Hydraulics of the Red River of the North

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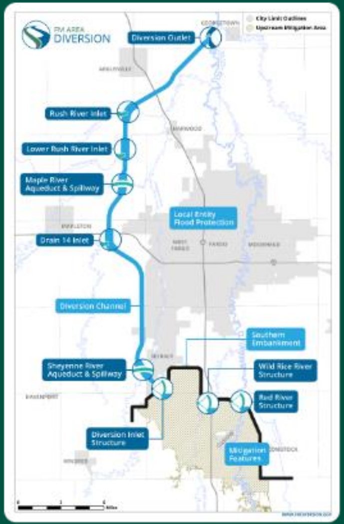
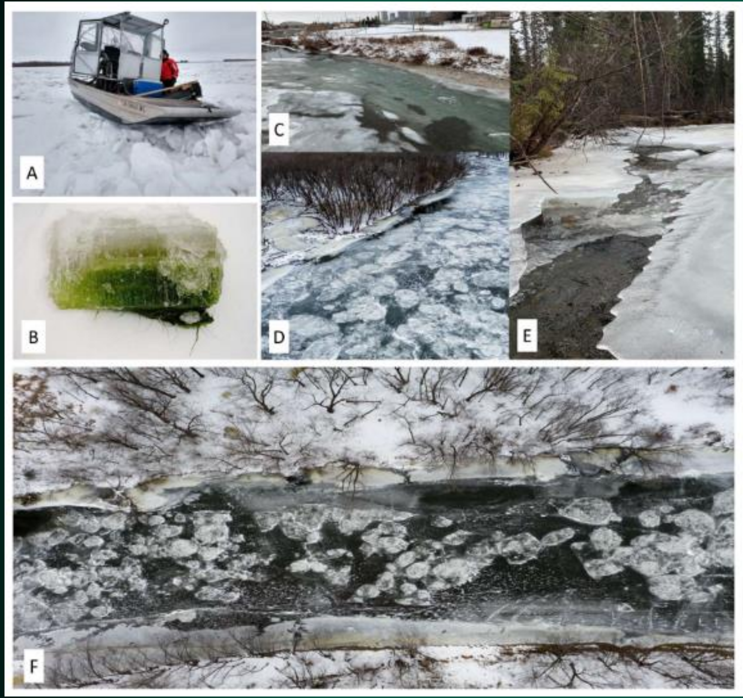
Motivation

Understanding river flow dynamics is important for many purposes

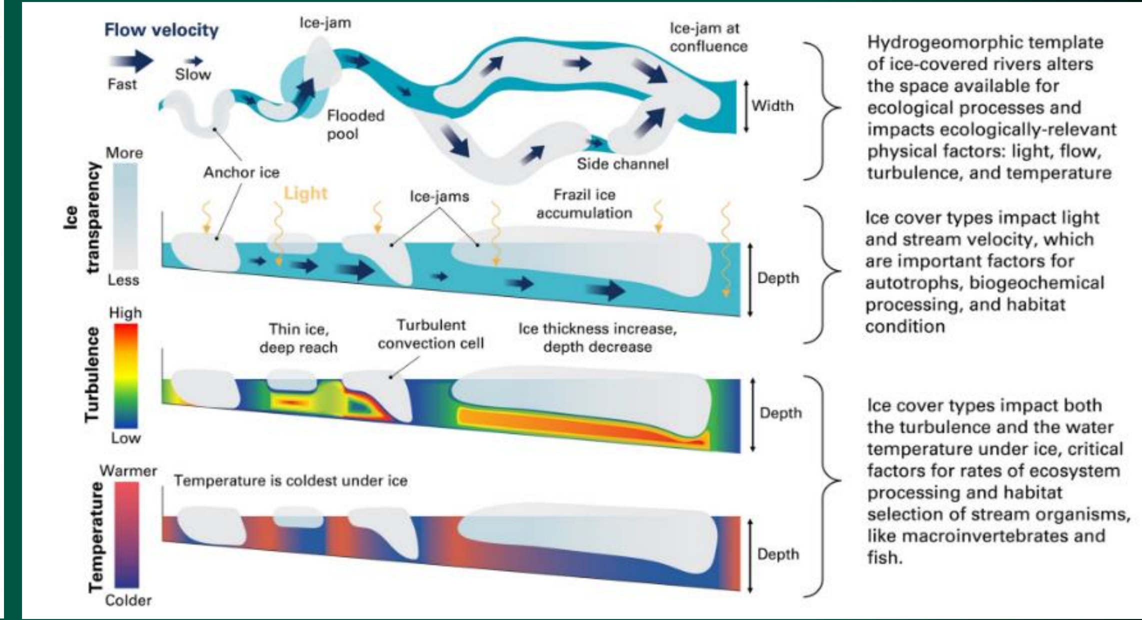
FM Flood diversion



Turbulent flows in ice-covered rivers



Common ice formations (Thellman et al. 2020)



How does ice cover impact the river flow and dynamics? (Thellman et al. 2020)

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Field measurements of icy flows under full coverage

- Winter measurement challenges:
- Safety (ice thickness to walk on ice and safety equipment)
- Minimum ice thickness for a 200-lbs person is suggested as 0.30 ft (~ 4 inch)
- During all our measurements, minimum ice thickness is measured as 0.75ft (10 inch)
- Extremely low temperature (generally -20oC to -10oC) makes the sensor difficult to operate
- Signal interference near the river bed (for both surface conditions)
- Difficult to derive shear velocity because profile assumption is required

Winter measurements on Feb/18/2020 (Trung on the left, and Berkay on the right)

Goals

The main goal is to understand the flow structures under the ice cover:

- Investigate the changes in flow profiles as the surface condition changes from ice-free to ice-covered conditions.
- Examine the cross-stream distribution of bed shear stress
- Evaluate the impacts of the ice-cover on the secondary flow structures in the bend
- Demonstrate the ability of Large-Eddy Simulation in replicating the dynamics of ice-covered flows
- Examine the impacts of the ice-covered on the flow planform

Field measurements of flow characteristics of a bend of the Red River

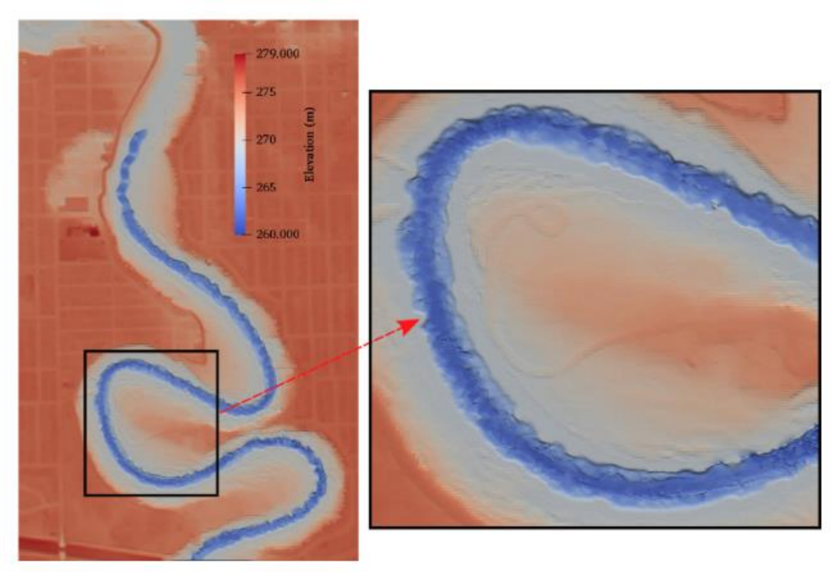
Modeled Red River Reach:

Downstream

Flow Direction

Upstream

Study site (Google Earth Image: 03/17/2021)



Three-dimensional model of the Red River reach

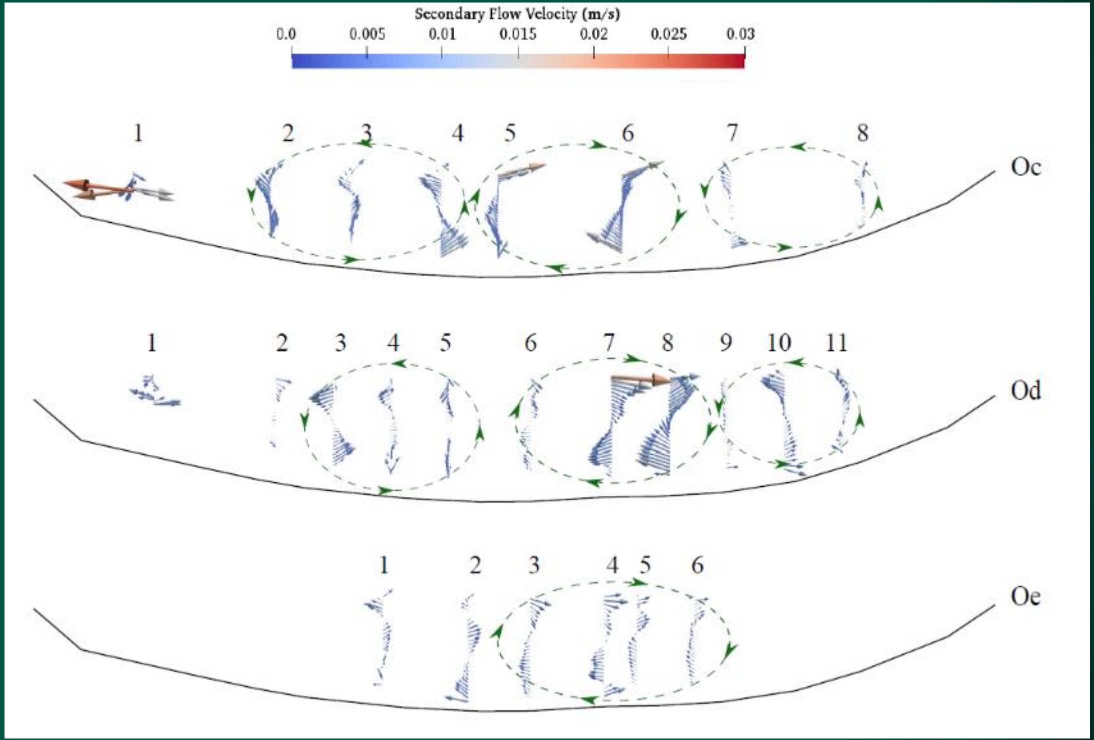
Field measurements under ice-free condition

Secondary Flow Patterns: rotation-based Rozovskii approach

Jun/22/2021: Q = 14.30m^3/s

Jun/24/2021: Q = 12.20m^3/s

Jun/30/2021: Q = 6.82m^3/s



Secondary flow patterns using rotation-based Rozovskii method

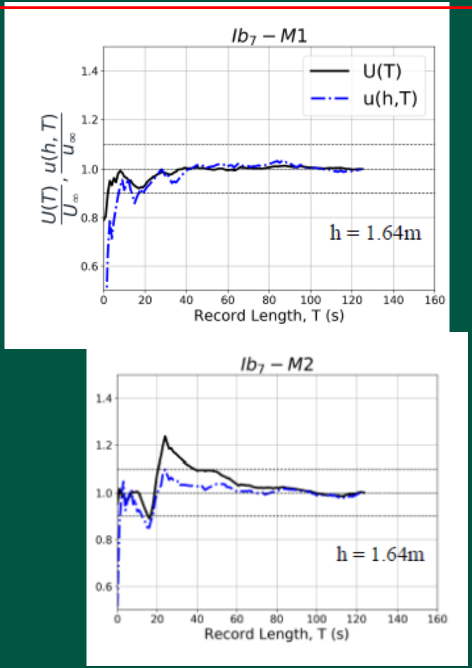
Field measurements of icy flows under full coverage

Depth-averaged velocity vectors:

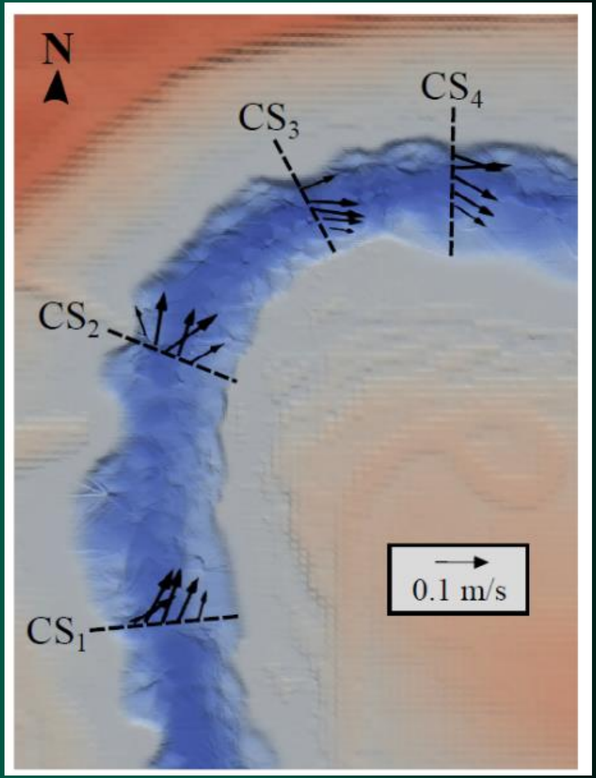
Stationary (fixed-vessel) deployment:

- ~2 to 4 min under ice coverage

Pedestrian bridge during winter



Long-term statistics of data sets



Depth-averaged velocity vectors at measured cross-sections (Feb/08/2022)

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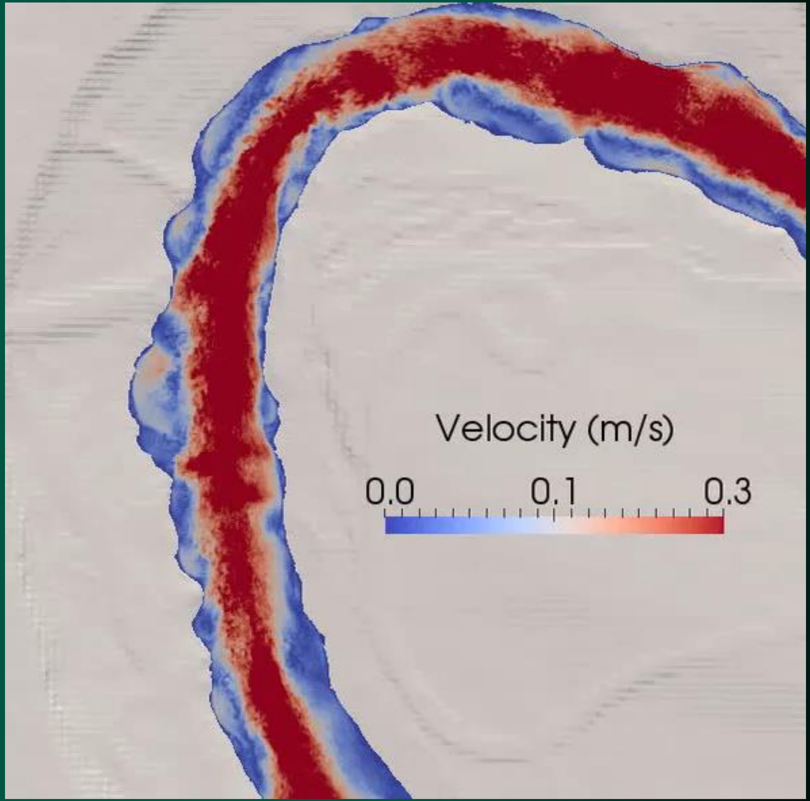
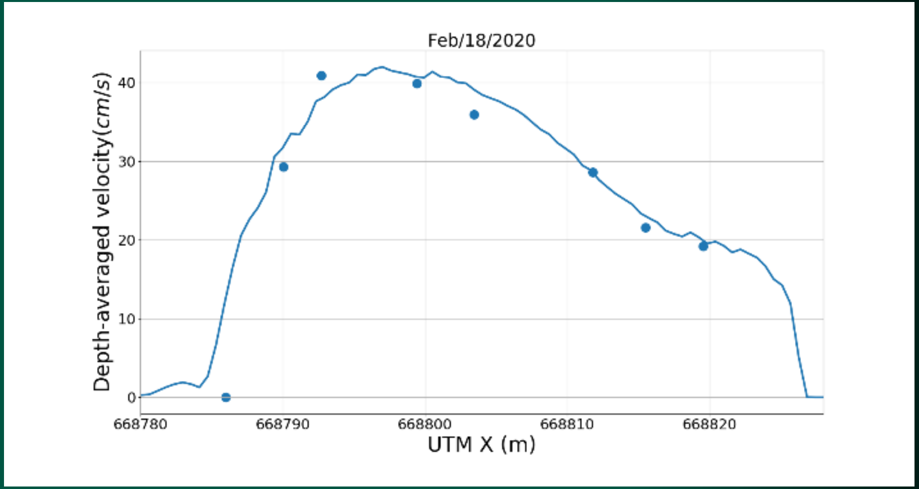
LES of river flows

<u>*LARGE-EDDY SIMULATION (LES):*</u>

- A structured grid is used with approximately 80M grid points
- Dynamic Smagorinsky model for the eddy viscosity
- Wall modeling for solid surfaces
- Assumed uniform flow at the inlet, fully developed flow at the outlet
- Using immersed boundary method (CURVIB) to handle complex bathymetry
- High performance computing (HPC) centers at NDSU (CCAST) and Pittsburgh Super Computing (XSEDE)
- LES model has been validated with field measurements (Le et al., 2019)



LES validation



Comparison between the depth-averaged velocity of LES (line) and measurements (dots)

Conclusions

- Under open-surface condition, the logarithmic layer can extend up to 50% of the total depth.
- Under ice-covered condition, the logarithmic layer is restricted in 20% of the total depth.
- The quartic solution (Guo et al., 2017) is helpful in determining these shear velocities. It is sensitive to the determination of maximum velocity, which might result in an underestimation of the shear stresses.
- The spatial distribution of the bed shear stress across the cross-section is changed by ice cover
- Under open-surface condition, the secondary flow pattern is dependent on the flow discharge. At high discharge, a single circulation dominates the overall pattern. At low discharge, two counter-rotating circulations, which have reverse senses of rotation to the high discharge one, mutually exist.
- Under ice-covered condition, the secondary flow pattern becomes highly complex. Multiple circulations are found simultaneously with alternating senses of rotation.