STRUCTURES OF ICY FLOWS IN RIVER BENDS

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Abstract

Flow dynamics under ice coverage has not been well understood despite its significance in alluvial morphodynamics. In this study, three-dimensional flow structures are analyzed in a river bend during winter to understand the link between ice coverage and velocity profile distribution. A river reach of the Red River of the North in Fargo, North Dakota is selected as the study site. Data monitoring is completed using Acoustic Doppler Current Profiler (ADCP) in both stationary and moving boat modes. Large Eddy Simulation (LES) is performed using ADCP data to provide detailed hydrodynamic data with the total grid points of 100 millions resolving flows in 1-kilometer ice-covered reach. We compare LES and ADCP to examine both the time-averaged profiles as well as turbulent statistics. Time-series analysis is carried out for ADCP data to analyze velocity profile distribution near the bend apex. Due to the difference in shear velocity of the bed and the ice surface, a double log-law is formed instead of the classical log-law in open channel flow. There exists three distinct layers: (1) ice-layer, (2) bed layer, and (3) the core flow. Distribution curves show that the location of maximum velocity is closer to the bed layer due to the non-negligible shear stress, which is caused by the ice layer at the top. The double log-law is modified following the suggestion (Guo et al., Journal of Hyd. Engr. 143.10, 2017) with two significant parameters: (1) flow condition (n), and (2) layer permeability (β). It is found out that the minimum β value gives the best fit in most of the measurements; however, the optimal n value varies. Further investigation from LES data shows that turbulent flows interact strongly with both the top and bed surfaces, which leads to the variation in local flow condition (n). This work is supported by a start-up package of T.Le from North Dakota State University and North Dakota Water Resources Research Institute. We also acknowledge the use of computational resources at the Center for Computationally Assisted Science and Technology (CCAST)-NDSU and an allocation (CTS200012) from the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number ACI-1548562.

INTRODUCTION

Motivation: Ice plays a critical role in regulating the environment for aquatic life during winter. Ice also contributes to flow dynamics significantly, especially early Spring. As the climate change accelerates, it is highly desired to understand how streamflow behaves under ice coverage
Problem Statement: Impacts of ice coverage of flow structures in meandering rivers are largely unknown. We study flow structures in a river bend under both open and ice-covered conditions.
Research Question:
1) Quantify statistics of turbulent flows in a medium-sized river bend at field scale.
2) Quantify the impact of ice coverage on the coherent structures of turbulent flows

Study Site: Red River – Fargo, ND, USA / Reach Length: 2.1km / Width: Approximately 40m

Measurement Campaign: Field measurement is carried out using Acoustic Doppler Current Profiler Sontek M9 starting from the upstream part (red circle) toward the river bend (blue circle) in Figure 1. The USGS station location is shown at the end of the river reach (yellow circle).

Measurement Dates:
- Sep/2019, Oct/2019 (Fall 2019)
- Jan/2020, Feb/2020 (Winter 2020)
- Sep/2020, Oct/2020 (Fall 2020)

Measurement Method:
- ADCP (Sontek M9)
- Stationary / Moving Boat
- Ice hole drilling
- Ice thickness measurement

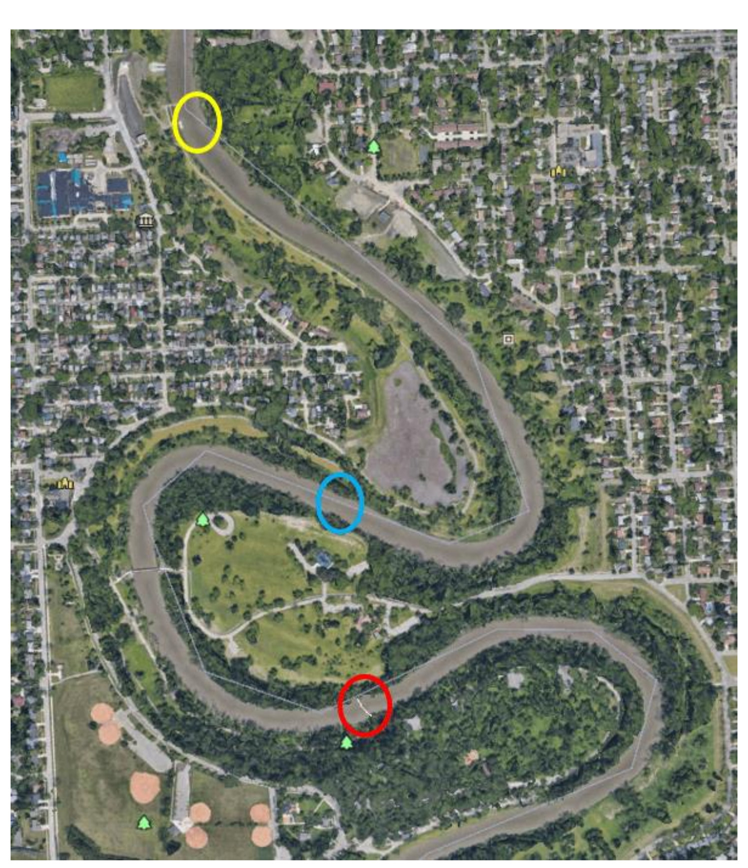

Fig 1. The study area locates at Lindenwood Park (Downtown Fargo, North Dakota, United States). One bend of the Red River of the North (between marks) is selected as the study site.

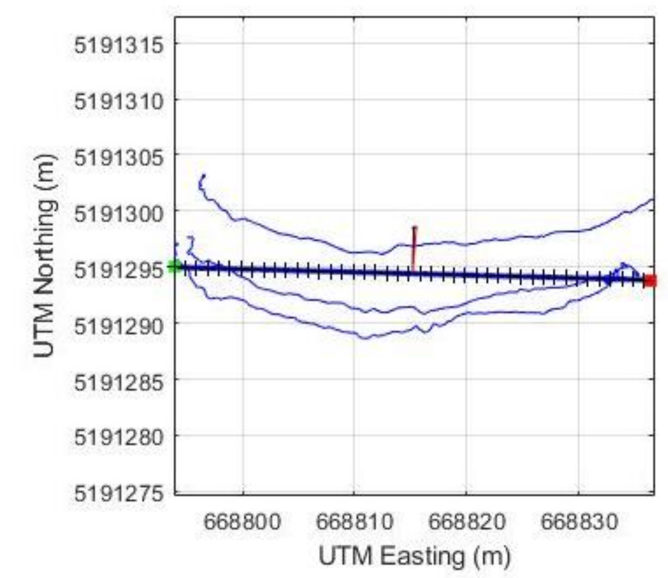

Fig 2. ADCP sensor (M9) is attached to a boat, which traverses one cross-section several times to create an averaged measurement for the cross-section. The measured data is processed using Velocity Mapping Toolbox (USGS) software.

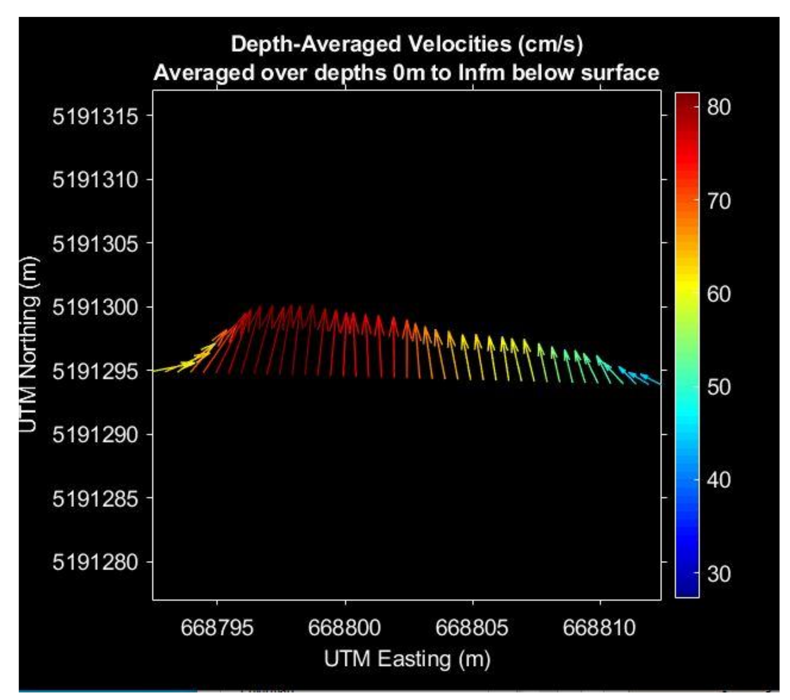

Fig 3. Flow distribution in the bend apex showing the high velocity core locates near the outer bank. The depth-averaged velocity profile is processed using the VMT software.

COMPUTATIONAL METHODOLOGY

Large Eddy Simulation (LES) is performed using ADCP data to provide detailed hydrodynamics data with the total grid points of 100 millions. We use our in-house Computational Fluid Dynamics code (Virtual Flow Simulator) to simulate turbulent flow dynamics under open surface and ice-covered conditions. We compare LES and ADCP to examine both the time-averaged profiles as well as turbulent statistics. To construct the computational model, the ADCP data is used to merge with the LiDAR data to create the Digital Terrain Model of the study area (Figure 5). We prescribe inflow and outflow boundary conditions using the measured ADCP data.

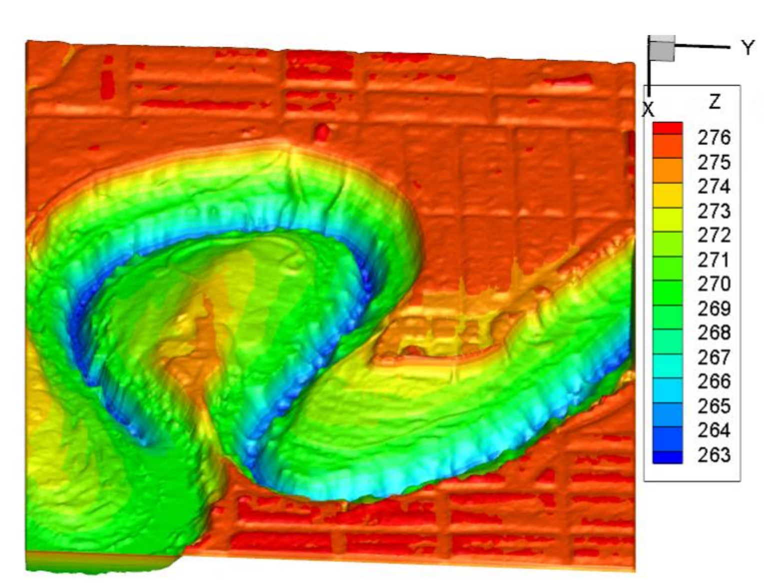

Fig 4. The Digital Terrain Model created by combining ADCP and LiDAR data

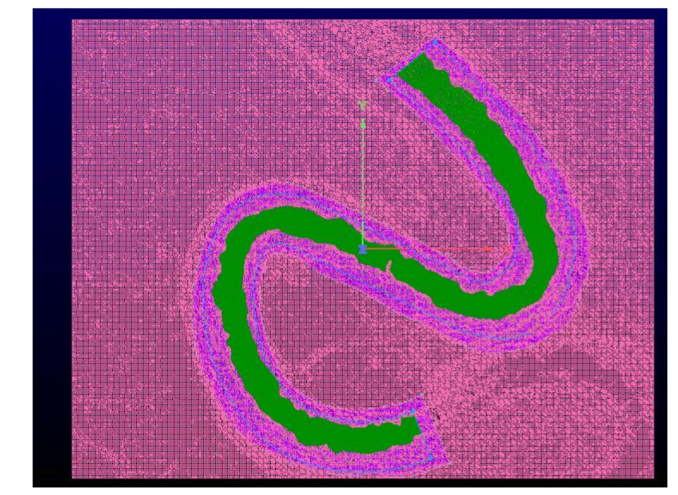

Fig 5. The computational mesh is created as a structured grid of 100 millions grid points

- From the field measurement data under open surface condition, high velocity cores are identified (Figure 6).
- Comparison of depth-averaged velocity distribution across the cross-section under open surface and ice covered condition (Figure 7).

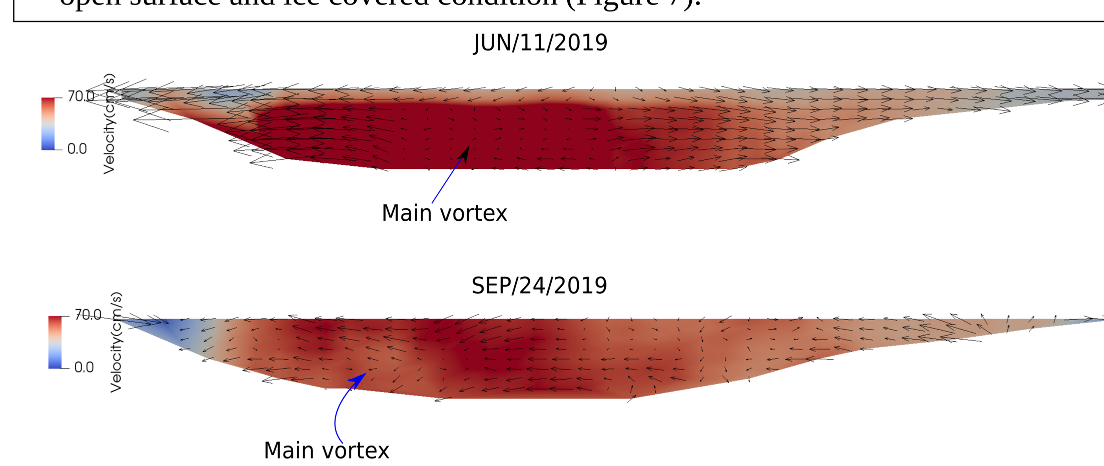

Fig 6. High velocity core (HVC) distribution at the bend apex in different measurement dates

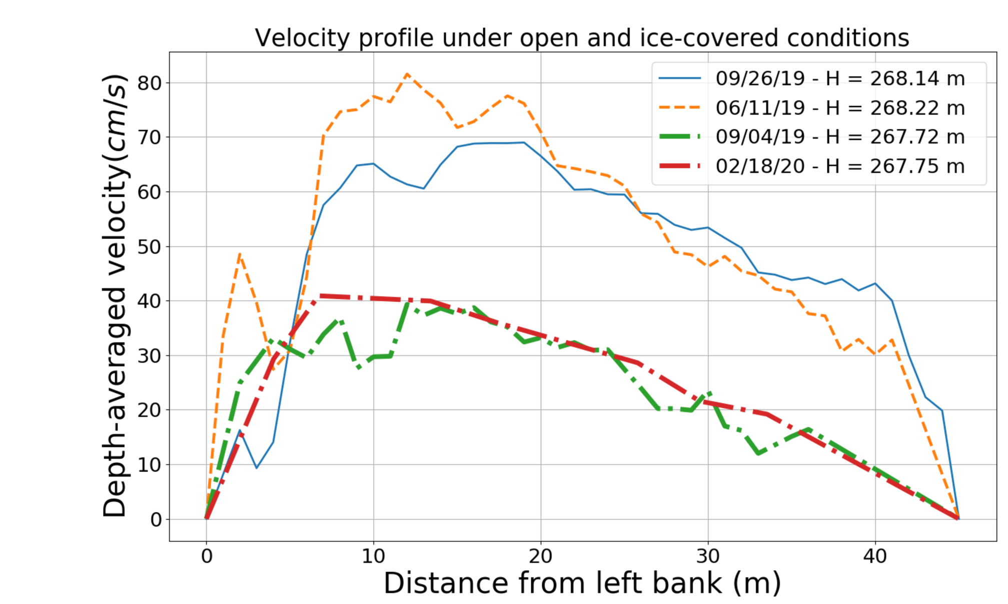

Fig 7. Changes in depth-averaged velocity distributions between open-surface and ice-coverage cases.

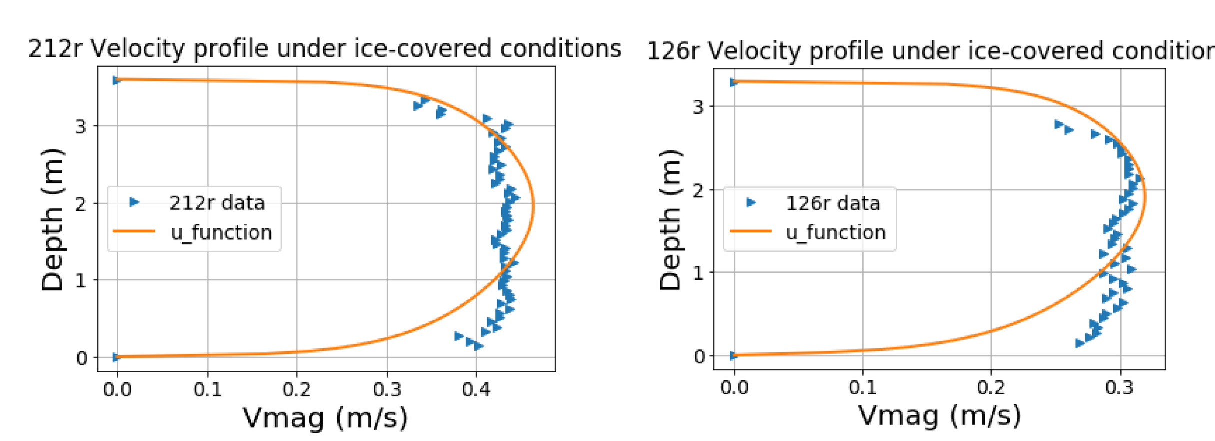

Fig 8. The impacts of ice coverage on flow distribution. Velocity distribution is shown along the depth of two ice holes: (a) the outer bank (left), and the center of the river cross-section (right).

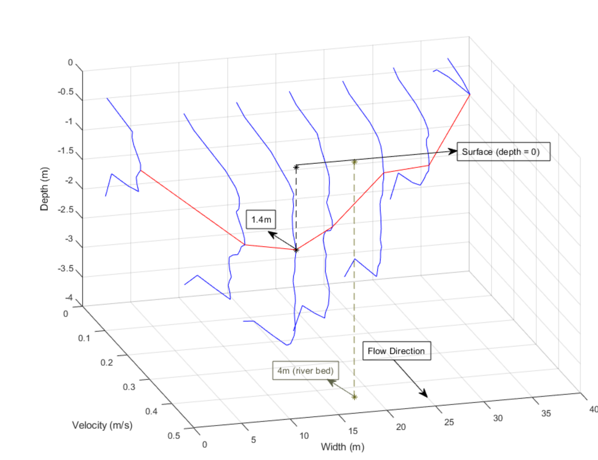

Fig 9. Three-dimensional structure of flow at the bend apex under ice-coverage. The vertical velocity distribution of all ice holes (ice thickness = 0.5m) is shown from the outer bank location (left) to the inner bank (right)

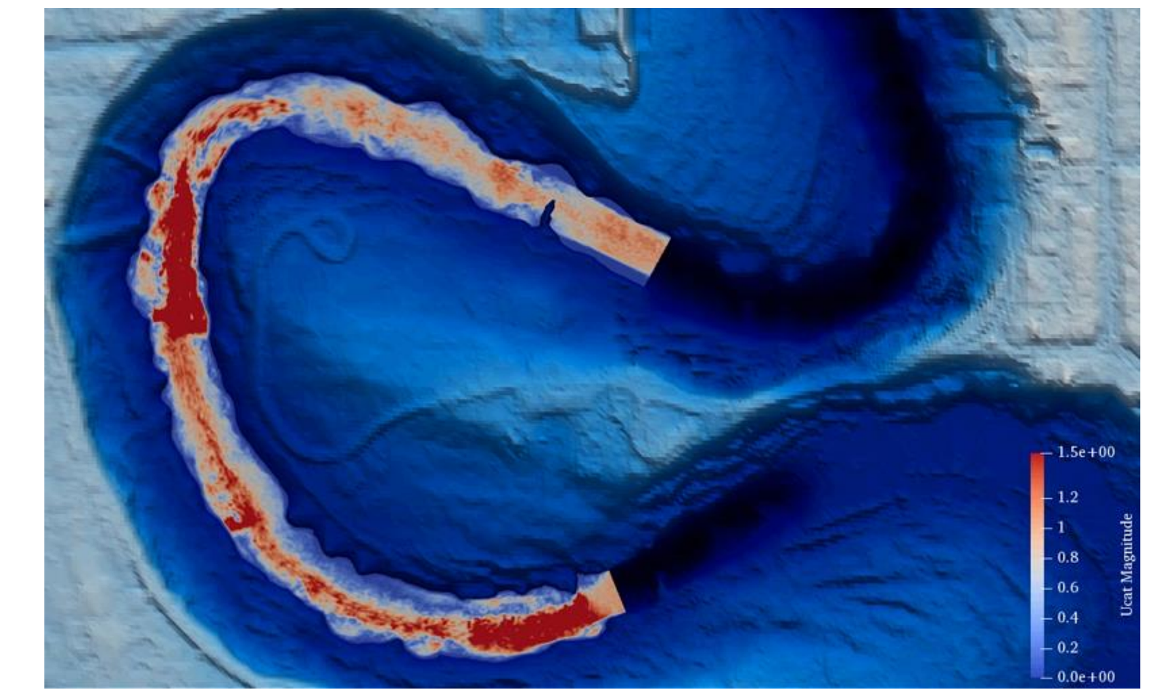

Fig 10. The formation of the jet at the bend apex. The instantaneous flow velocity is shown on the free-surface of the river bend.

- Location of maximum vertical velocity has shifted towards lower depths under ice-covered condition, especially where the streamwise velocity is high (Figure 9).
- The velocity distribution follows the classical flow profile in a bend (Figure 10).

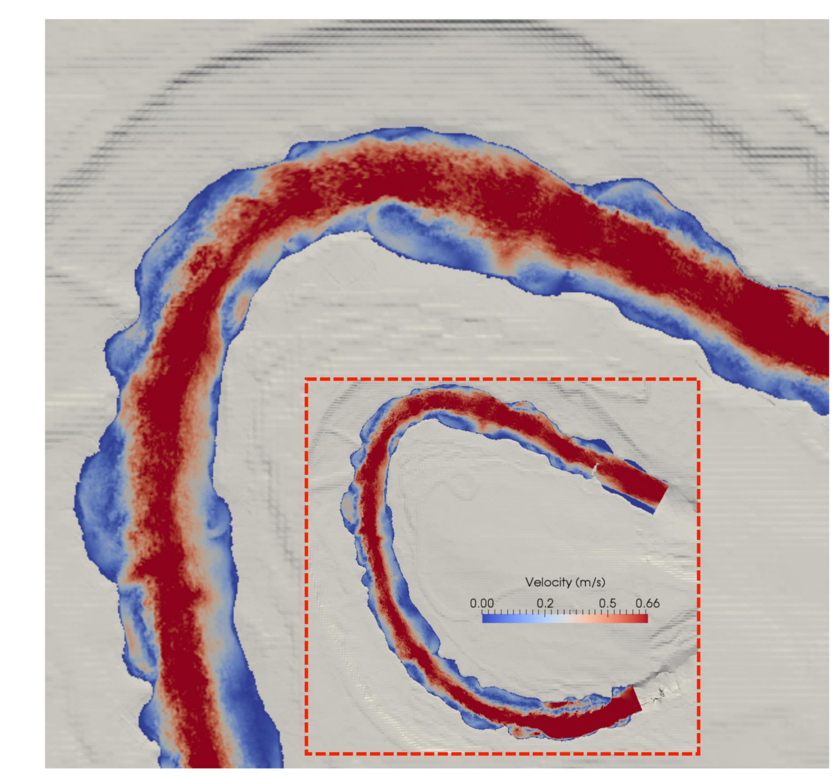

Fig 11. Velocity distribution under ice-coverage

CONCLUSION

- Higher values of (streamwise) velocity cores (HVC) is observed near outer bank as expected. This condition is valid for both ice and free surface cases.
- The maximum value of the streamwise velocity appears around 1m below the ice layer.
- The impact of ice is significant in changing the radial component of the velocity distribution.
- Our measurement data does not match with the two-layer hypothesis of ice-coverage flows. The impact of bend curvature might play a role in changing eddy viscosity distribution.
- High turbulent kinetic energy (TKE) under free-surface condition is observed near the outer bank at the bend apex. This distribution could contribute significantly on the sediment transport processes.

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