
Aklavik and Tuktoyaktuk Disaster Mitigation Study. Breakup of the river ice on the Peel Channel at Aklavik in spring 2019.

Northwest Territories Ice Jam Flood Mapping Guidelines V1.0

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1 INTRODUCTION

These guidelines, prepared for the Government of Northwest Territories (GNWT), provide guidance to program authorities and practitioners on methodologies to produce inundation, hazard and risk flood maps for communities that are subject primarily to ice jam floods. Existing data will vary from community to community and these guidelines pertain to communities with little to no data and communities where data is abundant.

1.1 Intended Use

Historically, ice jam floods are the dominant type of flood experienced in the Northwest Territories (NWT). Several communities experienced significant ice jam flooding in 2021 and severe flooding was experienced again in 2022, at the time of the writing of these guidelines. The focus herein is on best practices for developing engineered flood hazard maps where ice jam flooding is the dominant flood mechanism. Methodology for provisional and/or preliminary mapping of historical flood events is not covered under these guidelines.

The methodology provided herein is complementary to the Federal Flood Mapping Guidelines Series (FFMGS). The FFMGS is a set of evergreen guidelines addressing: the program framework; LiDAR data acquisition; hydrologic and hydraulic procedures; geomatics; flood damage estimation; climate change; and a bibliography of best practices and references for flood mitigation. The reader is encouraged to supplement the methodology, herein, with those found in the FFMGS.

Ice jam flooding is a very complex phenomenon that requires specialized expertise to analyze and map; it is advisable that ice jam analysis be completed by experienced practitioners. The objectives and requirements for flood mapping work are unique to each project and will vary depending on the needs of the community and the hydro-climatic setting. The methods for a particular study will vary somewhat on a case-by-case basis and the adopted approach should be established by experienced and qualified practitioners.

1.2 Methodology Overview

The methodology is organized according to the following tasks required to produce inundation, hazard, and risk maps.

- Data collection.
- Data review and assessment.
- Flood hydrology.
- Flood hydraulics.
- Flood mapping.
- Climate change considerations.

An overview of the methodology is provided in the flow chart in **Figure 1**. The tasks depicted in the flow chart are expanded with further detail in **Table 1**.

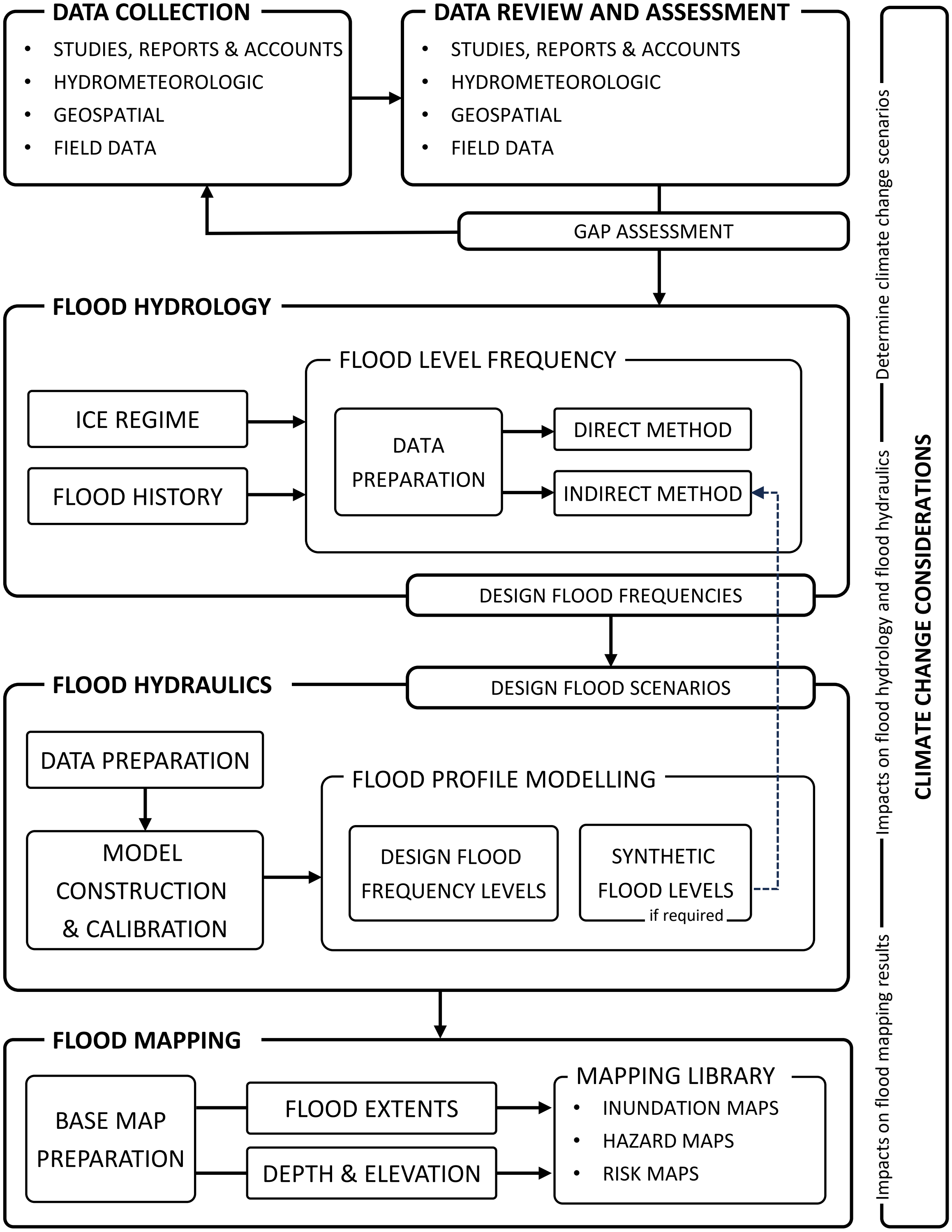

Figure 1 **Methodology Flow Chart**

Table 1 Methodology Overview

DATA COLLECTION			
STUDIES, REPORTS & ACCOUNTS • Documented events • Prior flood studies • Planning studies • Design reports • Regional studies • Hydrologic and hydraulic models • Indigenous Knowledge • Local accounts • Media accounts • Climate change studies • Guidelines	HYDROMETEOROLOGIC • Stream flow • Stream level • Direct discharge measurements • Rating curves • Meteorologic • Water temperature • River ice	GEOSPATIAL • Base maps • DEM / LiDAR • Aerial imagery • Radar satellite imagery • Optical satellite imagery • Local mapping • Previous flood mapping • Datums and projections	FIELD DATA • Survey plan • Survey control • River geometry • Highwater marks and ice scars • Hydraulic structures • Field notes, photos, and video • Ice jam observational information

DATA REVIEW & ASSESSMENT			
STUDIES, REPORTS & ACCOUNTS • Data extraction and collation • Dominant ice jam processes • Confirm ice jam is dominant flood mechanism (over open water)	HYDROMETEOROLOGIC • Data quality • Periods of record • Representative events • Representative of study reach	GEOSPATIAL • Coverage • Survey data comparison • Conventions and symbology • Preliminary base maps and geodatabase	FIELD DATA • Survey control • QA/QC • Bathymetry / bed survey • Hydraulic structures • Flood control structures • Field notes, photos, and video
GAP ASSESSMENT • Assess adequacy of data collected for hydrology, hydraulics, and mapping. • Assess the need to pursue collection of additional data that was identified during the data review (e.g., other published work, work in progress, additional local knowledge). • Assess the need to collect additional monitoring, observational, or survey data. • Develop methodology to rely on limited data.			

Table 1 Methodology Overview (continued)

FLOOD HYDROLOGY		

FLOOD HISTORY
• Overview of ice jam flood history and locations prone to flooding.
• Tabulated historical and observed ice-affected floods (dates, location, magnitude, and impacts).
• Detailed summary of major documented events with supporting information including:
  • Sequence of events leading to the evolution of the ice jam flood event.
  • Description of the ice jam development, the maximum flood condition, and ice jam recession.
  • Information collected during the event including survey data and ground observations (e.g., water level profiles, photos, ice conditions), and aerial observations by plane, helicopter, and/or drone (e.g., river reach extent and nature of ice conditions).
  • Post event information including survey data (e.g., highwater mark profiles, ice scars, shear walls), monitoring data (e.g., water levels), post processed data (satellite data, aerial imagery, ice mapping).		

ICE REGIME • Identify hydro-climatic conditions characteristic to the study reach. • Examine river morphology and identify locations of interest with respect to ice processes including hydraulic controls, steep sections, deep pools, sharp bends, geomorphic features, river encroachments. • Characterize various ice processes in relation to the study reach. • Determine causal factors for ice jam severity. • Determine typical ice characteristics (thickness, roughness, type).		
FLOOD LEVEL FREQUENCY		
DATA PREPARATION • Hydrometric records • Measured data (highwater marks, trees scars) • Model input data (where synthesized data is included)	DIRECT METHODS • Extreme value statistics • Frequency analysis	INDIRECT METHODS • Determine dominant causal factors • Modelling and data synthesis • Frequency analysis

FLOOD HYDRAULICS			
DATA PREPARATION	MODEL CONSTRUCTION & CALIBRATION	**FLOOD PROFILE MODELLING**	
		SYNTHETIC FLOOD LEVELS	FLOOD FREQUENCY LEVELS
• River geometry • Physical jam characteristics • Calibration data • Boundary conditions	• Model geometry • Jam stability parameters • Roughness • Calibration	• Calculate flood levels to support frequency analysis (if required)	• Calculate design flood frequency profiles

Table 1 Methodology Overview (continued)

FLOOD MAPPING			
BASE MAP PREPARATION • Layout and scale • Base data • Model information • Annotation • Symbology	FLOOD EXTENTS (VECTOR DATA) • Flood extents derived from flood profiles • Refinements / adjustments	DEPTH AND ELEVATION (RASTERIZED DATA) • Create water surface elevation and depth grids	MAP LIBRARY CREATION • Inundation maps • Hazard maps • Risk maps

CLIMATE CHANGE CONSIDERATIONS
• Determine climate change scenarios. • Assess potential impacts of climate change scenarios on flood hydrology and flood hydraulics. • Assess potential impacts of climate change scenarios on flood mapping results.

1.3 Flood Mapping Terminology

The following describes flood mapping terminology used in these guidelines. This terminology is consistent with those used in the FFMGS and other jurisdictions, including GNWT.

Flooding: The temporary inundation by water of normally dry land.

Flood Mapping: The delineation of flood extents and elevations on a base map. This typically takes the form of flood lines on a map that show the area that will be covered by water, or the elevation that water would reach during a specified flood event. The data shown on the maps, for more complex scenarios, may also include flow velocities, depth, other risk parameters, and vulnerabilities.

Hazard: A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption, or environmental degradation.

Risk: The combination of the likelihood and the adverse consequences of a specified hazard being realized, including potential economic, social/cultural, environmental, and human impacts.

Flood Inundation Maps: Maps that show the floodwater extent of historic past flood events, or that show potential floodwater coverage for flood events of different magnitudes. They are intended to aid in the management of emergency preparedness plans for communities situated within floodplains and flood hazard zones.

Flood Hazard Maps: Engineering maps that display the results of hydrologic and hydraulic investigations, including the extent of a regulatory design flood. These maps are used for regulatory planning purposes related to land use planning and flood mitigation.

Flood Risk Maps: Maps that show the flood hazard or inundation delineations along with additional socio-economic values, such as potential loss or property vulnerability levels. These maps serve to identify the social, economic, and environmental consequences to communities during a potential flood event.

2 DATA COLLECTION

The following describes the primary data sets and information needed to document flood history, characterize the ice regime, conduct flood hydrology and hydraulics analysis and modelling, develop flood maps, and assess the impacts of climate change.

2.1 Studies, Reports, and Accounts

Studies, reports, and accounts describe documented information that is relevant to the production of flood maps which are specific to a region. These data include past flood events (documented events and accounts), analyses (models, studies, reports), and reference documents (climate change studies, guidelines). These data are important as they will provide an understanding of the ice regime (necessary for flood hydrology), as well as information on ice jam physical characteristics (required for ice jam model parameters) and model calibration data.

Gathering information on historically significant or notable events which are most likely to be documented and found historical records is of particular importance. Historic data require some effort to collect and catalogue since it is not systematically stored and is found over a range of sources in varied formats.

Collected data can either be unpublished or published. Unpublished information, such as documented events or local accounts, should not be overlooked as it may contain valuable data and information. Published information include peer-reviewed publications, conference proceedings and papers, research study reports, post-secondary theses, and technical series or bulletins.

Documented events: Documented events may include both anecdotal or observation-based evidence of historic ice jams. This type of data may include flood extents and heights relative to known landmarks or a local datum, the sequence of events leading up to breakup and flooding, and consequences such as evacuations and number of homes affected. This information may be summarized as a standalone document or as component of a larger document and may be published or unpublished. Search for these reports in public, institutional (e.g., Hudson’s Bay Company records, church diaries, Royal Canadian Mounted Police diaries), and government libraries. Documentation of significant disaster events with an estimate of associated costs are included in the Canadian Disaster Database (Public Safety Canada). The Northwest Territories Hazard Identification Risk Assessment (NWT HIRA) also contains information about impactful flooding events.

Prior flood studies: Prior flood studies contain highly valuable data and provide sources for additional information and data. They help focus the search for historic data. They may also include hydrologic and meteorologic data, geospatial data, and field data. Prior studies may provide hydrologic models, hydraulic models, and calibration data.

Planning studies: Planning studies can provide local information on development and infrastructure. This information may be used for base mapping and as inputs used to develop hazard and risk maps. These studies may also provide salient background information about an area, including details of flooding history.

Design reports: Design reports that describe existing hydraulic structures are required if flood levels are to be modelled. Accompanying as-built drawings of bridges, culverts, weirs, and flood control structures should be obtained. Characteristics of existing structure data can sometimes be found in information databases from administrative bodies. Design reports may also include information valuable for model development and calibration, such as flood history and background information, hydrology, survey data, hydraulic model results, design considerations, and mapping data.

Regional studies: Regional studies include documented research that extends beyond the local study area, potentially at a basin scale, which is of importance to flood mapping. This may include information on geomorphology or geophysics, in addition to hydraulics, hydrology, or river ice related data. Regional study data may assist the search for local data, or they may extend outside of the Northwest Territories and include studies within other northern regions. Analysis from regional studies aim to inform understanding of the ice regime, river ice hydrology, and ice jam hydraulics.

Hydrologic and hydraulic models: Existing models are most likely to be found under prior studies or reports; however, it is possible that they are found as stand-alone products which can be obtained through academic researchers or industry practitioners.

Local accounts: Useful information can be found through local accounts of historic floods. These accounts may be documented, or they may be oral. Historic photographs and video supported with local accounts are quite valuable. The level of detail and accuracy will vary yet they may produce data that is essential to model calibration and validation. More often the flood accounts include information on the sequence, timing, and extent of flooding for a particular event. They may provide context on the relative magnitude between different events. The flood accounts can provide information on the hydrometeorologic setting prior to and during breakup. Together, this information offers valuable insights on the river ice regime including the dominant breakup and flooding mechanisms.

Media accounts: Historic information can be found by searching various media sources such as newspapers, radio, and web searches. They may include aerial images acquired from small low-flying aircraft, imagery from drones, and information shared on social media and other open domain platforms. Careful consideration is required if these data are to be relied upon. There may also be unique copyright considerations for republishing these data. Any media included in study reports requires permission to use and proper acknowledgement.

Climate change studies: Climate change studies contain data suggesting how climate change may affect hydrology and ice regimes within northern regions. This may include various scenarios for consideration and guidance on modelling parameters that can be applied within the context of flood mapping.

Guidelines: Guidelines from various jurisdictions (federal, territorial and provincial) can serve as reference documents for carrying out flood studies. Definitions, background information, and insight into processes can be gained from these data.

2.2 Hydrometeorologic Data

The required hydrometeorologic data include hydrometric data, meteorologic data, and river ice data. Hydrometeorologic data usually consist of time series observational data that have been collected, recorded, and archived in a systematic way by a public agency and may include collaboration with various partners. In some instances, data may have been collected by industry or educational institutions. These sources and supporting information for these data sets should be reviewed for documenting the data collection methods, data units, data attributes, collection equipment, and information describing data gaps, data status, and data availability. These data are primarily used for the hydrology analysis. In some cases, records pertaining to specific historic events may be used to support hydraulic model development.

2.2.1 Hydrometric Data

Hydrometric data are usually collected and stored in a systematic way by an agency such as the Water Survey of Canada (WSC), ECCC, along with various partners including provinces, territories, and other agencies. These data include both published and unpublished data. In some instances, the systematic hydrometric data may have been collected by other agencies for specific monitoring purposes, for example in support of research or operation of various riverside infrastructure (river intakes, for example).

Most hydrometric data come in the form of water levels expressed in a local gauge datum or height. Additional data, such as discharge, are then derived from the gauge height. Additional attributes that come with the data are useful for analysis. For example, information on station elevation datum(s), flags denoting the status or quality of published discharge estimates, and flags denoting ice-affected water levels.

2.2.2 Meteorologic Data

The requirements for meteorologic data will vary depending on the scope of the study. The data can be used to infer the nature of ice conditions over the ice-affected period (freeze-up, over-winter, and through break-up). Meteorologic data may also help with developing climate change assessment scenarios. The primary data parameters important for river ice processes include air temperature, humidity, wind, solar radiation, cloud cover, precipitation (rain, snow, total), and possibly evaporation. Most of the meteorologic data will come from the federal data sets collected and stored by the Meteorological Service of Canada (MSC), ECCC.

2.2.3 River Ice Data

In addition to hydrometric and meteorologic data, measurements of ice thickness data are very important for flood mapping where river ice is present or where risk of flooding due to ice jams is present. Ice thickness data are sometimes collected by WSC at hydrometric gauge stations several times throughout the season. These data are not usually published but may be requested from WSC. Associated data may include water level, discharge, date, time, and data quality rating. Thickness measurements collected late in the season are particularly useful as they help quantify ice thickness prior to spring breakup. It should be noted that WSC typically measures ice thickness from the water surface to the bottom of the ice (submerged ice thickness) and, at times, ice thickness may include a layer of frazil ice.

Additionally, river ice thickness data may have been collected by other agencies such as research institutions or industry or for specific monitoring purposes. Additional parameters such as water temperature, ice jam profiles, shear wall height, highwater marks, and ice scars may also be included with these data.

Finally, information of the river ice cover type is also very important for flood mapping. Radar satellite imagery can be collected from various sources, such as Radarsat Constellation Mission (RCM) and the Earth Observation Data Management System (EODMS) and processed by remote sensing specialists to classify river ice during breakup. The resulting ice cover maps can show locations of open water, non-consolidated /smooth ice, and consolidated / rough ice. Shore-based photography may also be available for the characterization of local river ice conditions.

2.3 Geospatial Data

Geospatial data include information in the form of points, lines, polygons, and gridded data that are required to produce flood maps. A description of the types of data that are used for mapping are listed below. The Federal Geomatics Guidelines for Flood Mapping (NRCan, 2019) provides an overview of coordinate systems and datums that are pertinent to geospatial data. While the most recent datasets are recommended for flood modelling and mapping, assumptions can be applied when using older datasets to obtain the greatest value from the available information.

2.3.1 Base Maps

Base maps are reference maps over which the flood data will be overlayed and provide spatial context for the results. Base maps are made from base data which is discussed in detail in the Federal Geomatic Guidelines for Flood Mapping (NRCan, 2019). The scale of the base maps should be selected to clearly detail the mapping extents. Draft base mapping should be developed early in the project since the choice of scale and layout will influence how features and labels are displayed on the map. The features presented on the base map should provide context to both inform members of the project team as well as members of the public who may not have the background information required to interpret complex maps. Typical features provided on base maps include:

- Administrative boundaries.
- Transportation features such as roadways and railways.
- Key infrastructure such as government, educational, community and or health care buildings.
- Locations of hydrometeorologic monitoring stations.
- Other landmarks that would enhance the spatial context of the results.

Features on the base maps should be labelled with a level of detail appropriate to the scale of the maps. The water bodies on the map should be labelled with the dominant flow direction and a north arrow must be provided to establish the orientation of the map.

2.3.2 Digital Terrain Model

Digital Terrain Models (DTM) are a key component for both flood hydraulics and flood mapping. The Federal Geomatics Guideline for Flood Mapping (NRCan, 2019) describes different types and formats of DTMs, guidance on their use, information on data sources, and DTM accuracy.

Sources of DTM data include Light Detection and Ranging (LiDAR), stereo images, or interpolated ground survey data. The standard data source is LiDAR as it is able to provide a high resolution DTM of the ground elevation (bare earth). Stereo images are not able to provide bare earth elevations in vegetation and are therefore only effective in areas of minimal vegetation (e.g. gravel deposits under low flow conditions). Interpolation of ground survey data requires very high-resolution ground survey data to meet typical DTM standards (e.g. 1 m resolution) so is generally limited to small areas.

The accuracy of the DTM will depend on the source of the data. For a DTM developed from LiDAR the Federal Airborne LiDAR Data Acquisition Guideline (2022) states that the horizontal accuracy of LiDAR should be 0.35 m and the vertical accuracy for non-vegetated and vegetated surfaces should be 0.10 m and 0.30 m, respectively.

It is recommended that DTM data be collected when water levels are low as the DTM data sources are not able to penetrate water. Under low water level conditions, the DTM elevations will provide better definition of the transition from the channel to the overbank. The DTM may even include depositional bars along the bank or islands in the channel. DTM information may extend to include channel bathymetry as new technologies for penetration below the water surface emerge.

Quality checks of the DTM elevations should be measured during field data collection. The DTM should include topographic breaklines along shorelines and flood control structures. If a hydro-flattened DTM is generated to obtain a more consistent surface across waterbodies, which may be preferable for mapping inundation extents, the non-hydro-flattened, bare-earth DTM should also be obtained as it includes additional useful information.

2.3.3 Radar Satellite, Optical Satellite, and Aerial Imagery

The Federal Geomatics Guidelines for Flood Mapping (NRCan, 2019) provides a thorough discussion of the importance of aerial photography and satellite imagery for flood studies. They can provide an estimate of inundation events during floods and changes in the channel planform over time. Images showing the inundation extents can help with calibration of hydraulic models. The images can also be used to define land cover characteristics in the overbank to assist with assigning overbank roughness values in hydraulic models.

In the specific context of flood mapping studies in the north, radar satellite, optical satellite, and aerial images can be used to track the progression of river ice breakup. The imagery can be used to observe the locations of ice jams, which often form in similar locations each year. Having images of the breakup progression can also be used to better understand water level changes at hydrometric gauging stations which would not be possible without imagery of the conditions. The imagery has also been used for flood emergency preparedness programs to predict when breakup will begin and to track progression. Satellite imagery is particularly effective for the large rivers in the NWT as it can cover very large areas on a regular basis at a relatively minimal cost. Obtaining the same coverage using aerial photography is only possible at significant cost. Radar satellite imagery can penetrate through clouds, which allows for data collection during times with cloud cover.

2.3.4 Local Mapping

Spatial information may be provided by local authorities or derived from consultation with local data providers. This may include mapping for tourism, trails, parks, local business, or other special interests. Local mapping may provide more appropriate labelling on maps as using local features and local naming conventions are more familiar to residents of the area. Ongoing flood watch or flood monitoring points of interests and local naming conventions should also be adopted to facilitate cross references between flood maps and information disseminated to the public during routine monitoring and during flood emergencies.

2.3.5 Previous Flood Mapping Information

Mapping information from previous studies can be an important piece of information that should be considered and possibly included with updated flood maps. This can take the form of flood lines on a map which show the area inundated by water, or water elevation for a specified event. These data can sometimes include flow velocities, depth, other risk parameters, and vulnerabilities.

2.4 Field Data

Field data refers to the data that are collected onsite. These include surveyed data that can be used to build and inform model development as well as observational data collected during a high flow event. While the most recent datasets are recommended for flood modelling and mapping, assumptions can be applied when using older datasets to obtain the greatest value from the available information.

2.4.1 Survey Plan

A survey plan identifies the proposed locations for survey data collection including survey cross sections, hydraulic structures, dikes, published control markers, and HWMs. The survey plan should be supported by a desktop review of available mapping and geospatial information (e.g., aerial imagery, DEM or LiDAR data) and prior survey data with information on published control markers or benchmarks. Available highwater mark (HWM) and high ice mark (e.g., tree scars) information should also be reviewed. A safety plan is included as part of the survey plan. It is advisable to plan for a site inspection prior to the data collection program to meet with local representatives and view the study area. Observations and information discovered during the site inspection will also help to inform site logistics, communication, and safety for the data collection program.

2.4.2 Survey Control

A local survey control network, consisting of a series of temporary, semi-permanent, or permanent benchmarks for which the horizontal and vertical position are known, is required when the study area is too large to survey from a single base station location. Temporary or semi-permanent benchmarks are typically established by a survey crew prior to a bathymetric survey at accessible locations close to the river. Whenever possible, new benchmarks established for a bathymetric survey should be tied-in to permanent government benchmarks that are proximate to the study area. WSC benchmarks can be also used as control points and their elevations should be surveyed to relate water level gauging records to the project survey datum. Survey data collected for the flood mapping study, including river bathymetry, highwater mark, ice jam (tree scar) levels, and structure geometry will be based on the local survey control network.

Survey control should be established to a standard spatial reference system. The Federal Geomatics Guideline for Flood Mapping (NRCan, 2019) provides guidance on selecting an appropriate spatial reference system for flood mapping projects. The standard NRCan spatial reference information currently in use is presented in **Table 2**; however, the horizontal and vertical datum should be specified in the project requirements by the territorial government before field surveys begin. When the most current datum and geoid defined by Natural Resources Canada are not used, the reasons for adopting an alternative should be provided in the project report.

Table 2 NRCan Standard Spatial Reference Information

Spatial Reference	Value
Horizontal Datum	NAD83 CSRS epoch 2010
Vertical Datum	CGVD2013
Geoid Model	CGG2013
Map Projection	Universal Transverse Mercator (UTM)

Benchmarks used as control points should be set well into the ground to avoid frost heave and displacement. It should be noted that benchmark coordinates may be revised over time, and such adjustments should be carefully considered.

2.4.3 River Geometry

Collection of river geometry is typically required to develop hydraulic models to simulate water levels and to confirm the elevations of any geospatial data required to produce flood maps. Stream cross sections are the basic geometric input for 1-D hydraulic models which are the predominant model type for ice jam modelling. The cross sections are typically constructed from a combination of survey data and DTM data when available. The survey data typically consist of ground-based survey points on the riverbanks and in the shallow water depths and boat-based sonar measurements (bathymetry) for the wetted portion of the cross section. In cases where a time series of river cross sections exists, morphologic change should be discussed and considered.

The location of cross sections should consider the following factors to ensure that they are adequate for simulating ice jam conditions:

- Cross sections may be spaced relative to the typical channel width, but it is important to capture representative planform channel and floodplain characteristics, slope changes, changes in discharge, structure locations, and potential overland flow routes. Brunner (2016) and Samuels (1989) provide further guidance on selecting appropriate cross section spacing open water hydraulic modelling.
- The location of the cross sections should consider the alignment in the overbank, particularly at confluences, to accommodate flood mapping.
- Cross sections should be surveyed at the location of hydrometric gauges within the study reach to facilitate comparison of measured and simulated water levels.
- Cross sections should be surveyed at the same location as any historical cross section to facilitate comparison of cross section shape over time. Where cross section survey data are available over many years, they can be examined for indications of changes in river morphology.
- Cross section surveys should be updated when flood maps are updated to reflect changes in channel geometry. Changes in geometry are most prominent following major floods and areas with significant sediment movement are susceptible to changes in channel geometry.
- Additional interpolated cross sections may be required by the ice jam model to adequately resolve the calculated ice jam profile (Beltaos and Tang, 2013; Flato and Gerard, 1986). It is therefore important to locate cross sections to capture variations in channel width; this ensures that cross section widths interpolated by the model are more representative of field conditions and limits the need for manual interpolation procedures.

Standard survey methods to measure horizontal and vertical position of the survey points are done using Real Time Kinematics Global Positioning System (RTK GPS). An RTK GPS is attached to a survey rod to measure the ground-based points or above a depth sounder that measures the water depth for the bathymetry survey points. Field verification of depths should be undertaken to account for potential errors in depth sounding including effects of sediment laden flows. The RTK GPS is extremely effective as long as there is open sky to track satellites during the survey. In cases where the sky is obstructed by thick vegetation, a total station may be required.

2.4.4 Highwater Marks and Ice Scars

Highwater marks are physical evidence of the water level which includes debris, sediment deposits, staining, and water damage. These marks can be found along various points within the floodplain including the inside of buildings. Ice scars are marks left on trees due to ice floes being pushed into the trees and provide a reliable indication of the maximum level of ice during breakup (Gerard, 1981). Care must be taken to consider whether scar elevations represent maximum water levels or if they are a factor of ice pile-up and ride-up, which can be considerably higher in elevation. The surveyed elevation of highwater marks and ice scars can be used to estimate the water level during a flood event; however, it may be difficult to determine during which flood event the highwater mark or ice scar occurred. Ideally highwater marks are surveyed shortly after the flood event to significantly reduce the uncertainty of what caused the highwater mark.

Ice scars in comparison to highwater marks can be evident on trees for decades over which several significant ice jam floods can occur. The age of ice scars can be determined by taking cores, wedges, slice cross sections of the scarred trunks (Smith and Reynolds, 1983) which requires a specialized field program. This would be most appropriate for a site with minimal documentation of historical ice jams and requires a history timeline. Without proper dating, it is very difficult to assign ice scar elevations to specific flood events. Instead, they generally represent an upper envelope for ice levels which could be assigned to the largest flood on record.

2.4.5 Hydraulic Structures

Collection of hydraulic structure data is required for hydraulic modelling and flood mapping. Hydraulic structures refer to structures inline with the channel such as bridges, culverts, and flood control structures which regulate the passage of water into the overbank of the channel. Flood control structures can also have culverts through them that could affect flood extents.

Data defining bridges and culverts are required for hydraulic modelling to define the flood levels. Surveyed data can be collected to complement as-built drawings of the structures and confirm potential changes in the structures since construction. The key dimensions include defining the hydraulic opening and the overtopping elevation of the structure, and in the case of a culvert, these data will be used determine whether the culvert operates under inlet or outlet control at high flows. For a bridge, this would include the location of the bridge abutments and piers, the shape and width of the piers, and the low and high chord of the bridge deck. For culverts, the data would include the invert and obvert of the culvert on both ends (which informs of slope), the shape of the culvert, and the crest of the fill through which the culvert passes. These key dimensions should be collected during the river geometry survey to ensure that the datum of the as-built drawings is the same as the survey. The survey data can also be used in place of as-built drawings, but the level of effort is increased to achieve equivalent definition of the hydraulic structure using surveys.

Data defining flood control structures are also required for both hydraulic modelling and flood mapping. Due to the importance of the elevation of flood control structures, it is recommended that the flood control structure is surveyed during field data collection. The survey should include a profile along the crest of the flood control structure as well as periodic cross sections of the structure at regular intervals. Any culverts or storm outfalls that pass through the flood control structure should be identified and surveyed.

2.4.6 Field Notes, Photographs, and Video

Field notes, photographs, and video form observational data that can include information on ice conditions and flood extents. Photographs and videos of highwater and ice conditions, descriptive notes, transcriptions of local accounts taken with observers in the field can all serve to validate flood maps. This can include information about the sequence of flood events, damage in areas, overtopping of linear features, flooding of homes, and even the direction of the flow of water within complex areas. Data may be collected on the ground or from an aircraft.

These data and information usually correspond to a location as provided as a geolocation or way point, a surveyed point, depiction on a map, photographs, videos, or written description in context of a landmark of physical feature that can be found in the field.

Conventions are recommended for metadata, naming, and classification of data and information types. Conventional terminology for river ice features or river ice physical characteristics are relevant when documenting information obtained from local knowledge.

2.5 Traditional Knowledge and Indigenous Knowledge

Traditional Knowledge and Indigenous Knowledge are often used interchangeably; however, their meanings differ. Younging (2018) notes that *“Traditional Knowledge” differs from the term “Indigenous knowledge” in that it does not include contemporary Indigenous knowledge and knowledge developed from a combination of traditional and contemporary knowledge*. The Impact Assessment Agency of Canada (2023) describes *“Indigenous Knowledge” as a term that refers to a set of complex knowledge systems based on the worldviews of Indigenous Peoples*.

It is important to recognize that Traditional Knowledge and Indigenous knowledge are owned and controlled by Indigenous Peoples. Practitioners must seek permission to publish such information and ensure that Indigenous Protocols are followed in the publication of Traditional Knowledge (and Indigenous Knowledge).

The First Nations Information Governance Centre (FNIGC) outlines principles of First Nations ownership, control, access, and possession (OCAP®) over data and information. These principles assert that First Nations have control over data collection processes, and that they own and control how this information can be used (FNIGC, 2023).

3 DATA REVIEW AND ASSESSMENT

The data collected requires review and assessment and a summary of the data review and assessment should be included with the flood mapping reporting deliverables. The data are assessed for quality, and potential gaps are identified. The assessment determines if the available data adequately supports the production of flood inundation, hazard, and/or risk maps. Where these needs are not met, recommendations are provided for the collection of additional data to fill gaps, and/or alternative methodologies that rely on the available data.

3.1 Quality Assurance Plan

Quality assurance and quality control (QA/QC) define the set of activities for *assuring* quality within the process of developing the data and *controlling* the quality of the resulting data products. The QA/QC process will vary depending on the information available, scale of the project, nature of data, and source of data, among other factors. And so, it is recommended that a *Quality Assurance Plan* be developed at the outset of a project. A quality assurance plan need not be exhaustive – it may be brief. Nevertheless, a successful plan will establish quality goals and criteria that are met through application of specific methods, processes, assessments, and/or metrics. The following offers a stepwise approach for developing the plan.

1. Identify the data collection activities anticipated for the study.
2. For each activity, establish a quality goal or criteria.
3. Identify the method for developing the data to meet the quality goal or criteria.
4. Identify the test and metric applied to control the quality.

3.2 Studies, Reports, and Accounts

These data include documentation of past flood events, local analyses, and reference documents that are useful for flood mapping. These data will provide an overview of flood history, an understating of the ice regime, as well as information on ice jam physical characteristics and model calibration data. A key objective to be gained from the collection of these data includes the confirmation of ice jams being the dominant flood mechanism, as opposed to open water flooding events. Additionally, understanding the dominant flood processes is critical for model development, calibration, and validation.

Since it is not always systematically stored and often found over a range of sources in varied formats, this type of data requires some effort to collect and catalogue. Historic flood records may be found in public, institutional, and government libraries and archives. Local accounts may be varied in detail and with respect to the amount of relevant information. Kriwoken (1983) ranked the sources of information accordingly to data reliability in the following order (beginning from most reliable to least): physical evidence, photographs, historical documents, and personal recollection. When accessing media accounts, care should be taken to consider the level of accuracy in the data reported as well as any copyright considerations.

Planning studies, design reports, and models may be found over a range of sources, including various government organizations, research institutions, or industry. Studies typically follow a consistent format which includes some form of background data, methodology, results, and conclusion or recommendations. This information is typically reviewed and may even include follow up studies carried out over longer periods of time.

Reference documents may help to provide definitions, insight into various processes, and may suggest methods of analysis for when there is limited data.

For all data which contain elevation information, the vertical reference datum should be scrutinised, especially when comparing datasets. Data conversions may need to be carried out or applied so that the information is consistent to a single datum.

3.3 Hydrometeorologic Data

Hydrometeorologic data are observational data that have been collected, recorded, and archived in a systematic way. Data collected by government organizations often undergo rigorous quality checks and have additional attributes denoting the status, quality, or local conditions applied to the data. The quality of any type of data received should always be examined and cross referenced with other data, where available. Often, the agencies responsible for collecting and sharing data can be contacted to provide more information if it is required.

Since hydrometric data are collected at specific locations, they must be evaluated to ensure that the station used is representative of the study reach and that the record length at the station is sufficient. Sometimes several stations near the study reach need to be considered and more than one station is ultimately used for analysis. Multiple stations can be useful in extending record lengths and filling in missing data. Additionally, they can help in determining outliers in the data and ensuring that representative events were captured. This is outlined in the Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation (NRCan, 2019).

For all data which contain elevation information, the vertical reference datum should be clearly denoted, and any required data conversions applied. As previously noted, elevations of benchmarks may be updated or modernized over time and such adjustments should be carefully considered when comparing datasets over time.

3.4 Geospatial Data

Various forms of geospatial data are required to produce flood maps. The quality of any type of data received should always be examined. A report outlining pertinent information regarding data collection often accompanies the available data. The accuracy of data is also important to consider. It is possible for spatial data to have high resolution and simultaneously have low accuracy. This can be determined through comparison with survey data that is referenced to a known datum. Adjustments of elevation or re-projections may be required such that all data reference a single preferred horizontal and vertical datum.

Data must also be evaluated to ensure that the coverage extends over the entire study reach and includes the overbanks. In situations where coverage does not include overbanks, data with lower resolution can be considered for use in data-void areas. Available metadata will confirm the accuracy of the lower resolution data and inform of any required adjustments or re-projections. The Federal Geomatics Guidelines for Flood Mapping discusses combination of elevation data from multiple sources and recommends a 1 m DTM resolution for flood mapping projects (NRCan, 2019).

When developing base maps, the features presented should provide context to both informed members of the project team as well as members of the public that may not have background information required to interpret complex maps. This includes naming conventions, symbology, and languages that can be understood by all the groups that will rely on these maps. The base maps should conform to standard cartographic conventions and specifications from the users.

3.5 Field Data

Field data are information that is gathered onsite. Data specific to a high flow event are collected during or directly after the event, while geometry data which describes the channel bed are often collected during low flow conditions that are free of ice and snow. Both types of data are very valuable for modelling and mapping efforts.

The quality of the survey data gathered must be examined. It should be confirmed that data were captured in representative locations, that sufficient points were collected to define the channel cross section, a sufficient number of cross sections were surveyed throughout the reach, and that the data extend far enough upstream and downstream to capture the entire study reach. Additionally, features such as hydraulic structures or river training works should be captured. Field notes, photos, and video taken during this time can be used to guide this process. The survey control information must be considered, and any potential adjustments or re-projections may be required such that all data reference a single preferred horizontal and vertical datum.

3.6 Gap Assessment

Each project is unique and the gaps and proposed approaches to in-fill these gaps will vary. Communities should rely on professional judgement for methods to in-fill gaps. When considering potential gaps in the data collected, the following aspects should be assessed:

- Adequacy of data collected for hydrology, hydraulics, and mapping.
- Need to pursue collection of additional data that was identified during the data review (e.g., other published work, work in progress, additional local knowledge).
- Need to collect additional monitoring, observational, or survey data.
- Development of methodology to rely on limited data.

4 FLOOD HYDROLOGY

4.1 Flood History

The flood history summarizes the historic flood information found during the data collection. It includes a summary of major events including details on the following.

- Sequence of events leading to the evolution of the ice jam flood event.
- Description of the ice jam development, ice jam extent, head and toe location, the maximum flood condition, and ice jam recession.
- Information collected during the event including survey data, ground observations (e.g., water level profiles, photos, and documented ice conditions), and aerial observations by plane, helicopter, and/or drone (e.g., river reach extent and nature of ice conditions).

- Post event information including survey data (e.g., highwater mark profiles, ice scars, shear walls), monitoring data (e.g., water levels), post processed data (satellite data, aerial imagery, ice mapping).

The major floods should be summarized in a table and include information on event date and duration, estimated discharge, highwater elevation, maximum ice jam extent (location of the head, toe, and length), and ice condition or ice jam type. Documents or accounts specific to the historic flood may be referenced.

From the flood history, it may be possible to infer the dominant ice jam conditions associated with major floods. The documented flood history will inform the severity and extent of ice jam flooding in and around communities which in turn provides guidance on the extent of mapping required by a particular community. Where possible, the flood history should provide a narrative that is supportive of specific rationale or assumptions used for ice jam flood hydrology or hydraulics.

4.2 Ice Regime

The ice regime describes the characteristic behaviour of the river ice under the prevailing hydro-climatic and morphologic conditions. It describes ice processes unique to the study reach over the ice-affected period, from freeze-up through winter and onto breakup. A clear understanding of the ice regime simplifies the flood hydrology. The description of the ice regime should address the aspects listed below. The Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation (NRCan, 2019) should also be reviewed when preparing this description.

Hydrometeorologic conditions: The prevailing climatic and hydraulic conditions drive ice cover formation, growth, and decay/breakup. It is important to characterize meteorologic and streamflow conditions from freeze-up through breakup. As air temperature drops below zero the water cools and the production of ice begins; soon after, a cover begins to form. The evolution of the ice cover over the winter period and subsequent breakup in the spring depend on the prevailing hydro climatic factors dominated by temperature, solar radiation, precipitation, and flow.

River morphology: The river morphology influences the ice regime. For a given hydro-climatic condition, the nature of the ice can vary with width, slope, planform, bed roughness, and bank conditions. The relationship between channel, floodplain and valley walls may also affect the river ice regime.

Ice processes: The dominant ice processes and resulting flood mechanisms depend on the hydro-climatic and morphologic conditions which vary over the ice-affected period and can differ along the reach. It is advisable to describe the ice processes and potential flood mechanisms according to freeze-up, over-winter, and breakup.

Causal Factors: Dominant causal factors for major floods should be identified. They may include a specific hydro-climatic condition or a condition indicative of a combination of hydro-climatic conditions. Specific conditions may arise due to a discharge increase, temperature increase, flood wave from ice jam release (jave), or a pre-breakup ice condition. The relative timing of breakup between main stem and tributary rivers may be indicative of either a thermal or dynamic breakup. Freeze-up conditions may be indicative of the pre-breakup condition. Break-up triggers are a type of causal factor. Certain causal factors may be used to inform indirect flood frequency methods. In these instances, the methods for determining or inferring the causal factors should be described.

Ice Characteristics: The ice characteristics should be identified and documented. Characteristics include information that describe the makeup of the ice cover by ice type and ice thickness. Types of ice may include border ice, thermal ice, snow ice, pan and/or slush ice, frazil ice, anchor ice, and so on. It may be appropriate to describe and group various ice characteristics according to the type of ice accumulation – for example, simple thermal cover, juxtaposed cover, hydraulically thickened cover (narrow ice jam), consolidated cover (wide ice jam), or frazil accumulation (hanging dam).

Regulation: For regulated rivers, the effects of flow regulation should be identified and documented. Regulation changes natural flows and water temperatures which change the natural river ice regime. These changes affect the frequency of occurrence and magnitude of ice jam flood events. The sequencing and timing of regulation projects should be described to provide context for the historical data.

As a minimum, the documented ice regime should identify the dominant mechanism or type of ice accumulation responsible for the largest ice-affected flood conditions. For example, freeze-up ice jams, winter ice jams, secondary consolidations, breakup ice jams, hanging dams, or some combination thereof.

4.3 Data Preparation

The purpose of the data preparation task is to develop a set of data that are ready for flood frequency analysis. The effort for data preparation depends on the data requirements for the type of flood map (inundation, hazard, or risk) and availability of the required data. For example, data requirements for direct methods of flood level frequency analysis may require far less effort than that required for indirect methods.

Activities for data preparation may include the following:

- Manual inference of data from "hard copy" data series or pen chart data.
- Data extraction from continuous electronic data series.
- Filling data gaps by direct regression (e.g., between average and peak values).
- Filling data gaps or extending records by regional analysis.
- Filling data gaps or extending record with synthesized data.
- Synthesizing full data records.
- Associating data with pre and post conditions where regulation is considered.

The data preparation phase builds a population of data suitable for the statistical methods used to estimate flood frequency. Gap filling may be required to provide a suitably long and representative record for statistical analysis. The methods for filling data gaps follows the normal conventions used for preparing data for open water flood frequency. For direct flood frequency analysis methods, flood level data is normally the parameter of interest. While for indirect methods, preparation of both flood level and discharge data will be required. Where data synthesis is required, some of the preparation will rely on hydraulic modelling. For example, an ice jam model may be used to estimate flood level data from a known breakup discharge distribution under an idealized ice jam condition.

Peak water level data collected at a gauge will typically form the basis of the ice jam flood frequency analysis and since much of this information is not typically published, the data may need to be acquired from unpublished files. Extraction of the peak water level for each year may be done by digitizing or manual scaling directly from the chart data.

Care should be taken when relying on published records. They may be incomplete or missing data for major events – ice can routinely damage the water level monitoring installation. The reported discharge values can also be highly inaccurate. Identifying and reconciling missing and inaccurate data requires careful examination of the published hydrometric record and possibly unpublished records. The process can be laborious and requires specialist expertise by an engineer with experience examining continuous ice-affected water level records.

4.4 Flood Level Frequency

Ice jam flood level frequency analysis is the core component of the hydrologic assessment for flood hazard maps. Whereas flood *discharge* is the parameter for open water floods, flood *level* is the parameter for ice jam floods. Unlike open water conditions, it is not possible to ascribe a unique flood level to each flood frequency discharge. For an ice jam flood condition, there are a range of flood levels that could be associated with a single discharge because the flood level magnitude resulting from an ice jam depends on factors other than discharge – for example: ice thickness, ice jam extent (with head and toe locations), toe thickness, and under ice roughness. And so, for ice jam flood frequency analysis, the more meaningful parameter for flood frequency is ice jam flood *level*. While the approaches are slightly different, the resulting flood frequency magnitudes are considered technically equivalent.

There are essentially two methods for determining flood level frequency: *direct methods* which derive flood level frequency directly from a population of *observed* ice-affected flood levels; and *indirect methods* which determine flood level frequency from a population of *synthesized* ice-affected flood levels. The former is a simpler approach requiring fewer assumptions than the latter which relies on experienced judgement and specialist expertise.

4.4.1 Direct Methods

An intuitive and simple approach is to review the historical record on a year-by-year basis to identify peak ice-affected water levels, and then undertake a simple frequency analysis by methods like those used for open water flood frequency analysis. This approach does not consider the causative factors that contribute to the peak water levels which may be an important consideration, especially if it is necessary to extrapolate to values beyond the range of the observed values. The standard statistical distributions that are most often applicable for open water are not always applicable for ice jam flood frequency distributions, particularly for very large flood magnitudes. One key aspect is that the incremental influence of ice effects on water levels for very large floods tends to diminish. There are two main influencing factors: (1) there is a practical limit to the supply of ice that can contribute to an ice jam, and (2) at some point most of the stream flows are no longer contained within the limits of the ice jam – the conveyance of water and ice in the floodplain becomes appreciable. Ice jam flood frequency curves tend to have more of an S shape owing to the changing incremental effects of ice conditions on water levels across the range of flood level magnitudes.

If the desired flood frequency values lie within the range of the observed values without the need for extrapolation, then there is merit in accepting this simpler approach. If extrapolation beyond the data is required to estimate the desired recurrence intervals, then an alternate approach by indirect methods warrants consideration.

4.4.2 Indirect Methods

An alternative approach is to use an indirect method. There are several methods for indirect frequency analysis and the reader is referred to a recent publication by Beltaos (2021) which provides an overview of direct and indirect methods for ice jam frequency estimation.

A common indirect method is to use statistical methods to quantify the causative factors that contribute to the characteristics of a whole set of data rather than individual events. This approach is akin to the so-called G-C method described by Beltaos (2021) which was introduced by Gerard and Calkins (1984). An approach of this kind is attractive because it accounts for physical inputs that impact ice-affected water levels. Data from individual events are not addressed explicitly, rather the data are aggregated and used to represent statistical distributions of the independent variables (input distributions) which are then transformed into statistical distributions of dependent variables (output distributions). The method relies on stage-elevation relationships (rating curves) for different ice conditions.

5 FLOOD HYDRAULICS

5.1 Data Preparation

The field data must be prepared after it has been reviewed to use it for the analysis of flood hydraulics. The survey data set used to produce a hydraulic model should only include ground elevation points for the model cross sections. Survey points of water levels, highwater marks, ice scars, and hydraulic structures should be removed from the data set for later use. The survey data should be imported into the model workspace along with critical data fields such as the survey date and time and the survey code. Having these data in the model workspace will assist with interpretation.

Additional filtering of the survey points should be considered depending on whether portions of each cross section above the surveyed water level will be defined using the survey data or the DTM. It is preferred to use the DTM data to define the cross sections whenever possible as the data sampling frequency is higher for the DTM than for the survey data (presuming the DTM is suitably accurate) and provides a better resolution of the transition of the channel and the overbank of the river. The extent to which the DTM can be used may be limited by the water level when the DTM was collected.

Surveyed water level data along with open water highwater marks should be compiled for use in model calibration. Though the primary cause of flooding in most communities in NWT are ice jams, open water calibration is still required before ice jam calibration can be done. The discharge corresponding to the different water level conditions (e.g., survey water level) should be extracted either from hydrometric records or from field measurements. The discharge will be used for the upstream (inflow) boundary condition for the hydraulic model. The downstream (outflow) boundary condition will be defined by the surveyed water level at the outflow boundary of the model.

5.2 Ice Jam Model Construction and Calibration

The basic inputs required by the ice model are much the same as those required by an open water model (i.e., river cross sections along known lengths of channel, roughness coefficients for the channel and overbank areas at each cross section, a specified or computed water level at the downstream model boundary, and a discharge at all upstream model boundaries). In addition to these basic inputs, the ice model requires at each model cross section: a prescribed ice cover condition; under ice roughness; and a set of ice jam parameters characterizing the properties of the ice jam. These ice model inputs are used to solve for the under-ice hydraulics and ice jam stability relationship.

Various models with similar capabilities are available for calculating ice jam flood levels (Carson, et. al. 2011). However, the most common and widely used model for flood mapping of both open water and ice jam flooding is the U.S. Army Corps of Engineer's Hydrologic Engineering Center River Analysis System (HEC-RAS) computer program (US Army Corps of Engineers Hydrologic Engineering Centre, 2016). The following descriptions for model development are written in the context of this model.

Ideally, the ice model should be calibrated to measured ice jam flood levels of magnitude comparable to the desired design event magnitudes (50-year, 100-year, and 200-year ice jam floods, for example).

Refinements in addition to a typical open water model include the following.

- Bank station location adjustments for a better representation of the ice jam "width" which is used by the model when solving the jam stability equation.
- Additional cross sections for improved stability of the HEC-RAS ice jam thickness computations and adequate resolution of the ice thickness profile. Ice jam modelling experience by the author and other investigators (Beltaos and Tang, 2013) suggest that the ice jam solution algorithm may require additional cross sections to adequately resolve the computed ice jam thickness profile. Further, model performance improves when cross section spacing is regular and any changes are gradual. Additional interpolated sections for ice jam modelling should provide an accurate representation of the variation in channel width.
- Define ice jam stability parameters required as input to the HEC RAS model to solve for the jam thickness profile including: the internal friction angle of the jam, ϕ; the ice jam porosity (fraction of voids between ice floes), p; and the coefficient of lateral to longitudinal stress in the jam, k_1. All other parameters are solved internally by the model. The computed water levels are not especially sensitive to changes of these values when the changes remain within the acceptable range of values cited in the literature.

- Calibrate the model to observed recorded highwater and ice levels by adjusting ice jam roughness.

Where calibration data are not available or insufficient, it may be appropriate to assume that the ice jam characteristics at the study site are comparable to those forming at other locations along the reach. This affords estimates of a typical ice jam roughness value based on observations at other similar river reaches. The calibration may be refined by comparing computed values to breakup ice jam rating curves determined at a gauge.

5.3 Flood Profile Modelling

In most instances, flood frequency levels are estimated at a single location within the study reach (a stream gauge site, for example). The flood profile is then extended from the single location throughout the study reach using the ice model. The flood profile usually corresponds to that calculated under a wide channel ice jam assumption. A further assumption is that the calculated ice jam profile is allowed to fully develop to an equilibrium condition throughout the entire study reach. The rationale is that while a fully developed ice jam extending the entire study reach may not be so likely, achieving an equilibrium flood level elevation for a given recurrence level is equally likely anywhere along the study reach.

6 FLOOD MAPPING

6.1 Base Map Preparation

Base maps should be created for review by the project team and project partners. Effective base maps communicate spatial context of flooding relative to key features in the study reach. The primary mapping scale should be selected to effectively communicate flood mapping information. The base maps will consist of a series of maps that cover the study area. The orientation of the maps can either follow the alignment of the water body or aligned with the cardinal directions (e.g., north-up). While fewer maps may be required when they are orientated along the study reach, consideration should be given to the interpretability of the maps – maps aligned with cardinal directions are generally more readable, especially in an urban setting.

The background of the base maps is typically a recent aerial photograph that shows the current level of development potentially affected by flood mapping. Modifications to the colour and opaqueness may be required to effectively display features and labels on the map. The maps should include administrative boundaries, transportation features such as major roadways or railways, key infrastructure such as government or health care buildings, or key landmarks that provide spatial context to local users of the flood maps.

The base maps should conform to standard cartographic conventions and specifications from the users. The Federal Geomatics Guidelines for Flood Mapping provides standard base map symbology for the different types of flood maps. Different jurisdictions may require modifications to the proposed symbology.

6.2 Analysis

6.2.1 Flood extents

The flood extents for a given flood scenario are provided on the base maps to show the flooded areas. Developing flood maps involves transferring simulated water levels from the model cross sections onto the DTM to determine the flood extents. A triangulated irregular network (TIN) must be developed between the model cross sections to allow interpolation of the water between the cross sections. The TIN must account for alignment of the channel and extent beyond the maximum inundation extents.

The flood extents are determined by comparing the water surface elevations from the TIN to the DTM elevations. This is done by converting the TIN to a water surface elevation grid with the same resolution as the DTM. The difference between the two surfaces is determined to generate a depth grid.

6.3 Mapping Library

6.3.1 Inundation Maps

Inundation maps show the extent of flooding for past flood events or for potential flood events which are typically defined by the annual exceedance probability. The water levels for potential flood events are typically determined by using a 1D hydraulic model. Due to the limitations of 1D hydraulic models there are areas in the inundation that may require special attention. These areas include backwater areas where flow overtops the banks at discreet locations, the failure of potential flood control structures, and isolated areas that have no direct hydraulic or overland flow connection to the main channel. Separate treatment of these areas by a 2D model or combining a 2D model with the 1D model (1D / 2D coupled model) may be considered for these areas.

6.3.2 Hazard Maps

Flood hazard maps define the flood hazard for areas flooded during the design flood event. The flood hazard area is typically divided into the floodway and flood fringe. The floodway carries most of the discharge during the design flood event. Under open water conditions, it is the area where the flow is deepest, fastest, and most destructive. For ice conditions it also includes areas exposed to moving ice – it is difficult to envision a condition under which moving ice would not be considered dangerous and destructive. For practical purposes, the floodway can be defined by areas where depths exceed 1 m, or areas of moving ice. Criterion based on flow velocities would rarely apply or be impractical since high velocities would most always be associated with depths greater than 1 m or a moving ice condition.

The flood fringe depicts areas of flood hazard area outside of the floodway. Under ice-affected conditions, the flood fringe may or may not be occupied by ice. This will depend on whether the ice thickness exceeds the water depth into specific areas of the flood fringe.

6.3.3 Risk Maps

Flood risk maps communicate the vulnerability and exposure due to flooding and is done by comparing flood extents to spatial data of social, economic, and environmental components. Risk levels consider the potential economic cost and potential loss of human life. Risk levels vary from low to high and typically consider developed and undeveloped land separately. Under ice-affected conditions the risk of impact due to ice will cause different types of damage in addition to the flooding that occurs during open water floods and should be considered when assigning the risk level.

7 CLIMATE CHANGE CONSIDERATIONS

This section provides practical guidance on methods for climate change considerations applicable to ice jam flood mapping. Context is provided on the climate change information relevant to ice jam processes and then a suggested approach is provided for assessing the potential impacts of climate change on the severity of ice jam flooding. The suggested approach integrates within the workflow used to develop the ice jam flood maps, described herein.

The objective of this guideline is to offer a strategy for developing a meaningful assessment of climate change that requires information with a level of detail and analyses that are commensurate with those used to develop the ice jam flood maps.

7.1 Current Understanding

While there has been a considerable amount of research pertaining to river ice and climate change considerations over the past few decades, in practice, the assessment and quantification of climate change impacts on ice jam flood mapping is limited.

The current understanding of climate change impacts on ice-affected flooding is based on our understanding on how changes in climate variables might impact various ice processes. Understanding the potential changes in river ice processes provides a rationale for predicting the affects of climate change on the river ice regime. The work of prior investigators offers practical guidance to the practitioner's work on a particular case study. Below is a list of relevant work that offer a place to start searching for information on the topic of climate impacts on river ice processes. At the time of this writing, more than 1000 citations were found for these publications.

Beltaos, S. and Prowse, T.D., 2001. Climate impacts on extreme ice-jam events in Canadian rivers. *Hydrological Sciences Journal*, *46*(1), pp.157-181.

Beltaos, S. and Burrell, BC, 2003. Climatic change and river ice breakup. *Canadian Journal of Civil Engineering*, *30* (1), pp.145-155.

Burrell, B.C., Beltaos, S. and Turcotte, B., 2022. Effects of climate change on river-ice processes and ice jams. *International Journal of River Basin Management*, pp.1-21.

Chen, Y. and She, Y., 2020. Long-term variations of river ice breakup timing across Canada and its response to climate change. *Cold Regions Science and Technology*, *176*, p.103091.

Environment and Climate Change Canada (ECCC). 2016. Climate change data and scenarios for Canada: Synthesis of recent observation modelling results. *Environment and Climate Change Canada, Gatineau, Que., Canada*

Newton, B.W., Prowse, T.D. and de Rham, L.P., 2017. Hydro-climatic drivers of mid-winter break up of river ice in western Canada and Alaska. *Hydrology Research*, *48*(4), pp.945-956.

Prowse, T.D. and Beltaos, S., 2002. Climatic control of river-ice hydrology: a review. *Hydrological processes*, *16*(4), pp.805-822.

Prowse, T.D., Bonsal, B.R., Duguay, C.R. and Lacroix, M.P., 2007. River-ice break up/Freeze up: a review of climatic drivers, historical trends and future predictions. *Annals of Glaciology*, *46*, pp.443-451.

Prowse, T.D., Furgal, C., Wrona, F.J. and Reist, J.D., 2009. Implications of climate change for northern Canada: freshwater, marine, and terrestrial ecosystems. *AMBIO: A Journal of the Human Environment*, *38*(5), pp.282-289.

Turcotte, B., Burrell, B.C., Beltaos, S. and She, Y., 2019, May. The impact of climate change on breakup ice jams in Canada: State of knowledge and research approaches. In *Proceedings of the 20th Workshop on the Hydraulics of Ice Covered Rivers, Ottawa, Canada*.

Turcotte, B., Morse, B. and Pelchat, G., 2020. Impact of climate change on the frequency of dynamic breakup events and on the risk of ice-jam floods in Quebec, Canada. *Water*, *12*(10), p.2891.

7.2 Climate Change Information

Climate change assessments often rely on Global Climate Models and General Circulation Models (termed collectively herein as GCMs) as the primary source of climate change information and data. Dozens of GCMs are available to simulate coupled physical processes between the atmosphere, ocean, cryosphere, and land surface. The models have differing assumptions and employ different analytical and numerical models to predict these physical processes. Scientists and practitioners often try to account for uncertainty associated with choice of the *best* model by relying on an ensemble of different climate models to predict future climate variables.

The parameter values predicted by GCMs may not be provided at the same resolution of the data required for analysis. And so, predicted variables derived from the GCMs may require downscaling for finer resolution in time and space; this is usually achieved by either regional climate models or statistical downscaling. Regional climate models simulate climate processes over a regional domain and rely on the GCM parameters at the lateral boundaries.

Climate modelling or the development of regional models is not expected under these guidelines. However, assessing the potential impacts of the predictions of climate variables on ice processes may be appropriate. Temperature is the primary climate variable predicted by these models that is of interest for assessing impacts of climate change on river ice processes. Other parameters such as precipitation, radiation, and snow-water equivalent have also been used.

Table 3 provides a list of relevant example case studies assessing impacts of climate change on river ice processes. Much of the work of these studies is considered research and the level of analysis may be beyond the scope of assessment appropriate for ice jam flood mapping. These studies do however provide practical insight on the types of climate information (GCMs and climate parameters) investigators rely on to assess climate change and guidance on how changes in a climate variable may affect the various ice processes. This information informs the practitioner's assessment on how changes in climate parameters affect the ice regime of the river under investigation.

Table 3 Example Case Studies using Climate Models to Analyze Impacts on River Ice Processes

Reference	Climate Models and Variables	Analysis
Climatic effects on ice-jam flooding of the Peace-Athabasca Delta. (Beltaos et al. 2006)		
	CGCM[1]2 air temperature, precipitation	Analytical and empirical relationships
Transferability of a neuro-fuzzy river ice jam flood forecasting model. (Mahabir et al. 2007)		
	CGCM air temperature, precipitation, SWE	Neuro-Fuzzy Modeling
River-ice break-up/freeze-up: a review of climatic drivers, historical trends and future predictions. (Prowse et al. 2007)		
	7GCMs air temperature	Analytical relationships with trend analysis
Simulating the effects of climate change on the ice regime of the Peace River. (Andrishak and Hicks 2008)		
	CGCM2 air temperature	RIVER 1D hydraulic and process modelling
Changing spring air-temperature gradients along large northern rivers: Implications for severity of river-ice floods. (Prowse et al. 2010)		
	CCSM3[6], CGCM3.1, ECHAM5 & HadGEM1 air temperature	Analytical relationships
Impact of Climate Change on the Frequency of Dynamic Breakup Events and on the Risk of Ice-Jam Floods in Quebec, Canada. (Turcotte et al. 2020)		
	9 GCMs air temperature	HYDROTEL model

7.3 Assessment Approach

The assessment approach assumes the decision to incorporate climate change considerations into the flood mapping project. It then provides guidance on where climate change considerations can enter the workflow for a typical ice jam flood mapping project. Including climate change considerations throughout the project provides a more thoughtful assessment and ensures a more efficient process, since the methodology for flood hydrology and hydraulics will influence the methods for climate change assessment.

The approach to assessing climate change impacts on ice jam flood mapping, herein, differs somewhat from the *Climate Change Considerations* offered in the Federal Guidelines for open water mapping. For example, these ice jam flood mapping guidelines do not suggest using a freeboard approach as a type of assessment. That is because changes to the causal affects of the various processes on flood levels is more complex for ice jam flood scenarios than for open water flood scenarios. Further, the implication of applying a freeboard to flood levels presumes that the severity of design ice jam flood levels can only rise under a changing climate.

Table 4 Climate Change Assessment Workflow

<table>
<tr><th colspan="2">DATA COLLECTION AND REVIEW & ASSESSMENT</th></tr>
<tr><td colspan="2">• Examine available studies and reports specific to climate change related research. Expand search to include major basin and regional scale for climate change studies and research.
• Seek out local accounts as well as Traditional Knowledge and Indigenous Knowledge on climate trends and understanding of these trends on ice jam severity.
• Assess potential benefit for collecting more novel field data sets, such as tree scar data or sedimentation sampling.
• Examine available information for evidence of historical trends in the severity of ice-jam flooding.</td></tr>
<tr><th colspan="2">FLOOD HYDROLOGY</th></tr>
<tr><td>ICE REGIME</td><td>FLOOD LEVEL FREQUENCY</td></tr>
<tr><td>• Based on the understanding of the existing ice regime identify the dominant ice processes that are susceptible to variation under a changing climate.
• Identify key climate parameters that can be used to inform potential changes in climate.
• Identify climate change scenarios (including applicable GCMs, where appropriate).
• Assess impacts of climate change on ice regime.</td><td>DIRECT METHOD
• Direct assessment of historical data for trends.
• May infer trends from regional data.
INDIRECT METHOD
• Assess synthetic populations adjusted to the adopted climate change scenario.
QUANTIFY IMPACTS
• Identify trends and estimate the magnitude of change in ice jam flood frequency.</td></tr>
<tr><th colspan="2">FLOOD MAPPING</th></tr>
<tr><td colspan="2">CLIMATE CHANGE FLOOD MAPPING SCENARIO
• Where it is feasible to simulate a climate change design flood scenario, indicate ice jam flood climate change scenario on a flood map. Depending on the needs of a particular study, it may be included on an existing map or as a separate map.</td></tr>
<tr><th colspan="2">CLIMATE CHANGE ASSESSMENT SUMMARY</th></tr>
<tr><td colspan="2">• Provide a summary of the climate change assessment approach.
• Discuss potential changes in ice jam regime.
• Provide a statement on the effect of climate change on ice jam flood severity.
• Identify the level of uncertainty.
• Identify needs for additional data and analysis for improved analysis.
• State assumptions and limitations.</td></tr>
</table>

The methods for assessing the impacts of climate change on ice jam flood mapping begin with an understanding of the river ice regime and identification of the dominant processes that can be characterized by future climate variables. Then, the influence of the future climate variables to the dominant processes are assessed. The combined influence of the various processes is then evaluated.

For most studies, a qualitative assessment will be feasible and viable. In some cases, it may not be feasible to predict a quantifiable change in flood severity. In some cases, it may be feasible yet not viable since the costs of analysis would be prohibitively expensive, or the expected impacts are small or trending toward less severe flood events.

7.4 Summary of Climate Change Impacts on River Ice Jam Flooding

The climate change assessment should end with a summary of the methodology and information collected to support the analysis. The summary should identify the effects of predicted changes in climate variables on those river ice processes impacting the dominant flood mechanisms. Based on the findings a statement on the effect of climate change ice jam severity is provided within a stated degree of uncertainty. Where possible, impacts on ice jam severity should be expressed in terms of flood frequency and flood magnitude. State assumptions and limitations.

8 ADDITIONAL RESOURCES

The following resources are key foundational texts that offer a wealth of information on the topic of river ice and provide leads to other topics relevant to ice jam flood mapping. Fundamental aspects on the characteristics of river ice jams can be found in these references.

Ashton, G. 1986. River Lake Ice Engineering. Water Resources Publications, LLC. 480 pp.

Beltaos, S. 1995. River Ice Jams. Water Resources Publications, Highlands Ranch, Colorado. 390 pp.

Beltaos, S. 2008. River Ice Breakup. Water Resources Publications, LLC. 480 pp.

Beltaos, S. 2013. River Ice Formation. Published by CRIPE. 552 pp.

Beltaos, S. and Tang, P. (2013). Applying HEC-RAS to simulate river ice jams: snags and practical hints. Edmonton, AB. Proceedings of the 17th Workshop on River Ice, Committee on River Ice Processes and the Environment, Edmonton, Alberta, July 2013.

Flato, G., and Gerard R. (1986). Calculation of Ice Jam Thickness Profiles. Proceedings of the 4th Workshop on Hydraulics of River Ice, Committee on River Ice Processes and the Environment, Montreal, Quebec, June 1986.

Hicks, F.E. 2013. The Weird and Wonderful World of River Ice. CreateSpace Independent Publishing Platform. 52 pp.

Hicks, F.E. 2016. An Introduction to River Ice Engineering. For Civil Engineers and Geoscientists. CreateSpace Independent Publishing Platform. 10 pp.

Michel, B. 1978. Ice Mechanics. Peeters Publishers & Booksellers, 1978

Committee on River Ice Processes and the Environment (CRIPE) Publications: http://www.cripe.ca/en/publications

9 REFERENCES

Andrishak, R. and Hicks, F. 2008. Simulating the effects of climate change on the ice regime of the Peace River. Can. J. Civ. Eng. 35(5): 461–472.

Beltaos, S. and Burrell, BC, 2003. Climatic change and river ice breakup. *Canadian Journal of Civil Engineering* , *30* (1), pp.145-155.

Beltaos, S. and Prowse, T.D., 2001. Climate impacts on extreme ice-jam events in Canadian rivers. *Hydrological Sciences Journal*, *46*(1), pp.157-181.

Beltaos, S., Prowse, T., Bonsal, B., MacKay, R., Romolo, L., Pietroniro, A., and Toth, B. 2006. Climatic effects on ice-jam flooding of the Peace–Athabasca Delta. Hydrol. Process. 20(19): 4031–4050.

Brunner, G.W., 2016. HEC-RAS, River Analysis System Hydraulic Reference Manual, US Army Corps of Engineers, Hydrologic Engineering Center Report CPD-69, February 2016, 547 pp.

Burrell, B.C., Beltaos, S. and Turcotte, B., 2022. Effects of climate change on river-ice processes and ice jams. *International Journal of River Basin Management*, pp.1-21.

Carson, R., Beltaos, S., Groeneveld, J., Healy, D., She, Y., Malenchak, J., Morris, M., Saucet, J-P., Kolerski, T. and Shen, H.T. (2011). Canadian Journal of Civil Engineering, 38: 669-678

Chen, Y. and She, Y., 2020. Long-term variations of river ice breakup timing across Canada and its response to climate change. *Cold Regions Science and Technology*, *176*, p.103091.

Environment and Climate Change Canada (ECCC). 2016. Climate change data and scenarios for Canada: Synthesis of recent observation modelling results. *Environment and Climate Change Canada, Gatineau, Que., Canada*

The First Nations Information Governance Centre (FNIGC). 2023. The First Nations Principles of ownership, control, access, and possession (OCAP®). [Online resource: https://fnigc.ca/]

Gerard, R.L. Calkins, D. 1984. Ice-related flood frequency analysis: Application of analytical estimates. In Proceedings of the CSCE Cold Regions Specialty Conference, Montreal, QC, Canada, 4–6 April 1984; pp. 85–101

Impact Assessment Agency of Canada (IAAC). 2023. Indigenous Knowledge. [Online resource: https://www.canada.ca/en/impact-assessment-agency/programs/aboriginal-consultation-federal-environmental-assessment/indigenous-knowledge-policy-framework-initiative.html]

Kriwoken, L.A. 1983. Historical flood review: Fort Simpson, Fort Norman, Fort Good Hope, Fort McPherson, Aklavik, Fort Liard, Nahanni Butte. Report for the Northwest Territories Technical Committee, Flood Damage Reduction Program, Yellowknife, NT.

Lindenschmidt, K.E., 2020. *River ice processes and ice flood forecasting*. Springer International Publishing.

Mahabir, C., Hicks, F., and Fayek, A.R., 2007. Transferability of a neuro-fuzzy river ice jam flood forecasting model, Journal of Cold Regions Science and Technology, 48(3), 188-201.

Newton, B.W., Prowse, T.D. and de Rham, L.P., 2017. Hydro-climatic drivers of mid-winter break up of river ice in western Canada and Alaska. *Hydrology Research*, *48*(4), pp.945-956.

Natural Resources Canada (NRCan). 2019. Federal Geomatics Guideline for Flood Mapping. Version 1.0. [Online resource: https://publications.gc.ca/collections/collection_2020/rncan-nrcan/m45/M45-114-2019-eng.pdf]

Natural Resources Canada (NRCan). 2019. Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation. Version 1.0. [Online resource: https://ftp.maps.canada.ca/pub/nrcan_rncan/publications/STPublications_PublicationsST/299/299808/gip_113_en.pdf]

Natural Resources Canada (NRCan). 2022. Federal Airbourne LiDAR Data Acquisition Guideline. Version 3.1. [Online resource: https://ftp.maps.canada.ca/pub/nrcan_rncan/publications/STPublications_PublicationsST/330/330330/gid_330330.pdf]

Prowse, T.D. and Beltaos, S., 2002. Climatic control of river-ice hydrology: a review. *Hydrological processes*, *16*(4), pp.805-822.

Prowse, T.D., Bonsal, B.R., Duguay, C.R. and Lacroix, M.P., 2007. River-ice break up/Freeze up: a review of climatic drivers, historical trends and future predictions. *Annals of Glaciology*, *46*, pp.443-451.

Prowse, T.D., Furgal, C., Wrona, F.J. and Reist, J.D., 2009. Implications of climate change for northern Canada: freshwater, marine, and terrestrial ecosystems. *AMBIO: A Journal of the Human Environment*, *38*(5), pp.282-289.

Samuels, P.G., 1989. Backwater lengths in rivers. Proceedings of the Institution of Civil Engineers, Part 2, Volume 87, p. 571-582.

Turcotte, B., Burrell, B.C., Beltaos, S. and She, Y., 2019, May. The impact of climate change on breakup ice jams in Canada: State of knowledge and research approaches. In *Proceedings of the 20th Workshop on the Hydraulics of Ice Covered Rivers, Ottawa, Canada, available at: http://cripe. ca/publications/proceedings/20 (last access: 20 July 2020)*.

Turcotte, B., Morse, B. and Pelchat, G., 2020. Impact of climate change on the frequency of dynamic breakup events and on the risk of ice-jam floods in Quebec, Canada. *Water*, *12*(10), p.2891.

US Army Corps of Engineers Hydrologic Engineering Centre, 2016. HEC-RAS River Analysis System Hydraulic Reference Manual. Version 5.0 February 2016.

Yang, X., Pavelsky, T.M. and Allen, G.H., 2020. The past and future of global river ice. *Nature*, *577*(7788), pp.69-73.

Younging, Gregory. 2018. Elements of Indigenous style: a guide for writing by and about Indigenous Peoples. Brush Education Inc. pp. 154.