Yukon University

Flooding in the Tr'ondëk (C-4) Subdivision: Exposure analysis and risk reduction recommendations

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Executive Summary

The YukonU Research Centre (YRC) worked with the Infrastructure Branch (IB) of the Department of Community Service (CS), Yukon Government (YG), to assess the flood vulnerability and protection in Dawson (downtown area). The report (Turcotte and Saal., 2022) was presented to YG in March 2022 and includes several Tr'ondëk Hwëch'in (TH) assets that could be affected by a flood from the Tágà Shäw (Yukon River). After a meeting in May 2021 with the TH Government, and following a discussion with the IB-CS, the YRC proposed to prepare a separate flood vulnerability and flood risk reduction assessment for the C-4 (Tr’ondëk) subdivision, located just outside of downtown Dawson, and potentially affected by floods from the Tr’ondëk (Klondike River).

The objectives of this project are to assess key aspects of subdivision exposure to flooding and to propose flood risk reduction strategies. The YRC conducted two main activities:

- Elevation survey of buildings and assets. This was completed using a digital elevation model made available by YG.
- Water level frequency analyses based on available historical hydrometric records and simulation of water levels in and out of the Tr’ondëk using a hydrodynamic model (Turcotte et al., 2021).

Results are presented in this Table:

	2-year flood	20-year flood	200-year flood
Water surface elevation upstream of C-4	321.7 m	323.3 m	324.8 m
Water surface elevation downstream of C-4	317. 4 m	318.2 m	320.0 m
Flood condition in C-4	None	Minor flood	Major flood

Flood simulation results suggest the upstream (eastern) portion of C-4, including the compound area, is exposed to floods once every 20 years, or so, whereas the downstream (western) portion of C-4 could be impacted less frequently, possibly once every 100 to 200 years.

A qualitative analysis of the potential impact of climate change reveals that ice jam floods could become more frequent along the lower reach of the Tr’ondëk. Indeed, thicker ice accumulations (i.e., freeze-up jams) and higher spring runoff rates could promote the formation of significant ice jams at C-4, a location that is already prone to ice jams on an annual basis.

Recommended flood reduction adaptation actions for C-4 include:

- Adapting the dike-like type of structure besides the C-4 compound area
- Removing tailing piles on the south shore and restoring the floodplain
- Adapting the east approach of the Klondike Highway bridge
- Creating a network of surface drains and culverts in C-4
- Installing a large culvert under the Klondike Highway at the bottom of Dome Road
- Flood proofing residences and public buildings on the upstream (east) portion of C-4
- Considering the use of adapted machinery to break i. the ice cover in the Tr’ondëk prior to spring breakup, when the probability of significant ice jams is high (this is a short-term preventive flood risk reduction approach informed by forecasters), or ii. an ice jam that is already in place (a reactive approach, if the safety of people is not compromised).

Project Team

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1. Context

1.1 General perspective

As part of a project funded by the Canadian Government's National Disaster Mitigation Program (NDMP) and the Yukon Government's (YG) Department of Community Services (CS), Infrastructure Branch (IB) on the assessment of flood vulnerabilities and flood protection in Dawson, the YukonU Research Centre (YRC) organized a meeting with employees of Tr'ondëk Hwëch'in (TH) Government on May 4, 2021, to better understand their needs. TH identified important assets that could be included in the project in the downtown Dawson area, and mentioned the importance of the C-4 Tr'ondëk Subdivision for TH.

The IB-CS agreed that the YRC could perform a separate flood assessment and flood risk reduction study for this subdivision, located along the Tr'ondëk (Klondike River) using in-kind money (ArcticNet North-by-North funds). This report presents the results of this study. The flood risk associated with some TH assets located in the downtown Dawson area is covered in Turcotte and Saal (2022).

1.2 Project objectives

Development at the C-4 Tr'ondëk Subdivision was initiated relatively recently. An extensive gravel pad was built on former placer mining tailings and ponds on the south-west side of the Klondike Highway along the Tr'ondëk. It is the YRC's understanding that the subdivision has not been flooded since development started. The highest water level on record at the Water Survey of Canada (WSC) hydrometric station 09EA003, located just upstream of the Klondike Highway bridge south-east of C-4, occurred in 1986, then in 2003 and 2004. The 1986 event is of particular interest since it may be associated with flooding of the Klondike Highway west (downstream) of the Klondike River bridge. As a result, questions may arise about the risk of flooding in C-4, especially in a context where an ice jam forms almost every year in the multichannel reach of the Tr'ondëk next to C-4.

The objectives of this project are to 1. assess key aspects of TH-C-4 exposure to flooding, and to 2. recommend flood risk reduction strategies.

Meeting the first objective involve surveying the elevation of buildings, assets, and infrastructure in C-4 (Section 2), developing a flood frequency analysis using data from the WSC 09EA003 station as well as an ice-hydrodynamic model for three flood scenarios in the Tr'ondëk at C-4 (Section 3). Next, spatial flood extent results are presented (Section 4). After a discussion about the documented and expected impact of climate change (Section 5), the second objective of the project is met through a discussion of the expected performance of current and potential flood protection measures (Section 6). The report ends with some concluding remarks (Section 7).

2. Asset Elevation Surveys

Tr'ondëk Hwëch'in (TH) owns and operates different buildings and assets in Dawson, including in the Tr'ondëk subdivision (C-4) as well as further east (e.g., TH farm close to the airport). This report focuses on the C-4 Subdivision. Following a meeting with TH on May 4, 2021, the elevation of several buildings and assets was surveyed. Key identified and surveyed assets include:

- Houses (ground elevation and first floor)
- Compounds (first floor, concrete or gravel pad)
- Boats (floatation line)
- Water distribution and electricity assets
- Transportation infrastructure

The approach used for all the surveyed assets was to measure, on site, the differential elevation between the asset and an open, flat area that is far enough from any building using a high-accuracy pressure differential instrument (ZipLevel Pro-2000 from Technidea Corporation). Back in the office, the absolute elevation of each open area was obtained using a LiDAR-derived Digital Elevation Model (DEM) provided by YG. Then, the elevation of the surveyed asset was calculated using the measured asset elevation differential relatively to the absolute elevation of the flat area.

A total of 19 assets were surveyed, mainly in C-4. The elevation of the surveyed features varied from 322.1 m (a water pumping station) to 324.9 m (bottom of Klondike Highway bridge structure). Appendix A presents a table of the surveyed assets with their respective elevation and flood return period ranges.

3. Flooding processes chronology and flood scenarios

3.1 General perspective on floods at C-4

Flooding processes taking place in the Tr'ondëk (Klondike River) have been explained in a report prepared for another project (Turcotte et al., 2021). This report shows that ice jams generate, by far, the highest annual water levels at most, if not all, locations along the Tr'ondëk from downtown Dawson to Rock Creek. A quantitative example is presented in Figure 3.1, with data obtained from the WSC station 09EA003 from 1985 to 2021. There are several gaps in the spring breakup historical record (8 years missing), but a sensitivity analysis indicates that low to average spring breakup water levels would not significantly alter the defined frequency analysis. Therefore, the authors assume that high (significant ice-jam-induced) water levels would have been documented in the WSC records if they had occurred during those missing years.

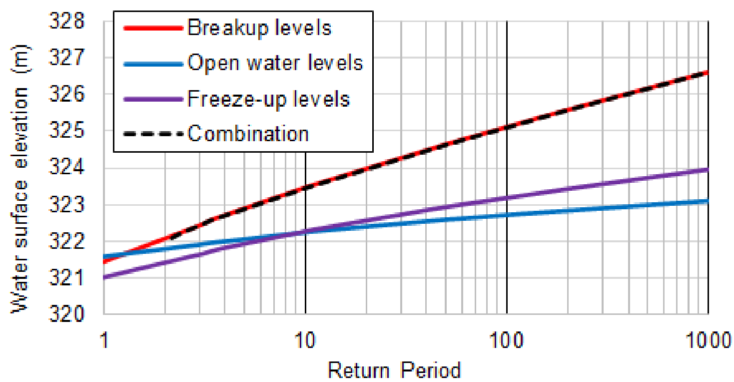

FIGURE 3.1. RELATION BETWEEN THE WATER SURFACE ELEVATION AND THE RETURN PERIOD FOR BREAKUP, OPEN WATER, AND FREEZE-UP (AS WELL AS COMBINED STATISTICS) AT STATION 09EA003 LOCATED AT THE KLONDIKE HIGHWAY BRIDGE UPSTREAM OF C-4.

Ice jams that form during the fall have also generated high water levels in recent years at the station (purple line in Figure 3.1), a reality that also applies downstream of the bridge. Including this flooding process in the combined flood return period trend (black dashed line in Figure 3.1) is not straightforward because of the statistical dependence between freeze-up and breakup (the probability of both processes cannot simply be summed). In turn, a simple addition of this process in the combined statistics does not change the results (spring breakup ice jams are too dominant).

Generally, ice movements occur first upstream and downstream of C-4. The downstream movement generates a weak ice jam against the Tágà Shäw (Yukon River) ice cover, with limited upstream backwater impacts, whereas the upstream movement initiates an ice jam just upstream or downstream of the Klondike Highway bridge. This is a normal ice jam location, given the large evacuation capacity of the multi-channel reach of the Tr'ondëk at C-4, and its lower gradient. Therefore, the C-4 ice jam is not mobilized (evacuated downstream) until extensive ice movements have taken place upstream, with the potential to worsen the C-4 ice jam. Determining a mobilization threshold (in terms of flow) for the C-4 ice jam requires extensive monitoring.

In summary, it is assumed that the 2-year flood event (annual probability of 50%), the 20-year flood event (5%) and the 200-year flood event (0.5%) are associated with spring breakup ice jams.

3.2 Flood of Record

The highest water surface elevation measured at station 09EA003 since it started to operate was measured on May 8, 1986, at 324.8 m (the bottom of the current Klondike Highway bridge superstructure is also at about 324.9 m). A helicopter survey took place during the event and Figure 3.2 (photo probably taken in the morning of May 8) clearly shows an ice jam in the middle of the multichannel reach at what is now the developed C-4 Tr'ondëk subdivision. This figure also shows that the Klondike Highway is flooded (bottom right corner) by the event, and that the ice jam toe is very wide and grounded: there is no obstacle, such as an intact ice cover, holding the ice jam in place; water just filters between the thick ice floes at multiple locations, including through forested areas.

Figure 3.2. Ice jam in the Tr'ondëk just below (downstream) of the Klondike Highway bridge. This picture was probably taken on May 8, 1986.

It is of interest to mention that the presence of longitudinal tailing piles on both banks of the Tr'ondëk upstream of the multi-channel reach and downstream of the bridge probably partially explain why water levels at station 09EA003 in May 1986 were so high: the water had limited access to any floodplain and the pressure on the ice jam could not be released laterally, therefore generating higher water levels. Nowadays, channel and floodplain conditions have changed and evolved, but tailing piles are still in place on the southern bank of Tr'ondëk. If the same ice jam event was to occur in the presence of a developed C-4 subdivision, it is likely that its south-eastern (upstream) portion would be flooded.

3.3 Tr’ondëk model

A model was developed to simulate hydrodynamic processes in the Tr’ondëk from its outlet into the Yukon River (Km 0.0, or 0 m) to upstream of the Klondike River bridge (Km 2.65, or 2650 m). This model uses a platform called HEC RAS and is described in detail in a companion project report (Turcotte et al., 2021). It relies on high-definition topographic information (the same information used to determine the absolute elevation of buildings and assets), and an approximate river channel bathymetry informed by satellite images and model calibration.

Figure 3.3 shows a part of the model, with a moderate flow without an ice cover or ice jam. Various features can be distinguished:

- Multichannel segment of the Tr’ondëk (with islands and secondary channels)
- Tailing piles and ponds of different shapes and sizes
- C-4 with streets and developed lots (some houses are built on elevated platforms)
- Dome road forming a loop at higher elevation (yellow to dark green on North-east corner)
- The Klondike Highway (high elevation line) crossing this area from south-east to north-west (note that the bridge is not presented)
- Bonanza Creek (defined blue line) joining the Tr’ondëk on the south side

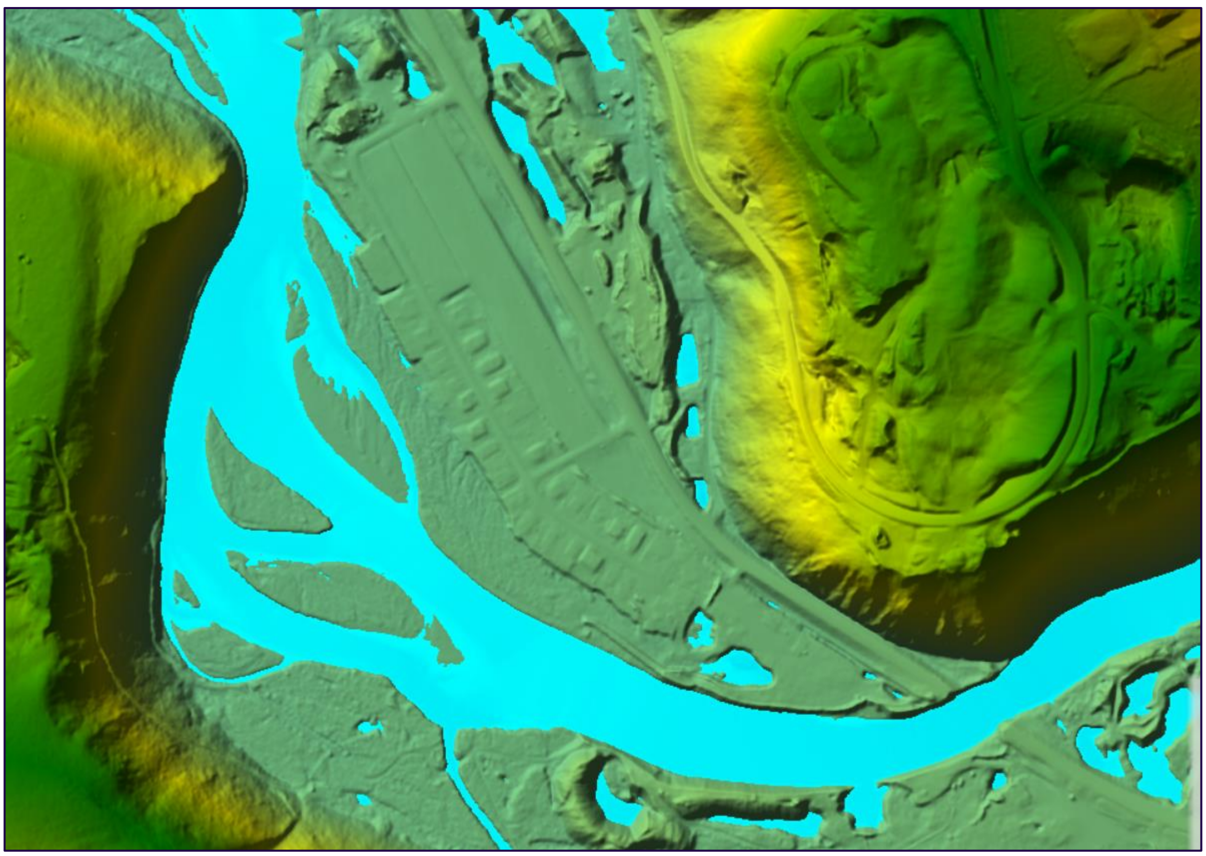

Figure 3.3. Plan view of a portion of the HEC RAS model with a low water level in the Tr’ondëk between Km 1.1 and Km 2.9. The background image is a digital elevation model with hill shades.

3.4 Proposed flood scenarios

The model briefly presented in the previous subsection was used to simulate flood scenarios for C-4. Several ice jam scenarios could lead to the same water level at a specific location (e.g., at the calibration point, station 09EA003). Based on observations, interpretation of satellite images, and a knowledge of the link between river morphology and ice processes (e.g., Turcotte and Morse, 2013), it appears that ice jam toes (downstream portion where an ice jam formation process initiates) in the lower Tr'ondëk can form at:

- Km 0.0, against the intact ice cover of the Tágà Shäw (an early breakup phase every spring)
- Km 1.6, within the multichannel reach, against islands and protruding river-bed features (like in Figure 3.2.1)
- Km 2.0, the head of the multichannel reach (as observed in May 2021)
- Km 2.9, against a thick ice cover (or a freeze-up jam) located downstream of a reach where the ice cover is weaker and more prone to early-spring mobilization

The fourth option can be discarded from the flood scenarios at C-4 for two reasons:

- This ice jam does not generate any water level rise at C-4.
- This jam is normally pushed downstream to Km 2.0 at a later phase of the river ice breakup process, and this is where it starts affecting C-4.

The proposed 2-year scenario is associated with an ice jam at Km 1.7 causing a water surface elevation of 322.2 m at the Klondike Highway bridge (this water level would also happen every 10 years during the open water season, Figure 3.1). Figure 3.4 presents the model results (lateral view of the river). The simulated ice jam extends upstream to Km 2.6 (Klondike Highway Bridge) with an initial ice thickness of 1.5 m and a very common breakup flow of 60 m^3/s. This event does not cause any flooding (actually, no ice jam scenario that meets the corresponding 2-year water level at Km 2.6 can cause flooding at C-4).

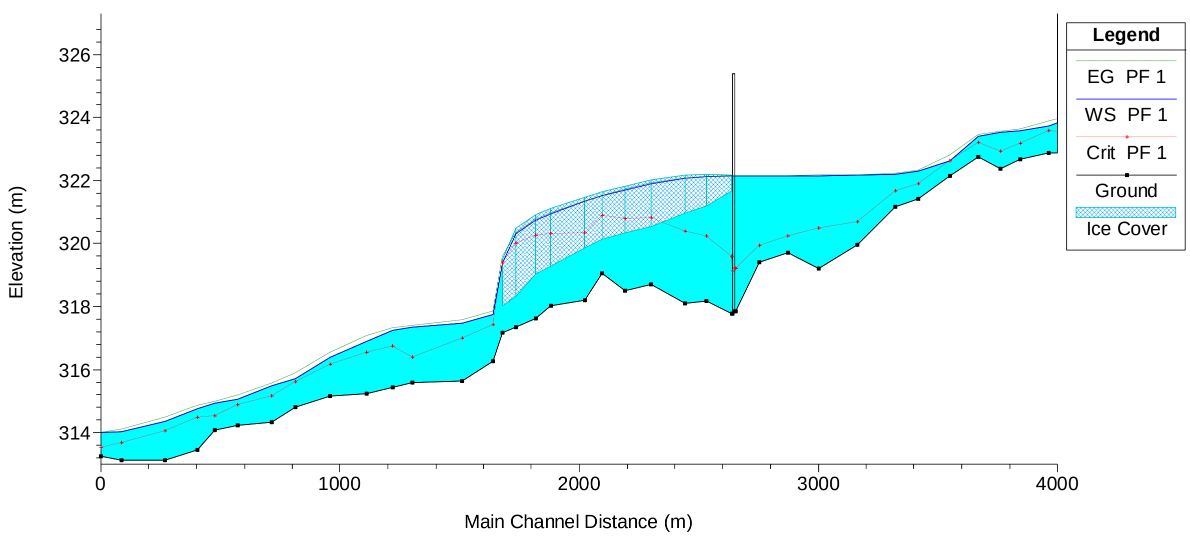

Figure 3.4. Lateral HEC RAS model output showing water levels and ice jam location for the proposed 2-year high-water scenario at C-4. The vertical line is the Klondike Highway bridge (C-4 is located between the distance of 1300 m and 2500m on the horizontal axis, this is the distance along the Tr'ondëk upstream of its outlet).

The proposed 20-year flood scenario at C-4 also involves an ice jam from Km 1.7 to 2.6, but with a thicker ice cover (a freeze-up jam, like in 2002 and 2015), a flow of 180 m^3/s (a very dynamic breakup event), and ice accumulation at the channel margin impeding flow towards the floodplain (just as presented in Figure 3.2). This scenario, with side-view model results presented in Figure 3.5, generates minor flooding in the C-4 compound area (Km 2.3 to 2.6, or 2300 m to 2600 m in Figure 3.5) and is a few centimeters away from affecting the southern tip of the C-4 subdivision residential area (Km 1.3 to Km 2.3). It is technically possible to simulate an ice jam that would respect the 20-year water level at station 09EA003 while generating minor flooding at C-4, but the proposed ice jam presents more realistic characteristics and is largely based on the photo presented in Figure 3.2.

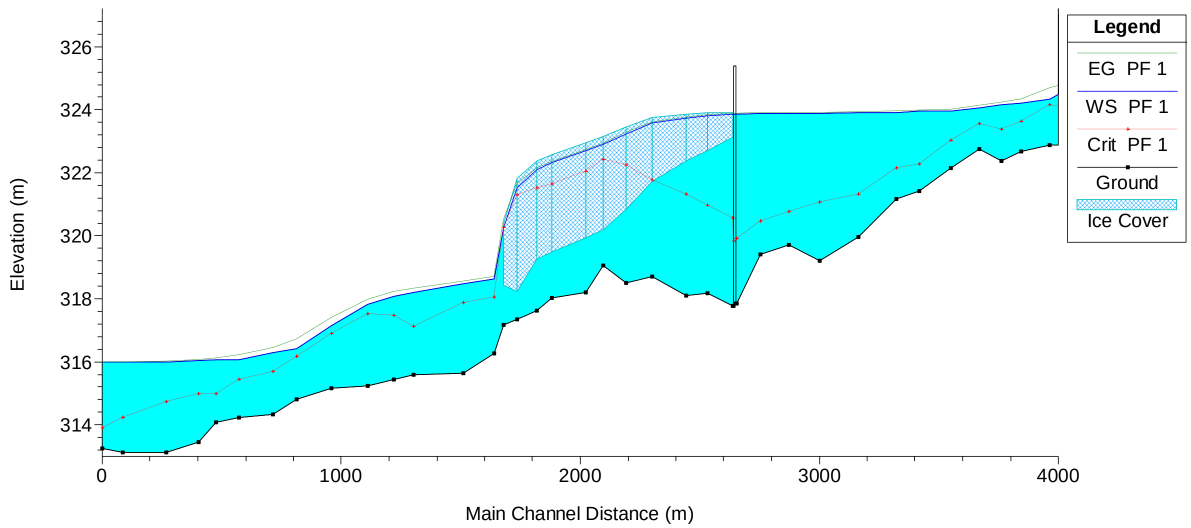

Figure 3.5. Lateral HEC RAS model output showing water levels and ice jam location for the proposed 20-year high-water scenario at C-4. The vertical line is the Klondike Highway bridge.

The proposed 200-year scenario is largely experimental because such an event has not been observed: it represents a statistical extrapolation of what has been seen in recent decades, which is not unusual in flood risk studies. On one hand, the local morphology and watershed hydrology can probably generate a water level that corresponds to the statistically estimated 325.6 m at station 09EA003 (water touching the bridge structure, not to mention ice). On the other hand, the extent, thickness, and condition of the ice jam that would cause this water level is unknown and cannot be simulated using any combination of previously documented hydrological conditions.

The proposed 200-year ice jam flood scenario at C-4 that matches the calculated 200-year water level at station 09EA003 (results presented in Figure 3.6) is associated with:

- A 50-year ice jam in the Tágà Shäw (that does not significantly affect C-4),
- An ice jam with an extent comparable to the 1986 event (Figure 3.2 shows the downstream limit, and the upstream limit is not relevant as long as it reaches station 09EA033),
- An ice jam thickness corresponding to a breakup jam arrested by a significant freeze-up jam (2.5 m to 4.6 m),
- A flow of 250 m^3/s, caused by a fast and sudden snowmelt (but not a catastrophic one).

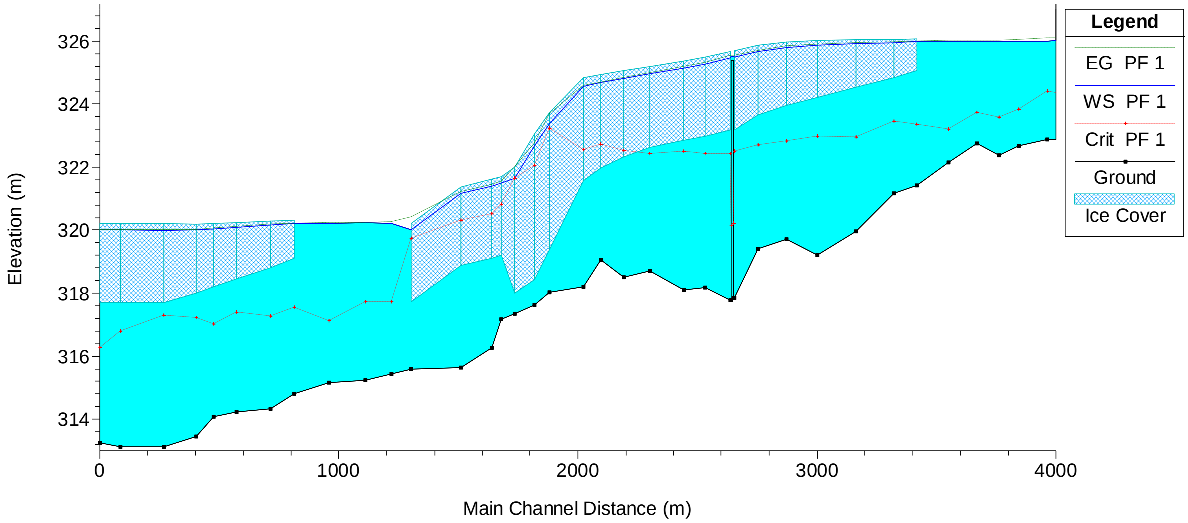

Figure 3.6. Lateral HEC RAS model output showing water levels and ice jam locations for the proposed 200-year high-water scenario at C-4. The vertical line is the Klondike Highway bridge.

Several possible ice jam parameter combinations could generate flooding at C-4 while meeting the 200-year water level criteria at station 09EA003 (325.6 m) and remaining within theoretically acceptable ranges (e.g., Beltaos and Tang, 2013). The objective of the YRC is not to present an ideal or worse-case scenario, but a realistic one, based on knowledge of ice processes and familiarity with the studied reach. The lateral and streamwise (following the river) flood extent of the proposed event are presented in Section 4. In addition to causing flooding in C-4 and possibly damaging the Klondike Highway Bridge, this event could also generate significant erosion where the terrain elevation on the floodplain changes abruptly.

4. Results summary

This section presents the results from two spatial perspectives: A lateral view of the Tr'ondëk and C-4 as if someone is going upriver in a boat and an aerial view, as if someone is flying above C-4. Tables also summarize flood return period statistics for some assets, and the detailed information for each asset is presented in Appendices A and B.

4.1 Spatial flood modeling using HEC RAS outputs

Tables 4.1 present water surface elevations for each flood scenario. As presented in Section 3, water surfaces are not declining linearly in the downstream direction as they are controlled by simulated ice jams in a channel that is largely heterogeneous in terms of width, depth, gradient, and morphology.

TABLE 4.1. WATER SURFACE ELEVATION FOR THE 2-YEAR, 20-YEAR, AND 200-YEAR FLOODS IN THE TR'ONDËK UPSTREAM OF DAWSON CITY.

	2-year flood	20-year flood	200-year flood
Water level at WCS station 09EA003	322.2 m	324.0 m	325.6 m
Water surface elevation upstream of C-4	321.7 m	323.3 m	324.8 m
Water surface elevation downstream of C-4	317.4 m	318.2 m	320.0 m
Flood condition in C-4	None	Upstream tip flooded	almost covered by water

Results produced by HEC RAS are unidimensional (1D) from a hydrodynamic perspective. This means that HEC RAS only calculates an average flow velocity and a horizontal water surface elevation between the left and the right bank (or in isolated depressions on the floodplain) for each cross-section of the simulate channel. Although the initial hydrodynamic calculation performed by HEC RAS represents an important step to assess flood elevations and extents, the raw results do not accurately simulate the water surface of the Tr'ondëk at C-4 because of the multiple secondary channels of different lengths and elevations, the tailing ponds, and a complex overbank topography.

For the 2-year flood level scenario, water levels remain mostly constrained within the channel banks and HEC RAS results can be presented with a minor 2D adjustment: water evacuated by a small secondary channel needs to be added since HEC RAS assumes that this channel becomes dry downstream (as if water would start flowing underground). This water surface adjustment is performed using ArcGIS with results exported from HEC RAS.

For the 20-year scenario, overbank flooding does occur on the right bank where C-4 is located, including behind tailing piles and low areas that are only partially connected with the river channel. HEC RAS results are exported in ArcGIS and several adjustments are performed: bathtub filling of areas hydraulically disconnected from the Tr'ondëk and secondary channel flow connected to the Tr'ondëk along C-4. The compound area of C-4, located upstream of the Tr'ondëk subdivision, is partially affected by water (mostly stagnant) under this ice jam flood scenario.

For a 200-year event, extensive flooding of C-4 results from the HEC RAS ice jam simulations. Water upstream of the ice jam flows onto C-4, and ArcGIS is used to carry this surface water downstream, through C-4, and back to the Tr'ondëk channel. Water also crosses the Klondike Highway towards the Bottom of Dome Road Development Area (as observed in Figure 3.2), and ArcGIS tools are used to alter HEC RAS results by extending the overflow in the downstream direction back to the Tr'ondëk. Two scenarios are considered: a current infrastructure scenario with a bathtub type of water filling and with water levels on the northeast side of the Klondike Highway controlled by the pavement surface of the road, and a flow by-pass scenario with a large culvert that would be installed under the Klondike Highway at Dome Road and that would carry the overflow back to the Tr'ondëk. In the later 200-year flood scenario (with a large culvert), flooding would be reduced at the bottom of Dome Road, but not at C-4.

4.2 Flood extent results

Figures 4.1 presents the lateral (from the river looking at C-4) view of the simulated high-water event profiles and including surveyed assets. It shows that no asset is affected by a 2-year flood event, but that the 200-year flood event affects most assets, including Joe Henry Road (JHR).

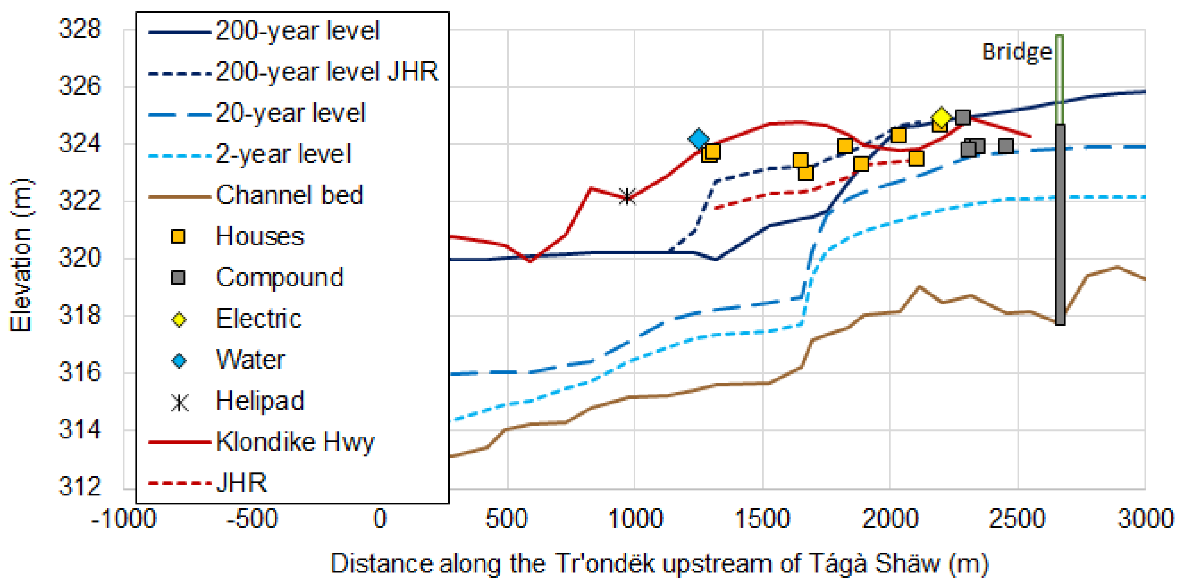

FIGURE 4.1. SURVEYED ASSETS, WATER SURFACE PROFILES OF THE TR'ONDËK FOR 2-YEAR, 20-YEAR, AND 200-YEAR HYDROLOGICAL EVENTS, AND WATER SURFACE ELEVATION ASSOCIATED WITH OVERBANK FLOODING FOR CORRESPONDING EVENTS. JHR STANDS FOR JOE HENRY ROAD.

Figures 4.2 to 4.5 present this information, but from a spatial point of view, superposed to the digital elevation model (DEM). Four flood scenarios are presented:

- 2-year flood event (water contained in the river channel)
- 20-year flood event (minor flooding)
- 200-year flood event with current infrastructure (major flooding)
- 200-year flood event with a culvert between Dome Road and the Tr'ondëk channel under the Klondike Highway (major flooding)

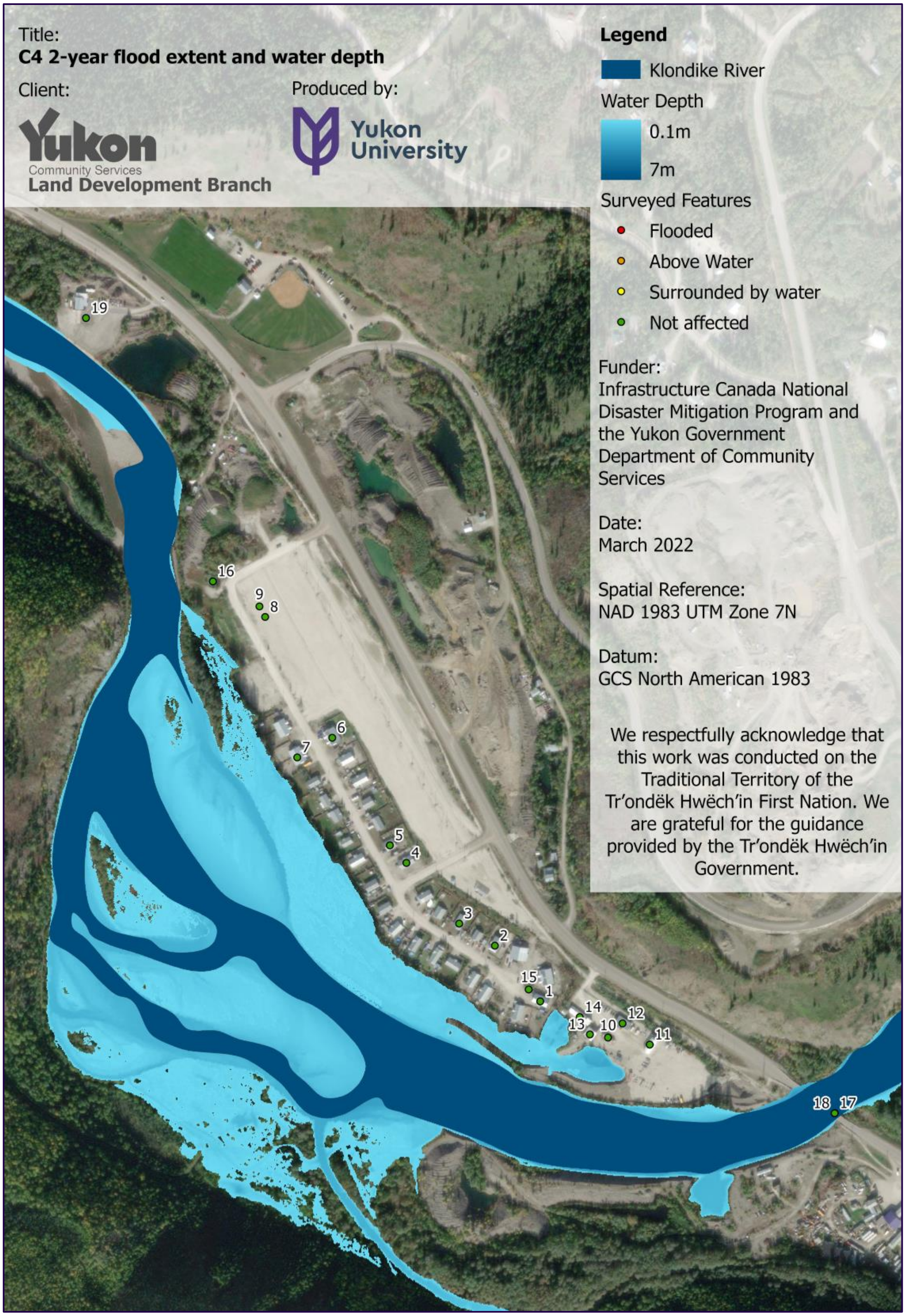

FIGURE 4.2. 2-YEAR FLOOD EXTENT, WATER DEPTH AND SURVEYED ASSETS CATEGORIZED BY FLOOD EXPOSURE. NO FLOOD DAMAGE TO REPORT IN C-4.

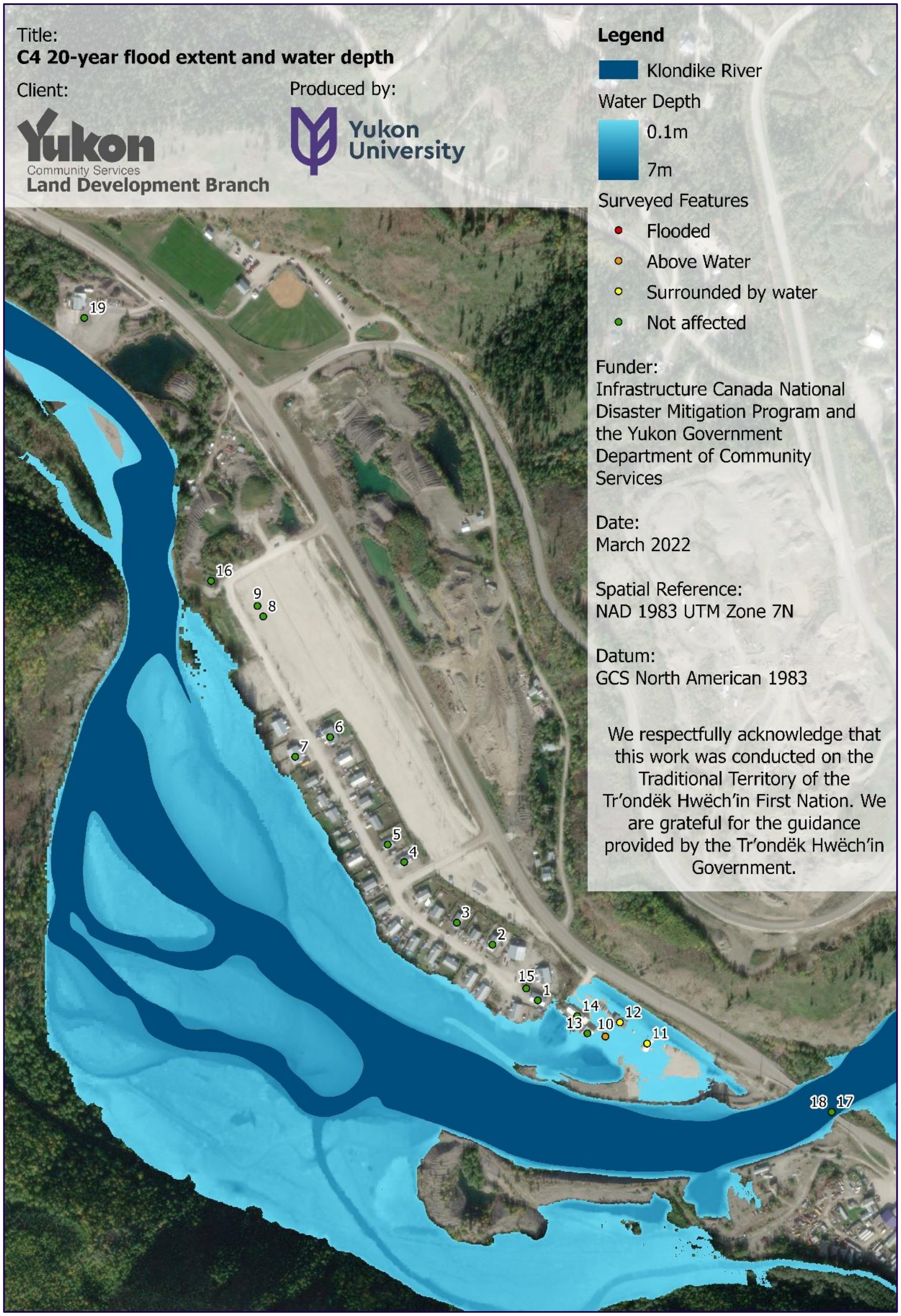

FIGURE 4.3. 20-YEAR FLOOD EXTENT, WATER DEPTH AND SURVEYED ASSETS CATEGORIZED BY FLOOD EXPOSURE. MINOR FLOOD DAMAGE TO REPORT.

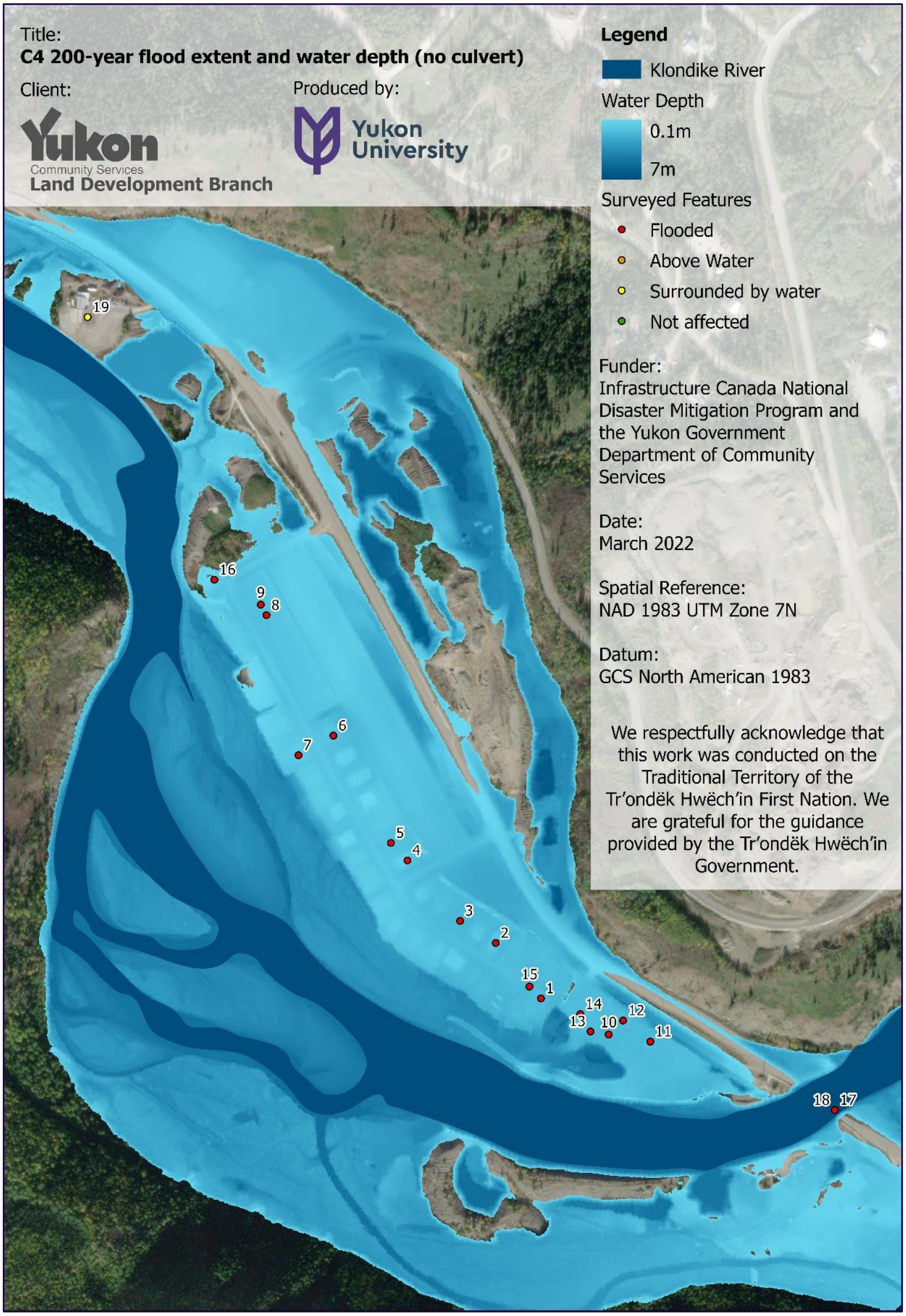

Figure 4.4. 200-year flood extent, water depth and surveyed assets categorized by flood exposure with current infrastructure. Extreme flood damage to report.

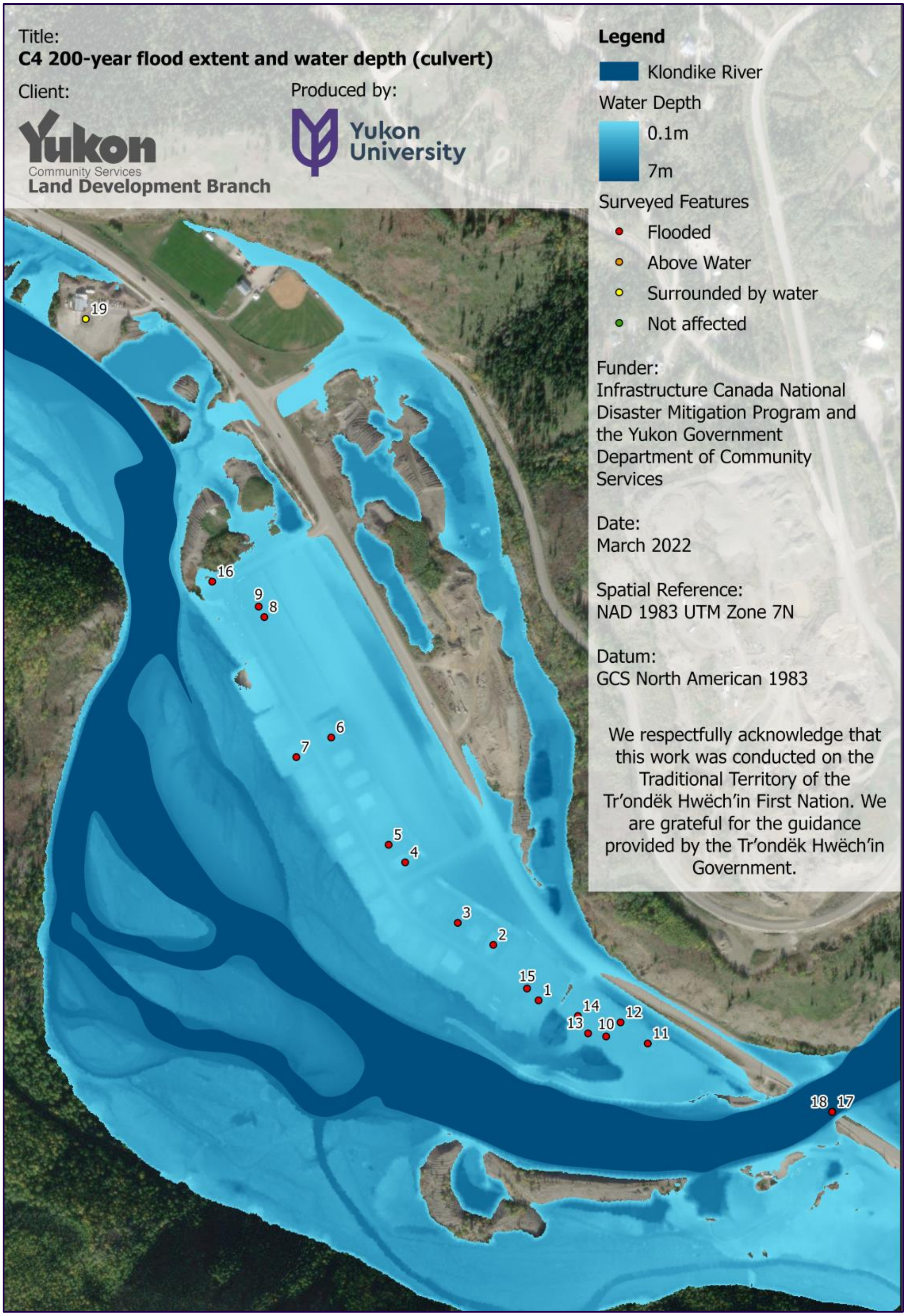

Figure 4.5. 200-year flood extent, water depth and surveyed assets categorized by flood exposure with new culvert at Dome Road. Extreme flood damage to report.

The water depth on each figure is shown when the water level is higher than the DEM. Since only approximate bathymetric information is used for this assessment (LiDAR data cannot be obtained under water), the Tr’ondëk’s main channel is presented in dark blue. In addition to the flood extent and depth, the flood impact for each asset is categorized as not affected (green), surrounded by water (yellow), first floor above water (orange), and flooded (red).

4.3 Flood exposure assessment for specific community assets

The following list of surveyed assets are associated with different ranges of flood return periods (the complete list, with corresponding numbers in Figures 4.2 to 4.5, is presented in Appendices A and B):

- Residences in the eastern and central portion of C-4 are mostly affected by flood events associated a return period of 40 to more than 200 years.
- The lowest compound owned by Tr'ondëk Hwëch'in is exposed to floods with a return period of about 25 years, and the entire TH compound area is affected by water at least once every 100 years (water on first floors)
- The Klondike Highway bridge located just upstream of C-4 could be affected by an ice jam on average once every 50 years or even less, based on historical statistics, and assuming that ice pieces reach a higher elevation than the water they float on.
- Some electric assets in C-4 could be impacted by water every 20 years, or even less.

The most likely ice jam scenario would be progressive: a small ice jam would form in the vicinity of the Klondike Highway bridge, and additional ice runs from upstream would accumulate against this ice jam during the flowing hours or days, pushing its toe further downstream to the multi-channel reach, and this is when overflow would begin. However, there is a possibility that a sequential breakup in upstream reaches of the Tr’ondëk would generate a massive ice jam at C-4 rather suddenly. In any case, if flooding occurs, it would begin in the forest on the side of C-4, then in the compound area, and in the case of a significant jam, water would enter the Tr’ondëk subdivision from upstream.

5 Climate change perspective

Water surface elevations associated with specific return periods, as presented so far in this report, are based on hydrometric data at Water Survey of Canada station 09EA003 for the 1985-2021 period. This data does not reveal what is going to happen in the future.

Three aspects of climate change may play a direct role in current and future ice jam floods in the Tr'ondëk at Dawson:

- Changes in seasonal, watershed-scale precipitation patterns (in the fall, winter, and spring)
- Extreme watershed-scale warm conditions (more importantly in the spring)
- Rain-on-snow events (mainly caused by atmospheric rivers form the Gulf of Alaska)

The consequences of these processes, combined with the influence of a progressive rise in average temperatures, may also trigger changes in other parameters affecting ice jam floods:

- Altered river ice cover thickness (e.g., affecting the potential intensity of ice jam floods)
- Increased forest fire hazards (e.g., impacting surface runoff rates and evaporation)
- Increased landslide hazards (e.g., modifying channel bed elevation and channel width)

A first attempt to quantify the impact of climate change on floods along the lower Tr'ondëk was presented by Turcotte (2021) and is presented in Figure 5.1. Results suggest no defined historical trend for all three flooding processes, and a large inter-annual variability with several data gaps (it is challenging to operate a hydrometric station in a very cold climate, even when this station is located close to a community).

This is the only accessible quantitative analysis about the impact of climate change on flood return periods along the Tr'ondëk that can be performed without a complex hydrological and ice processes simulation, a challenging research task for a mid-size watershed like the Tr'ondëk (about 8000 km^2). However, qualitative analyses informed by climate projections and an understanding of flooding mechanisms may provide an idea about the frequency and intensity of future ice jam floods (e.g., Burrell et al., 2022).

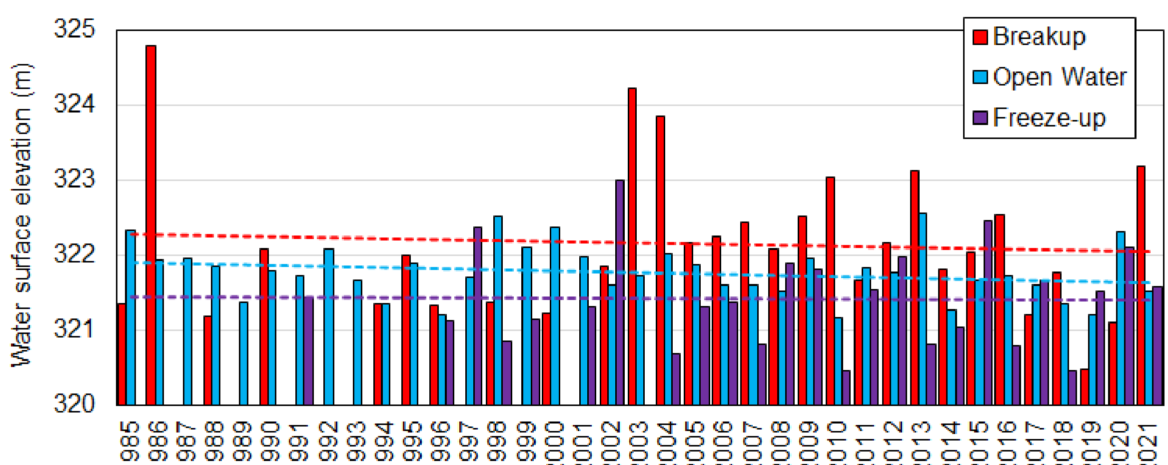

FIGURE 5.1. PEAK WATER LEVELS FOR THREE FLOODING PROCESSES AT STATION 09EA003 ON THE TR'ONDËK BETWEEN 1985 AND 2021 (WITH SEVERAL GAPS).

It is known that severe breakup ice jam floods are the result of two forces: a resisting and a driving force. The resisting force mainly consists of the ice cover strength and the ice cover–bank interaction, and it delays ice movements. The driving force is essentially the (rising) discharge at the end of winter, followed by ice runs coming from upstream reaches that are pushing on the ice cover. If the discharge rises slowly, even if the ice cover is very strong, no major ice jam should happen. Similarly, if the discharge rises quickly but the ice cover offers no resistance, large ice jams are unlikely to form. However, if the discharge rises quickly when the ice cover is very resistant, the probability of an ice jam flood is high.

A strong ice cover in the Tr'ondëk can be the result of:

- A very dynamic river ice formation event, which means that a lot of ice is produced rapidly and generates thick and rough accumulations at specific locations (generally caused by high fall flows or a melting period taking place after initial freeze-up) and/or
- A very thick ice cover (generally resulting from a cold winter)

Figure 5.2 presents the average annual hydrograph (flow over time) of the Tr'ondëk at station 09EA003 for three consecutive 20-year periods. Late-fall and early-winter (respectively calculated and estimated) discharges during the 2000-2019 period have clearly increased (note the vertical logarithmic scale; this change is important at about 35%). This indicates that freeze-up is probably becoming more dynamic. Unfortunately, this cannot be verified directly because maximum water levels during the formation of the ice cover have not been regularly monitored prior to 2000 (Figure 5.1).

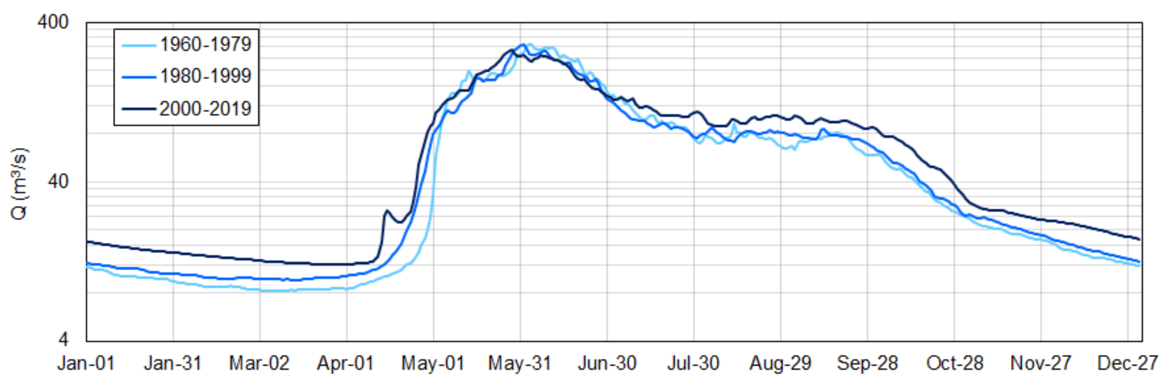

FIGURE 5.2. DAILY-AVERAGED DISCHARGE IN THE TR'ONDËK FOR THREE PERIODS OF 20 YEARS. THE 2000-2019 PERIOD SEEMS TO PRESENT HIGHER DISCHARGE VALUES IN THE SPRING AND FALL.

In turn, Figure 5.3, showing maximum cumulated degree-days of freezing at Dawson (a direct indicator of winter coldness), reveals that winters are becoming warmer, which would translate in a thinner and weaker average ice cover at the end of winter.

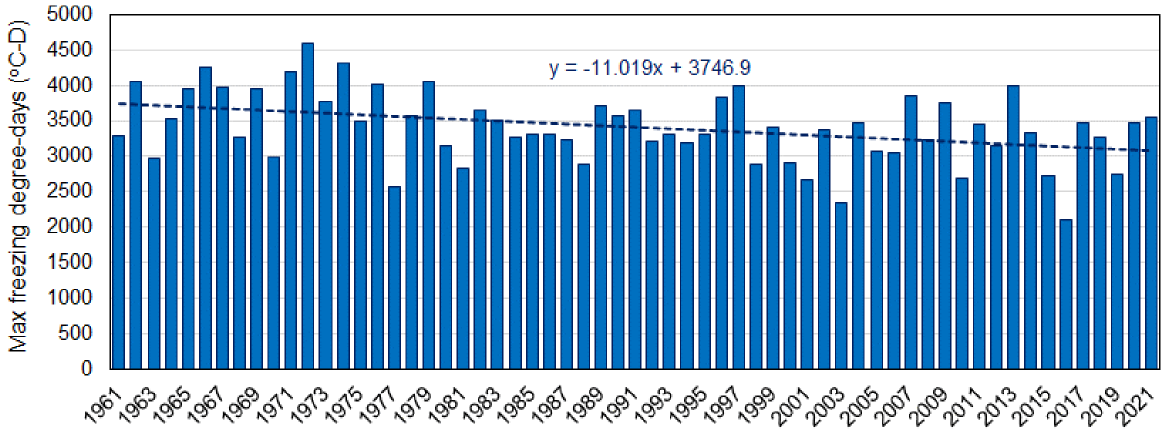

Figure 5.3. Maximum cumulated degree-days of freezing (CDDF) at the Dawson airport from 1961 to 2021. The trend is declining, in line with the expected impact of climate warming.

Janowicz (2010) had suggested that mid-winter rain-on-snow events, a new reality for Yukon, may cause winter breakup events that would exacerbate spring ice jam flood risks along the Tr'ondëk. Despite the interpretation of the 2002 event reported by Janowicz (2010) being reexamined in Turcotte and Nafziger (2021), it seems that unstable weather during freeze-up and early winter (October to December) will cause thick ice accumulations at predictable locations (research is underway to identify ice jam-prone locations along the lower Tr'ondëk). Therefore, the ice cover resistance will likely increase at few to several locations in the future despite warmer winters.

It has been argued that a thick (even record-high) snowpack (in 2022) may insulate the channel against cold weather, therefore leading to a more fragile ice cover prior to breakup. Although this makes sense, it is important to note that more snow also adds weight on the ice cover and promotes the formation of white ice (by saturation and freezing), with more sun-light resistant ice crystals. The WSC measured a thicker-than-usual ice cover in the Tr'ondëk (and in Tágà Shäw) in 2022. This means that the impact of an expected increased snowpack (as a result of climate change) may not reduce the resistance of the ice cover after all.

A potentially stronger ice cover is only one part of the equation. For significant ice jams to form in the Tr'ondëk, a sudden and sustained rise in the spring discharge must also occur. Figure 5.2 shows that the spring freshet for the period of 2000-2019 is beginning earlier than during previous decades. In addition, it is known that climate change should bring more snow to most parts of Yukon. These two conditions point towards advanced breakup dates at the end of April and early in May, and higher late-May and June peak flows. However, these are not direct indicators of fast rising spring flows in a near future. The most important known impact of climate change that may affect breakup intensity is the projected increased variability in weather conditions (including at the end of winter). This would lead to weaker-than-average breakup events in some years (like in 2019), but to extremely dynamic breakup events in other years as the ice cover would be mobilized by unusually high snowmelt runoff rates and by a massive release of ice from upstream.

When taking both resisting and driving forces into account, it appears that breakup ice jams that generate floods could become more frequent in the future for a steep (hydrologically reactive) and medium size (entirely affected by significant weather anomalies) watershed like the Tr'ondëk. Evidently, other factors also influenced by climate change, such as forest fires (impacting snow accumulation, snowmelt rates, and snow sublimation) and landslides, combined with human activities (e.g., ice bridges, placer mining), could exacerbate or attenuate this expected tendency.

The assessment presented in Section 4, based on recent statistics, suggests that the C-4 subdivision (and especially the compound area) is flooded by an ice jam once every 20 years on average. It is not possible to quantify the expected impact of climate change on this flood return period, but it can be assumed that a worse case scenario (combination of significant freeze-up jam, cold winter, and sudden spring snowmelt) is more likely to materialize in the future.

Ice jam floods represent the dominant flooding process in the lower Tr'ondëk: it is almost impossible for a high discharge to generate water levels that are as high as those caused by the most severe ice jams (Turcotte, 2021). As a result, even if maximum open water levels would rise in a future (a tendency that is not currently observed using data from recent years, as presented in Figure 5.4*), it seems very unlikely that high flows without ice could generate floods as frequently as ice jams, especially in the C-4 reach of the river, where an ice jam forms almost annually.

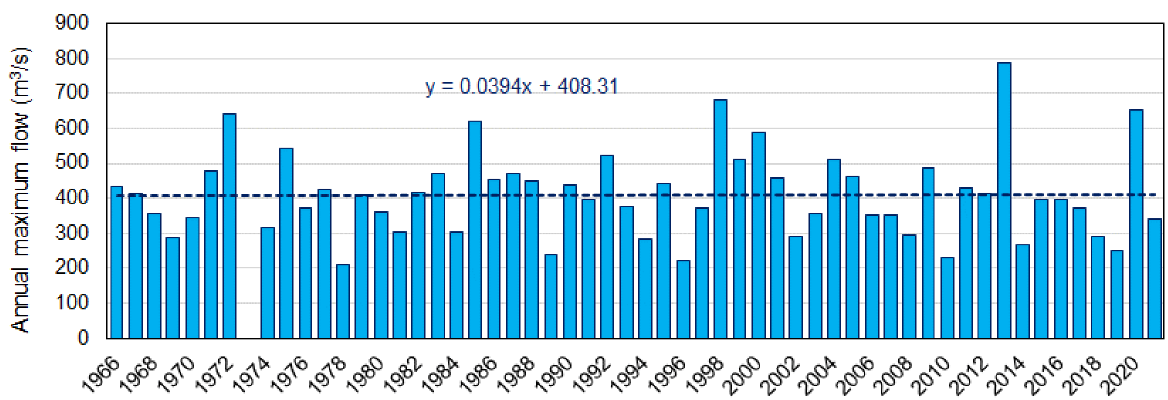

FIGURE 5.4. MAXIMUM ANNUAL FLOW IN THE TR'ONDËK AT STATION 09EA003 FROM 1966 TO 2021. THE INTERPOLATED TREND REVEALS NO TENDENCY.

*Nature is producing more precipitation extremes, but the expected rise in liquid precipitation intensity or snowmelt runoff rates could be partly countered by permafrost melting, as more water can be stored in the ground and this water is subtracted from the surface runoff that causes open water floods.

6. Recommendations to improve flood protection and reduce flood vulnerability

Previous sections of the report demonstrate that ice jams represent the greatest flood hazard along the Tr'ondëk at C-4 and that climate change could generate floods more frequently in the future (qualitative assessment with no specific horizon). The next large flood may hit in 2023, or in 50 years from now, and depending on the level of adaptation, consequences could be limited or extensive. Sandbagging may not be an option against ice jam floods: the phenomenon happens too quickly for effective sandbag deployment and large ice sheets can easily push sandbag dikes.

Ice jams in the Tr'ondëk are different from most ice jams reported in the river ice literature (e.g., Beltaos, 2008): They are grounded, which means ice pieces are in contact with the channel bed, therefore preventing water from flowing under the jam and providing stability to the accumulation. Moreover, lateral overflow that normally bypasses an ice jam through the floodplain is impeded by placer mine tailings, which means that water levels in the channel are higher than they would be in a more natural setting.

This section presents a series of recommendations to reduce the risk of flooding in the lower reach of the Tr'ondëk, more specifically from the Klondike Highway bridge to downstream of C-4. A reduction in both the frequency of high water events and the vulnerability of the infrastructure to those events is considered. Figure 6.1 presents a map of the area with the locations for the different recommended measures. Numbers on this figure correspond to the following list:

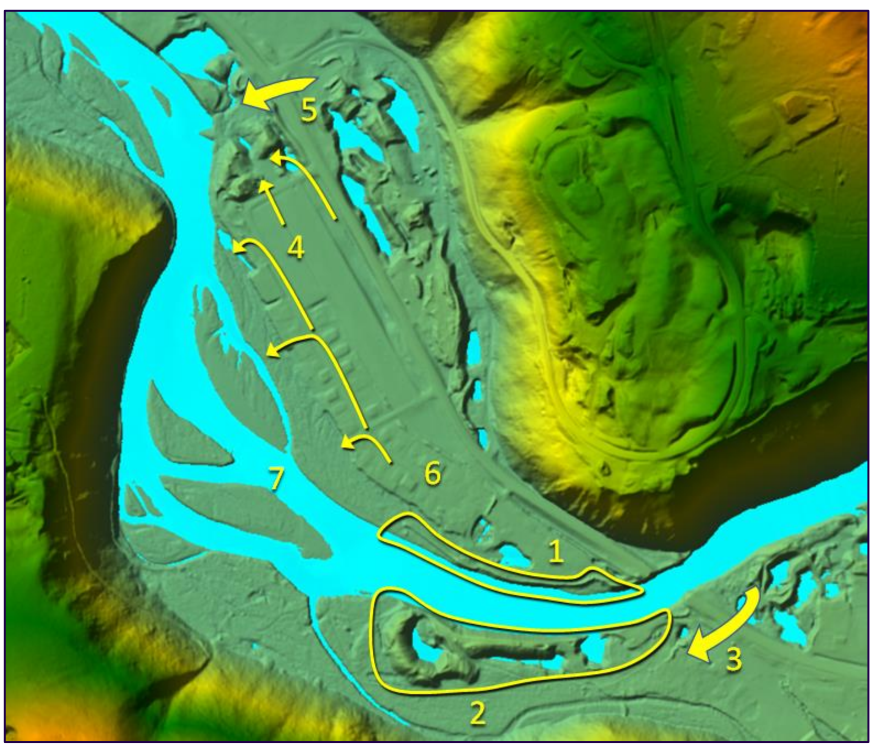

FIGURE 6.1. MAP SHOWING THE LOCATION OF DIFFERENT FLOOD RISK REDUCTION MEASURES UPSTREAM, AT, AND DOWNSTREAM OF C-4. THESE MEASURES ARE SPECIFICALLY TARGETING ICE JAM FLOODS.

1. There is a legacy mine tailing beside the compound area that has been shaped like a partial dike, extending about 350 m from the Klondike Highway bridge on the north shore towards the West. Although covered with bushes and trees, this structure is probably not strong enough to resist the pressure and abrasion caused by a major ice jam, but it has an interesting elevation and length. In the event of a moderate-to-significant ice jam just downstream of the bridge, an improved version of this partial dike could allow a thin layer of water to flow across its crest towards the compound area, and then downstream following its north face. In other words, the dike would create an overflow channel on the floodplain next to the compound area and the southeastern tip of C-4. In the event of a major ice jam that would form further downstream, this structure would not aggravate flooding consequences (it would have a neutral impact). **<u>It is recommended</u>** to further analyze the hydrodynamic impact of such an overflow structure under different flood scenarios in order to confirm if its presence would reduce the risk of ice jam floods, and to assess if its current shape, length, elevation, and resistance could be optimized.

   In turn, a long and high dike structure (as found in downtown Dawson) is not recommended for C-4: if would reduce the evacuation capacity of the floodplain and it could prevent water from flowing back to the Tr'ondëk during an ice-jam flood.
2. There are high tailing piles on the south shore of the Tr'ondëk in front of the dike described above. Such piles represent a significant obstacle to ice jam overflow; they contribute to exposing the Klondike Highway bridge to higher water levels and moving ice pieces, and they expose the Klondike Highway to overflow on both sides of the bridge. **<u>It is recommended</u>** to remove these piles and to restore the floodplain in order to increase its overflow capacity (it was recommended in Turcotte et al., 2021, that no development should occur in that area because the Tr'ondëk needs its floodplain).
3. The Klondike Highway completely blocks the floodplain of the Tr'ondëk at the bridge, just like a dam. This means that, in the event of a flood (not only caused by an ice jam, but also an extreme open-water flood), the bridge could be damaged by ice and debris (as often as once every 50 years). During such condition, the Klondike Highway surface would remain essentially dry (It is not that the bridge structure is not high enough above the Tr'ondëk, but the ground elevation on each side of the river is simply too high). Repairing a highway is less expensive than replacing a bridge, and this means that lowering the highways surface, and possibly designing an erosion failing mode of the highway immediately east of the bridge could save the most important component of the Klondike Highway. **<u>It is recommended</u>** to explore the feasibility of this adaptation measure, especially in the context where the Klondike Highway bridge is the only access point to Dawson. Considering its low elevation, the property where the gasoline station and RV park is located (just east of the bridge) would need to be protected against flooding from the Tr'ondëk (as well as from Bonanza (Rabbit) Creek).

4. The flood probability for the upstream (east) portion of C-4 is higher than for the downstream (west) portion simply because ice jam toes are often located in the multi-channel reach (as presented in Figure 3.2). It is extremely difficult to confirm where excess water from a major ice jam would flow through the relatively flat C-4 area (the simulated flood extent in Figures 4.4 and 4.5 is uncertain). However, it is a fact that, if the overflow is not channelized through ditches and culverts back to the Tr'ondëk (as drafted using arrows in Figure 6.1), it will find its own path, and will affect more people and properties. **It is recommended** to design a network of surface ditches to reduce the impact of ice jam overflow. This network would also support C-4 snowmelt and rain runoff drainage, although it would be overdesigned for this specific purpose (more water is expected from a major ice jam than from local rain or snowmelt).
5. The assessment presented in Section 4 shows that, in the case of a major ice jam with overflow across the Klondike Highway (Figure 3.2), the overflow ratio of the Tr'ondëk discharge would need to be guided back to the river downstream of the jam in a manner that reduces downstream consequences. Since an ice jam is unlikely to extend past C-4 (this is the first river segment to breakup at the end of winter) and given the proximity between the Tr'ondëk channel and the highway, it appears that installing a large culvert under the Klondike Highway just east of Dome Road would reduce water levels through the Bottom of Dome Road development area. **It is recommended** to consider the addition of this drainage structure, especially in a context where development of the Bottom of Dome Road area would also require adequate surface drainage (as presented in Turcotte et al., 2021).
6. Residences and properties located on the upstream portion of C-4, including the compound area, are exposed to ice jam floods (for events with a return period of 20 years or more). Constructions and buildings could be flood proofed to reduce the damage for a given water level. Flood proofing can involve raising the elevation of electric systems, using water resistant insulation material, protecting oil tanks against ice impacts, and moving vulnerable objects (lifting important documents and appliances, relocating vehicles) if an ice jam flood was forecasted. **It is recommended** to explore various flood-proofing options, most of which could prove to be cost-effective.
7. Finally, in the presence of a significant freeze-up jam in the Tr'ondëk at C-4, or if a very dynamic breakup event was forecasted in the coming days, heavy machinery could be used to break the intact ice cover in the Tr'ondëk at C-4 (mostly along the north bank) as an ice-jam flood preventive measure (breaking the ice cover makes it less resistance, therefore reducing the probability of a major ice jam). Access to the area would be facilitated by the presence of an adapted dike-like structure (described in 1). **It is recommended** to explore different mechanical options (access to a light or to a long bow excavator) to safely break an ice accumulation in the Tr'ondëk.

   An early warning system composed of upstream real-time observation stations could also be used to notify downstream residents (in C-4) about the possible arrival of a major ice run. This could inform an emergency intervention such as moving vulnerable assets and belongings to higher elevations, but also a mechanical intervention on the ice cover (or on an existing ice jam) using heavy machinery. Ice runs in the Klondike River can travel at about 5 km/h to 10 km/h, which would provide one to two hours of reaction time between the ice run detection at Bear Creek and its arrival at C-4.

As a worse case intervention scenario, and if deemed safe, heavy machinery could attempt accessing and breaking the toe of an ice jam that would have formed at C-4 in order to promote its mobilization, or at least to reduce upstream water levels by increasing the overflow capacity of a side channel and floodplain. This type of reactive mechanical intervention **would only be recommended** in non-live-threatening situations.

Given the complexity of river ice processes, it is preferable to compare the advice of independent river ice experts before adopting an ice jam flood mitigation plan.

7. Conclusions

The flood exposure assessment presented in this report suggests that C-4 is vulnerable to floods with a return period of more than 20 years and that ice jams represent the dominant flooding process at that location. Beyond the results of the hydrodynamic simulation, based on a state-of-the-art frequency analysis of historical water levels, these results are supported by a photo, shared by the Water Survey of Canada, showing an ice jam that would have flooded C-4 if it had been developed back in 1986 (assumed year of this photo, Figure 3.2).

Other techniques exist to assess the risk of flooding along an ice-jam prone river reach (some of which are presented in Kovachis et al., 2017). There are different versions of the hydrotechnical approach that involves some form of river modeling. Performing hundreds or thousands of ice-hydrodynamic simulations with different ice jam input parameter combinations, often referred to as the Monte Carlo approach (Das et al., 2020), is one of them, and it could be argued that such an approach could have been adopted in this study. However, there are still scientific limitations to this approach: it does not adequately consider the interdependency between input parameters, results may be contaminated by simulated ice jams that are impossible, it can hardly justify a range of possible historical discharges (given that these discharges are rarely accurately quantified), it does not consider ice cover decay or ice jam mobilization thresholds (there are years where no ice jams form), and it does not rely on a true probability of input parameter combinations to generate outputs (the statistical nature of outputs may not be tied to reality). A recent master's thesis by Ladouceur (2021) reveal that Monte Carlo simulation results could be representative or largely inaccurate, and that a local hydrometric station could be needed to confirm this (and the data can be used directly to obtain reasonable results). The current project has applied a different hydrotechnical approach, using three different realistic ice jam simulations associated with calculated water level return periods.

This project has used different sources of information, including knowledge of ice jam floods in small and steep rivers, to establish that the probability (or frequency) of significant ice jams in the Tr'ondëk should increase in the future. This assessment is mainly based on the fact that more variable weather (and therefore hydrological) conditions, as projected by climate simulations (e.g., Zang et al., 2019), will affect the watershed in the future, including atmospheric rivers and sudden spring melting conditions. This statement cannot be applied to all watersheds of Yukon, the Tr'ondëk watershed is small enough to be entirely affected by intense weather systems and its hydrological reaction time is relatively short.

Finally, the report has proposed mitigation measures that are based on an understanding of ice jam dynamics. Optimal flood risk reduction (in terms of cost-benefit) does not necessarily depend on the implementation of all seven measures. In turn, all measures complement each other, they focus on a specific aspect of ice jam floods, they target a specific structure or list of vulnerable assets, and they are considered feasible at a cost that would probably prove affordable. In a context of uncertainty in which the next flood will happen sooner than sought, agencies around the world remind us that every dollar invested in climate change adaptation can save many dollars in the future (UN Press Release, 2019). It is never too early to adapt.

8. References

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Appendix A: List of surveyed assets

ID#	Lat	Long	Surveyed assets		Elev. (m)	Flood return Period	Annual flood prob.
			Description	Surveyed feature			
1	64.04355	-139.41769	House 52	Door Step / First floor	324.6	180	0.6%
2	64.04388	-139.4189	House 46	Door Step / First floor	324.2	160	0.6%
3	64.04408	-139.41985	House 42	Door Step / First floor	323.2	40	2.5%
4	64.04484	-139.42169	House 34	Door Step / First floor	323.9	120	0.8%
5	64.04484	-139.42169	House 32	Door Step / First floor	323.0	40	2.5%
6	64.04604	-139.42366	House 22	Door Step / First floor	323.4	200	0.5%
7	64.04604	-139.42366	House 23	Door Step / First floor	323.6	220	<0.5%
8	64.04739	-139.42587	New House South	Door Step / First floor	323.2	>200	<0.5%
9	64.04739	-139.42587	New House North	Door Step / First floor	323.1	>200	<0.5%
10	64.04329	-139.41548	Compound Office	Door Step / First floor	324.2	80	1.3%
11	64.04295	-139.41444	White Compound	Ground level	323.7	25	4.0%
12	64.04329	-139.41548	Boat Storage	Flour / ground level	323.9	50	2.0%
13	64.04329	-139.41548	3-door garage	Concrete pad	323.8	40	2.5%
14	64.04329	-139.41548	4-door garage	Concrete pad	323.7	25	4.0%
15	64.04355	-139.41769	Electric Box concrete pad	Ground level	323.4	15	6.7%
16	64.04771	-139.42625	Water pumping station for C4	Ground level	322.2	200	0.5%
17	64.04246	-139.4091	Bridge structure	Lower elevation	324.9	60	1.7%
18	64.04246	-139.4091	Bridge abutment	Concrete surface	324.2	30	3.3%
19	64.05061	-139.4308	Helipad	Ground level	321.6	>200	<0.5%

Appendix B. Detailed surveyed assets

Community	Dawson / Tr’ondëk Subdivision
ID #	1
Asset	House 52
Location	Eastern end of the residential area, Joe Henry Road

Surveyed feature	First floor / top of outdoor stairs		
Elevation	324.6 m	Flood return period	180 years
		Annual flood probability	0.6%

Community	Dawson / Tr’ondëk Subdivision		
ID #	2		
Asset	House 46		
Location	Eastern end of the residential area, Joe Henri Road		
			
Surveyed feature	First floor / top of outdoor stairs		
Elevation	324.2 m	Flood return period	160 years
Note this house sits on a higher gravel pad		Annual flood probability	0.6%

<table>
<tr><td>Community</td><td colspan="3">Dawson / Tr’ondëk Subdivision</td></tr>
<tr><td>ID #</td><td colspan="3">3</td></tr>
<tr><td>Asset</td><td colspan="3">House 42</td></tr>
<tr><td>Location</td><td colspan="3">Residential area, Joe Henri Road close to Han Hwëch’in Street</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Surveyed feature</td><td colspan="3">First floor / doorstep</td></tr>
<tr><td>Elevation</td><td>323.2 m</td><td>Flood return period</td><td>40 years</td></tr>
<tr><td colspan="2">This house is among the lowest in the area</td><td>Annual flood probability</td><td>2.5%</td></tr>
</table>

Community	Dawson / Tr’ondëk Subdivision		
ID #	4		
Asset	House 34		
Location	Residential area, Joe Henri Road and Han Hwëch’in Street		
			
Surveyed feature	First floor / doorstep		
Elevation	323.9 m	Flood return period	120 years
Note this house sits on a higher gravel pad		Annual flood probability	0.8%

Community	Dawson / Tr’ondëk Subdivision
ID #	5
Asset	House 32
Location	Central portion of the residential area, Joe Henri Road

Surveyed feature	First floor / doorstep		
Elevation	323.0 m	Flood return period	40 years
This house is among the lowest in the area		Annual flood probability	2.5 %

<table>
<tr><td>Community</td><td colspan="3">Dawson / Tr’ondëk Subdivision</td></tr>
<tr><td>ID #</td><td colspan="3">6</td></tr>
<tr><td>Asset</td><td colspan="3">House 22</td></tr>
<tr><td>Location</td><td colspan="3">Central portion of the residential area, Joe Henri Road</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Surveyed feature</td><td colspan="3">First floor / top of stairs / doorstep</td></tr>
<tr><td>Elevation</td><td>323.4 m</td><td>Flood return period</td><td>200 years</td></tr>
<tr><td colspan="2">These houses have a high foundation, but the crawl space probably includes components below the first floor (e.g., water pipes).</td><td>Annual flood probability</td><td>0.5 %</td></tr>
</table>

<table>
<tr><td>Community</td><td colspan="3">Dawson / Tr’ondëk Subdivision</td></tr>
<tr><td>ID #</td><td colspan="3">7</td></tr>
<tr><td>Asset</td><td colspan="3">House 23</td></tr>
<tr><td>Location</td><td colspan="3">Central portion of the residential area, Joe Henri Road</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Surveyed feature</td><td colspan="3">First floor / top of stairs / doorstep</td></tr>
<tr><td>Elevation</td><td>323.6 m</td><td>Flood return period</td><td>220 years</td></tr>
<tr><td colspan="2">These houses have a high foundation, but the crawl space probably includes components below the first floor (e.g., water pipes).</td><td>Annual flood probability</td><td>0.5 %</td></tr>
</table>

Community	Dawson / Tr'ondëk Subdivision
ID #	8
Asset	New house (YukonU training in progress)
Location	Western end of the residential area, Joe Henri Road

Surveyed feature	Doorstep / assumed first floor		
Elevation	323.2 m	Flood return period	>200 years
Note: this house is considered to be at a safe elevation because of the significant overflow capacity at the downstream end of C-4.		Annual flood probability	<0.5%

Community	Dawson / Tr’ondëk Subdivision
ID #	9
Asset	New house (YukonU training in progress)
Location	Western end of the residential area, Joe Henri Road

Surveyed feature	Doorstep / assumed first floor		
Elevation	323.1 m	Flood return period	>200 years
Note: this house is considered to be at a safe elevation because of the significant overflow capacity at the downstream end of C-4.		Annual flood probability	<0.5%

Community	Dawson / Tr’ondëk Subdivision		
ID #	10		
Asset	Office / TH management		
Location	C-4 Compound area		

Surveyed feature	Doorstep / top of outdoor stairs		
Elevation	324.2 m	Flood return period	80 years
		Annual flood probability	1.3 %

Community	Dawson / Tr'ondëk Subdivision		
ID #	11		
Asset	White compound		
Location	C-4 Compound area		

Surveyed feature	First floor / ground level		
Elevation	323.7 m	Flood return period	25 years
		Annual flood probability	4.0 %

Community	Dawson / Tr’ondëk Subdivision		
ID #	12		
Asset	Boat storage building		
Location	C-4 Compound area		
			
Surveyed feature	Gravel pad, ground level		
Elevation	323.9 m	Flood return period	50 years
		Annual flood probability	2.0 %

Community	Dawson / Tr'ondëk Subdivision		
ID #	13		
Asset	3-door garage building / TH Housing and Infrastructure		
Location	C-4 Compound area		
			
Surveyed feature	Concrete pad / ground level		
Elevation	323.8 m	Flood return period	40 years
		Annual flood probability	2.5 %

Community	Dawson / Tr'ondëk Subdivision		
ID #	14		
Asset	4-door garage building / TH Housing and Infrastructure		
Location	C-4 Compound area		
			
Surveyed feature	Concrete pad / ground level		
Elevation	323.7 m	Flood return period	25 years
		Annual flood probability	4.0 %

Community	Dawson / Tr’ondëk Subdivision		
ID #	15		
Asset	Electric box		
Location	Eastern end of the residential area, Joe Henry Road		
			
Surveyed feature	Ground level		
Elevation	323.4 m	Flood return period	15 years
Note: It is unclear if this asset is vulnerable to water at the ground level.		Annual flood probability	6.7 %

Community	Dawson / Tr'ondëk Subdivision		
ID #	16		
Asset	Water building		
Location	Northwest end of the residential area, Joe Henry Road		
			
Surveyed feature	Ground level		
Elevation	322.2 m	Flood return period	200 years
		Annual flood probability	0.5 %

Community	Dawson		
ID #	17		
Asset	Klondike Highway bridge		
Location	Klondike Highway just out of Dawson and besides C-4		
			
Surveyed feature	Bottom of superstructure		
Elevation	324.9 m	Flood return period	60 years
Note: ice pieces can reach more than one meter above the water level, and this flood return period is underestimating the potential damage by ice.		Annual flood probability	0.4 %

Community	Dawson		
ID #	18		
Asset	Klondike Highway bridge		
Location	Klondike Highway just out of Dawson and besides C-4		
			
Surveyed feature	Top of concrete abutment		
Elevation	324.2 m	Flood return period	30 years
Note: ice pieces can reach more than one meter above the water level.		Annual flood probability	3.3 %

Community	Dawson		
ID #	19		
Asset	Helipad		
Location	Between C-4 and downtown Dawson		
			
Surveyed feature	Ground level / pavement		
Elevation	321.6 m	Flood return period	> 200 years
Note: As stated in Turcotte and Saal (2022), this property is not threatened by floods, but it is vulnerable to erosion.		Annual flood probability	< 0.5%