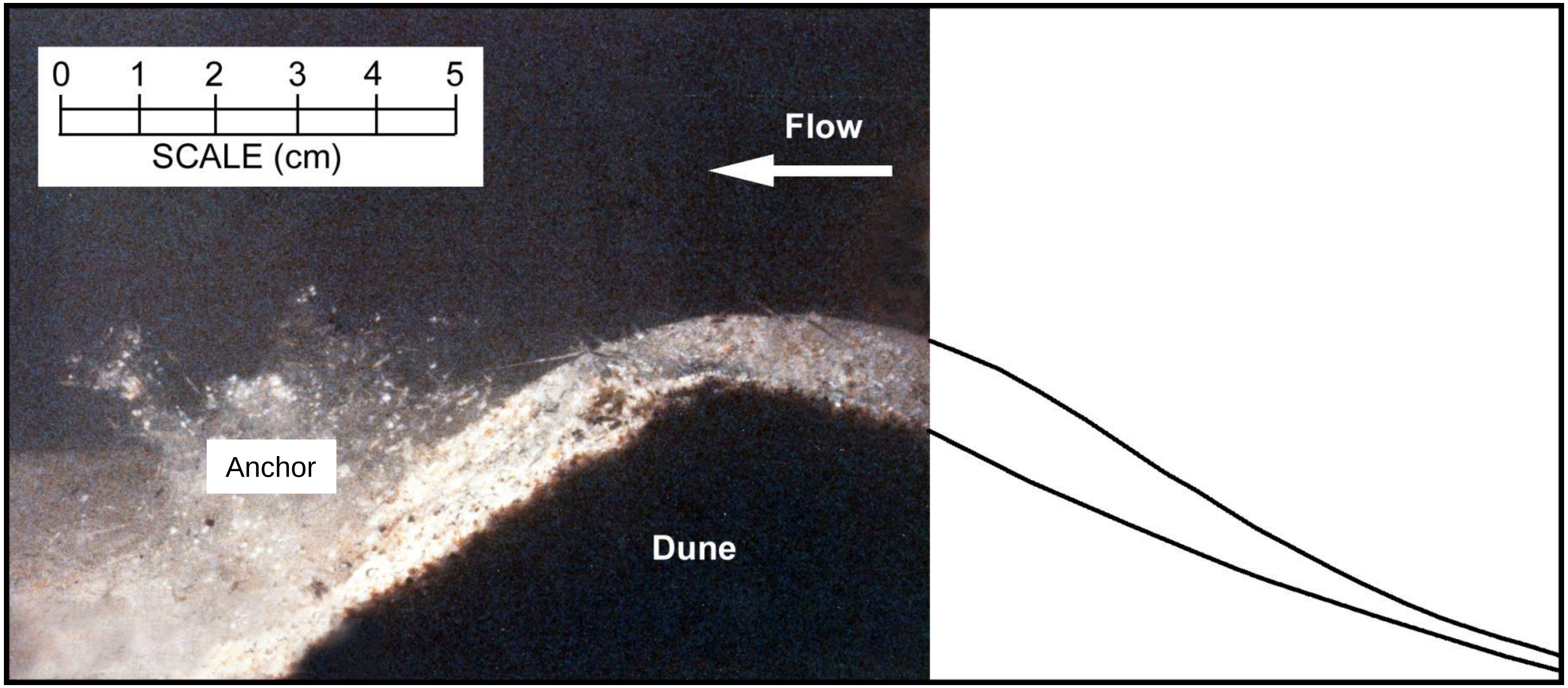
Ice rafting transports coarsest sediment during a period of low flow at site

Ice Rafting

Ice rafting capable of moving very large material

Ice Reinforcement of Dunes

Anchor ice collects in dune wake then embeds



Ice Rafting

Observations in Missouri River, MT show sands and gravels included in accumulation ice cover

Ice Rafting

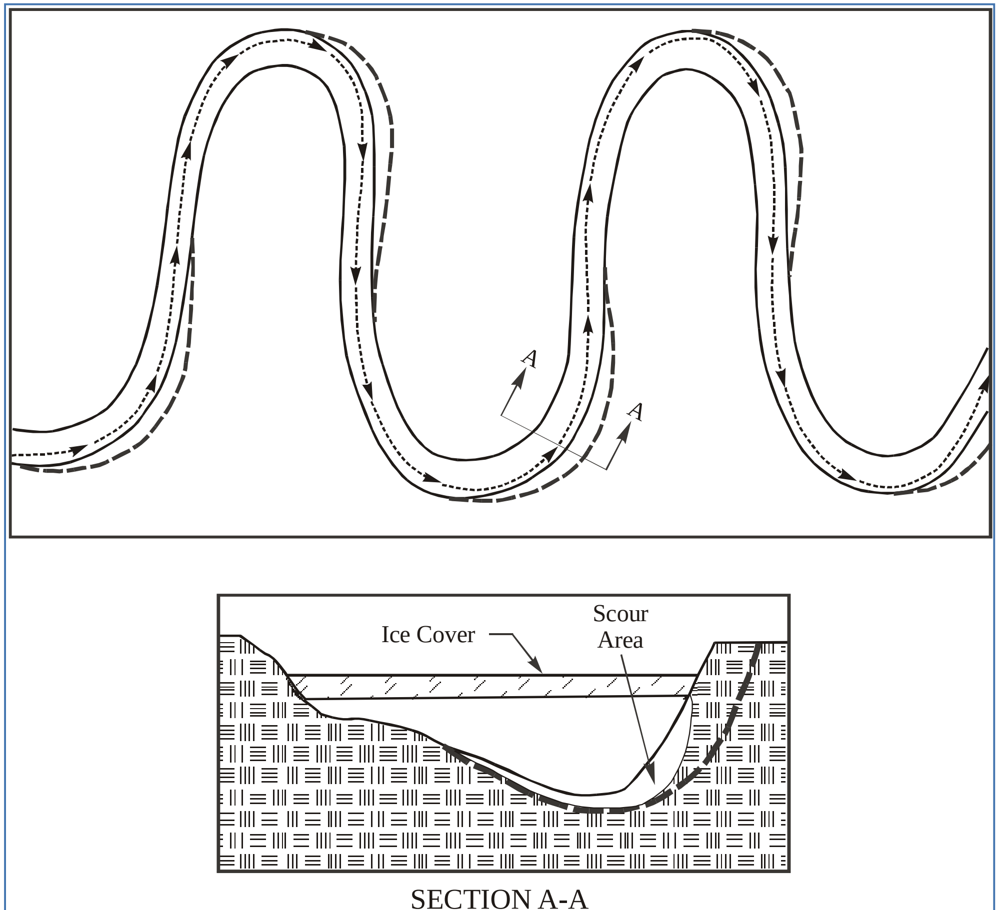
Observations in Laramie River typical of larger rivers

Slush ice drifting on Platte River, Nebraska
(Laramie in Platte River watershed)

Channel Cross-section

Ice shifts (possibly widens) channel cross section, but net effect unclear, especially for gravel-bed channels

Temporary local deepening at outer bend (ecological benefit)

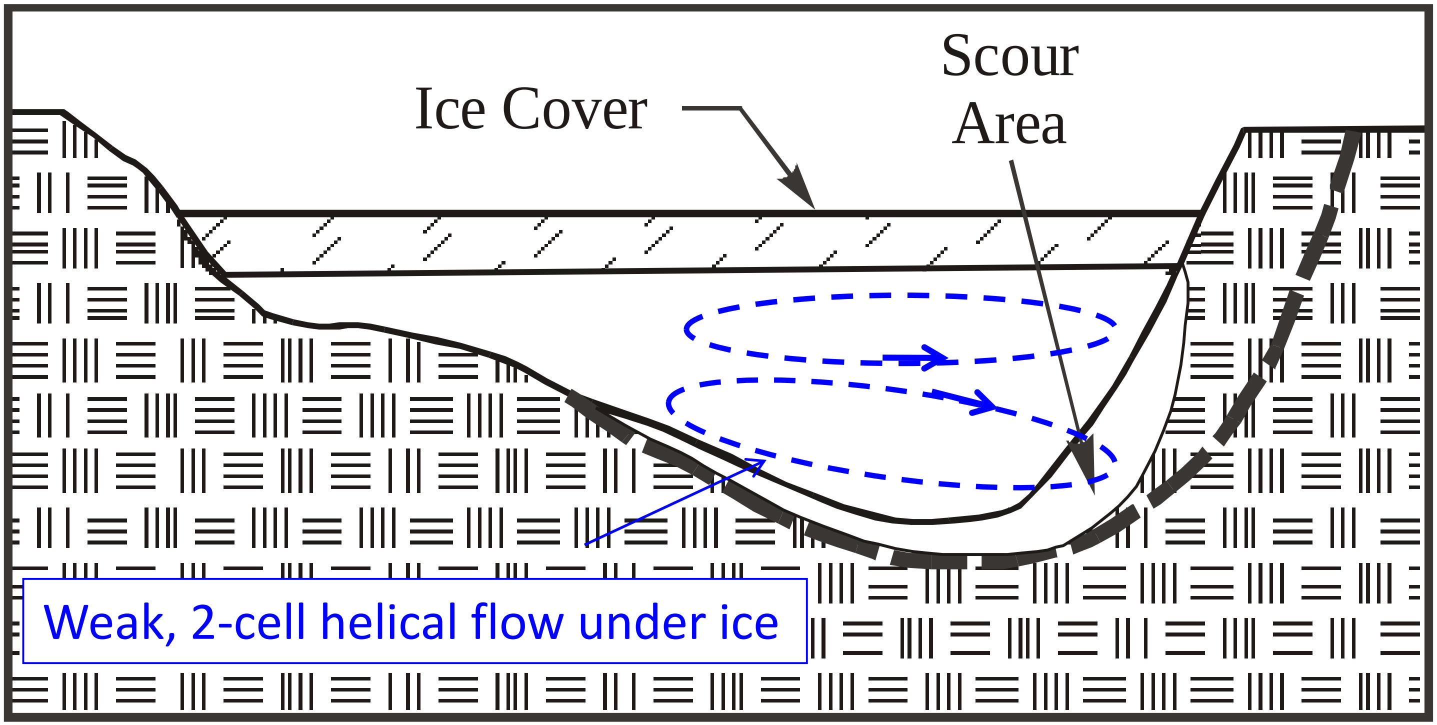


Extent of erosion depends on flow rate

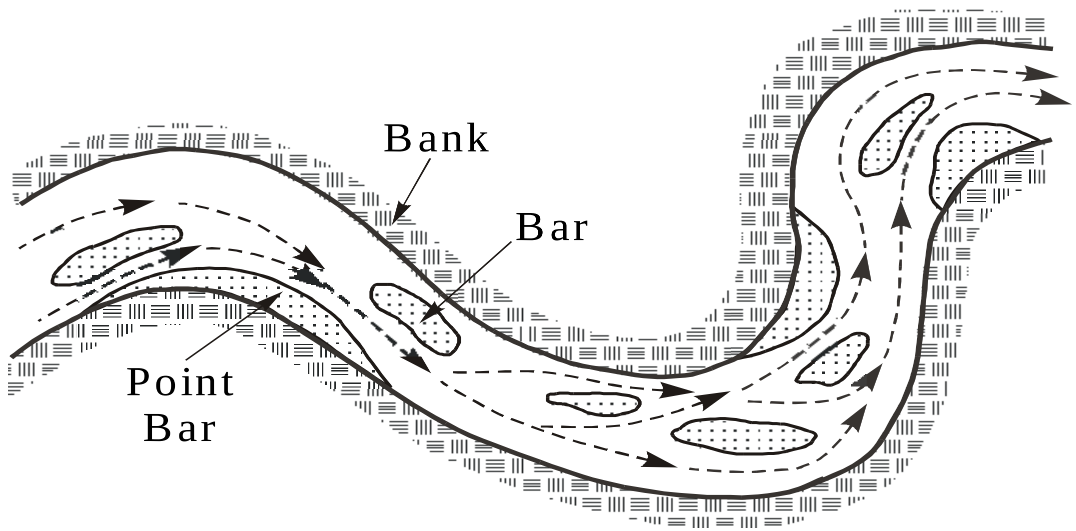
A bend in the Missouri River Ft Peck Reach, MT

Bend Cross-section

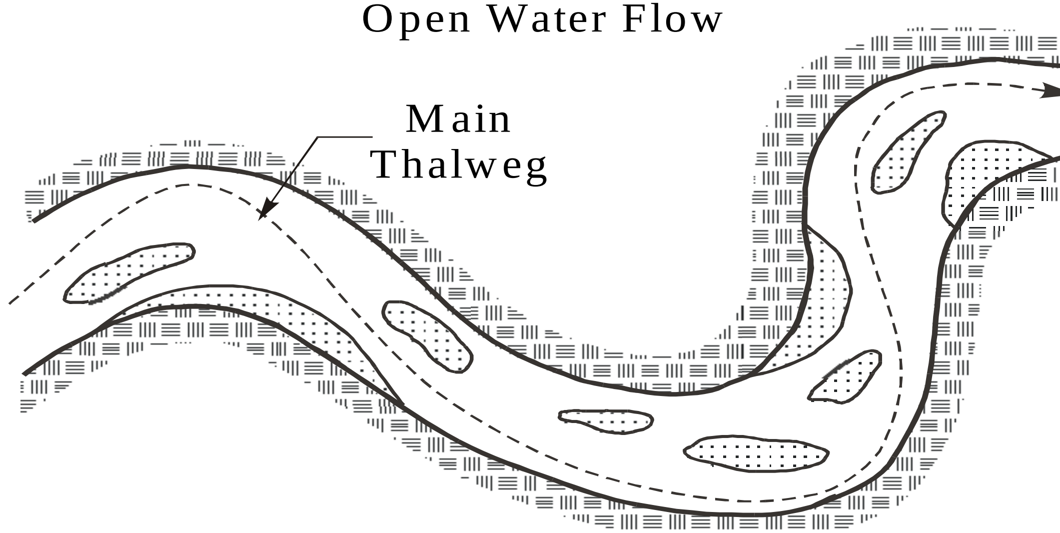
Helical flow feature of bend flow dampened in ice-covered bend



Ice may make thalweg more sinuous in sinuous-braided channels (?)



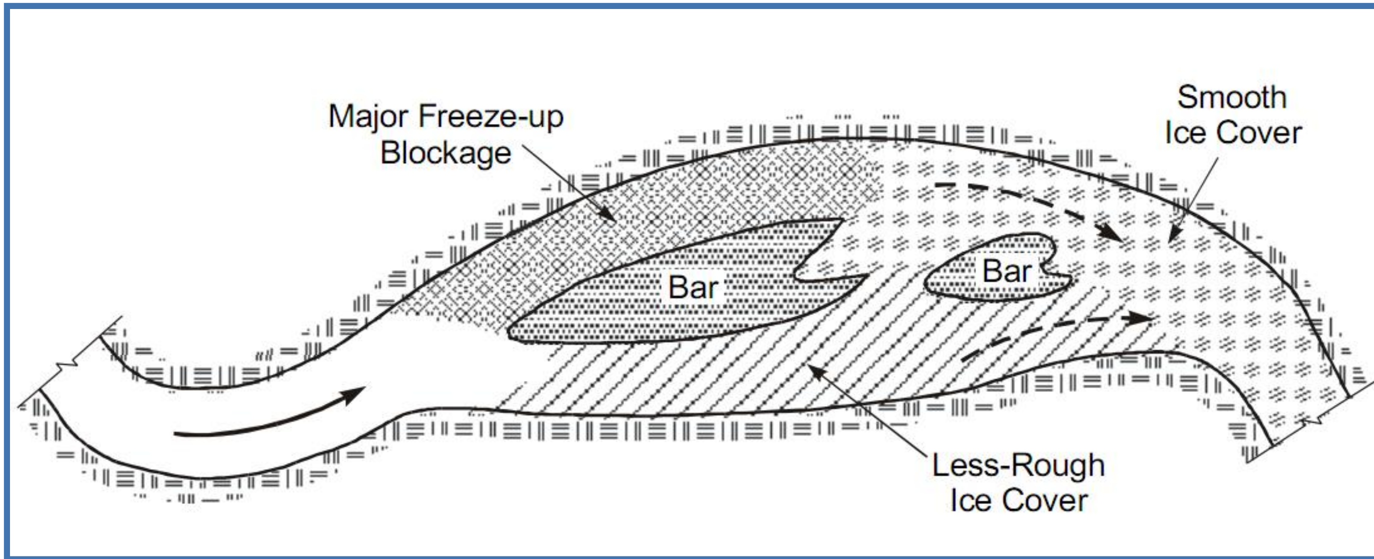
Open Water Flow

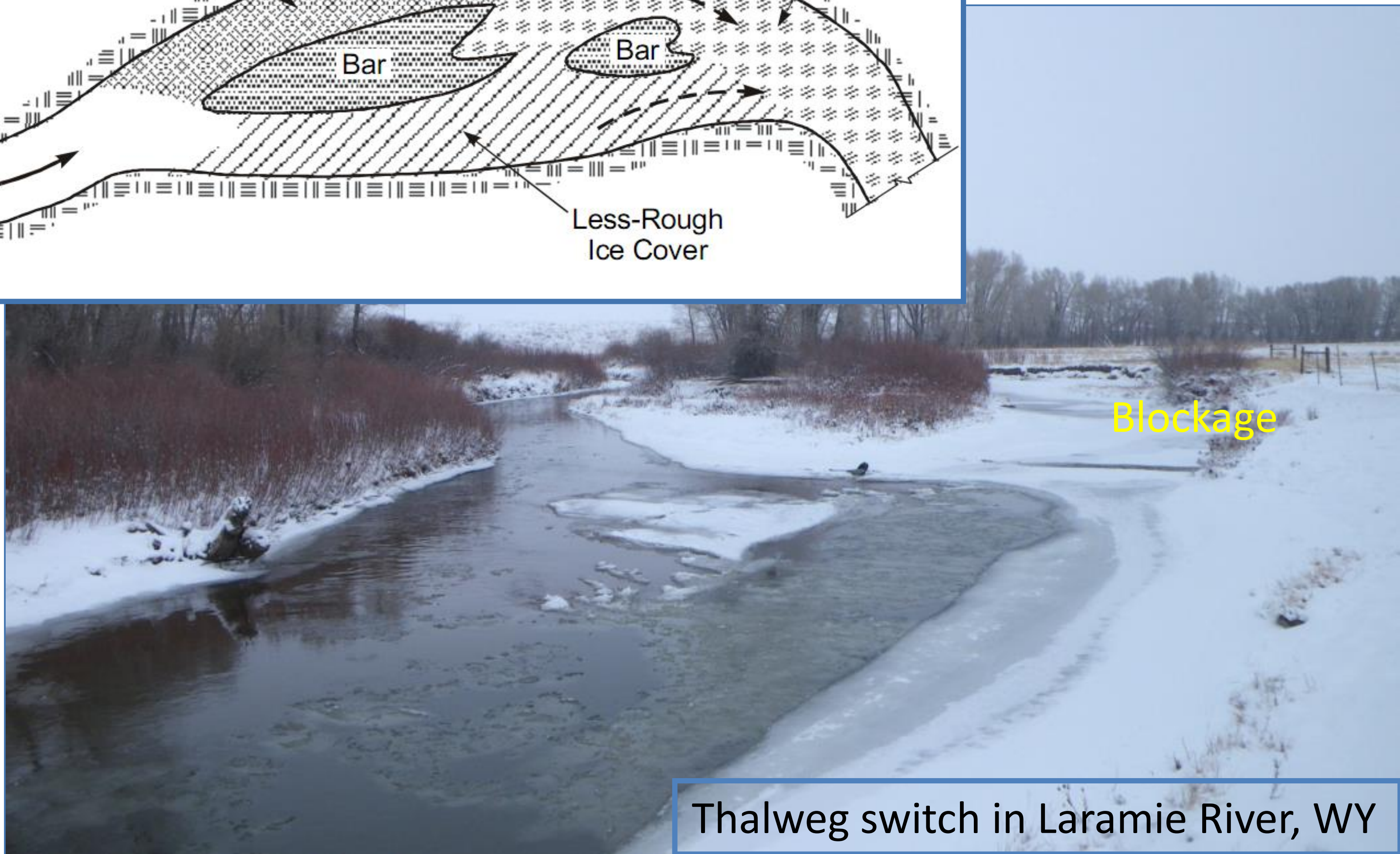


Ice-covered Flow

Thalweg Shift around Bar or Island

(Flow concentrates in alternate sub-channels)





Thalweg switch in Laramie River, WY

b. Effects of ice break-up

Dynamic breaking front

(In north-flowing rivers or regulated rivers [peaking hydro-power])

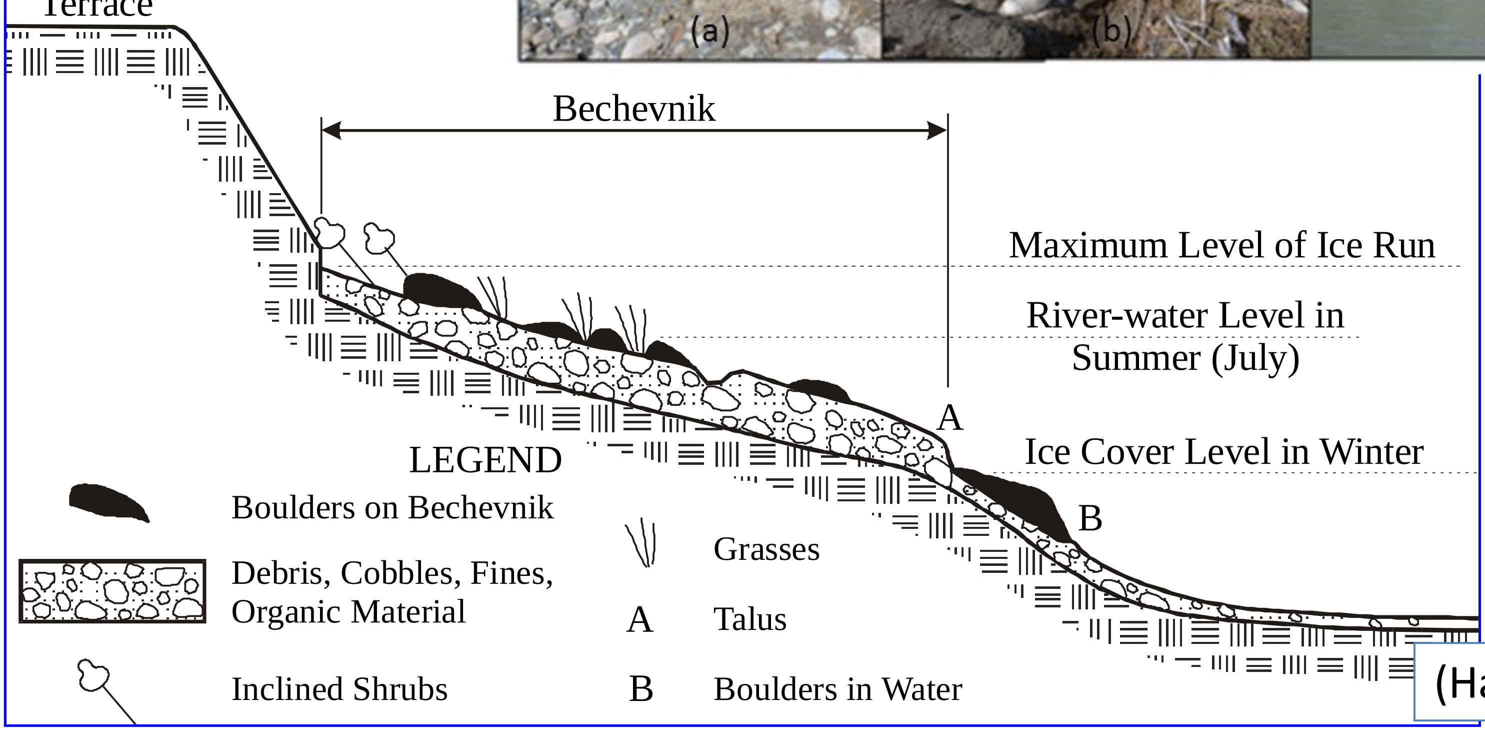
Liard River, British Columbia

Ice run on Peace River, Alberta

In early times, ice-adapted low-banks benefited navigation

(Russian “bechevnik,” useful as boat towpath)

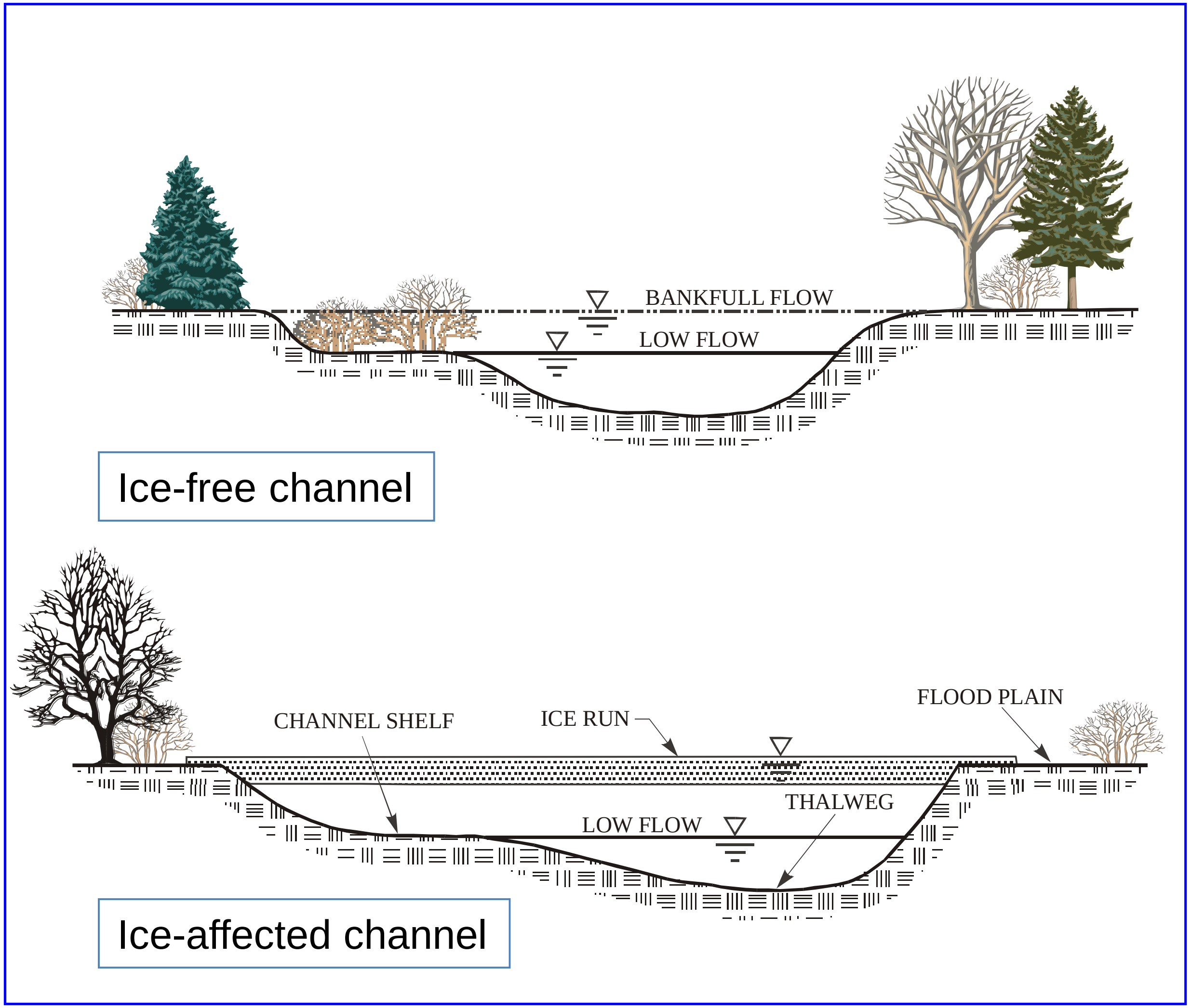
Susitna River



(Hamelin 1979)

Bank Vegetation Adapted to Ice

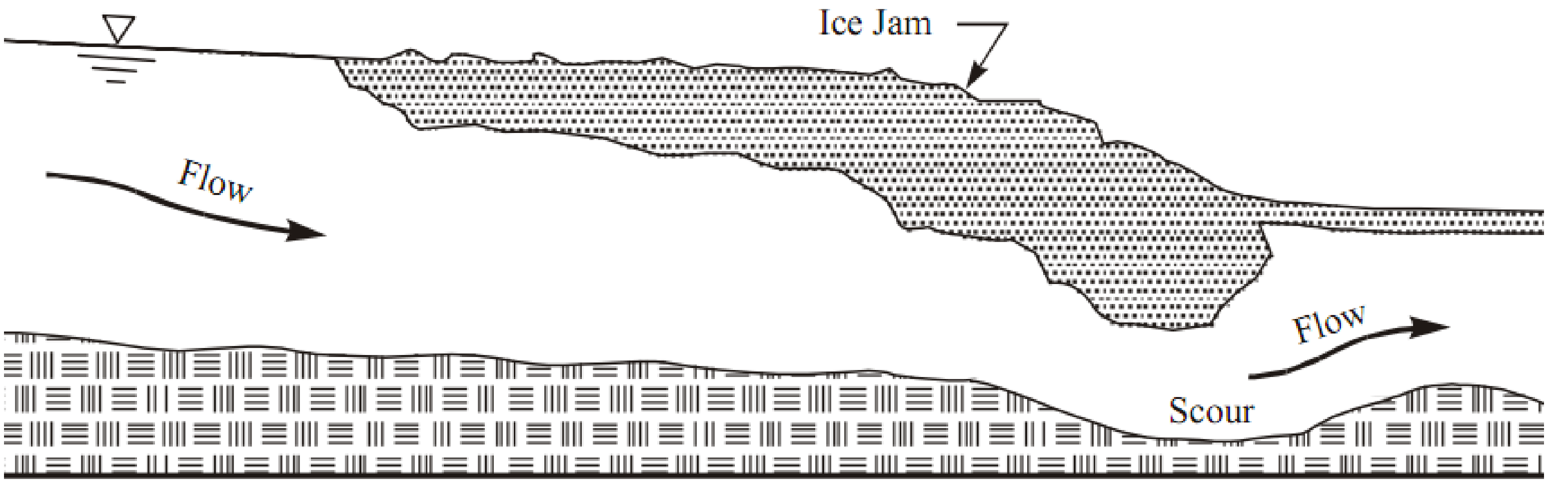
Low-bank vegetation cleared



Missouri River, MT

Vertical Concentration of Flow (Beneath Jams)

(Flow concentration may cause a localized scour, and possible failure of adjacent bank)

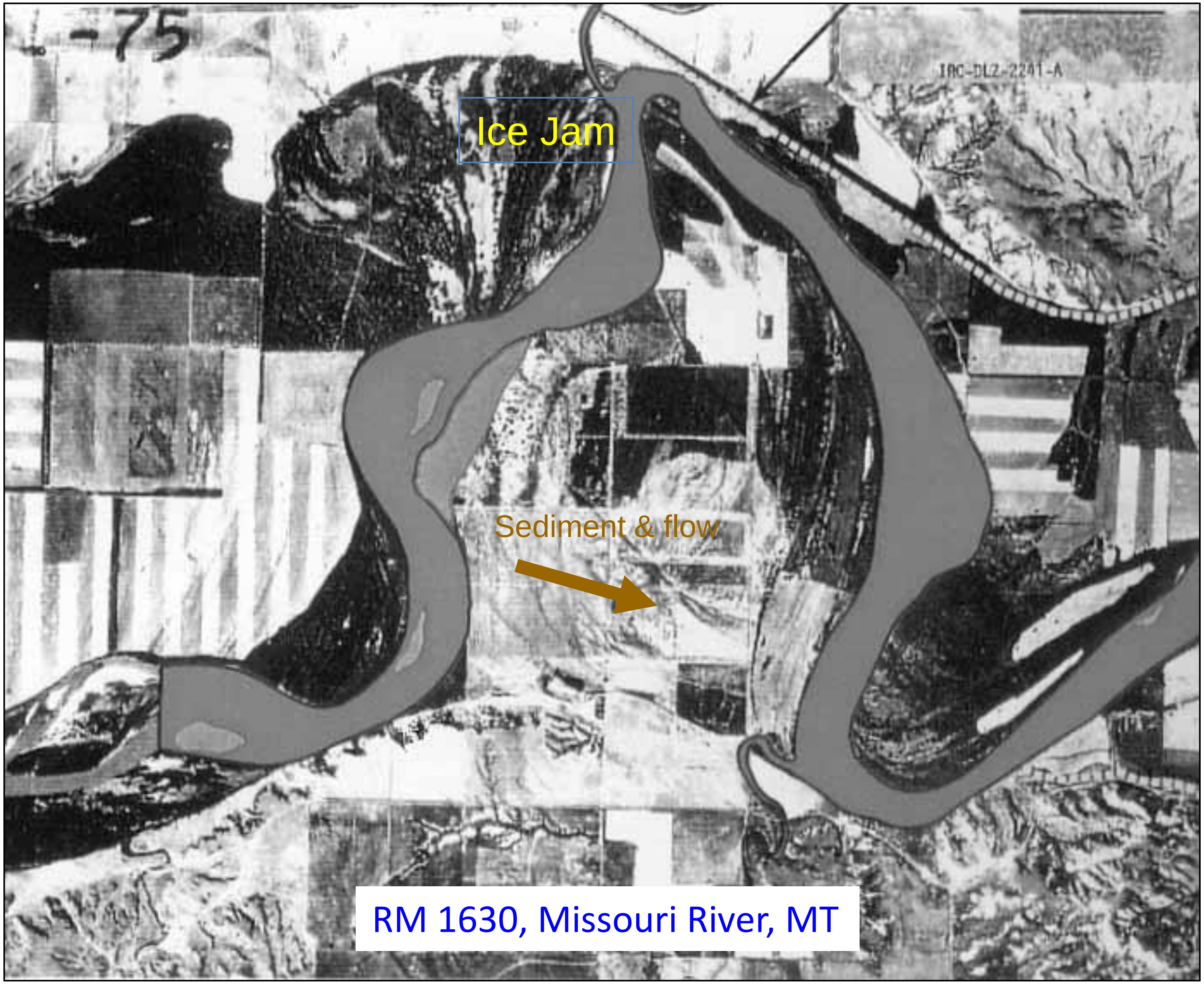


Channel cut-off

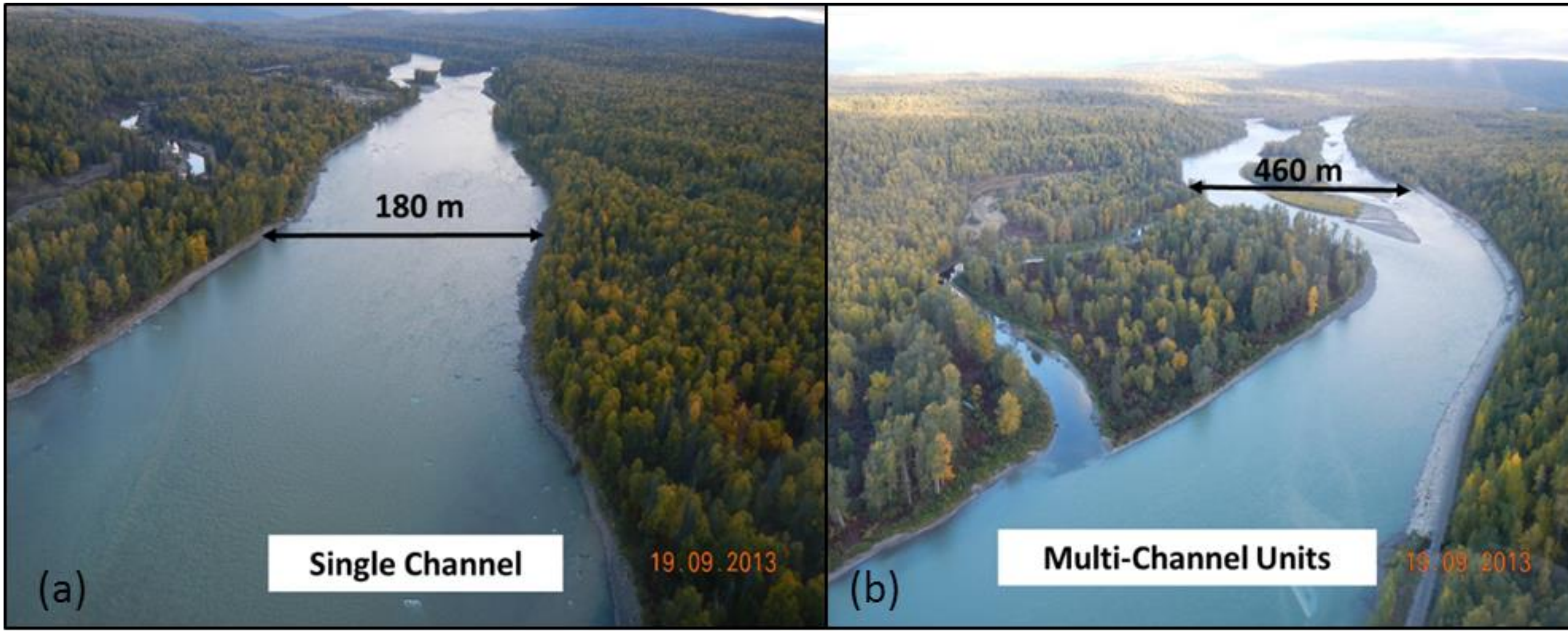
(Jam-initiated cut-off)

Meander-loop reinforcement

(Jam-initiated deposition of sediment on floodplain)



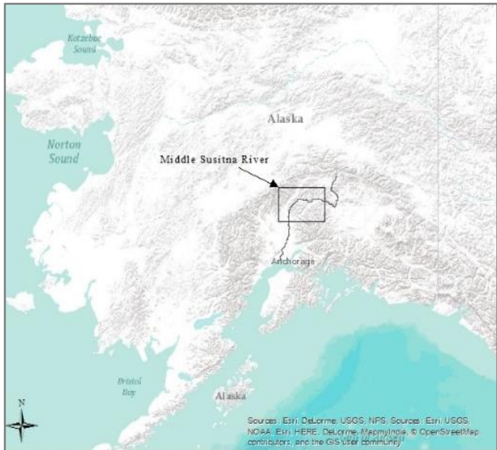
Ice destabilizes, especially notably multi-channel reaches

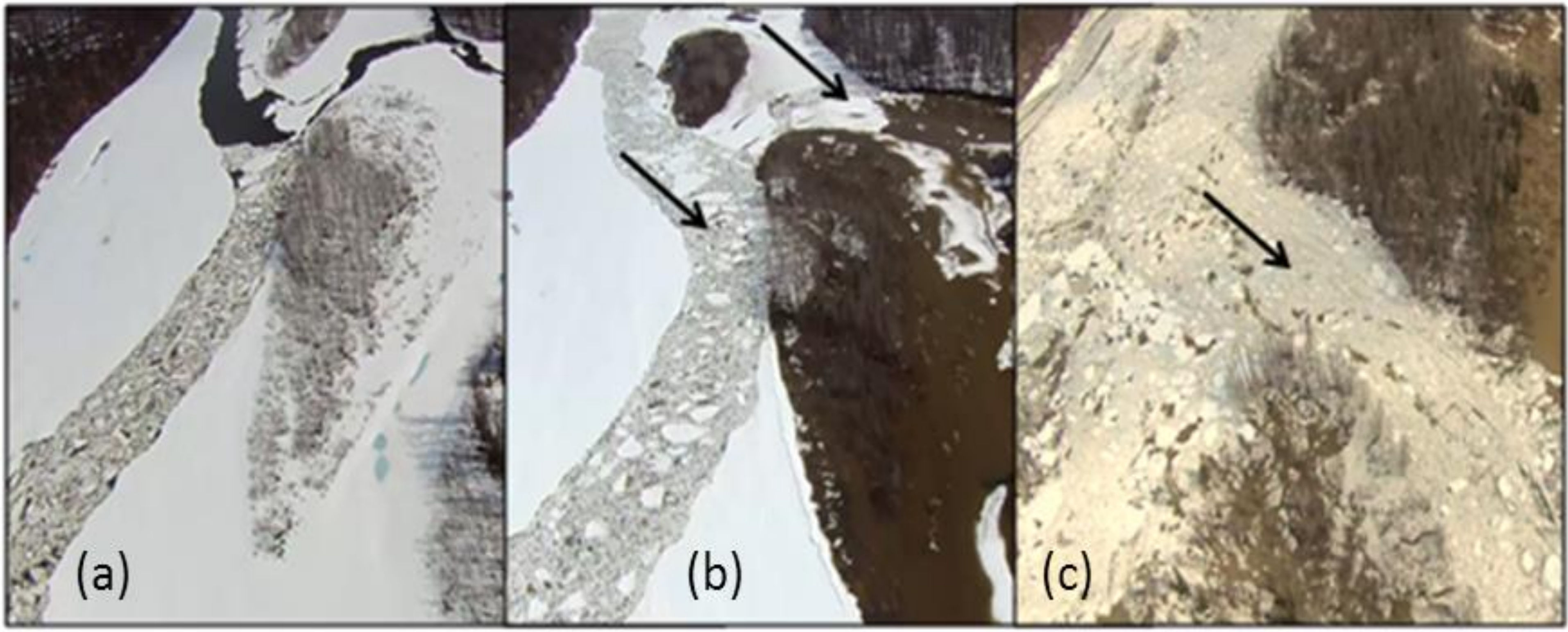


Middle Susitna River:

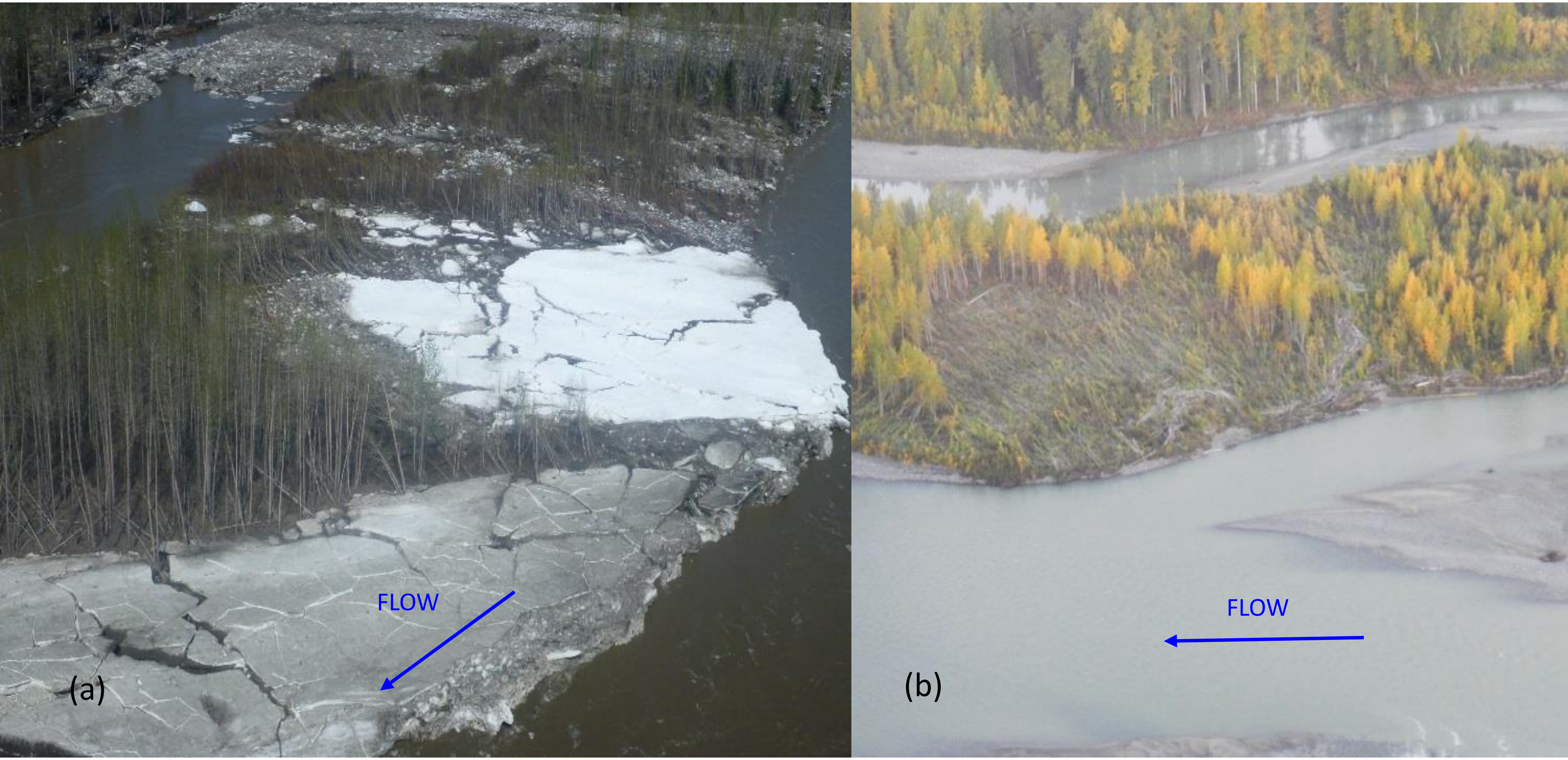
(a) single channel reach with floodplain and limited in-channel sediment storage

(b) multi-channel reach with mid-channel bars and islands





Middle Susitna River during break-up:
(a) May 23, 2013, with ice jam in main channel;
(b) May 25, 2013 with ice-induced diversion of flow into side channel
(c) May 26, 2013 diversion of flow and ice into side channel

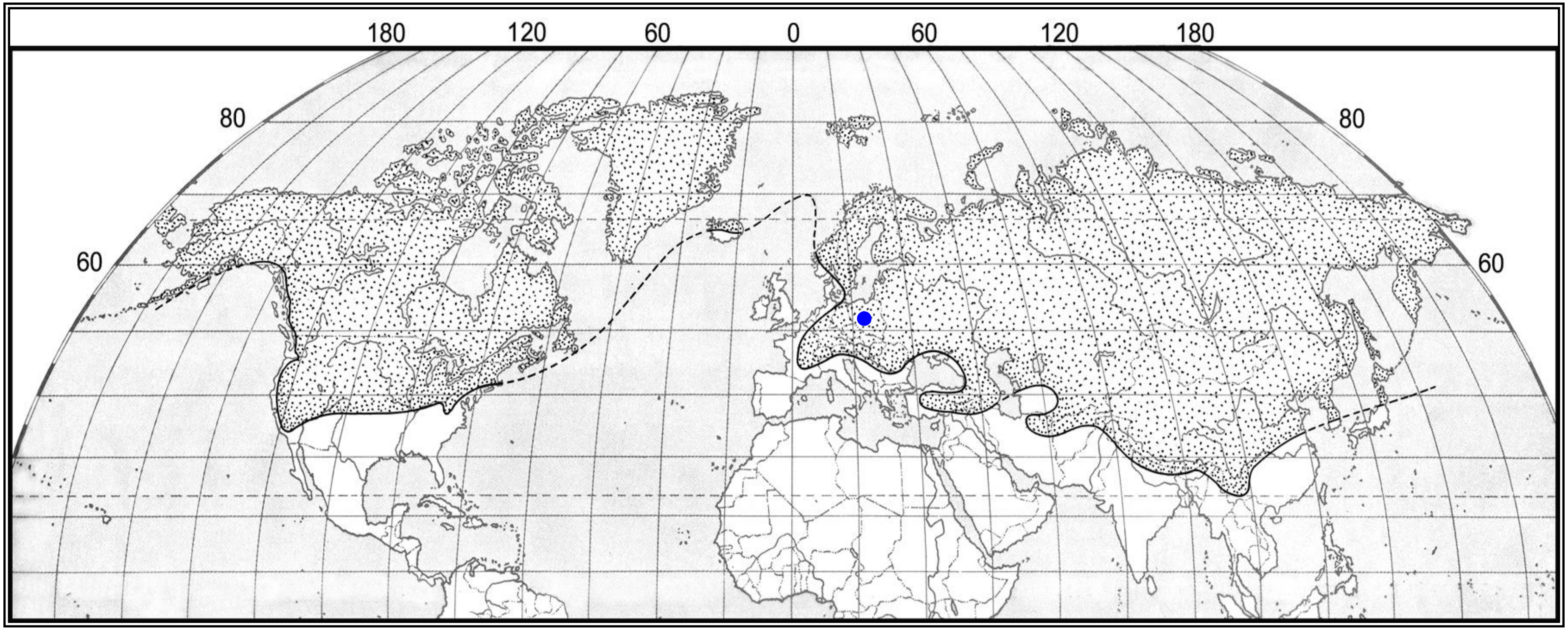


Middle Susitna River during break-up:

(a) ice shearing vegetation, May 29, 2013

(b) sheared vegetation viewed at same location on September 19, 2013

Extensive regions can be freezing cold



Don’t forget Jack Frost!

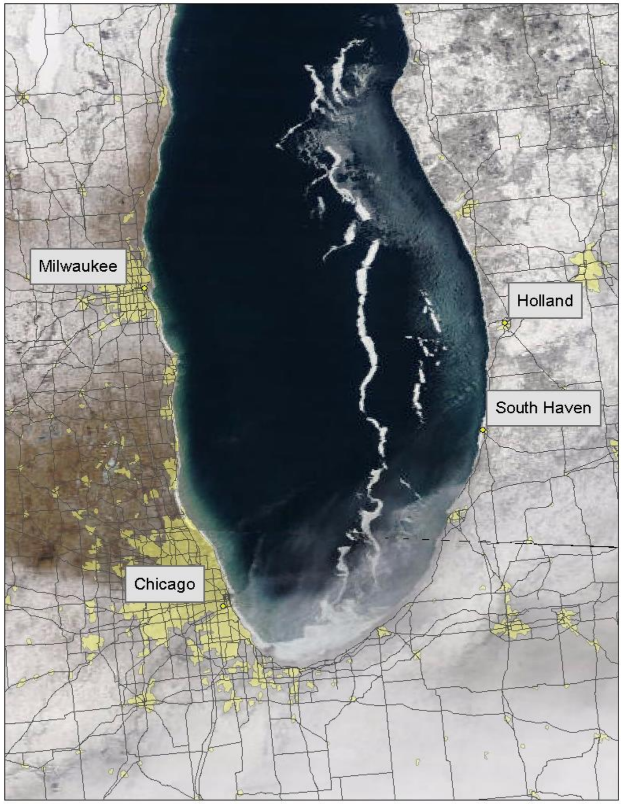
Topics for More Research

- Ice cover formation, esp. anchor ice
- Anchor ice transport of bed material
- River ice effects on channel morphology
- Combined effects of permafrost and river ice
- Ecological aspects of river ice
- Instrumentation and methods to overcome accessibility difficulties with field work
- Numerical (CFD) modeling of ice effects

Also, …

Ice in Large Lakes and Reservoirs

(A Hydraulics Problem in Lake Michigan)



Anchor Ice the Silent Strangler

Manitowoc, WI Lake Anchor Ice – January 2008