# Representing the Unrepresented Impact of River Ice on Hydrology, Biogeochemistry, Vegetation, and Geomorphology: A Hybrid Physics-Machine Learning Approach

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## Focal Areas

**(2)** Predictive modeling through the use of AI techniques and AI-derived model components; the use of AI and other tools to design a prediction system composed of a hierarchy of models (e.g., AI driven model/component/parameterization selection).

**(3)** Insight gleaned from complex data (both observed and simulated) using AI, big data analytics, and other advanced methods, including explainable AI and physics- or knowledge-guided AI.

## Science Challenge

A scale- and context-aware framework that employs artificial intelligence (AI)-based methods to learn and model the hydrological, biogeochemical, vegetation and geomorphological impacts of river ice dynamics by using remote sensing and ground-based observations.

## Rationale

River ice plays an important role in modulating hydrological, biogeochemical, and ecological processes in freshwater and coastal ecosystems of the cold Arctic region. It has an important effect on the global hydrologic cycle, particularly in the Northern Hemisphere, where 29% of total river length develops major ice cover, and seasonal ice affects 58% of total river length (Prowse et al. 2007). It is also responsible for extreme hydrological events, such as ice-jam flooding, which can have major economic costs estimated at $300 million in 2017 in North America (Rokaya, Budhathoki, and Lindenschmidt 2018). Patterns of weather extremes (temperature and precipitation) in heterogeneous landscapes along the riverine channel can lead to complex and compounding effects on river ice phenology (such as spring breakup and fall freeze-up) and associated flooding in the floodplains. Increasing intensity and frequency of climate extremes not only have regional impacts on ice dynamics, but also alter stream thermal and hydrological regimes and floodings, and influence physical, chemical, and biological processes in streams and carbon-rich permafrost soils. Moving river ice and floods can also erode floodplains, damage riparian vegetation, and alter vegetation composition and species diversity. Many of these processes operate at spatial scales unresolved by current generation of land surface models (such as ELM) and therefore, their representation is completely missing in the models. Water, energy, nutrients, and sediments are transported downstream by the river to the ocean and influence near-shore biogeochemistry and sea ice. An AI-based framework trained using observations can provide an accurate representation of the influence this cold region hydrological process has on the surrounding ecosystem. Embedded within a model such as ELM, in a hybrid physics–machine learning (ML) modeling framework, the AI-based framework can allow representation of hydrological, biogeochemical, and geomorphological impacts of river ice and their feedback to the climate system. This research would advance the Integrated Water Cycle Scientific Grand Challenges (Benson et al. 2020, Davidson et al. 2016, de Rham et al. 2020, Elder et al. 2020) identified in the Earth and Environmental Systems Sciences Division's Strategic Plan (US DOE 2018).



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## Narrative

Earth system models compute the numerical solutions to physics processes based on fundamental laws of fluids, thermodynamics, and chemistry. Processes operating at scales below the model grid resolutions, although important for Earth system predictability, cannot be resolved and thus are ignored/overlooked. Targeted high-resolution simulations and an ML-based framework that exploits global observations offer the opportunity for improved parameterization of physical, biological, and chemical process models (Schneider et al. 2017). Dynamics of river ice often occur at scales unresolved by the current generation of land surface models and are thus underrepresented in existing models. Ground-based observations and remote sensing platforms provide rich time series of information to monitor and understand the river ice–dominated landscapes. An AI-based framework can integrate and extract the wealth of available information from various data sources to detect and assess the dynamics of river ice in global cold regions, and identify the trends and relationships with the large-scale environmental drivers at local to regional scales for historical periods of observation. ML models can be further integrated within ELM in a hybrid process/ML–based architecture to represent river ice dynamics processes and model-associated impacts and feedbacks. For instance, a region-specific model trained using river ice phenology built using remote sensing of river ice, observations of freeze-up/breakup events, regional landscape properties, and meteorology can provide prediction of river ice extreme events within a hybrid model using modeled meteorological conditions as input. A regional topography and landscape-aware ML-based model can further estimate potential flooding damage, estimate biogeochemical and erosional impacts, and provide feedback to the physics-based host model. We suggest a hybrid physics/ML–based modeling framework to better represent the impact of ice dynamics on hydrological, biogeochemical, geomorphological, and vegetation dynamics processes. Development and application of novel AI-methods can improve the representation of these processes in land surface models and improve Earth system predictability.

### *1. AI methods to detect and model river ice–driven hydrological extremes*

Variability and extremes in regional temperature and precipitations regimes in basins dominated by seasonal river ice can lead to abrupt freeze-up/breakup events. The timing and location of such events can have a compounding effect of ice jams and lead to extreme and abrupt flooding events. Databases such as the Global Lake and River Ice Phenology Database (Benson et al. 2000) and Canadian River Ice Database (de Rham et al. 2020) provide observational time series records of river ice–related events in major North American rivers. Increasingly available satellite remote sensing provides high-resolution imageries to monitor and detect the river ice extent and associated extreme events. Previous studies have successfully detected the ice-break events using MODIS and Landsat data sets (Pavlesky et al. 2004, Cooley et al. 2016), but only for large rivers. High-resolution remote sensing can enable detection of river ice across large numbers of connected river tributaries globally. They pose challenges of computational scalability and call for robust and transferable supervised and unsupervised ML algorithms that can not only be applied in large data-rich rivers but can also be applied comprehensively to rivers across the global cold regions. Landscape and riverine characteristics combined with trends in meteorological patterns can be mined to model and predict the onset of river ice–related events and can thus provide representation to potentially embed within Earth system models.

### *2. Modeling biogeochemical processes driven by river ice dynamics*

Frequent floods and deepening active layers can accelerate flow through thawed soils, lateral solute transport, and increased availability of permafrost carbon for decomposition. Soil hydrological conditions affect vegetation growth and substrate availability, and influence ecosystem carbon input and microbial community structure, altering the transport and production of $CH_4$ and root and microbial respiration (Davidson et al. 2016). Complex microtopography controls the fine-scale variability in soil moisture, active layer depth, and vegetation, thus affecting $O_2$ diffusion and $CH_4$ and $CO_2$ fluxes (Wang et al. 2019). Flooding of wetlands can alter the soil moisture and soil thermal regimes, and enhance anaerobic decomposition of carbon, leading to increased emissions of $CH_4$. Ground-based observations and hyperspectral remote sensing have shown that $CH_4$ hotspots are especially clustered along river banks, lakes, and wetlands (Elder et al. 2020). Changing hydrologic regime also leads to changes in the riverine biogeochemistry and nutrient inputs from the floodplains, which lead to delivery of increased nutrient loads to the oceans. Although ground-based observations of biogeochemical fluxes are sparse and limited, AI-based methods that can combine various data sources, along with models, can allow improved modeling of biogeochemical impact of river ice dynamics and flooding and their impact on regional to global biogeochemical cycles.

### *3. Impact of river ice on floodplain erosion and geomorphology*

Movement of river ice in seasonally frozen rivers causes significant riverbank erosion of ice-rich sediments. Erosion rates are highly variable and strongly dependent on geomorphology and ground-ice content of permafrost. Erosion can be directly driven by physical abrasion of the ice on river banks and by flood waters associated with ice jams. The location and magnitude of erosion may be strongly influenced by the morphological characteristics of river reaches, which can be readily learned through AI-based methods. The strong seasonality of ice-influenced bank erosion and the apparent stochasticity of ice-jam events makes direct observation of local drivers extremely challenging. By aggregating historical events over space and time, ML offers the possibility of identifying key morphological and hydrological attributes of river reaches prone to ice jams. Therefore, AI-based methods can help synthesize sparse observations assets to derive fundamental understanding of patterns and trends of erosion processes in cold-region rivers.

### *4. AI approaches to model river ice impacts on riparian vegetation*

Changes in the hydrological regimes of Arctic rivers can significantly alter and modify the vegetation composition. During ice breakups, moving ice can damage riparian vegetation, erode floodplains, and create open sites for colonization. The establishment of vegetation on floodplains depends on life-history traits and the frequency and magnitude of disturbance (Lind et al. 2014). Fast-growing and tall vegetation can better withstand erosional disturbance. River ice–driven flow and erosion processes act as disturbance agents, allowing less competitive species to establish and increasing species diversity in the riparian zone (Lind and Nilsson 2015). Changing river ice phenology and flood frequency and intensity can modify the vegetation community distribution and affect ecosystem carbon balance. ML approaches combining ground observations and time series of multispectral and hyper-spectral remote sensing from airborne- and satellite platforms have been effective for mapping vegetation communities in Arctic tundra landscape (Langford et al. 2016, 2017, 2019). AI methods can be employed to better understand vegetation dynamics and to characterize potential community shifts under various scenarios of shifts in river ice and hydrological regimes.

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