MORRISON HERSHFIELD

REPORT

Project Planning Guidelines for Permafrost Management in Old Crow

Prepared for:

Government of Yukon
Community Services Infrastructure Development Branch

Vuntut Gwitchin Government

Report No. 2100767.00
Date: March 30, 2022

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MORRISON HERSHFIELD

March 30, 2022

Michael B. Edwards
Project Manager
Government of Yukon Community Services, Infrastructure Development Branch

Dear Mr. Edwards:

Re: Old Crow Permafrost Management Plan

Morrison Hershfield is pleased to provide our Final Report on the above noted project. This report presents the findings of the Plan and provides recommendations for future infrastructure projects in Old Crow, along with other actions that may assist in managing permafrost in Vuntut Gwitchin traditional territory under the effects of a changing climate.

If we can be of further service, please do not hesitate to contact me. We look forward to future opportunities to work with you supporting community infrastructure in Old Crow.

Sincerely,
Morrison Hershfield Limited

Roger Hosking, P.Eng.

Project Engineer

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Acronyms and Abbreviations

ARF	Airport Refueling Facility
CRU	Climate Research Unit
CSA	Canadian Standards Association
ERT	electrical resistivity tomography
GHG	greenhouse gas
GPR	ground penetrating radar
GSC	Geological Survey of Canada
GTNP	Global Terrestrial Network for Permafrost
IPCC	Intergovernmental Panel on Climate Change
LTF	Land Treatment Facility
mASD	metres above select datum
mbgs	metres below ground surface
NCE	Northern Climate ExChange
NRC	National Research Council of Canada
NWT	Northwest Territories
ppt	parts per trillion
RCMP	Royal Canadian Mounted Police
RCPs	Representative Concentration Pathways
WSC	Water Survey of Canada
VGFN	Vuntut Gwitchin First Nation
VGG	Vuntut Gwitchin Government
YG	Government of Yukon

Definitions

Active Layer	The layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost.
Aquiclude	A geologic formation or stratum that confines water in an adjacent aquifer.
Aquitard	A geologic formation or stratum that lies adjacent to an aquifer and allows only a small amount of water to pass.
Beringia	A historical landmass including portions of 3 modern nations (Canada, United States, and Russia) and extending from the Siberian Kolyma River and Kamchatka Peninsula, through Alaska and Yukon Territory, to the Mackenzie River in the Northwest Territories.
Colluvium	Material that has been transported down slopes, causes local variations in the composition.
Cryosols	Mineral soils formed under conditions of permafrost. Water is present primarily as ice, and ice-related processes are the dominant pedogenetic processes involved in the soil formation.
Groundwater	The regional aquifer, located below the permafrost, at approximately 80 meters below ground surface in Old Crow.
Latent Heat Effects	The rate of ground warming or cooling typically slows as temperatures approach 0ºC because of the large amounts of energy associated with changing water into ice or vice versa.
Permafrost	Any ground (soil, rock, ice or organic material), that remains at or below 0°C for at least two consecutive years (IPA, 2008).
Portable Thermistor Port	A thermistor port that consists of an empty PVC standpipe, either on its own or nested with a monitoring well. These ports are intended to be used to collect temperature measurements using portable thermistor strings, rather than long term data loggers.
Sheet wash (or sheet-flow)	An overland flow or downslope movement of water taking the form of a thin, continuous film. In Old Crow, sheet wash occurs on sloping frozen ground.
Sub-permafrost Water	Regional groundwater located below the permafrost.

Supra-permafrost Water	Water present in saturated soil, within the thawed layer, above permafrost.
Talik	An area of unfrozen ground surrounded by permafrost.
Thermokarst	A form of periglacial topography resembling karst, with hollows produced by the selective melting of permafrost.

1. INTRODUCTION

1.1 Need for this Technical Guide

Permafrost exists in a delicate thermal equilibrium that is susceptible to natural or human-made changes in the environmental conditions under which the permafrost exists, such as removal of vegetation, disruption to snow cover and/or drainage, construction of structure, climate warming, etc. Degradation of permafrost in soils that are not thaw-stable makes it difficult to build and/or maintain infrastructure due to its impact on ground subsidence and bearing capacity. This in turn results in direct and immediate implications for land use, the economy, and community life. The development and maintenance of infrastructure in such areas demands an understanding of, and the ability to cope with, problems of the environment dictated by the presence of permafrost. In northern Canada and Alaska, permafrost degradation is leading to unprecedented spending on maintenance and rehabilitation of infrastructure, particularly linear infrastructure.

Old Crow is the most northern community in the Yukon Territory. It lies within a continuous permafrost zone, meaning that cryotic conditions underlie more than 90% of the land surface, only absent beneath large lakes or continuously flowing rivers. Much of the critical community infrastructure has been or is built, and/or maintained by the Government of Yukon (YG), as is commonplace for many Yukon communities. Safe and practical methods to construct and maintain functional infrastructure such as schools, health centres, firehalls, and airports, through a changing climate is needed to maintain the resiliency and adaptability of the community.

This technical guidance document is intended as an informative document, with the objective of identifying the actions, principles, and guidelines that would inform the necessary protection of the permafrost in the community of Old Crow, and of any risks to public infrastructure. The protection of the permafrost would have direct results on the protection and integrity of the current and capital infrastructure investments made by both YG and the Vuntut-Gwitchin Government (VGG). It is intended for this guide to be reviewed and updated as required, every three to five years.

1.2 Intended Users of This Guide

This technical guide is for those carrying out development activities in Old Crow intended to assist decision makers who are not experts in permafrost, geotechnical engineering, or climate change adaptation planning by providing them with:

- Improved understanding of guidelines and principles for the protection of permafrost, along with mitigation and restoration techniques that could be applied to impacted landscapes and structures.
- A means for locating key information on these topics.
- A preliminary assessment of existing structures and areas affected in Old Crow.
- Specification guidance and an ability to ask key questions of those they retain to carry out the planning, assessment, engineering and design, and construction of project.

- An additional tool for identifying work that may require government funding, and a reference to include in applications for such funding.

This guide is intended to be recognized by the VGG at the council level, similar to a by-law, to help with implementing permafrost (and vegetation) protection.

1.3 Limitations of this Guide

This technical guide has been prepared for the use of the Government of Yukon by Morrison Hershfield Limited (Morrison Hershfield).

In preparing this report Morrison Hershfield has relied in good faith on information provided by individuals and companies noted in this report. Morrison Hershfield assumes that the information provided is factual and accurate.

This technical guide is intended to provide information to guide decision makers prior to site specific investigations. This guide touches upon issues relating to permafrost and climate change, structures, foundation design and selection, roadway design, and revegetation, as it relates to Yukon Government managed sites and other sites within the Old Crow community. Information herein does not replace the expertise provided by such professionals/experts and cannot be used or relied upon for design or construction of infrastructure and does not replace in any way the required due diligence and site-specific investigations by qualified person(s), to determine the actual conditions at a specific location. Use or reliance upon information herein for any other purpose is solely at the user's own risk and Morrison Hershfield accepts no liability under any circumstances for any loss or damage arising from the use of information provided in this document.

2. METHODOLOGY

2.1 Background Review

The project objective was established by the YG's Department of Community Services (Infrastructure Development Branch) with support from Vuntut Gwitchin First Nation (VGFN). Once the objectives of the guidance document were identified, a background review was performed. The background review was completed in a more or less systematic way, with the collection and synthesis of previous research, creating a foundation of knowledge integrated from multiple sources.

Sources of information included special-purpose maps (buildings, zoning, geology, hazards etc.), previous studies, academic papers, book chapters, existing guides/manuals, national standards, news articles, local knowledge, and the Yukon Geological Survey permafrost database. These resources were provided by the Yukon Government and the project collaborators mentioned above, or they were gathered from publicly accessible reference sources online (digital university libraries, the Canadian Standards Association, the Government of Canada Historical Climate Data, etc.).

Generally, the review was completed to seek, identify, and summarize relevant research and information available from a local to national scale, to determine at a high level the applicability and implications of existing methods in meeting the objectives of this guidance document as it pertains to permafrost management in Old Crow.

2.2 Desktop Preliminary Site Reconnaissance

A desktop preliminary site reconnaissance was carried out for Old Crow through characterization of the environmental conditions (geological, hydrogeological, climate, permafrost etc.) within the community, identifying the existing public infrastructure (and their level of importance to the community), and pre-assessing the vulnerability of the identified infrastructure to changing permafrost conditions.

The desktop reconnaissance was completed concurrently with the background review and was conducted based on information available, without any on-site physical inspection. Information gained through this process was used to guide the subsequent on-site assessments in Old Crow.

2.3 On-Site Inspections and Assessment

On-site visual inspections of infrastructure were completed between September 13th and 14th, 2021. Site inspections were carried out in the fall as permafrost thaw problems are greatest at the end of summer and differentiable from seasonal frost problems typically seen in the spring.

The inspections were limited to visual observations only and were completed in general accordance with the Canadian Standards Association (CSA) standard CAN/CSA-S501014: *Moderating the effects of permafrost degradation on existing building foundations* (CSA Group, 2021) and with consideration of CAN/CSA-S503:20 *Community drainage system planning,* *design, and maintenance in northern communities* (CSA Group, 2020), with the exception that only outdoor spaces and building exteriors could be inspected due to access restrictions with COVID-19.

No site-specific subsurface data was collected through any subsurface investigations (geotechnical, lithological etc.).

For consistency, a site inspection checklist/form was developed for the on-site inspections. The inspections included checks for indicators of potential permafrost related impacts, including foundation distress, exterior, evidence of ground surface settlement or heave, vegetation, and surface drainage characteristics and drainage issues (such as blocked surface run-offs from roadways) around the community. The checklist, along with a summary of the completed inspections and findings are provided in Appendix A.

3. CONTEXT AND BACKGROUND

3.1 Community

The focus of this guideline is the community of Old Crow, which is the most northern community in the Yukon Territory and is situated roughly 130 km north of the Arctic Circle, on the banks of the Porcupine River and at the mouth of the Old Crow River (Figure 1). The community lies in an area of continuous (90-100%) permafrost, within the Old Crow Pediplain physiographic region (Smith et al., 2004).

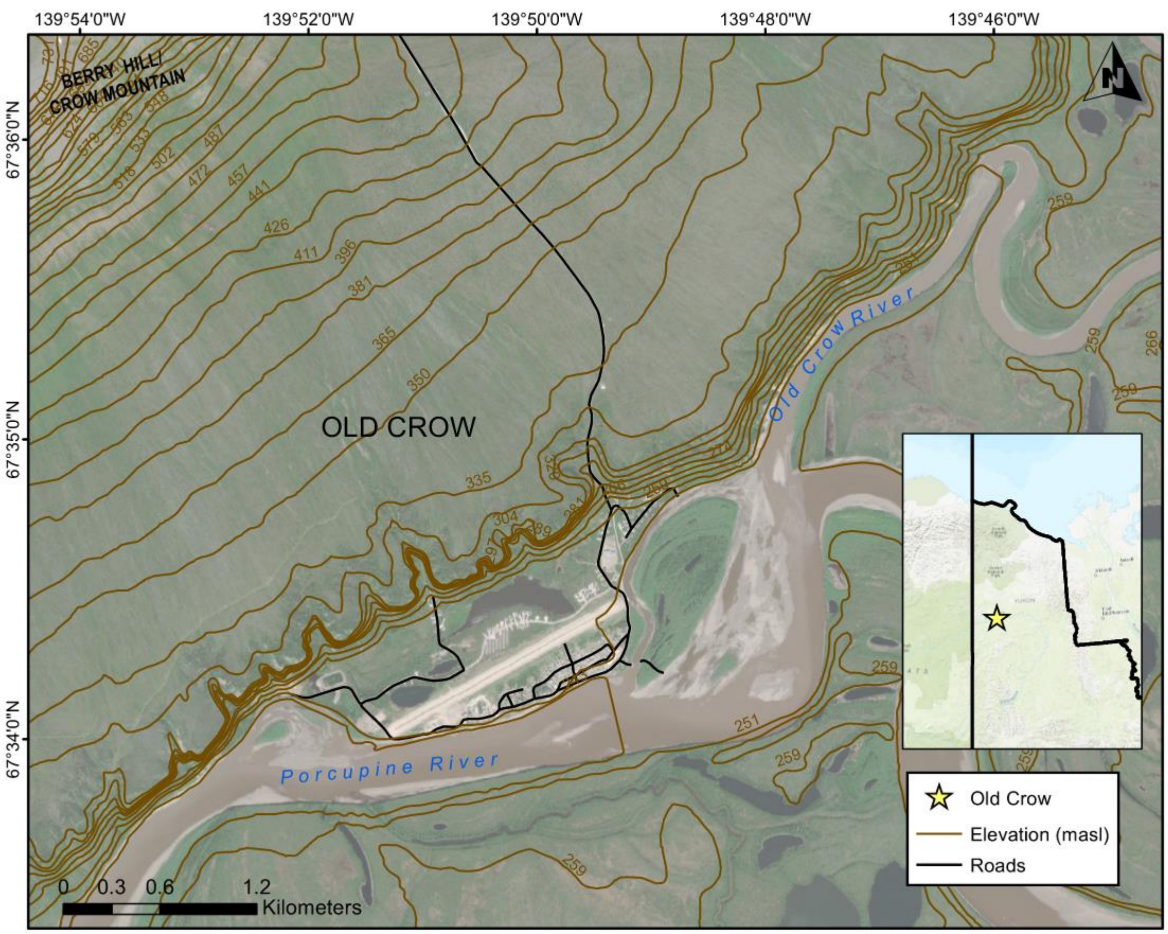

Figure 1: Location of Old Crow, Yukon.

3.2 Land Use and Infrastructure

Old Crow is an unincorporated community, as most of the land within the community is settlement land of the Vuntut Gwitchin First Nation (VGFN). The non-settlement lands are owned by either the YG or Canada.

Planning and land use management decisions within the community of Old Crow are guided by the Old Crow Zoning Bylaw (#02-2014) (VGG, 2014). Permitted land uses are as shown in Figure 2. Per this bylaw and under new construction, all works and changes in use, must comply in all respects with provisions of the *Yukon Building Standards Act* (RSY 2002 c.19). The bylaw also states under general regulations that in regard to permafrost "*ALL areas outside of the existing development zones must have geotechnical approval prior to construction*", and "*ALL new heated construction must be stamped by a civil engineer to show that heat intrusion to permafrost will not occur due to development*". The bylaw recognizes that non-settlement lands within Old Crow, which are owned by the Yukon Government, are not under legal authority of the bylaw, but it is anticipated that the Yukon Government will voluntarily work with and through the provisions of the bylaw (VGG, 2014).

The Yukon Government and VGFN share responsibility for the provision of municipal services in Old Crow (VGFN, 2009; VGG, 2014; VGG, 2016).

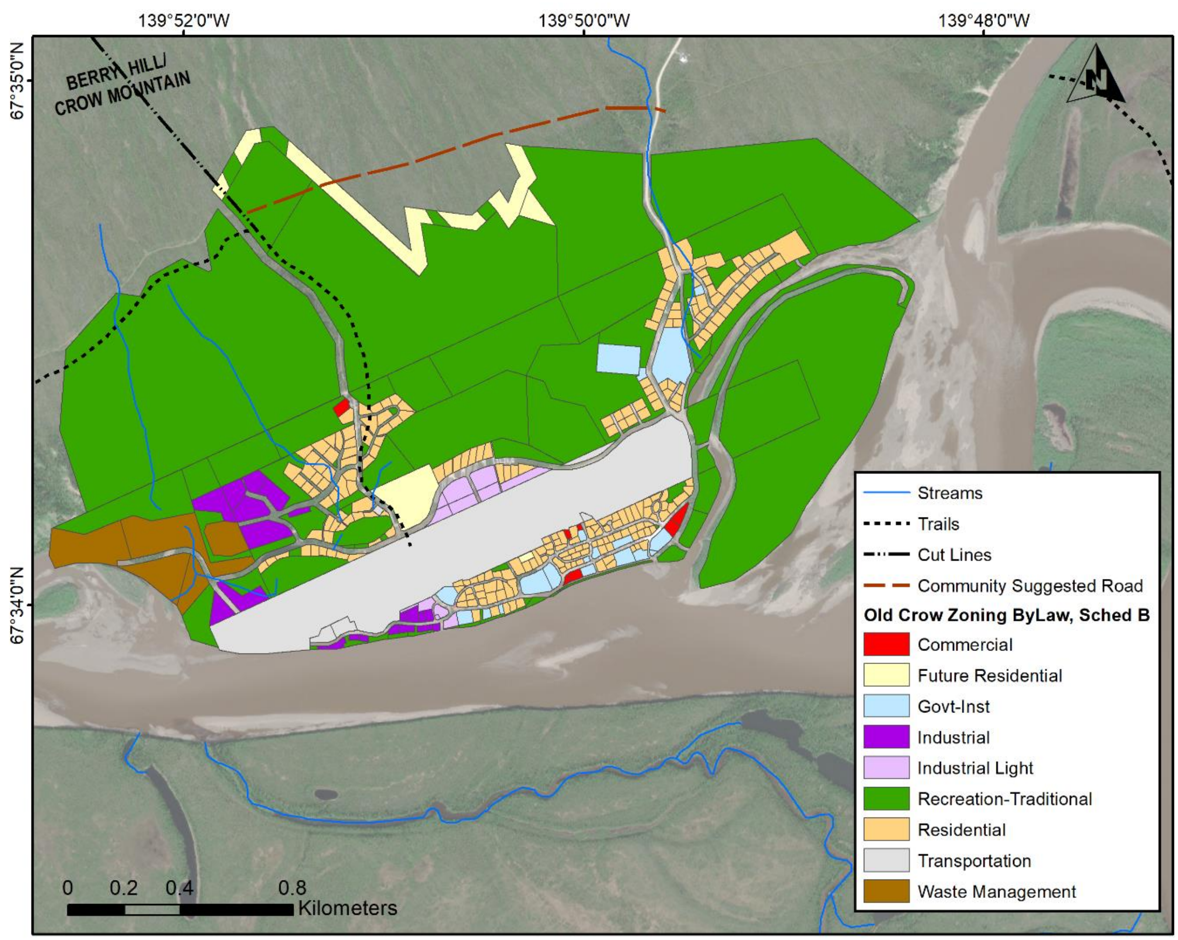

Figure 2: Permitted Land Uses in Old Crow, per Old Crow Zoning Bylaw, Schedule 'B' (VGG, 2014).

3.2.1 Infrastructure Managed by the Government of Yukon

The Yukon Government retains a number of infrastructure program delivery responsibilities in Old Crow. Services provided and managed by the Yukon Government include the Health Centre (a.k.a Nursing Station), Chief Zzeh Gettlit School, Water Treatment and Truck Supply Plant, the airport, sewage lagoon, fire hall, and solid waste disposal facility. The Yukon Government also is responsible for roads, including any upgrades and on-going maintenance, with the exception of Crow Mountain Road (VGFN, 2009; VGG, 2014).

Public buildings utilized for the delivery of municipal services in Old Crow, that are under the responsibility of the Yukon Government are summarized in Table 1, below.

Table 1: Summary of Yukon Government Buildings in Old Crow.

Building Name	YG Building Number (VGFN Building Number)	Property Description
Grader Station	2660 (130)	Lot 1021-2, L.T.O. 2000-0176, C.L.S.R. 96569
Air Terminal	2675 (145)	Lot 1021-2, L.T.O. 2000-0176, C.L.S.R. 96568
[1]Airside Storage Sheds	2672, 2673	-
[2]Firehall/3 Bay Garage	2659 (2659)	Commissioner's Land, C.L.S.R. 96604
[2]Ice House/Storage	2651	Lot 1025, L.T.O. 116 0/12, C.L.S.R. 96604
[2]Storage Shed	2658	Lot 1025, L.T.O. 116 0/12, C.L.S.R. 96604
[1]Storage Shed	2655, 2656	-
[2]Water Treatment and Truck Fill Plant	2681	Lot 1026, 116 0/12, C.L.S.R. 96604
[2]Health Centre/Nursing Station	2934 (205)	Lot 1012, 116 0/12, C.L.S.R. 78133
[2]John Tizya Centre (Visitor Reception Center)	2943	Lot C-3A-1, XXX, C.L.S.R. 92598
[2]District Office	2676	Lot 1012, 116/ O/12. C.L.S.R. 78133
[2]Chief Zzeh Gittlit School	2648 (999)	Lot 1019, 116 O/12, C.L.S.R. 81462
[2]Teacherages	XXXX (898/899, 895/897)	Lot 1019, 116 O/12, C.L.S.R. 81462
[1]Warehouse	2646	Lot 1021-2, L.T.O. 2000-0176, C.L.S.R. 96569
[3]Sewage Lagoon	-	Disposition Number: 116O12-024
[3]Solid Waste Landfill	-	Disposition Number: 116O12-024

<u>References</u> [1]Foundation Assessment Report – Yukon Buildings (Tetra Tech, 2018).
[2]2012 – OC – YG Buildings Mapped (CAD file).
[3]VGFN, 2009 – Appendix A.

3.2.2 Infrastructure Managed by VGG

The VGFN assumes responsibility for the general welfare of citizens as stated in the Mission statement of the Strategic Plan (VGFN, 2006). The Government Services Department of the VGG, strives to provide the best community infrastructure and housing to the citizens Old Crow (VGFN, 2021b).

Some of the services managed by the VFGN include the First Nation Office, Skating Arena, Youth Centre, and Community Centre. The capital buildings associated with services provided to the community by the VGFN, along with some buildings of historical importance (VGFN, 2009; VGFN and YG, 2018) are summarized in Table 2, below.

Table 2: Summary of VGFN Buildings in Old Crow.

Building Name	VGFN Building Number	Description of Use
Arena	660	Hockey Arena – currently not in use.
Community Hall	600	Community centre, recently replaced by new building in 2020-2021.
Chief Peter Moses Centennial Hall	570	Constructed as community hall, commemorating late Peter Moses, a former Chief in Old Crow. Also marked, Canada’s 100-year centenary. Today is in use as community fitness centre.
Sarah Abel Chitze Building (Administration Building)	775	Houses VGG departments and offices of the Executive and Chief and Council.
Community Youth Centre and Radio Station	700	Offers after-school programs, concerts, fun nights, and houses local radio station.
St. Luke’s Anglican Church	495	Church; built in ~1959.
Alice Frost Community Campus	460	Satellite campus for Yukon College.
Archdeacon McDonald Memorial Church	(west of RCMP)	Historical building, used prior to construction of St. Luke’s in ~1959.

3.3 Physiography, Glacial History, and Geology

Old Crow is located within the Porcupine River Valley, one of two physiographic units within the Bluefish Basin. The other being the Bluefish Plain, located 40 to 50 metres higher than the Porcupine River Valley and characterized by numerous flat-bottomed shallow lakes, and scars of former lake basins, infilled with peat and a mix of shrubs, grasses, and moss.

The Porcupine River Valley formed along the northern rim of the Bluefish Basin via the incision of Porcupine River following the drainage of glacial Lake Old Crow (Lauriol et al., 2009).

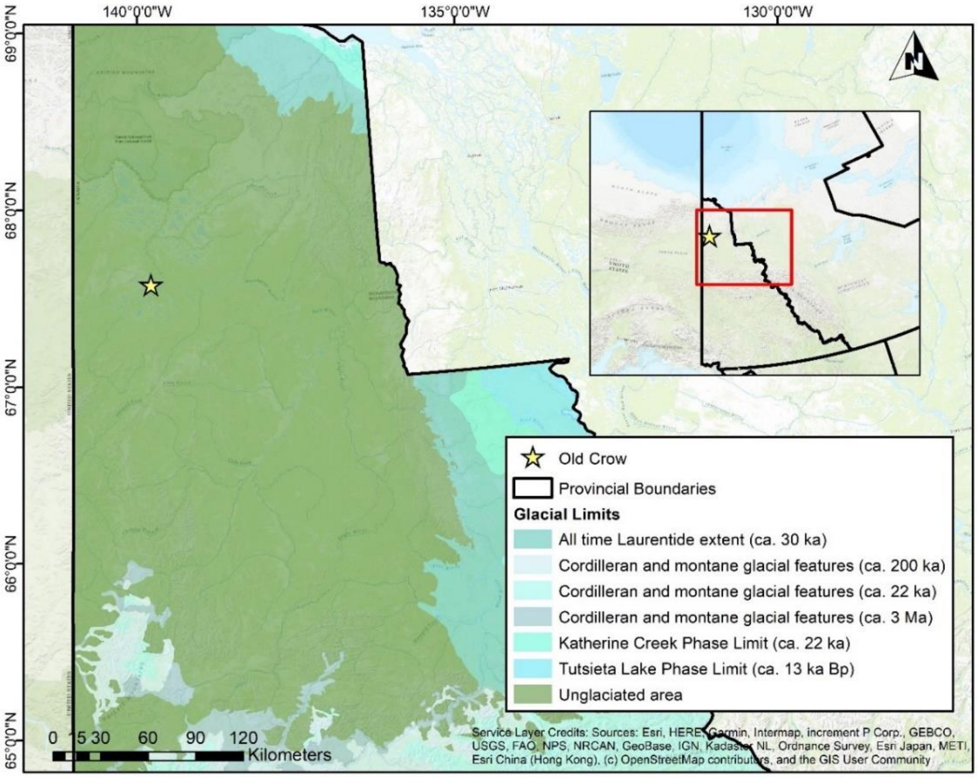

Figure 3: Glacial Limits within the Yukon Territory.

Lake Old Crow was an extensive glacial lake that occupied the Bluefish Basin, as well as the much larger Old Crow Basin (to the north) between approximately 20,000 and 15,000 years ago. Permafrost was likely eradicated from beneath the lake at the time (Smith et al., 2004; Lauriol et al., 2009). The Old Crow region remained ice free during the Late Pleistocene and was within the larger unglaciated landmass known as Beringia (Hughes, 1972) (Figure 3). The neighboring ice sheets significantly affected the hydrogeology of the Old Crow region (Lemmen et al., 1994). Lake Old Crow resulted in the deposition of metres of silty-clay sediments, before draining westward through the present-day Ramparts of the Porcupine to Alaska, allowing for the aggradation of permafrost in the thick glaciolacustrine deposits and formation of thermokarst lakes (Morlan, 1980; Lauriol et al., 2009).

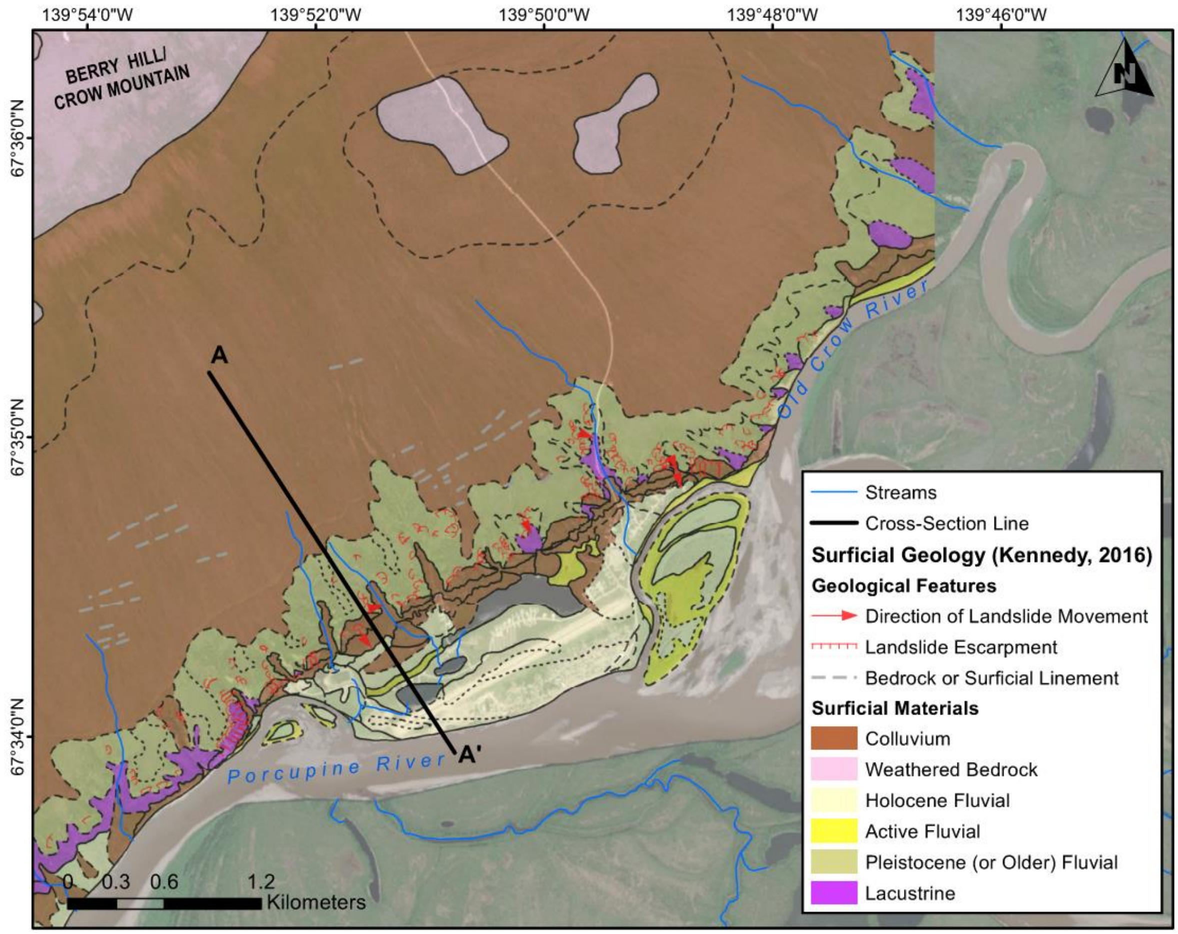

Figure 4: Old Crow Surficial Geology (Kennedy, 2016) and Cross Section (A - A') Corresponding to Figure 5.

Incision of the Porcupine River, following the drainage of Lake Old Crow, created vertical bluffs more than 30 metres high. The community of Old Crow is located on the floodplain along the northern bank of the Porcupine River, bound in the north by a steep fluvial escarpment. This escarpment separates the community from the upland pediment approaching Berry Hill (a.k.a. Crow Mountain), further to the north. Per the Old Crow Zoning Bylaw (VGG, 2014) and the Community Plan (VGG, 2016), the community plans to expand in the future, with development of residential properties to the north of the escarpment, along a portion of the pediment slope (Figure 2), referred to as the benchlands (VGG, 2016).

The surficial geology (Figure 4) of the community of Old Crow is the product of a Late Pleistocene to Holocene fluvial geologic setting of a vertically meandering river across the valley bottom, with erosion on the outside bend and deposition of finer grained sediments on the inner bend (Smith et al., 2004). The community of Old Crow lies directly above inactive fluvial deposits of the Holocene, ranging from silty, sand-rich gravel channel deposits to fine-grained sand and silt overbank and back-channel deposits. These fluvial deposits are commonly overlain by organics and are ice rich with permafrost. The fluvial deposits are underlain by approximately 30 metres of stratified fine silt, clay, and sand deposited on the bed of a pre-quaternary lake (and therefore prior to the Pleistocene changes in regional hydrogeology)

(Figure 5). At the escarpment to the north of the community, the lacustrine sediments are overlain by fluvial sediments consisting of sandy pebble and cobble gravel, deposited by streams having a fluvial source graded to a former base level of the Porcupine River (possibly at approximately 280 masl) (Benkert, 2016; Kennedy, 2016).

The underlying bedrock of the area consists of sedimentary rocks. Crow Mountain and the approaching pediment slope is comprised of the distinctly light coloured orthoquartzitic sandstone (with intervals of shale and rare dolostone) and is the primary source of aggregate used for infrastructure development in the Old Crow community. The pediment slope consists of the weathered sandstone bedrock overlain by a blanket of silty-clay colluvium (Norris, 1981; Yukon Ecoregions Working Group, 2004). The colluvium is highly variable and is transported down-slope towards to the south and often onto the slope of the fluvial escarpment, by gravity-driven processes such as solifluction and landslides (Benkert et al., 2016; Kennedy, 2016). There is limited information available on the depth to bedrock along the pediment, especially within the area referred to as the benchlands (within the community plan - VGG, 2016). A drilling program completed by Morrison Hershfield higher up the mountain (380 masl) reached bedrock at a depth of 4.7 m (MH, 2020a).

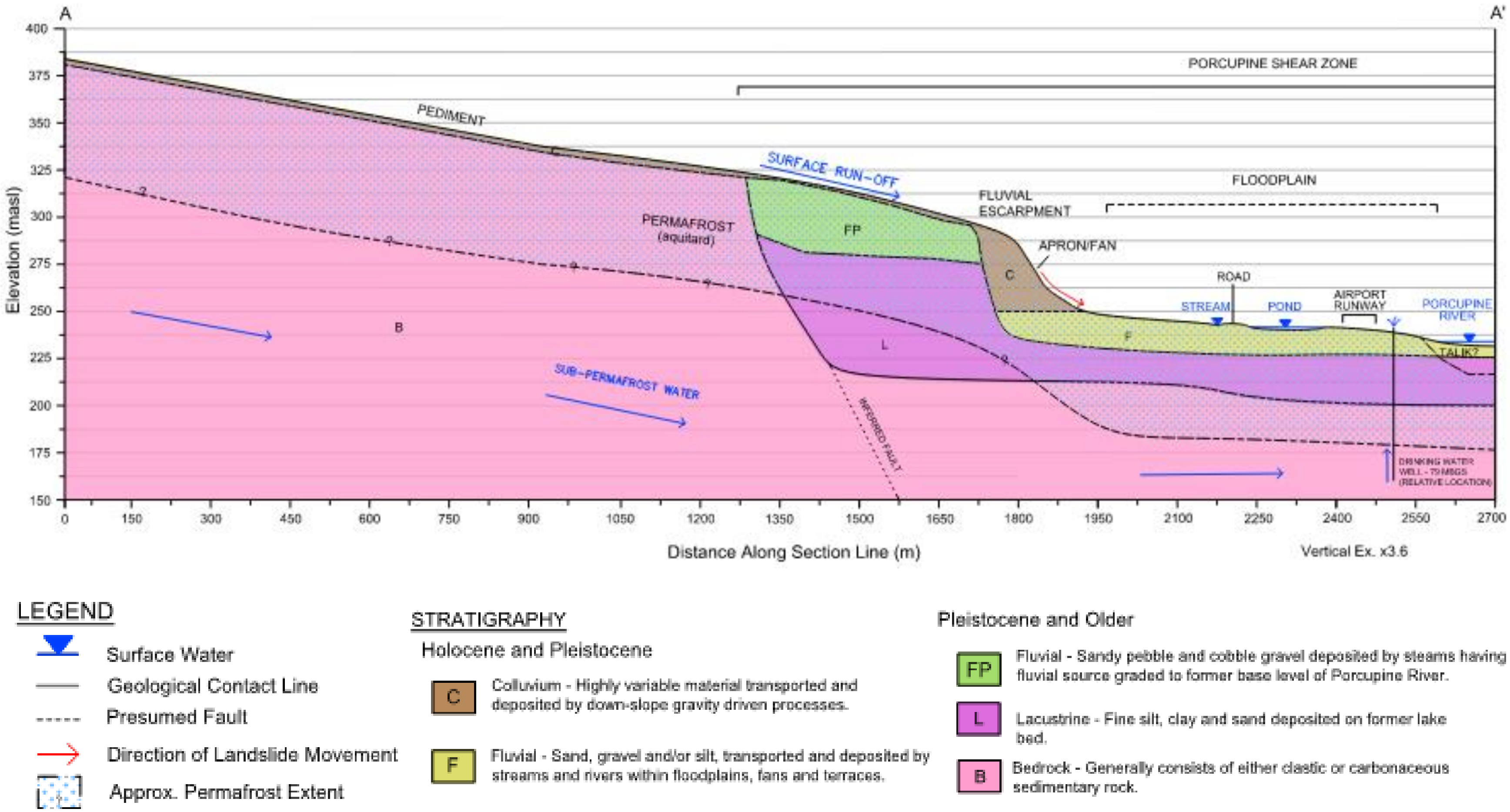

Figure 5: Geological Cross Section, A-A', of Old Crow, adapted and Modified from Kennedy, 2016.

3.4 Local Hydrogeology

Permafrost usually behaves like an aquiclude or an aquitard (Woo, 2012), by restricting groundwater recharge, discharge, and flow paths. Supra-permafrost water is seasonal groundwater within the active layer located above the permafrost table and existing water year-round of closed taliks, while sub-permafrost water is groundwater below the permafrost, found in water-bearing horizons and zones of jointing.

There are two sources of supra-permafrost water, including meteoric sources (i.e., snowmelt in the spring and summer rain), and seasonal active layer ice melt. Snowmelt is likely a minor contributor to supra-permafrost water, as there is little, if any, active layer present during the spring thaw. The thin to non-existent active layer at this time inhibits infiltration and snowmelt is therefore forced to run-off instead. Summer rainfall therefore appears to be the major contributor to supra-permafrost water (Throckmorton, 2016).

Permafrost inhibits the mixing of supra and sub permafrost water (Frampton et al., 2011). Recharge and discharge of water to sub-permafrost aquifers is limited to fault lines and unfrozen zones perforating the permafrost (Williams, 1970).

The regional groundwater aquifer, which is the primary source of drinking water in the community of Old Crow, is the sub-permafrost water, confined beneath the permafrost, within a bedrock aquifer. Sub-permafrost water was discovered during the groundwater investigation in 1982, which included the construction of the community's two current water supply wells, with termination depths at 79 and 122 mbgs (EBA, 1982). The drilling revealed an overburden thickness of approximately 38 m and the water wells were noted as under flowing artesian conditions. Permafrost was determined to extend to 63 mbgs. Subsequent testing prior to the construction of the Water Treatment Plant found aquifer properties were generally unchanged since the wells were constructed (Tetra Tech, 2017).

The regional aquifer is interpreted to recharge seasonally by water moving along faults present on Crow Mountain and the Shahtlah Mountains, located up-gradient of the Old Crow community (CH2M, 2016).

3.5 Local Hydrology

The community is surrounded by several water bodies, including the Old Crow River to the east and the Porcupine River to the south. There are also several lakes within the community to the north of the airport runway that appear to be remnant of a former channel of the Porcupine River. The community sewage lagoon is west of the community.

Seasonal flows measured in the Old Crow and Porcupine Rivers show maximum flow during the spring freshet (May and June), and during this time the community experiences downslope sheet wash (Figure 6), and occasionally flooding (Benkhert et al., 2016).

Figure 6: Sheet Wash Pooling Along Cutline Along Crow Mountain. Photo Courtesy of Paul Josie.

Historically, there have been severe floods in Old Crow, with the largest known events occurring in 1973 and 1991 (Figure 7). Flooding in the area is typically caused by downstream ice jams during spring break up and backwater effects on the Porcupine River. The extreme water level in May of 1991 was estimated to be approximately 248.8 metres above select datum (mASD) (based on an old datum1) as recorded by the Water Survey of Canada (WSC) via a gauging station located approximately halfway along the river front. Based on the statistical analysis of historical water level data recorded at the WSC gauging station, the return period (average estimated time between such events) for the extreme water elevation of 248.07 mASD is approximately 20 years (MH, 2020a).

[1] Most design and infrastructure elevations in Old Crow, including historical data from WSC, are relative to Old Crow local datum control monument GSC 848163, which was destroyed during upgrades to the Airport in 2006. This datum is approximately 2 m different from geodetic elevation. Recent mapping in the community is based on geodetic and thus care must be exercised to know which reference system elevations are relative to. Currently the recommended practice is to retain elevation relative to the local historical datum to avoid confusion.

Figure 7: Old Crow Flooding in May 1991. Photo curtesy of the Yukon Government.

3.6 Local Climate

The climate is dominantly defined by the winter season (October to mid-May), which is generally a long, bitterly cold period with short, clear days, relatively little precipitation, and low humidity. The sun does not rise above the horizon for two weeks during the winter and remains above the horizon continuously for two weeks in the summer. Summers are generally short and mild.

Warming and/or thawing of permafrost due to climate change have been recorded throughout the north (CSA Group, 2019a). Climate change is a significant challenge for northern communities, and community-based adaptation planning must consider the impacts of climate change on permafrost in the development and management of infrastructure.

Canada's Changing Climate Report, which was released in April 2019 (Bush and Lemmen), reported that between 1949 and 2016, the Canadian Arctic experienced a 2.3 ̊C rise in average annual temperature, which is three times the global rate. Enhanced warming for Canada as a whole and for the Canadian Arctic in particular, is part of a climate phenomenon known as "Arctic Amplification".

In acknowledgement of the global climate crisis, on May 19th, 2019, the Vuntut Gwitchin Council gathered in Old Crow and declared a climate emergency, titled "Yeendoo Diinehdoo Ji'heezrit Nits'oo Ts'o' Nan He'aa" (After our time, how will the world be?) (VGFN, 2019).

3.6.1 Contemporary Climate

A weather station has operated at the Old Crow Airport with limited interruptions since the early 1950's. Based on climate normal data collected by Environment Canada between 1981 and

2010, the mean annual air temperature in the area is -8°C, with the daily minimum and the daily maximum being -13°C and -3°C, respectively. The average daily temperature in January, the coldest month of the year, was -29°C, while the average daily temperature in July, the warmest month of the year, was 15°C. The average annual precipitation was recorded as 277 mm (Environment Canada, 2019).

The climate normal data for Old Crow are summarized and presented month-by-month in Figure 8.

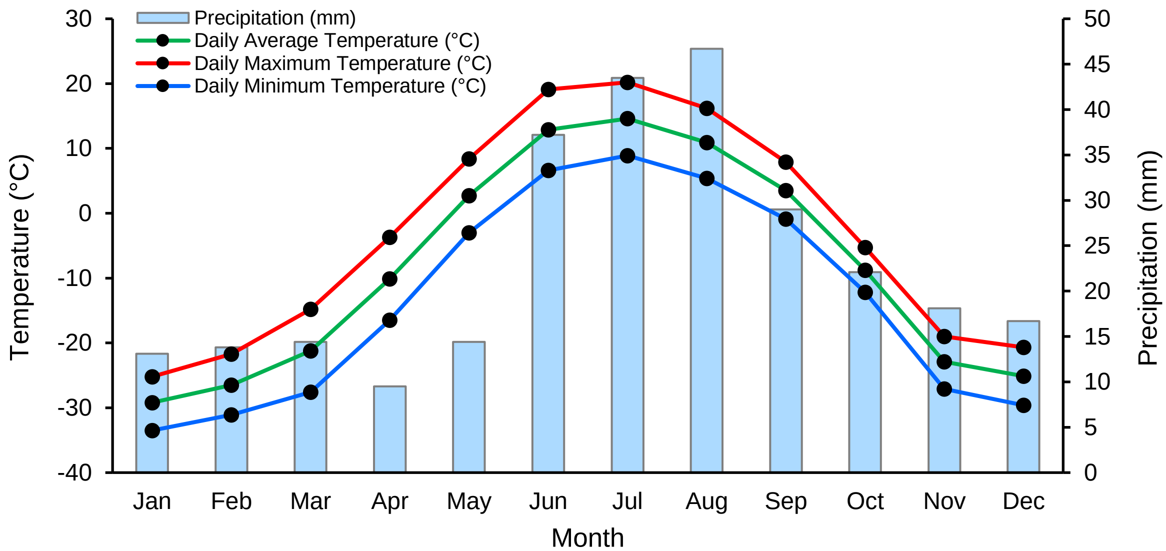

Figure 8: Climate Normals (1981 - 2011), based on data from Meteorological Station "Old Crow A" (YOC) (Environment Canada, 2019).

Studies in the southern Yukon has shown that a relationship exists between surface lapse rates (the relationship between air temperature and elevation) and the probability of permafrost (Bonnaventure et al., 2012). Work in the Dawson area has indicted that the warmest locations on an annual basis are at the tree line, a consequence of the pooling of cold air in the valley bottoms in winter, which offsets the more normal warmer conditions in the valley bottoms in the summer (Lewkowicz and Bonnaventure, 2011).

3.6.2 Projected Climate

Warming and/or thawing of permafrost due to climate change have been recorded throughout the north (CSA Group, 2019a). The Intergovernmental Panel on Climate Change (IPCC), has developed climate change scenarios spanning a range of possible greenhouse gas (GHG) concentration trajectories, known as a Representative Concentration Pathways (RCPs). The RCPs are consistent with a range of possible future anthropogenic GHG emissions and represent atmospheric concentrations.

The RCP were adopted by the IPCC for the Fifth Assessment Report (AR5), released in 2014. There are four RPCs which are named based on their radiative forcing values (the difference between solar energy absorbed by the Earth vs. energy radiated back to space) in the year

2100 (in W/m^2, respectively). RCP 8.5 is the path we are currently on and is the most extreme. RCP 8.5 assumes that radiative forcing reaches greater than 8.5 W/m^2 by 2100, and then continues to rise for some amount of time (IPCC, 2020; SNAP, 2020).

For the purpose of determining the potential change in climate conditions in Old Crow, the projected RCP scenario in regard to air temperature and precipitation for the area have been summarized in Table 3 and Table 4, below. The summarized projected climate conditions are based on publicly available data, provided by the Scenarios Network for Alaska and Arctic Planning (SNAP) (using baseline Climate Research Unit (CRU) data and projection downscaling using ~18km CRU grids).

Table 3: Summary of Projected Increases in Temperature for Future Decades.

RCP	Month	Temperature (°C)					
		2020-2029	2030-2039	2040-2049	2050-2059	2060-2069	Change
8.5	January	-30	-29.1	-27.9	-27.3	-25.9	4.1
	July	15.2	15.5	16.8	17	17.5	2.3

Over the course of the projection (2020 to 2069), the projected models show an increasing air temperature over time for the Old Crow area, and with a greater increase in the winter (January), than in the summer (July). Between 2020 and 2070, air temperatures in January are projected to increase by 4.1°C, while air temperatures in July are expected to increase by 2.3°C.

Precipitation in January is projected to stay the same, while precipitation in July is expected to increase by up to 9 mm, resulting in wetter summers.

Table 4: Summary of Projected Increases in Precipitation for Future Decades.

RCP	Month	Precipitation (mm)					
		2020-2029	2030-2039	2040-2049	2050-2059	2060-2069	Change
8.5	January	11	9	11	11	11	0
	July	41	43	39	37	50	9

3.7 Local Vegetation

The Old Crow area is capable of supporting stands of black spruce, tamarack and minor white spruce, with ground cover of dwarf birch, willow, ericaceous shrubs (such as blueberry and Labrador tea), cottongrass, lichen, and moss (Figure 9 and Figure 10). Cryosols, the soils formed under conditions of permafrost, in the area either consist of static cryosols (no cryoturbation, mineral parent material, ≤1 m depth to permafrost) on sandy alluvial material or turbic cryosols (cryoturbated, mineral parent material, ≤2 m depth to permafrost) on lacustrine deposits (Ecological Stratification Working Group, 1995). Trees in the area may appear stunted or with a “bent knee”, in-part due to the underlying permafrost marking the limit of rooting or changing conditions in permafrost causing displacement from normal vertical alignment. The tree line sits at approximately 600 masl, along Crow Mountain (Smith et al., 2004), above which only low-lying ground vegetation is supported (Figure 11). Due to the subarctic climate, the growing season in Old Crow is short, but intense because of the long periods of daylight.

The vegetative mats present in and around the Old Crow area, largely consist of moss, along with lichen and Labrador tea. Moss cover plays a significant role in heat exchange at the surface in Arctic environments. It has a low thermal conductivity in the summer and a high thermal conductivity in the winter, leading to lower mean annual temperatures through facilitating cooling and storage of cold within permafrost (Riseborough and Burn, 1988). A study carried out in northern Alaska supports this theory, as it indicated that the addition of 10 cm of moss, can result in almost a 3°C decrease in mean summer soil temperature and a reduction in thaw depth (Kade and Walker, 2008).

Figure 9: Ground vegetation, including Caribou Lichen, Labrador Tea, Moss, etc.

Figure 10: Stands of Spruce Along Crow Mountain Road.

Figure 11: Sparse Low-Lying Vegetation Above Tree Line on Crow Mountain.

3.8 Local Hazards

Geoscience mapping was completed for Old Crow, for climate change adaptation planning purposes in 2016 (Benkert et al.). Hazard maps were developed by the Northern Climate ExChange (NCE). The maps were created to help identify potential future risks associated with natural phenomena such as permafrost thaw, landslides, and flooding. The maps delineate and/or highlight areas on land that are affected by, or vulnerable to, a specific hazard, and also rank by risk severity.

4. PERMAFROST

4.1 Formation and Degradation

Permafrost is any ground (soil, rock, or organic material) that remains at or below 0°C, throughout the year, for at least two consecutive years (IPA, 2008). The ground above permafrost that thaws each summer and refreezes each fall and winter is the active layer. Permafrost is thaw sensitive as it usually contains ice in various forms, from non-visible pore ice (i.e., within the pores of soil or rock) to visible ice lenses and veins, to massive bodies of ice (Risborough et al., 1990) (Figure 12 and Figure 13).

Permafrost can either be thaw-stable or thaw-unstable (a.k.a. thaw-sensitive). Poorly drained, fine-grained soils are thaw-unstable, as the ice content is typically high. Thaw-unstable soils will significantly settle or even flow upon thawing. Bedrock, well drained coarse soils, and clast supported material are more thaw-stable, and do not usually experience significant loss of strength upon thawing.

Figure 12: Visible Ice Lenses in Intact Section of Soil from Subsurface in Old Crow

Figure 13: Ice Rich Interval Encountered during Drilling of Borehole in Old Crow.

Permafrost is a climatic phenomenon that may take decades to centuries or millennium to form and/or degrade, although degradation can be accelerated from human and environmental disturbances such as wildfire, extreme climate events, poor drainage, exposure, construction, changes in land use, and surface vegetation damage or removal (CSA Group 2019a-b). Permafrost is an indicator of past and current climates. The upper layer is subject to seasonal temperature fluctuations, both regionally and site specific, and typically with a lag in reaction; while at greater depths (>10-20 m), the temperature regime reflects climatic conditions of earlier periods (Risborough et al. 1990).

Permafrost is sometimes referred to as “warm permafrost” or “cold permafrost”. Warm permafrost generally refers to permafrost within discontinuous permafrost zones with a mean annual ground temperature of between 0°C and -2°C, while cold permafrost is found in continuous zones and have mean annual ground temperatures lower than -4°C. It is generally accepted that warm permafrost has a higher risk of degradation due to climate change and anthropogenic effects. Permafrost with mean annual ground temperatures of between -2°C and -4°C will behave as either warm or cold permafrost depending on the ground ice content and soil composition (CSA Group, 2019a).

Annually, heat transferred into permafrost due to the thaw season is removed or compensated for during the freeze season, maintaining the established upper limit of the permafrost known as the permafrost table. Disturbance to the surface temperature of the ground, adding energy to the thermal regime of the permafrost without any compensating heat removal, will force the permafrost table to lower in depth (increasing the active layer thickness) and reach a new equilibrium (Brown, 1963; Mackay, 1970). Ground surface temperatures are determined by the interaction between climate and surface conditions, and the degree of ground temperature response to surface temperature depends on the thermal properties of the ground (e.g., thermal conductivity, heat capacity as they relate to ground material, ice/water content etc.). Vast differences in ground thermal conditions may occur within areas with the same air temperature, influenced by site specific factors (Risborough et al. 1990).

The presence of water at ground surface can have a significant impact on ground temperature, including smaller volumes of accumulation along the side of roads where drainage is not adequate, or larger bodies like lakes or rivers where the temperature at the bottom does not drop below 0°C. The unfrozen ground around and below lakes and rivers are known as talik (CSA Group 2019a-b).

The main features of the ground temperature regime in areas of continuous permafrost, including the mean annual ground temperature, the temperature envelope (defined by seasonal maximum and minimum temperatures at specific depths), the permafrost table (a.k.a. base of the active layer), and the depth of zero annual amplitude (the depth below which there is no seasonal variation in ground temperature), are presented on Figure 14.

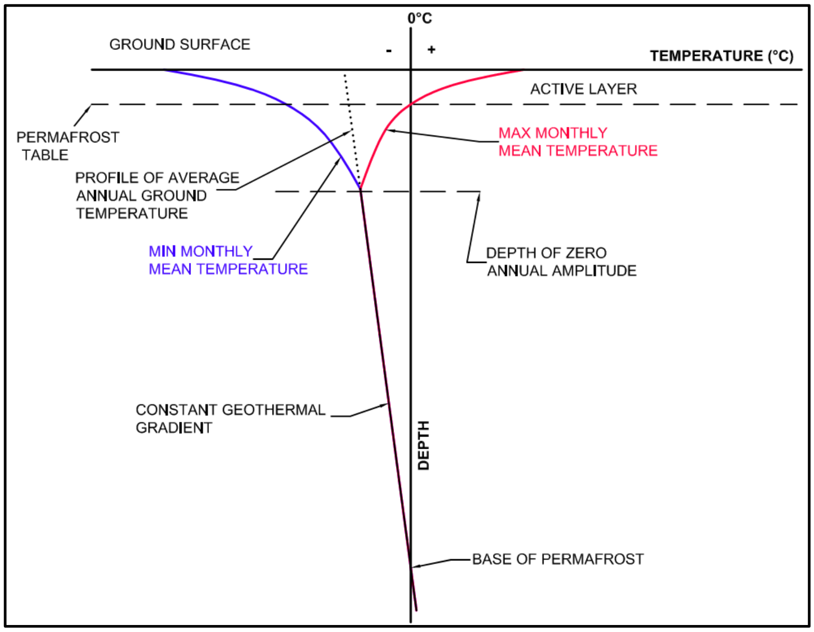

Figure 14:Temperature Profile for Permafrost (Modified from Osterkamp and Burn, 2003).

4.2 Effects of Surface Disturbance on Permafrost

Activities often related to site preparation and construction of infrastructure, such as vegetation clearance, surface grading, and removal or compression of the organic layer, usually result in an increase in ground temperature, disparate from the effects of climate change (CSA Group, 2019a). Land use practices (e.g., snow management, water tank overflows) and the infrastructure itself (e.g., heated structures close to ground, faulty eavestroughs, restricted ventilation) may also result in an increase in ground temperature (CSA Group, 2021).

For example, clearing and construction associated with a pipeline right-of-way in Norman Wells (NWT), has caused at least a 2°C temperature increase in mean annual ground surface temperature compared to the adjacent undisturbed areas (Riseborough et al., 1990). The installation of snow fences near Barrow (Alaska), and along the Dempster Highway (Peel Plateau, NWT) has been shown to cause warming of the ground and upper permafrost thaw (Hinkel and Hurd, 2018; O'Neill and Burn, 2015).

4.3 Site-Specific Factors that Affect Permafrost Conditions

The CSA Technical Guide titled, *Design and construction considerations for foundation in permafrost regions* (CSA Group, 2019b) defines five main site-specific factors that are known to affect the temperature of permafrost, as summarized in Table 5.

Table 5: Summary of Five Main Site-Specific Factors Affecting Ground Temperature (CSA Group, 2019b).

Site Specific Factor	Effect
Snow	Snow can act as insulation to the ground due to its low thermal conductivity, keeping it warmer than that which would occur under less abundant cover, or snow-free conditions. Early snow (> 50 cm) can reduce heat loss from the ground to the air, causing warmer ground temperatures in winter, while late winter snow results in colder ground temperatures. Construction activities and new structures change the distribution and accumulation of snow at a site by altering snow drifting patterns.
Vegetation Canopy	Vegetation canopy (trees, willows, etc.) reduces the amount of solar radiation reaching the ground surface (a.k.a. provides shade) and has a variable impact on snow accumulation and persistence of cover.
Mosses and Peat at Ground Surface	Moss and peat, which makes up the vegetative mat at surface in the north, moderates the transfer of heat in and out of the ground. Thereby, it significantly influences the thickness of the active layer below. Evaporation from peat also disperses much of the heat otherwise available to warm the ground in the summer. When dry, peat acts as an affective insulator.
Thermal Properties of the Soil or Bedrock	The latent heat of the ground (heat used to thaw ice) aids in controlling the response of permafrost to surface warming, while the thermal conductivity is a function of water content, density, mineralogy and organic content, and other factors. In dry ground or relatively cold permafrost, where ground can warm without melting ice, the response to a change in surface temperature can be rapid.
Water Bodies/Accumulation	Water bodies that accumulate on the side of the roads or where drainage is not adequate, have a significant impact on ground temperatures.

4.4 Impact of Warming on Frozen Soil Strength

Serious impacts are associated with the warming of permafrost and the melting of shallow ground ice under existing infrastructure. This is due to the apparent strength presented by the ice lenses/veins and the pore ice, which binds the soil particles together. Through thawing, the permafrost transforms; excess water content causes an increase in porewater pressure and reduces the strength of the soil before it drains. As the excess water drains, subsidence occurs (also called thaw settlement or thaw consolidation), and on sloping ground may even result in mass movement (e.g., landslides, slumps, debris flows). Rapid and high magnitude warming of air temperatures and/or ground temperatures will most dramatically impact the foundations of existing structures.

Poorly drained, fine-grained soils (silts and clays) are especially thaw-unstable, while bedrock, well drained coarse soils (sand), and clast supported materials (gravels, and rockfill) are more thaw-stable, and movement when thawed is diminished. Unsaturated (a.k.a. ice poor, where the volumetric water content of the ground is lower than the volume of the soil pores) or dry permafrost does not generally pose a high risk upon thawing, as there is no excess water content as water will remain in the soil porosity or will drain away.

As frozen soil warms and approaches 0°C, the creep or deformation rate increases. Under constant load, ice-rich soil will creep at a predictable rate which may be considered when determining design loads for a structures service life, to restrict deformations to acceptable limits.

Soil salinity and organic contaminants (e.g., hydrocarbons from a spill) may augment the reduction of permafrost strength with warming. Soil salinity can result in freezing point depression (Hivon and Sego, 1995) at a rate of 0.28°C for every 5 parts per trillion (ppt) of salinity. Old Crow is not situated on an Arctic coast; however, the presence of salinity is not only limited to former marine environments.

The active layer experiences cyclical warming, lagging slightly behind the seasonal air temperatures. This can result in frost heave/jacking with freezing of water in the active layer, expanding, and pushing things upwards. The magnitude of frost heave depends on soil type, rate of freezing, and water content.

4.5 Description and Distribution of Permafrost in Old Crow

Old Crow is within the continuous permafrost zone (Heginbotom et al., 1995). Since 1982, over 100 boreholes have been advanced and over a dozen ground penetrating radar (GPR) and electrical resistivity tomography (ERT) transects have been completed. These exploratory techniques were carried out for environmental and/or geotechnical purposes. The vast majority of the boreholes drilled were terminated soon after reaching the permafrost table; those that extended into the permafrost were likely often for the purpose of installing thermistor strings for ground temperature monitoring. A limited number of boreholes were completed to evaluate talik extents around the Porcupine River, and two boreholes were advanced through the permafrost and into the regional aquifer below to source a local water supply. Through these activities, the permafrost conditions and extent in the Old Crow area have been more or less characterized. The data is considered inexact as the depth to frozen ground is seasonally dependent and these investigations are disparate, having been carried out at different times of the year (though often in the summer and fall) and over a significant period of time (~40 years), and changes to the permafrost table may have occurred.

Existing borehole data was obtained via the Yukon Government from the YGS Permafrost Database[2], along with previous investigation reports (EBA, 1982 & 2011; CH2M, 2016; Benkert et al., 2016; MH, 2020a-c). The data within the YGS Permafrost Database has been integrated (along with data from other branches of the Yukon Government) into a publicly accessible web application for permafrost related data by the Yukon Government, and is called the Yukon

[2] YGS Permafrost Database contains information from previous investigations related to the Old Crow airport and grader station, airport refueling facility, aircraft apron/parking area, water supply, sewage lagoon, 3-bay garage, and new generator building.

Permafrost Database. This database is a valuable resource and was developed to make permafrost data available to a variety of users, including governments, academics, consultants, and the public.

In areas absent of any nearby borehole data, ERT and/or GPR survey data was reviewed (Benkert et al., 2016). The available data was from several sites in the community, including along Crow Mountain, within the community core, nearby north road, and nearby the local ski lodge. The approximate borehole and ERT/GPR transect locations and the depth to frozen ground (or the average depth of frozen ground for the transects) are presented on Figure 15 and Figure 16.

Based on the available data, the active layer thickness generally ranges from 0.5 to 3.5 m, and the observed geology is consistent with the characteristics expected for the geological setting. Ice rich permafrost is not ubiquitous, but it is common; particularly at shallow depths with insulating organic cover and/or finer textured soils, with ice content percentages ranging up to greater than 95% by total volume. The ice may be visible (lenses, veins, grains, massive layers, etc.) or nonvisible. Ice rich permafrost may even be present in moderately to well-drained materials underlying the community.

Near surface permafrost (<1m) is encountered on most slopes and level valley-bottoms with the insulating cover of organic material and/or finer textured soils. Given the high volumetric ice contents present, equivalent natural moisture content for thawed samples can be greater than 100%, as noted for the proposed new Health Centre location (Tetra Tech, 2019), which would be considered super-saturated soil. Based on the drilled water supply wells, the base of the permafrost is as deep as 60 mbgs, terminating in the underlying sandstone bedrock.

Deviations in permafrost depth (extending to ~3 to 4 mbgs) have been observed and linked to the presence of gravel pads or roadways and shrubbed areas resulting in snow accumulation in the winter months, increasing insulation. Variations in permafrost depth (extending to > 4 mbgs) were also observed under some older abandoned houses or lots located to the east of the tank farm, interpreted as having a deep seasonal thaw or a supra-permafrost talik. Potential talik have been encountered under or nearby gullies, streams, ditches, nearby the Solid Waste Management Facility, and under the John Tizya Centre. A talik is also present around the Porcupine River and may be present around the small lakes within the community, located to the north of the airport runway. Taliks exist beneath and/or around water bodies that do not freeze solid in the winter. Borings advanced to 18 m depth in the overburden of the north bank of the river did not intercept frozen ground. Open talik are also suspected to be present in the ground surrounding the drinking water supply (<30 cm in radius around each well), due to the pumping of relatively warm water from the wells (EBA, 1982).

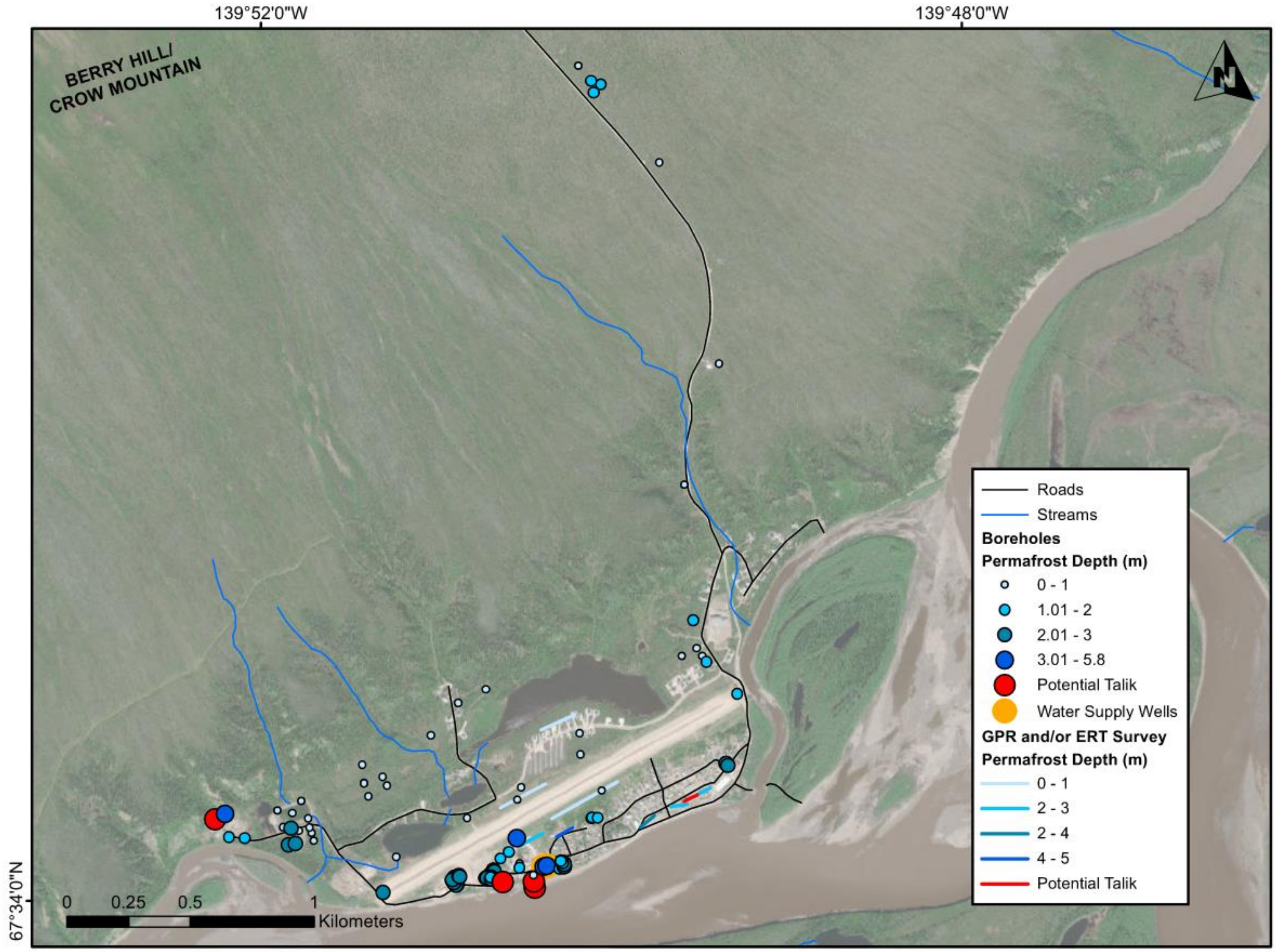

Figure 15: Available Borehole Data and ERT and/or GPR Survey Data Locations, Along with Permafrost Depths (YGS Permafrost Database; CH2M, 2016; Benkert et al., 2016; MH, 2020a-c).

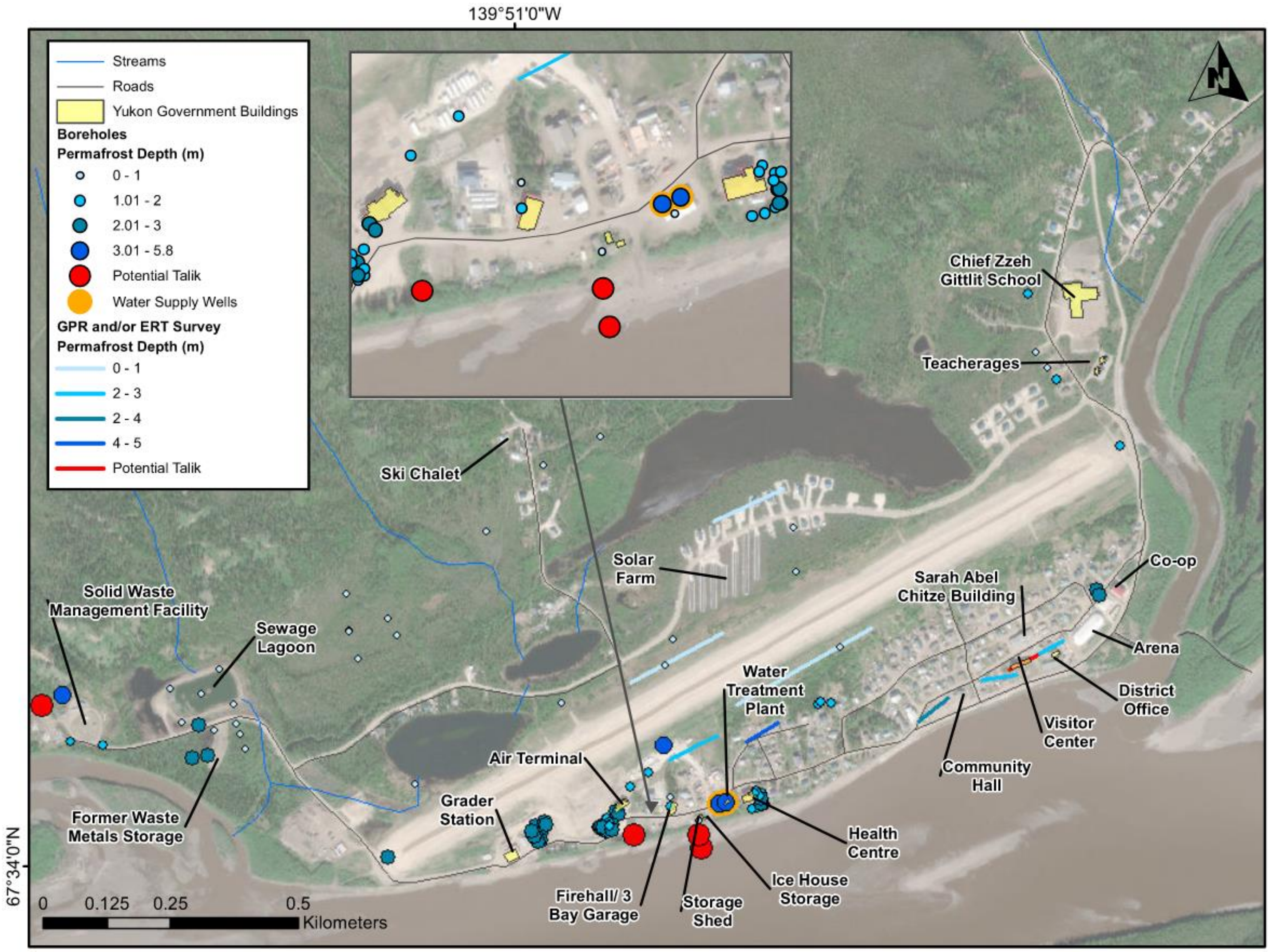

Figure 16: Available Borehole, ERT, and GPR Data Locations, Along with Permafrost Depths (YGS Permafrost Database; CH2M, 2016; Benkert et al., 2016; MH, 2020a-c), and Yukon Government Buildings Along with Other Community Sites.

Porewater salinity of permafrost was measured for a number of samples from various strata encountered in boreholes as part of previous geotechnical investigations in Old Crow. Soil samples from half-way up Crow Mountain and from the low-lying area east of the sewage lagoon, all reported soluble salt concentrations of ≤1 parts per trillion (ppt) (Thurber, 2020), and samples collected from the proposed new location of the Health Centre in the eastern portion of the community (nearby the Chief Zzeh Gittlet School) reported similarly low concentrations, between 1 and 3 ppt (Tetra Tech, 2019).

The presence of organic contaminants (such as hydrocarbons from a spill) in permafrost may reduce the soil strength (CSA Group, 2019b). Petroleum hydrocarbon contaminated soil has been investigated and characterized at the Old Crow Health Centre, the Airport Refueling Facility (ARF), and the Airport Maintenance Fuel Facility. These sites are planned for restoration, with contaminated material removed and to be treated via bioremediation at a future local Land Treatment Facility.

Benkert et al. (2016), classified the seven different soil types found in Old Crow as part of a geotechnical study. The permafrost risk associated with the different soils, is summarized in Table 6 below.

Table 6: Summary of Permafrost Risk Associated with Different Soils in Old Crow.

*Risk of Permafrost Related Instability	Surface Material Type (USCS)	General Description for Permafrost Conditions
Lower	**Sand**	Medium to coarse sands are well drained and do not contain excess ice and are not frost or thaw susceptible. Fine sands can contain excess ice and are frost and thaw susceptible. Upon warming fine sands will result in thaw settlement and will drain slowly.
	Silty-sand and Sandy-Silt	Coarse silt and fine sand may contain a significant amount of excess ice in various forms and be thaw-unstable. However, if unsaturated (therefore with no excess ice) would be mechanically stable upon thawing.
	Silty Sand with Gravel	Silty sand and gravel, if saturated, may contain a significant amount of excess ice and be thaw-unstable. If present in unsaturated condition (therefore with no excess ice), would be thaw-stable as water would remain in the soil porosity.
	Sandy Organic Silt	Organic matter increases water retention capacity of sandy organic silt and may be ideal conditions for development of excess ice in permafrost. Organic matter has a high compaction potential and therefore an increase in settlement potential under load.
	Silt	Silt drains slowly and is highly frost susceptible. When present in the active layer (with available water), is susceptible to frost-heave settlement. The presence of silty layers at or below the permafrost table generally comes with ice rich and therefore thaw-unstable upper permafrost.
Higher	**Peat**	Peat is highly porous and therefore can retain water and has a high compaction potential. In permafrost, it is usually ice rich and upon thawing, drains, and has a high settlement potential under load.

*This a general ranking of risk; actual risk would depend on specific soil conditions, e.g., sand is not always lower risk than silty sand with gravel, depending on respective saturations.

In 2006, a thermistor cable was installed to a depth of 16.5 m on a terrace of the Porcupine River, approximately 3.5 km west of Old Crow (elevation of 250 masl). The area was described as taiga with an understorey of tall shrubs. The subsurface stratigraphy consisted of organic matter over organic-rich silt, above sand with gravel lenses. The annual mean ground temperature at a depth of zero annual amplitude for 2013 was -3.1°C (Roy-L´eveillee et al., 2014). Similarly, per the Global Terrestrial Network for Permafrost (GTNP) (as input by the Yukon Geological Survey, 2014), the mean annual ground temperature for Old Crow is -3.3°C.

Ground temperatures have been measured at significant depths in the community, due to the installation of permanent thermistor strings with data loggers at multiple locations. Ground temperatures measured via strings installed at a depth of 15 mbgs (within sandy overburden) at the proposed new location for the Health Centre were -2.2°C to -1.7°C, and the geothermal gradient calculated for this area (using a permafrost base depth of 60 mbgs), was approximately 0.048°C (Tetra Tech, 2019). A deeper thermistor string installed near the Water Treatment Plant found colder temperatures in silty soil, approximately -3.5°C at 15 mbgs (EBA, 1982). Ground temperatures in that borehole increased with depth including past the bedrock interface, reaching 0°C at 60 mbgs.

Ground temperature data was also collected for a full year via permanent thermistor installations at the two potential Land Treatment Facility locations in Old Crow. The annual ground temperatures measured at 10 mbgs (within silty gravel overburden) at the potential LTF site located to the east of the sewage lagoon (along the ski trails) ranged from -3.2°C to -2.0°C. Ground temperatures measured at the potential LTF location along Crow Mountain (approximately 380 masl), at a depth of 10 mbgs and within orthoquartzitic sandstone bedrock, ranged from -1.0 °C to -0.8°C. At a separate installation nearby, terminated at 6 mbgs and within colluvial overburden, the annual temperatures ranged from -1.3°C to -0.7°C (MH, 2020c). The bedrock permafrost was warmer and experienced less temperature variation annually, when compared to the shallower overburden.

There are also visible indicators of the presence and changing conditions of permafrost in and around Old Crow. Trees and land along the bank of the Porcupine River in some areas are slumping into the river (Figure 17), possibly as a result of the permafrost retreating deeper into the earth causing the land above to start to slide. The banks are also often rectilinear, possibly from wave action removing slumped sediment from the bank foot, allowing contact between the water and permafrost, resulting in thermal erosion.

Figure 17: Tree Slumping Along the Riverbank in Old Crow (September 2021).

Active layer detachment slides, a type of fast periglacial mass wasting where thawed or thawing portion of the active layer detaches from the underlying frozen material and moves downslope may also occur in Old Crow. These may be triggered by rapid thawing from forest fires, and hot and/or wet weather. In late summer of 2010, heavy rainfall resulted in seven landslides in the community of Old Crow, and three of them impacted infrastructure. One of the slides was an active layer detachment slide beside the Crow Mountain Road and deposited debris on the roadway. Two other slides combined, deposited debris within 40 m of a residence (Benkert et al., 2016). Trees with knees, which is evidence of slope movement, possibly due to changing permafrost conditions are also visible in some areas of the community.

4.6 Existing Ground Temperature Monitoring Locations in Old Crow

Known ground temperature monitoring instruments (thermistor ports, strings, etc.), in Old Crow and their approximate locations are summarized below. There is no guarantee that these instruments are active, accessible, or in good condition. It is understood that the majority of these instruments were installed as part of investigations completed on behalf of or in cooperation with the Yukon Government.

- Meteorological station with buried thermistor cables along Site 17, east side of Crow Mountain Road, approximately half-way up the mountain, and also at another station located 3 km downstream of Old Crow nearby Portage Trail (Benkert et al., 2016).
- At two potential LTF locations, LTF 2, located along the cross-country ski trails in a low-lying area to the east of the sewage lagoon, and LTF 10, located on Crow Mountain, to the east of Crow Mountain Road (Thurber, 2019; MH, 2020a,c).
- Thermistor strings installed near the water supply wells in 1982 (EBA, 1982).
- Multiple thermistor strings installed at the Old Crow Health Centre (MH, 2020a). Proposed Health and Wellness Centre, located in the eastern part of the community, nearby the Chief Zzeh Gittlet School (EBA, 2011; Tetra Tech, 2019).
- Thermistor strings and/or ports have been installed at the Aviation Refueling Facility and the Airport Maintenance Fuel Facility (Aperture, 2018). Thermistor cables may also be installed at the air terminal building (Tetra Tech, 2018).

- Thermistor cables are installed under the Chief Zzeh Gittlet School (Tetra Tech, 2018).
- Ground temperature monitors at present at three locations (western and eastern portions of the community and just up the road on Crow Mountain), though the exact locations are not known. They were installed and are managed by Yukon University Research Centre (in partnership with others) to monitor permafrost conditions (YukonU, 2021).

The only thermistor strings from the above list that are known to be operational are those at the potential LTF locations and the Health Centre, which are equipped with data loggers and monitored by the Site Assessment and Remediation Unit of the Yukon Government.

Ground temperature monitoring systems with thermistor strings likely are set up as a data logger system, with the string hooked up with a data logger (electronic device) which automatically monitors and records the environmental parameters such as temperature over time, allowing conditions to be measured, documented, downloaded, and analyzed. These electronic systems usually run off a battery and, depending on the system installed and the frequency of autonomous data collection, the system may operate on the same battery for multiple years. Any accessible data loggers installed without any available battery life remaining, could have the batteries replaced and the system redeployed.

5. GUIDELINES AND PRINCIPLES FOR DEVELOPMENT ON PERMAFROST

5.1 Site Screening and Useful Resources

Overall decision making for infrastructure development should consider first maximizing the use of existing infrastructure and minimizing the footprint of new land development, for both protection of the permafrost and to support sustainable use of the local aggregate resources.

For all construction projects in Old Crow, all reasonable care should be taken to ensure that detrimental conditions are not produced by changes in, or disturbance of, the existing permafrost environment. The community is within a region underlain by continuous permafrost and therefore proper attention must be given in the early project stages to site selection, and structure design. Per the *Government of Yukon Design Requirements and Technical Standards Manual* (2020), all projects in permafrost are to include risk-based screening to assess the structure in terms of permafrost sensitivity and failure consequences. Application of the screening process will achieve a preliminary determination of the level of climate warming related risk associated with the project and the design services required to address the risks. It also facilitates appropriate structure design. Guidance to perform such a screening can be found in CSA Plus 4011-10, *Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation*.

Significant consideration needs to be given to the expected conditions and the existing conditions for the lifespan of the structure, and to site reclamation following construction. The *Design Requirements and Technical Standards Manual* (2020) notes that for new buildings, a full assessment with data from boreholes located on-site will be required to allow for proper assessment of the site to determine whether there are any conditions that could impact project viability. Additionally, all buildings constructed on permafrost must be provided with a means for leveling within a range specified by the structural engineer. Correspondingly, per the Old Crow Zoning Bylaw (#02-2014) (VGG, 2014), for new construction and all works and changes in use, must comply in all respects with provisions of the *Yukon Building Standards Act* (RSY 2002 c.19). The bylaw also states under general regulations, that in regard to permafrost, all areas outside of the existing development zones must have geotechnical approval prior to construction, and new heated construction must be stamped by a civil engineer to show that heat intrusion to permafrost will not occur due to development.

Any required subsurface investigations such as geotechnical or hydrogeological investigations should be carried out through minimally destructive means, appropriate to the level of detail and reliance required, such as drilling and/or geophysical surveys.

There are a number of useful resources identifying design requirements, technical standards, and/or best practices, when it comes to new construction and building practices in northern regions overlying permafrost, as summarized in Table 7. These resources may be relevant at the site screening stage of any future infrastructure project in Old Crow.

Table 7: Summary of Useful Resources for Screening and New Construction in Old Crow.

Resource	Description
Government of Yukon, Design Requirements and Technical Standards	This document provides standards, strategies, and technical requirements for the planning, design and construction of new buildings, additions, renovations, major system upgrades, and maintenance projects for the Government of Yukon (June 2020). Website Link: Government of Yukon, Design Requirements and Technical Standards
Vuntut Gwitchin Government – Old Crow Zoning Bylaw #02-2014	This document is a statement of objectives and policies to guide planning and land use management decisions within the community of Old Crow, in accordance with the provisions of the Vuntut Gwitchin First Nation Final Agreement (2014). Website Link: Vuntut Gwitchin Government – Old Crow Zoning Bylaw #02-2014
CAN/BNQ-2501-500: Geotechnical Site Investigation for Building Foundations in Permafrost Zones	This is a national standard that describes how to perform geotechnical site investigations to aid in designing building foundations. It takes into consideration (in a risk management framework) the conditions at the building site including local and distinct permafrost characteristics, seasonal and inter-annual climate conditions, and projected climate conditions over what will be the service life of the building foundations (2017). Website Link: Geotechnical Site Investigation for Building Foundations in Permafrost Zones
CSA PLUS 4011:19 Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation	This document provides information on the issues related to the design and construction of foundations in permafrost regions. Provides guidance on completing risk-based site screening to assess potential structures in terms of permafrost sensitivity and failure consequences (2019). Website Link: Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation
CSA PLUS 4011.1:19 Technical Guide: Design and construction considerations for foundations in permafrost regions	This is a guideline for climate change adaptation. The intent of the document is to provide stakeholders with information on the potential impacts of climate change on infrastructure in Canada's permafrost regions (2019). Website Link: Technical Guide: Design and construction considerations for foundations in permafrost regions
CAN/CSA S503:20: Community Drainage System Planning, Design, and Maintenance in Northern Communities	This Standard specifies the minimum planning, design, and maintenance requirements for community drainage systems in Canada's northern communities. The purpose of this Standard is to increase the capacity of communities and individuals to prepare and implement effective community drainage plans (2020). Website Link: Community Drainage System Planning, Design, and Maintenance in Northern Communities
***Yukon Building Standards Act* (RSY 2002 c.19).**	This Act was prepared by the Yukon Legislative Counsel Office. Website Link: *Yukon Building Standards Act*

Resource	Description
CAN/CSA-S500-21: Thermosyphon Foundations for Buildings in Permafrost Regions	This Standard specifies guidelines or standards for the design, construction, and maintenance for thermosyphon supported foundations (2021). Website Link: Thermosyphon Foundations for Buildings in Permafrost Regions
Good Building Practice for Northern Facilities, Government of the Northwest Territories	This guide presents practice recommendations learned over many decades of cold region experience while incorporating modern and effective technologies and methods involving all aspects of northern infrastructure. Touches environmental regulations/permitting, climate change impacts and permafrost conditions, geotechnical, civil, structural, architectural, mechanical, and electrical considerations, energy efficiency, and accessibility for persons with disabilities (March 2021). Website Link: Good Building Practice for Northern Facilities
National Building Code of Canada 2015	This code was published by the National Research Council of Canada (NRC) and developed by the Canadian Commission on Building and Fire Codes, sets out technical provisions for the design and construction of new buildings. Website Link: National Building Code of Canada 2015

5.2 Site Preparation

Following the necessary site-specific investigations required as part of the site screening process for the construction of infrastructure, careful site preparation is important, as it may negatively impact the thermal regime of the permafrost. General site preparation approaches in permafrost regions as adapted from CSA PLUS 4011:1:19, includes the following:

- Leave surface organic mat in-place and reduce the disturbance of the mat to the greatest extent practical. Often infrastructure projects require a base layer of granular fill to either level the surface of the site or act as an engineered pad on which to construct a structure. Even in a compressed state, the organic mat will to some degree insulate the permafrost soils below, while separating them from the imported fill above.
- If infrastructure is to be developed in a treed area, it is desirable to minimize disturbance to the ground surface during any tree removal activities.
- The thickness of engineered fill can have a positive or negative effect on the geothermal regime. Thin mineral soil fills can induce long-term permafrost degradation, whereas thick mineral soil fills can induce permafrost aggradation. The desired outcome of fill placement is to achieve a neutral geothermal balance.
- Timing of the site preparation - it can affect the ground thermal regime (e.g., locking the summer heat into the foundation if fill or thermal insulation is placed at the end of the summer); or it could result in inadequate compaction (e.g., if frozen fill is used and compacted during the winter). Fill should be thawed prior to placement and compaction. If possible, building pads could be placed one year in advance and relevelled prior to the

installation of the structure. Closing buildings in before severe winter conditions set in is critical.

- Avoid excavating/cutting into existing soils of the active layer and permafrost. This exposes frozen soil causing degradation.

5.3 Considerations for Foundation Design

Foundations for most northern buildings are designed for light structural loads, recognizing the limits imposed by partially or permanently frozen soils. Buildings are often elevated above ground surface to eliminate heat flow from the building into the thaw susceptible soils below (supported by steel piles or wood/metal framing system etc.). Alternatively, they are set on grade, but utilize a thermosyphon or other sub-floor ventilation/heat extraction and control system.

Elevated buildings require careful design of air, vapour and thermal barriers because of the additional exposed exterior envelope created, compared to those on grade (Government of Yukon, 2020). There are no basements for Old Crow structures, as they are not practical. Installation of utilities in the subsurface to support infrastructure in the community is typically avoided, where possible. Where possible, it is best practise to build structures on bedrock and avoid building on permafrost terrain. Because the only exposed bedrock in the Old Crow area is at the top of Crow Mountain, and with bedrock depths halfway up the mountain of 6 mbgs, and bedrock depths within the community centre being approximately 38 mbgs, building on permafrost is necessary.

The National Building Code (NRC, 2015) states "*Buildings erected on permafrost shall have foundations designed by a designer competent in this field*" and "where conditions of permafrost are encountered or proven to exist, the design of the foundation shall be based upon analysis of these conditions by a person especially qualified in that field of work". Geotechnical investigations should be undertaken as soon as a site is identified, and well in advance of design. Geotechnical investigations should also address the availability of construction materials, schedule, vulnerability of structure to the potential for differential settlement and surface drainage that may affect the thermal regime of the foundation. Geotechnical investigations should follow the recommendations of CAN/BNQ 2501-500 (Yukon Government, 2020).

Some technical considerations for foundation design include:

- Design ground temperatures
- Subsurface conditions
- Minimum dimensions
- Lifespan of structure
- Structure tolerance for movement
- Specific utilities required
- Maintenance and repair needs
- Available materials, equipment, and labour

- Applicable building codes
- Community bylaws
- Timeline
- Construction logistics, and
- Budget

The Yukon Government Design Requirements and Technical Standards (2020) require that the installation of thermistors for all foundations in permafrost soils to allow for ongoing monitoring of ground temperatures and the design and layout of the thermistors must be carried out by a geotechnical engineer. It may take several years for permafrost temperatures to reach a new equilibrium following construction. Foundation failure does not normally occur in a short period of time; sudden collapse related to changing permafrost conditions is rare and more likely related to thermal erosion by water.

5.3.1 Foundation Types

5.3.1.1 Shallow Foundations

Figure 18:Shallow Foundation - Pad and Wedge, Old Crow.

Figure 19: Shallow Foundation - Space Frame, Old Crow.

Shallow foundations (or footings) are considered the most common foundation systems in use in northern Canada, particularly for smaller buildings such as residential buildings. These types of systems either support the building on the ground surface (i.e., pads and wedges or spaceframes), or they transfer the load to more stable permafrost/bedrock layers beneath (i.e., buried shallow footings or piles) (CSA Group, 2019a).

Shallow foundations are at risk for differential movements caused by thaw settlement or frost heave and could require periodic levelling, unless thermosyphons are installed to maintain the frozen soil beneath the footings. Sites with thick organic layers may be problematic to structures with shallow or surface foundations as organic layers have higher probability of large settlement over time.

Buried shallow footings are generally used in combination with built-up granular pads that must be of sufficient thickness and material type to protect the underlying permafrost from thawing due to heat flowing out of the building above. This can be achieved through elevating the structure to at least 0.9 m (approximately) above the pad to allow for air to circulate below the insulated floor of the building and minimized the potential for snow drifting. Larger structures, such as multi-unit dwellings or public buildings may need to be elevated greater than 1 m from the ground. Work on a gravel pad cannot typically proceed until early summer when conditions permit excavation (if required, should be avoided if possible) and proper compaction of fill (CSA Group, 2019a).

According to Allard et al. (2010), buildings construction on properly designed, compacted, granular pad foundations should not experience significant thaw settlement due to the adjustment of the thermal profile to the new geometry, leading to a rise of the permafrost table into the gravel pad and limiting the active layer to the non-frost sensitive foundation, ensuring stability over cycles of freeze-thaw. Gravel pads may also be constructed with insulant panels. Allard recommends compact granular foundations should be constructed at least two years in advance of structure construction, to allow for the permafrost table to rise and the soil to stabilize. If soft ground conditions exist, it may be necessary to install a geotextile to provide long-term separation of the aggregate base from the subgrade soil (CSA Group, 2019a).

Adequate diversion of surface runoff away from shallow building foundations is important for long-term stability. An impermeable liner could be installed to divert surface water away from the granular pads, rather than allow it to seep under or through it, to prevent potential permafrost degradation or foundation heave (CSA Group, 2019a; Yukon Government, 2020; Government of Northwest Territories, 2021).

The variations of shallow foundation types are summarized in Table 8, as adapted from CSA PLUS 4011:1:19 (2019a), *Government of Yukon Design Requirements and Technical Standards Manual* (2020) and the *Government of Northwest Territories Manual for Good Building Practice* (2021). Ultimately, shallow foundation design would be based upon the site-specific conditions and the proposed building requirements and would be completed by a structural engineer.

Table 8: Summary of Shallow Foundation Types.

Shallow Foundation Type	Basic Description
Surface Footings	Set on or near the ground surface (being generally built-up granular pad). Tends to be used for light loads, such as residential construction. If not properly anchored, buildings could be blown off footings in high winds, and they often have shortened lifespan due to movements. Variations of this foundation type include: ▪ Timber pads with wedges (Figure 18) or screw jacks - common economical variations. Constructed to ~ 1 m in height to create airspace beneath building. Limited to small buildings not likely to suffer damage from reasonable degree of movement. Low initial cost and easy to construct. Screw jacks allow for easy raising or lowering of building height. If screw jacks not available, timbre blocks can be used but requires a hydraulic jack to lift load to allow for adjustment of blocks for leveling, which is labour intensive. Building damage may result from lack of continued maintenance/levelling. Requires preserved wood pads for longevity. ▪ Timber sills - simplest variation. Seldom used except for small unheated structures. Typically, the minimum air space between pad

Shallow Foundation Type	Basic Description
	and floor is not achievable. Easy to construct and inexpensive. Requires preserved wood for longevity. ▪ Post and Pad - spread footings made of lumber (or concrete) attached to vertical riser made of timber or steel. Pads are on or just below surface of fill pad (or installed in an excavation to the permafrost surface and would be then a buried footing, with each footing installed and backfilled quickly). May utilize screw jacks to allow for adjustments. Differential movement from frost heave and thaw settlement expected. Easy to construct and inexpensive. May be constructed of one or combo of timber, steel, or concrete.
Buried Spread Footings	Buried spread footings with ventilated airspace under building, such as buried post and pad. Are installed with insulation either above or below the footing, such that it is situated near the top of permafrost with the objective of limiting seasonal frost movements. Construction is more labour intensive and therefore buried spread footings are not commonly used.
Space Frame Foundations	Variation of surface footings that uses a three-dimensional framework of tubular steel or aluminum to develop a rigid truss system (Figure 19). Has load transferring capability allowing system to work on relatively weak soils. Commonly used for housing but has also been used for larger structures. Constructed of relatively light materials for shipping, no speciality tools required for construction, and can be assembled using local labour with minimal training. Typically requires more than 1 m of clearance under a building. Are quite expensive and are often only used for service buildings and large public infrastructure.
Slabs-on-Grade (insulated ground supported slab)	Typically, widely used where ground and thermal conditions permit. Requires careful consideration to ensure that heat from the structure does not cause thaw-settlement of the underlying permafrost. May be permissible in thaw-stable permafrost for unheated structures (provided that the structure does not become heated in the future). Typically requires insulation and method to maintain permafrost such as forced ventilation/cooling system.

5.3.1.2 Deep Foundations

Figure 20: Pile Foundation for Building in Iqaluit, Nunavut.

Figure 21: Adfreeze Piles Supporting Building, Barrow, Alaska (Thester11, 2008).

Deep foundations consist of piles driven into the ground to stabilize overlying buildings (Figure 20 and Figure 21). There are two types typically in use in northern (permafrost region) Canada, being rock socketed piles and adreeze piles, as summarized in Table 9, below. Pile foundations are designed to be stable and low maintenance systems and require little to no gravel. The best time to install piles is generally in the spring before thawing of the active layer starts, allowing the ground to provide a strong platform and limiting water inflow (CSA Group, 2019a-b; Yukon Government, 2020; Government of Northwest Territories, 2021). Pile installation methods include driven piles, predrilled holes for installation and backfill with slurry or grout, and screw piles (emerging technology). Historical methods have included soil thawing and then pile driving, but this can cause a significant thermal disturbance and is not recommended when trying to protect the permafrost (CSA Group, 2019a-b).

Ultimately, deep foundation design would be based upon the site-specific conditions and the proposed building requirements and would be completed by a structural engineer.

Table 9: Summary of Deep Foundation Types Used in Permafrost Environment.

Shallow Foundation Type	Basic Description
Rock Socket Steel Pipe Piles	Piles anchored into the bedrock when present at a practical depth (typically < 8 m depth) to provide a stable foundation by transferring the full load of building to the bedrock. Does not require permafrost to be maintained. May require ventilated spaced under building depending on the nature of the soils. Requires piles and specialty equipment (e.g., drill rig) for installation in bedrock.
Adfreeze Steel Pipe Piles	Often installed where permafrost extends to substantial depths in overburden. Piles are embedded and frozen into the permafrost where they transfer their load to frozen ground by developing a shear, or adfreeze, bond between the pile shaft and the surrounding ground. Often designed assuming the pile will undergo settlement/creep over time or can be fitted with heat tubes (a.k.a. thermosyphon technology, and then called a thermopile) for refrigeration. Requires piles and specialty equipment (e.g., drill rig) for installation in overburden.

5.3.1.3 Foundations with Heat Exchangers

Foundation systems did not commonly incorporate heat exchangers (such as forced air ventilated slabs or mechanically chilled slabs) for public buildings before 2000. With the development of thermosyphon technology, heat exchangers are more commonly used for foundations of public buildings, as they can be used to achieve barrier-free access designs (at-grade instead of elevated), enabling compliance with applicable building codes. Even though the technology for heat exchangers has advanced, they are not typically used for residential construction due to the high cost (CSA Group, 2014; 2019a). Heat exchangers are utilized for thaw susceptible sites to artificially cool the ground and prevent heat transfer from the building, and therefore may protect the permafrost and maintain foundation bearing capacity.

Figure 22: Thermosyphons at the Fairbanks Airport in Alaska, Used to Chill the Permafrost Beneath the Airport Structure (Ryu,2008).

Thermosyphons (Figure 22) are devices with high thermal conductivity that can transfer high quantities of heat from the ground to the atmosphere. A thermosyphon is a hollow metal pipe, charged by working fluid that evaporates at temperatures below 0 °C. The fluid in the evaporator section (where heat is delivered from the ground) evaporates and rises upwards to the above ground radiator, where in the winter, it cools and condenses, releasing the heat to the atmosphere. Thermosyphons can also be designed to be resilient to climate change impacts. Thermosyphons are passive devices, but they do often require annual inspection as their effectiveness needs to be monitored because if one or more pipes fail, it may take several years for indicators of permafrost distress to appear leading to the need for potentially high-cost mitigation strategies. There is also a period in the summer, where heat is not transferred from the ground leaving potential for permafrost warming or thaw. The design, construction, and maintenance of thermosyphon foundations is described in CAN/CSA-S500-14 (CSA Group, 2014).

Thermopiles are essentially combinations of thermosyphons with adfreeze piles. Like a thermosyphon, they are equipped with an evaporator and radiator section, but like an adfreeze pile, they carry a structural load. Thermopiles are sometimes referred to thermosyphons, as they were called that when first developed as vertical supports for the Trans-Alaska Pipeline system in the 1970s (CSA Group, 2014). A thermopile foundation is currently being considered for the new Old Crow Health and Wellness Centre (Tetra Tech, 2019).

5.3.2 Foundation Selection

Figure 23 presents a high-level foundation system selection flow chart, modified for Old Crow and focusing on general technical aspects (adapted from CSA PLUS 4011:1:19)

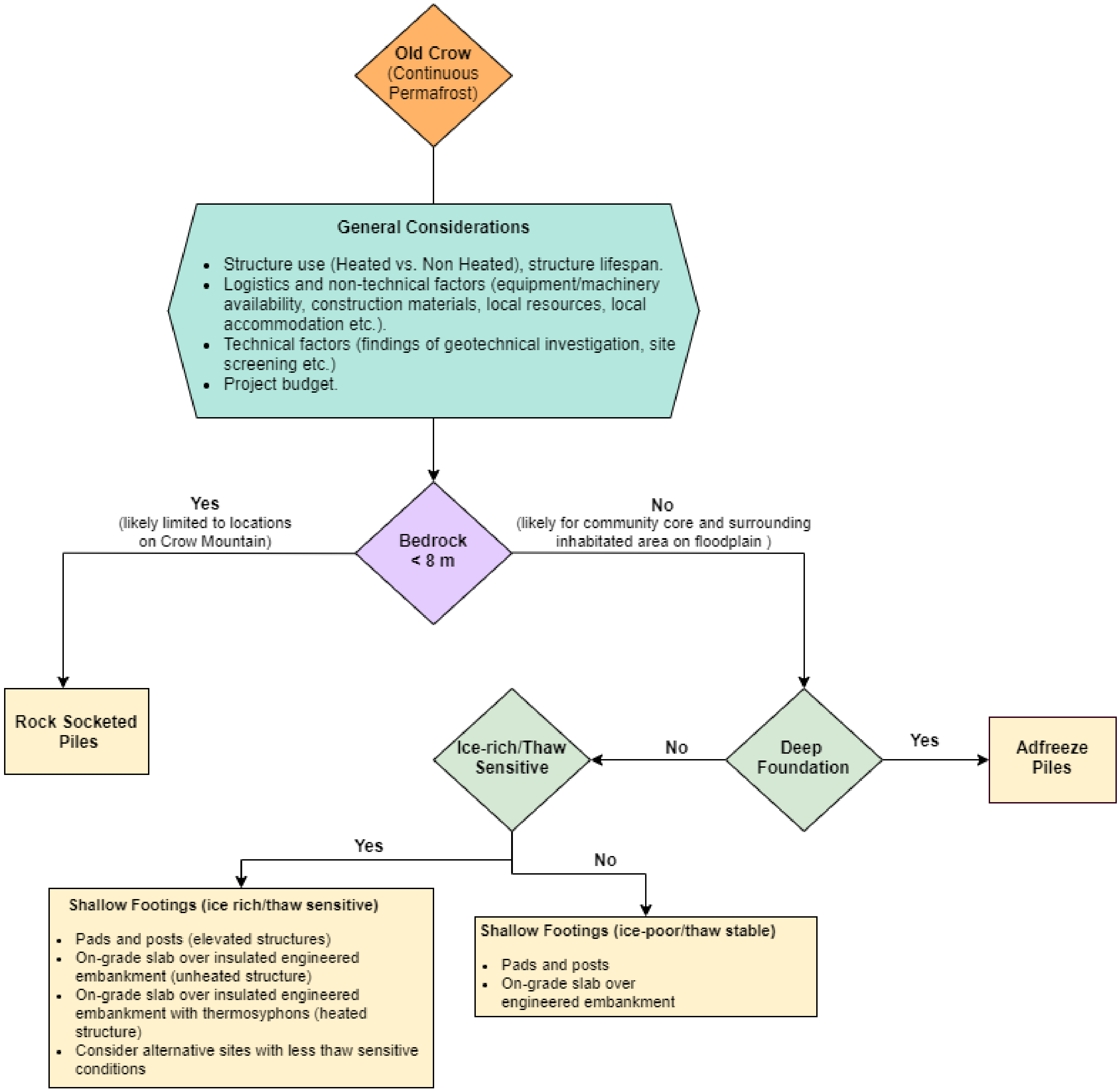

Figure 23: High-Level Foundation System Selection Flow Chart, Modified for Old Crow (Adapted from CSA PLUS 4011:1:19, 2019b).

5.4 Considerations for Roadway Design

Most infrastructure development in Old Crow aggregate resources for surfacing and/or pad construction, as-well-as for ongoing maintenance. The need for aggregate and the quality of existing housing stock in Old Crow are somewhat interdependent (VGFN, 2009). Historically, aggregate has been locally sourced from the active Porcupine River channel directly or as crushed rock from Crow Mountain. In-stream gravel resources from the river were extracted for many years at bars located to the west and east of the community. Concerns over depletion of the accessible gravel bars and fisheries management resulted in the development of the Crow Mountain quarry and access road in 2004. Use of gravel bars as a community source of gravel has historically been viewed unfavourably VGFN, and if needed will require an extraction plan (2009). The Crow Mountain bedrock geology permits the use of crushed rock to produce aggregate but crushing rock to create usable aggregate is a costly alternative to naturally occurring sand-gravel deposits (NYPC, 2007). Furthermore, when crushed, the resulting aggregate is not as desirable a surfacing material for the community as the end product is very dusty (EDI, 2010).

Generally, the river gravel is comprised of rounded pebbles to cobbles and varies in colour (Figure 24 and Figure 25)while the crushed aggregate from the mountain quarry is distinctly light coloured sandstone (Figure 26 and Figure 27) (Morrison Hershfield, 2020a). Asphalt is usually very dark in colour and traditionally has a low albedo, which means it reflects radiation poorly and instead absorbs. Heat absorption of the pavement can then result in a temperature increase and possible thawing of the permafrost beneath the roadway embankment. In comparison, the light-coloured quarry rock often used in Old Crow likely has a higher albedo than asphalt (as well-as the river rock, but less so), and other darker coloured aggregates used elsewhere for gravel roadways, which is preferable for permafrost protection. A study by Liu (2020), which compared average road temperatures for asphalt, chipseal, and gravel using thermistor data from down to a depth of 0.3 m below and along the Ingraham Trail (NWT Highway 4), in Yellowknife, determined that chipseal was the most heat absorbent, followed by asphalt, and then gravel on average. The use of pavement or chipseal in construction is not practical in Old Crow. Gravel roadways are common in areas of continuous permafrost because they are less costly to construct and easier to maintain than paved surfaces.

Figure 24: River Stone Along Bar of Porcupine River.

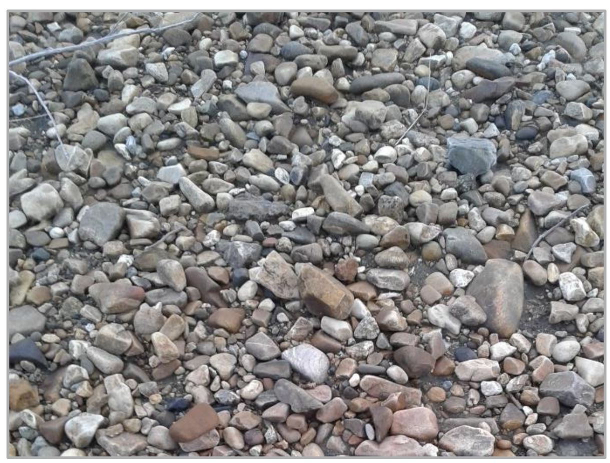

Figure 25: Pebbles and cobbles, varying in Colour, Along Porcupine River.

Figure 26: Light Coloured Crushed Quarry Rock Forming the Crow Mountain Road.

Figure 27: Crushed Quarry Rock at Top of Crow Mountain, at Quarry Site.

There is no one standard design procedures or guidelines for permafrost conditions and roads. A number of permafrost protection techniques for road structures have been developed and tested, but their costs remain high and therefore implementation remains low. The majority of existing permafrost protection techniques available are designed for warm permafrost (permafrost of discontinuous permafrost zones), rather than for cold permafrost (permafrost in continuous zones) (Liu, 2020).

Some permafrost protection techniques for warm permafrost include reflective surfaces, shading, snow removal, ventilation pipes, thermosyphons, air convection, geosynthetics, pre-thawing, permafrost excavation and replacement, and heat-dissipating structures and materials. The only permafrost protection techniques deemed suitable for protection of cold permafrost is embankment insulation and potentially heat-dissipating pavement structures (Zarling et al., 1984; Goering, 1998; Calmels et al., 2016; Liu, 2020). Heat dissipating pavement structures is not a practical option for Old Crow. Embankment thickening may provide protection of cold permafrost as the thickness of overlying embankment appears to greatly impact the thermal regime. Thick embankments, exceeding 5 m, usually provides considerable thermal insulation, while thick embankments of less than 2 m, can contribute to permafrost degradation (Guzman et al., 2019). Thick roadway embankments or roadbeds would require significant amounts of material, which may not be easily sourced in Old Crow. It is important to note that these mitigation techniques will not stop the rise of mean annual ground temperature as a result of climate change.

Embankment insulation (typically polystyrene, polyurethan, or sometimes peat) is a passive technique that can reduce heat flow between the road surface and the permafrost subgrade through increasing thermal resistance. It has been shown to be beneficial in regions where the mean annual ground temperature remains well below 0°C, even though it has been determined to be an ineffective method for the protection of warm permafrost (Nidowics and Shur, 1998; Lui, 2020). As permafrost is warmer than the air in the winter, insulation acts as a heat preserver, which can decrease heat extraction. In the summer, when permafrost is colder than the air, the insulation acts as a cold preserver, reducing heat absorption (Calmels et al., 2016). Embankment insulation is most effective when installed during winter months as it will prevent the material below from being infiltrated by heat from the surface during warmer months (Doré and Zubeck, 2009). Board insulation can be susceptible to mechanical damage and overlying loads could compress or fracture the board, resulting in a reduced effectiveness (Calmels et al., 2016). Foamed in place insulation may be an alternative option and with respect to installation and shipping, a cost-effective alternative. Insulation is elaborated on further in Section 5.6.

Gravel roads built on continuous permafrost can alter surface and subsurface conditions, which influence the surface energy balance, near-surface ground thermal properties, and the temperature regime of the underlying and adjacent permafrost (Gill et al., 2014; von Deimling et al., 2020).

Changes in vegetation structure adjacent to many northern roads have been extensive, resulting in potential to alter ground temperatures adjacent to roadbeds by influencing the snowpack (Marsh et al., 2010; Sturm et al., 2001). The Dalton Highway in Alaska has been shown to have contributed to altered vegetation community composition, vegetation structure, soil moisture, a deeper snowpack, and increased active layer thickness adjacent to the road (Auerbach et al., 1997; Myers-Smith et al., 2006). Similarly, the Dempster Highway (740 km gravel road between Dawson City, Yukon, and Inuvik) in the area of the Peel Plateau (Northwest Territories), has been shown to enhance alder growth and recruitment significantly, and where alder shrubs formed closed canopies, it resulted in dramatic alterations to plant community composition, soil properties, and ground temperatures. Additionally, where the road facilitated shrub dominance, it was shown that feedbacks were initiated that enhanced snow accumulation and altered ground temperatures and soil chemistry, and in turn promoted further shrub recruitment and growth (Gill et al., 2014).

Von Deimling et al., (2020) through heat conduction modelling (CryoGrid3), simulated permafrost degradation affected by linear infrastructure of a section of the Dalton Highway (Alaska), a gravel road built on continuous permafrost. They forced the model under historical and strong future warming conditions (following RCP 8.5 scenario, as touched upon in Section 3.6.2) and found that the presence of a gravel road in the model lead to higher net heat flux entering the ground compared to a reference run without infrastructure, and thus a higher rate of thaw. The results also suggested that road failure would likely be a consequence of lateral destabilization due to talik formation in the ground beside the road, rather than a direct effect of a top-down thawing and deepening of the active layer below the centre of the road. Similar to the other studies mentioned, they found enhanced snow accumulation (resulting in strong winter ground warming) and ponding due to the presence of the road, as key factors for increased soil temperatures and road degradation. The results suggested that permafrost degradation is a two-phase behaviour, with initial slow and gradual thaw, followed by a strong increase in thawing rates after exceedance of a critical ground warming.

In summary, the main factors to consider for roadway design in Old Crow includes:

- Gravel roadways are used in Old Crow because they are practical, less costly to construct and easier to maintain compared to paved or chipseal roadways. Gravel when compared to pavement or chipseal roadways has lower heat absorbance.

- The distinctly light-coloured quarry rock often used for roadways and infrastructure pads in Old Crow has a relatively high albedo due to its light colour, which is favourable for permafrost protection.
- Permafrost protection techniques that may be beneficial for protection of cold permafrost is embankment insulation and potentially heat-dissipating pavement structures, thought heat-dissipating pavement is not a practical option in Old Crow.
- For preservation of permafrost, cuts into native soil should be avoided.
- Embankment thickening may provide protection of cold permafrost as the thickness of overlying embankment appears to greatly impact the thermal regime. Thick embankments, exceeding 5 m, usually provides considerable thermal insulation, while thick embankments of less than 2 m, can contribute to permafrost degradation (Guzman et al., 2019). Thick roadway embankments or roadbeds would require significant amounts of material, which may not be readily available in Old Crow.
- Destabilization of roadways is likely due to lateral destabilization due to talik formation in the ground beside the road, linked to enhanced snow accumulation (in-part due to vegetation presence, resulting in strong winter ground warming) and ponding. Snow accumulation and ponding are key factors for increased soil temperatures, active layer thickening, and road degradation.

5.5 Considerations for Site Drainage

Figure 28: Culvert under North Road, Old Crow.

Drainage is an important to consider for permafrost protection. Even though precipitation is generally low, standing or flowing water can impact permafrost due to both its heat transfer capacity and ability to cause erosion.

In northern regions such as Old Crow, the winters are cold and long, the summers short and mild, and maximum seasonal flows occur with the spring freshet, often creating surface drainage issues. General drainage issues in northern communities may include culvert freezing in the spring, damaged culvert ends, eroded drainage courses/ditches, and pooling of water due to poor grading, snow accumulation, or underlying frozen ground. Surface drainage should be designed to positively drain water away from community sites to a point down gradient, reducing pooling and infiltration nearby infrastructure. If possible, surface water should be directed to natural drainage paths such as streams (CSA Group, 2020). Underground drainage via piping is not a practical option for Old Crow, and there are no buried storm sewers. Drainage is generally conveyed in

Figure 29: Drainage Ponding Along Roadway in Old Crow.

roadside ditches and through culverts where drainage must cross roadways (Figure 28). In areas that do not have defined drainage systems, pooling water along the roadways may occur in Old Crow, as shown in (Figure 29).

Precipitation, topography, soil type, vegetation, infrastructure/construction, and maintenance are all factors affecting site drainage, as summarized in Table 10, below (Government of the Northwest Territories, 2021).

Table 10: Summary of Factors Impacting Site Drainage.

Factor	Description of Influence
Precipitation	Spring freshet, or snowmelt, is the biggest event.
Topography	Flat topography does not drain well and is susceptible to ponding. Steep topography has more defined drainage channels, generally, but can be more difficult to construct upon or may be unstable.
Soil Type	Granular material such as gravel or coarse sand generally have fewer drainage issues when compared to finer materials such as lacustrine deposits (clays and silts). Granular materials are less susceptible to freeze-thaw, while finer materials may heave when the ground freezes.
Vegetation	Vegetation can slow precipitation flow. Vegetation reduces erosion potential as a canopy, by softening the impact of rainfall, and as a root system, by binding soil. Non-maintained vegetation may block drainage channels and may cause snow accumulation in the winter.
Infrastructure/ Construction	Mistakes in construction may occur, including lack of erosion protection, poor grading of sites or ditches.
Maintenance	Lack of maintenance can result in faulty eavestroughs, leaking water or sewage systems, and drainage channel blockage by vegetation and sediment (as noted above).

Going forward, a changing climate may impact weather conditions that relate to drainage in a variety of ways, including (as adapted from CSA Group, 2020):

- Increase in frequency of extreme weather events resulting in greater snow accumulation, winter rain, icing, and higher winds
- More rapid spring melting
- More sudden, intense precipitation events
- Greater weather instability in general

For building foundation design, geotechnical investigations should address the vulnerability of the structure to the potential for differential settlement and surface drainage that may impact the thermal regime of the foundation. Geotechnical investigations should follow the recommendations of CAN/BNQ 2501-500 (Yukon Government, 2020).

For planning, design, and maintenance requirements for a community drainage system for northern communities, the CSA standard CAN/CSA-S503:20: *Community Drainage System Planning, Design, and Maintenance in Northern Communities*, is a good resource.

General considerations for drainage as it pertains to infrastructure design, construction, and maintenance, are summarized below, as adapted from the references cited:

- Surface drainage should be designed to convey water away from community sites to a point down gradient, reducing pooling and infiltration nearby infrastructure. If possible, surface water should be directed to natural drainage paths. Spring freshet, or snowmelt can occur rapidly, and this water must be directed away from infrastructure. Gravel pads can be severely eroded by water seeping under or through the pad, resulting in structural damage (CSA Group, 2020).
- Inlets and outlets of drainage features should be armored with the appropriate construction materials to mitigate erosion and subsidence (such as riprap and artificial materials such as geotextiles and geomembranes) (CSA Group, 2020).
- Drainage channels/paths should be in place on construction sites before spring runoff; this may require temporary installations of swales or berms (Government of Northwest Territories, 2021).
- Eavestroughs shall be designed to accommodate local weather conditions, contain roof water runoff and direct it to suitable locations away from the building walls and grade perimeter, prevent ice damming, and withstand ice and snow structural loading (Yukon Government, 2020). Exterior drainage paths may benefit from installation of heat traces to prevent them from freezing or backing up.
- Building envelopes must be designed to control surface and groundwater as specified in the National Building Code of Canada. All infrastructure should direct water away from the building through grading and means for drainage (Yukon Government, 2020).
- All roofs must be designed to shed snow and water away from entrance doors and adjacent pedestrian walkways and roadways (Yukon Government, 2020). This should aid in ensuring positive drainage and will avoid ponding.
- Designs are to consider potential for increased drainage requirements, to avoid overloading drainage infrastructure and reduce the risk of flooding, ponding and ground erosion (Government of Northwest Territories, 2021).
- Drainage systems should be designed to minimize surface disturbance in permafrost areas. Where surface disturbance (the removal of the organic insulating layer) is unavoidable, designs shall include steps to replace the insulation. It is preferable, in general, to convey surface water in ice rich permafrost areas using armored berms or shallow swales rather than ditches. (CSA Group, 2020).
- Where practicable, drainage system designs should be designed to allow water and sewer trucks to cross safely. This facilitates the delivery of water or removal or sewage (CSA Group, 2020).
- Ditches shall be constructed to a depth that ensures the road structure is adequately drained (CSA Group, 2020).
- Culverts require constant maintenance and should only be used when necessary. Where large diameter culverts cannot be avoided, it is recommended to use riveted or bolted culverts and consider installation of polystyrene insulation beneath the culvert bedding material on the bottom and slopes sides of the excavation (TAC, 2010). Care shall be

taken to avoid damage to permafrost during the installation of culverts. Where disturbance to the permafrost is unavoidable, designs shall incorporate a means to re-establish and reinsulate the permafrost (CSA Group, 2020).

- Community drainage systems should be regularly inspected. For example, in the spring culverts should be inspected to determine if backed-up melt water is present and the cause for the blockage is (e.g., frozen snow, ice, debris) and the blockage removed (CSA Group, 2020).
- Existing drainage patterns should be maintained and stream and creek crossings by infrastructure should be minimized (TAC, 2010).

5.6 Ground Insulation

Thermal insulation is a passive method to protect permafrost and prevent frost heave, which is achieved through increasing the resistance to heat flow. Historically, types of insulation have varied from natural materials such as peat, wood chips, straw, and sawdust, to synthetic materials such as foam, including polystyrene (Figure 30), polyurethane, and polyisocyanurate. Natural insulations are often lower cost and may be more readily available. (CSA Group, 2019b). Mulching over disturbances, with removed tree canopy along infrastructure corridors has been proposed as a best management practice to help reduce permafrost thaw (Aaron et al., 2017), and could be considered for infrastructure development projects requiring removal of canopy (while hopefully leaving the low-lying vegetative mat in-place).

As permafrost is warmer than the air in the winter, insulation acts as a heat preserver, which can decrease heat extraction. In the summer, when permafrost is colder than the air, the insulation acts as a cold preserver, reducing heat absorption (Calmels et al., 2016). Insulation may not be able to stop the rise in mean annual ground temperature, but it may slow down or stabilize permafrost degradation. The use of insulation may be more effective if combined with heat extraction methods. Ground insulation should be used only on the recommendation of a qualified professional, and with consideration for the site-specific conditions.

Selection of the appropriate insulation for an infrastructure project would depend on Old Crow climate, the target R-value (measure of the capacity of material to resist heat flow, higher the R-value the more resistant and better insulating), whether insulation will be in contact with soil and/or water, and the level of environmental impact. The water absorptivity of insulating material significantly reduces R-value because water conducts heat. Structures may be built directly on insulating material. Insulation is commonly applied along with construction of gravel pads and is most effective when installed during winter months as it will prevent the material below from being infiltrated by heat from the surface during the warmer months (Doré & Zubeck, 2009).

An insulated layer that is intended to be in contact with the soil must be able to withstand deterioration of its thermal properties and physical shape in the presence of soil moisture, soil chemicals, physical loading, and other outside forces (Permafrost Technology Foundation, 2000). Insulation is generally vulnerable to degradation from the hydrocarbon spills (CSA Group, 2019b).

Polystyrene, polyurethane, and polyisocyanurate are rigid foam insulations that are commonly used for construction applications. For additional information on these insulation types and their advantages and disadvantages, see CSA Group, 2019b.

Polystyrene has been used as roadway insulation in cold regions to attenuate frost penetration under roadways and to allow for a reduced pavement structure for decades and is increasingly used to protect infrastructure from permafrost degradation (Beaulac and Dore, 2006). For roadways, insulation will be most effective if placed as close as possible to the surface, but the depth of cover above has to be thick enough to prevent damage to the insulation (Esch, 1996). A downside to polystyrene is that it has relatively low recyclability, which is a quality of some importance in modern construction (Lui, 2020).

Figure 30: Extruded Polystyrene Insulation Mats Installed in Ground for New Water/Wastewater Trench in Norway (Øyvind Holmstad, 2017).

The use of insulation has been implemented in Old Crow infrastructure for the protection of permafrost. For example, the solar farm foundation incorporating a combination of insulation, geotextiles, and drain tile, and the civil team designed piling foundations for the e-building that are height adjustable with more than two feet of flexibility (BBA, 2019).

5.7 Monitoring Efforts During Construction

The completion of a pre-construction and post-construction survey would allow for the assessment of site topography changes over time. Accurate record drawings of the construction should be prepared by the designer and contractor. Owner should have copies (hardcopy and digital) of all record drawings and related documentation for future reference (CSA Group, 2019b).

6. MITIGATION AND RESTORATION TECHNIQUES FOR IMPACTED STRUCTURES

This section is adapted from Part 6 of the CSA standard CAN/CSA-S501:21 Moderating the effects of permafrost degradation on existing building foundations (CSA Group, 2021), with additions from other sources where cited, similar to the approach used for the Ross River (south-central Yukon) infrastructure assessment report (Calmels et al., 2016). Part 6 of the CSA standard (hereafter referred to as "the CSA Standard" prescribed mitigation and restoration techniques that may be useful in the specific context of Old Crow. Choosing and implementing measures described for specific sites in Old Crow should be done in consultation with a qualified professional, and with consideration for the site-specific conditions.

The CSA Standard (CSA Group, 2021) identifies various techniques to restore foundation stability where affected by changing permafrost, based on foundation type and categorized into those applied to the site and those applied to the structure or foundation.

6.1 Techniques Applied to the Site

The CSA Standard highlights three mitigation and restoration techniques that may be applied to a site, including:

1. Shading and albedo
2. Site grading and drainage
3. Snow management

These techniques are applicable to site with either shallow foundations (surface footings, buried footings, or slab on-grade) or deep foundations (adfreeze piles, rock-socketed piles).

6.1.1 Shading and Albedo

The CSA Standard (CSA Group, 2021) notes that vegetation may be planted around structures to shade the ground surface in the summer and help moderate ground surface temperatures and that albedo can be increased to reduce the absorption of solar radiation. It recommends the following related measures:

a) Ensure that planted vegetation does not restrict airflow under an elevated building or structure

b) Vegetation that provides natural shading should not be removed

c) Sunscreens, including elevated wooden decks, may be constructed on south-facing locations

d) Surface covers or treatments may be applied to increase albedo

The standard notes that changes in shading or albedo should not be relied upon to resolve permafrost degradation impacts without detailed numerical modelling as a conducted by a qualified professional.

The CSA standard only considered vegetation from a shading perspective (Calmels et al. 2016.) Shrub and tree-like vegetation may accumulate snow, resulting in increased insulation which may negatively impact permafrost. Deviations in permafrost depth in Old Crow have been linked to shrubbed areas resulting in snow accumulation (as described in Section 4.5). Shading may also delay snow melting in areas of accumulation, prolonging the insulating effect. Therefore, vegetation for shading should be used only in conjunction with a snow management strategy. Considering the physical characteristics and the short growing season in Old Crow, it may be difficult to implement vegetation shading.

6.1.2 Site Grading and Drainage

Site drainage considerations are discussed in detail in Section 5.5, and in CSA standard CAN/CSA S503:20 *Community drainage system planning, design, and maintenance in northern communities* (CSA Group, 2020). The importance of drainage for the preservation of permafrost is reiterated in the CSA Standard (CSA Group, 2021), where the following additional measures are identified:

a) Drainage ditches or swales may be excavated in the active layer but only if detailed design and measures to control erosion and prevent progressive permafrost degradation are implemented.

b) Berms can be effective to control surface drainage but should only be constructed with detailed design and measures to control erosion.

c) Liner material could be installed to impede infiltration in the vicinity of buildings.

d) The area within 4 m of the perimeter of the structure should be graded so as to facilitate drainage of surface water away from the structure and prevent ponding at any location within 4 m of the structure.

e) Water shall be kept from ponding under the structure or foundation. Additional fill should be placed at select locations as needed to promote positive drainage.

f) Downspouts from buildings or structures should be directed onto splash pads that discharge to natural ground at least 4 m away from all structures. Where no eavestroughs are installed, areas surrounding the building permitter should be sloped away from all structures at no less than 4% slope.

g) Construction around existing or adjacent buildings or structures that negatively impacts the permafrost should be avoided.

h) For Old Crow, overfills of drinking water tanks should be avoided to prevent spillage to the ground. This could be achieved through installation of overfill spouts that carry water to 4 m away from the building or with the installation of tank whistles that sound when the tank is full. An alternative option to a whistle would be a water tank overflow light, but it would require a power source and should be installed by an electrician.

6.1.3 Snow Management

The CSA Standard (CSA Group, 2021) identifies the following measures in regard to snow management:

a) Excess snow should be cleared away from buildings and structures to allow frost penetration and cooling of permafrost during winter. Snowbanks and snowdrifts impede airflow to the ventilated space below buildings and also insulates the ground, potentially leading to permafrost progressively warming or even thawing. Accumulations of snow may also lead to ponding of meltwater.

b) Snow management activities should be documented in the foundation maintenance plan.

c) Though not mentioned in the CSA Standard, use of snow fences in Old Crow should be considered with caution, as snow fences have been shown to cause warming of the ground and upper permafrost thaw in other northern locations (Hinkel and Hurd, 2018; O'Neill and Burn, 2015).

6.2 Techniques Applied to Impacted Structures

6.2.1 Applicability of Techniques Based on Foundation Type

The CSA Standard (CSA Group, 2021) identifies various techniques to restore foundation stability where affected by changing permafrost, based on foundation type and divided into those applied to the site and those applied to the structure or foundation. The potential techniques and their applicability based on foundation type is summarized in Table 11 and discussed as follows:

Table 11: Applicability of Restoration Techniques for Impacted Structures, Based on Foundation Type (Adapted from CSA Group, 2021).

Mitigation Technique	Shallow Foundations			Deep Foundations	
	Surface Footings	Buried Footings	Slab-on-grade	Adfreeze Piles	Grouted/ End-bearing or Rock Socketed
Ventilation	Yes	Yes	No	Yes	No[5]
Ground insulation	Yes	Yes	Maybe[1]	Yes	Maybe[2]
Foundation modification to allow for adjustment and levelling	Yes	Yes	Maybe[3]	Yes	Yes
Mechanized refrigeration	Yes	Yes	Maybe[5]	Yes	Yes
Thermosyphons	Yes	Yes	Maybe[5]	Yes	Yes
Foundation replacement	Yes	Yes	No[5]	Maybe[4]	Maybe[4]

Notes:

1. Perimeter insulation might be effective. Insulation under slab likely not feasible, except as per Note 3.
2. Perimeter insulation will be feasible. Feasibility of insulation under the building will depend on access.
3. Relevelling by grout or foam injection might be feasible.
4. Replacing piles with adjustable footings could be considered. It might be feasible to replace piles under a building with beams and outrigger piles. Less likely would be underpinning with micropiles.
5. Might be feasible under rare circumstances.

6.2.2 Ventilation

Passive ventilation systems permitting winter air flow under a structure promotes ground freezing and maintenance of permafrost. Per the CSA Standard (CSA Group, 2021), the following should be considered:

a) If a building or structure is equipped with a ventilation system, regular checks should be made to ensure that the space or ducts are not obstructed. Vegetation and snow accumulation that restricts foundation ventilation shall be removed. Mesh such as chicken wire or chain link fence should be installed to protect air spaces or ducts from the accumulation of debris and other items that might restrict winter airflow.

b) The building or structure shall be elevated to maintain a clear ventilated air space of at least 0.6 m to permit winter air flow under and around the foundation (though CSA standard CSA PLUS 4011:1:19 recommends for residential structures an air gap of 0.9 m or more).

6.2.3 Ground Insulation for Existing Foundations

Ground insulation should be used only on the recommendation of a qualified professional and with consideration for following:

a) In areas where mean annual ground temperatures are between -4°C and 0°C, ground insulation would be detrimental, but exterior perimeter ground insulation placed where solar radiation is the greatest may be used to moderate permafrost degradation beneath a building; and,

b) Ground insulation may also be used in conjunction with mechanized refrigeration or thermosyphons.

Considerations for ground insulation are discussed further in Section 5.6.

6.2.4 Foundation Modification or Replacement

Per the CSA Standard (CSA Group, 2021), periodic adjustment or levelling may be possible for some foundation types, or a specifically designed retrofit could be designed and installed to allow a foundation to be adjusted (such as a lift) and therefore increase the service life of the structure. It may also be possible to replace the foundation on an existing site, though this option should be assessed by a qualified professional and the technique used would be specifically designed for the existing structure.

6.2.5 Mechanized Refrigeration or Thermosyphons

Per the CSA Standard (CSA Group, 2021), a refrigeration or thermosyphon system may be installed under a shallow foundation or slab, or around deep foundations to chill the soils to a stable condition. However, these mitigation measures are susceptible to frost heave. To use these as a mitigation technique, geothermal modelling would be required, and the system would be designed and installed by a qualified professional.

6.2.6 Abandonment and Demolition

The CSA Standard (CSA Group, 2021) addresses the possibility of abandoning or demolishing structures affected by permafrost thaw if considered to be non-repairable or unusable. In some cases, structures may be relocated to new locations with the construction of a new foundation.

Abandonment, demolition, or relocation may be considered for buildings in Old Crow, if applicable. This would need to be assessed by a qualified professional and discussed with the asset stakeholders.

7. RESTORATION OF DISTURBED LANDS TO STATUS EQUIVALENT OF GREENFIELD LAND THROUGH REVEGETATION

7.1 Impact of Vegetation Removal and its Recovery After Disturbance of Permafrost

Permafrost requires an insulating surface cover, consisting of accumulated organic matter and living plants (Figure 31) to remain cool and stable. Without vegetative cover, the permafrost may melt quickly and result in melted ground, ground saturation, and then slumping and erosion (Matheus and Ontzigt, 2012). Vegetation removal and recovery after disturbance prompts changes in not only the active layer thickness, but also sensitivity to erosion and soil moisture levels. The shallow active layer is a nutrient source for vegetation, maintaining water and nutrient supplies close to the surface. Black spruce, for example, and forest floor moss, have adapted to the presence of permafrost and often sustain permafrost as well as being sustained by it (Riseborough et al., 1990).

Figure 31: Vegetative Cover in Old Crow, East of the Sewage Lagoons. Vegetative Mat and Some Trees Visible.

With construction activities in northern communities such as Old Crow, where the insulating surface cover of a site is disturbed or removed, the challenge is to recreate that insulative and protective layer, as quickly as possible. Insulating layers that are stripped away rather than left in-place and built upon, should be stockpiled for quick reapplication. Once permafrost melting begins, it is very difficult to halt, and nearly impossible to reverse (Matheus and Ontzigt, 2012). It is important to recognize that revegetation will not prevent ground warming related to climate change and therefore climate warming is leading to a loss of permafrost regeneration potential after disturbance (Klinge et al., 2021).

With development projects, revegetation planning should be an integral part of the project design and should allow for good decision making with respect to site preparation, logistics (material stockpiling), and areas to avoid disturbing (to avoid difficult or costly revegetation). It is recommended that a vegetation specialist be consulted in the early stages of any project design, and that details of vegetation removal and recovery be included in site plans or reclamation plans.

Revegetation is usually carried out with the objective to stabilize and protect ground surfaces and for ecological restoration purposes. Less often, it is completed to maintain permafrost and/or to improve site aesthetics (Matheus and Ontzigt, 2012). A good and detailed resource for planning and carrying out revegetation is the *Yukon Revegetation Manual* (Matheus and Ontzigt, 2012), which is an update to the *Guidelines for Reclamation/Revegetation in the Yukon* (1993, and 1996). This section is largely based upon the findings and recommendations of this manual (referred to as “the Manual”).

7.2 Revegetation Methods

There are two main types of revegetation; active and passive. Active restoration is where management techniques such as fertilizing or planting seeds or seedlings are implemented, and passive is where no action is taken except to cease any environmental stressors (e.g., construction activities).

Passive revegetation allows for natural colonization and succession by local plant species and is a significantly longer and slower process for revegetation of northern sites compared to active methods. Northern sites are generally cold, low-nutrient environments with short growing seasons, and little precipitation; all factors that generally restrict plant growth. Without the use of active revegetation, it would likely be difficult to achieve any revegetation goals for a disturbed site. Passive approaches can be applied where disturbance is relatively light and natural recovery is already well underway, or where access may be restricted.

Active revegetation involves the following critical steps:

- Minimize ground disturbance and compaction (though this may not be possible).
- Collection of baseline information about the site conditions.
- Preservation or stockpiling and reapplication of soil and/or organic materials.
- Proper preparation of ground prior to seeding, with attention paid to decompacting soils.
- Fertilization, when necessary, with appropriate blends and at the appropriate rate.
- Proper appointment and sowing of seed mix with the right species and appropriate diversity for the site conditions.
- Proper timing of each step noted above.

Additionally, the Government of Yukon *Design Requirements and Technical Standards Manual* (2020) recommends the following for site landscaping:

- Existing Vegetation – Maintain as much existing boreal forest on site as possible and protect from vehicular traffic. Most boreal forest is a natural asset in the Yukon and takes a long time to grow. Best practices for the protection of existing vegetation are noted in Appendix B.
- Plantings – Any plant material added to the site must be hardy, suitable for the locality and require little or no maintenance. Transplanting of local species may be considered where an acceptable source can be found in the community.
- Soil – Generally, if soil or topsoil is required, it will need to be imported to the site. Most sites do not have a significant layer of topsoil that can be used. All soil must be provided with the necessary additives to achieve effective plant nutrition.

- Irrigation – Permanent irrigation systems are recommended and are preferred over temporary irrigation when landscaping is installed. Where installed, additional requirements apply.

7.3 Site Preparation

7.3.1 Assessing the Site

Revegetation success largely depends on making informed planning decisions, which requires:

- Site assessment and gathering of baseline information through a background record review (regional data, photos, studies)
- Collection of site-specific baseline data (slope, aspect, moisture, level of surface disturbance, sediment structure, drainage etc.)
- Survey the local plant communities
- Collection of soil samples for nutrient testing and pH

Soil nutrient testing is often the most neglected aspect of revegetation work in the Yukon and is important as it aids in determining the required fertilizer mixes and application rates.

7.3.2 Replacement of Surface Materials

A site with intact soils and organic materials will recover quicker than stripped and compacted sites and will also require less effort and cost. Intact soil and organic materials will provide good soil conditions for plant growth as it will have an intact seed bank of native plants to recolonize. If site stripping cannot be avoided, any surface organic materials that are stripped should be preserved through stockpiling and reapplied. The reapplied material will provide insulation and can include stumps, slash, rotting logs etc.

If site disturbance takes place in early to mid-summer, stockpiled materials should be reapplied to provide insulation as soon as possible. If the site is disturbed in late summer or fall, then the site should be left exposed and stockpile maintained, to promote deep frost penetration, with application of the stockpiled materials as soon as possible in the spring.

Even organic material that is stockpiled and stored for multiple years is advantageous for reapplication as it retains a seed bank, requiring less seeding to promote revegetation.

7.3.3 Ground Conditioning and Fertilizing

For successful revegetation, it is often necessary to improve poor soils and growing conditions. Increasing organic soil levels and providing decompaction (i.e., tillage) are the main methods used to develop good soil structure and fertilization of nutrient poor soil will provide nutrient input in the short term to enhance initial plant growth. However, decompaction activities may be counterproductive for disturbed sites by increasing the level of disturbance and the rate of permafrost melting. If equipment has recently been used on-site, severely compacting the surface, then harrowing or raking (shallow tilling) could be beneficial to promote drainage and seed germination on flat sites but care should be taken to not till organic material into the soil (losing its insulation value).

Sloped surfaces may require special treatment. Methods such as track walking (up and down slope, with proper rollover protection) could be an alternative, leaving tracks that act like small pockets to catch seed and water.

When it is possible to apply thick layers of organic material for insulation, it is usually unnecessary to fertilize. Fertilizer should not be applied if there is significant standing water present for extended periods at the site. Fertilizer should also not be added to saline sites and its use should be avoided in areas where it could pollute water bodies through surface run-off.

Applicable fertilizer mixes and application rates can be determined through soil testing and utilization of numerical formulas provided in the Yukon Revegetation Manual. Common parameters for nutrient testing of soil includes pH, calcium carbonate, electrical conductivity, nitrogen, phosphorous, potassium, sulfur, and organic matter.

7.4 Planting Recommendations and Seeding Methods

New vegetation will help insulate the ground and prevent any further permafrost thawing for disturbed sites. For a lowland permafrost site with disturbed ground ice (e.g., human caused thermokarsting), for the objectives of revegetation for permafrost protection, it is generally recommended that seeding rates should be at least 1,500 seeds/m^2, ensuring even coverage, and mixes should include 10% annual grasses (for rapid cover), with balance of perennial grasses that are adaptable to the cold, low-nutrient environment.

Permafrost sites that are essentially stable, with a thin active layer and cold soils (e.g., the active layer may not have been removed or disturbed, but new material such as gravel will have been added to the surface), following site conditioning and fertilization (if required) should generally be lightly seeded with a target of 1,000 seeds/m^2, using a mix of locally collected seeds, except where impractical or where immediate erosion control is important.

Seed species should be matched with the site to be revegetated based on the site-specific conditions, and through matching with the recommended and approved species in the Yukon Revegetation Manual. Collecting and sowing local seeds may not be a practical option. Native species are the best adapted plants for a respective site, however, currently there is no known commercial production of native plant cultivars in the Yukon at this time (Matheus and Ontzigt 2012; Vogt and Janin 2017).

The Yukon Revegetation Manual emphasized that commercial seed must be sourced from suppliers in western Canada (excluding southern/coastal British Columbia) or interior Alaska, as those cultivars are adapted to Yukon conditions.

Hand seeding would be required to avoid operation of equipment on-site. If equipment can be used, then a broadcast spreader would be useful, with care to spread evenly and follow up with any missed areas. Seed spreading in the fall means that the subsequent freeze-thaw cycle in spring could mechanically work seed into the ground.

7.5 Specific Strategies for Revegetation of Disturbed Gravel Areas

Gravel surfaces are common in northern communities, including pads, pits, and roads, and are often built to protect permafrost. Gravel surfaces are difficult to revegetate due to the absence of organic layers, little moisture holding capacity, low nutrients, limited seed banks, and high compaction (Johnson 1987, Jorgenson and Joyce 1994).

In Alaska, eight years after abandonment of gravel pads, natural recovery only achieved a native plant species cover of 2.7% (Bishop and Chapin III, 1989). Active revegetation methods would be required to make disturbed gravel areas in Old Crow more hospitable for colonizing vegetation. The addition of organic matter would be beneficial for revegetation, however there is likely limited soil availability in Old Crow and its remoteness makes sourcing material from elsewhere impractical. Additionally, erosion would be a concern for surface applied topsoil and control methods would likely need to be explored and implemented. Erosion control methods may include planting rapidly growing vegetation, surface contouring, addition of soil conditioners, or erosion control blankets, although success may vary depending on site-specific conditions. Applications of such materials like mulch could be easily removed by wind with no vegetation to hold it in place.

Application of fertilizers can stimulate germination on gravel surfaces in the short term, but the low organic cover would result in leaching of nutrients, though as vegetation grows and decomposes it could contribute to the development of organic matter on the surface. The depth of gravel would also be an important factor in revegetation efforts, as plant cover on gravel pads has been shown to be inversely related to gravel depth as it influences groundwater uptake (Walker, 1996). Any revegetation efforts would also need to consider that shrubbed areas can result in snow accumulation in the winter months, increasing insulation, which is undesirable for the protection of permafrost. Grasses would have less potential for snow accumulation as it bends or folds in winter. Grasses are also rapid growers and can prevent erosion through stabilization of the substrate, and over time increase the organic and nutrient content through decomposition.

Figure 32: Grasses Near the Bank of the Porcupine River, in Old Crow.

For gravel bars or riverbanks, one revegetation option is the live staking method where stakes are inserted diagonally into the substrate with the top facing the stream flow to slow water flow when the bank floods, resulting in deposition of fine sediments and debris, which in turn provides suitable substrate for native plant establishment. This has proven a successful method along the Klondike River at Germaine Creek and near Beaver Creek Bridge (EDI Environmental Dynamics Inc., 2009). Willows (from the genus Salix) are native to Old Crow; are known to be hardy, fast growing woody vegetation, and would be ideal for the live staking method, as-well-as other bioengineering techniques like spiling or fascine. The spiling method utilizes live stems as rods, woven between live upright stems, essentially forming a retaining wall that is filled on one side with soil for rooting. The fascine method uses bundles of stems staked to a slope (CSA Group, 2020). As permafrost is often absent beneath large lakes, continuously flowing rivers, or other natural watercourses, revegetation through these methods would not have the main objective or providing protection to permafrost but would be for habitat restoration or aesthetic purposes.

7.6 Revegetation Monitoring

It is important to make periodic site visits to monitor progress of plant growth and also erosion as part of revegetation efforts. Yukon weather can be unpredictable and plant growth could be impacted positively by a wet year, but also on the other hand negatively by a dry year which could result in sparse or no plant growth. In the case of sparse or no plant growth, follow up efforts (such as additional seeding), would require further invention under the guidance of a vegetation specialist.

8. RESOURCE AND LOGISTICAL CONSIDERATIONS

Old Crow has a short construction season, is a remote fly-in/out community and has limited community capacity. These along with the presence of permafrost ground conditions makes for the carrying out of any infrastructure project work challenging.

Equipment/machinery and supplies required to complete subsurface investigations or to construct infrastructure, must be sourced and transported to site well in advance of when it is needed. It would need to be transported by air or temporary winter road. Availability of local manpower and equipment cannot be assumed as these resources may already be committed to other projects during the brief construction season. Similarly, though there are multiple options for local accommodation, these usually book up quickly during the construction seasons.

For geotechnical and/or hydrogeological investigations that require borehole drilling, the appropriate drilling equipment (often being air-track (percussion) drills and augers for drilling and sampling, or possibly even core drills) is often unavailable in remote communities such as Old Crow.

Porcupine Enterprises is the local Vuntut Gwitchin contractor in Old Crow. They complete and/or provide significant support on number of local construction projects in the community, such as road construction, riverbank stabilization, rock crushing and hauling of gravel from the Crow Mountain Quarry. As the construction season in Old Crow can be somewhat limited, Porcupine Enterprises should be contacted well in-advance for scheduling of any construction works. It is understood that Porcupine Enterprises has the following equipment in Old Crow, which may be utilized:

- Pickup trucks and trailers
- Track mounted excavator & mini-excavator
- Off-highway trucks (x2)
- Highway trucks (x2) with end dump boxes
- Wheel loader
- Dozers (x2)
- Grader
- Skid steer
- Vibratory compactor & plate tamper
- Drill capable of installing adfreeze piles

9. SPECIFICATION GUIDANCE FOR CONSTRUCTION DOCUMENTS/TENDERS

When planning projects in Old Crow, the protection of permafrost is a critical project consideration. There are several applicable guidelines, standards, and references for project planning and design of projects in Old Crow and its permafrost conditions. The following table summarizes the various project components, tasks, and the applicable references that should be referred to. This list is intended to guide project developers to the applicable guideline or standard that should be referenced when procuring planning and development services. These can form the basis for works scopes and/or specifications.

Table 12: Project Components, Tasks, and Applicable References for Consideration when Procuring Planning and Development Services

Item to Consider	Reference
Site Screening	
Risk-based screening for permafrost sensitivity	Government of Yukon, Design Requirements and Technical Standards
Site investigations (drilling, etc.) designed to protect permafrost	Government of Yukon, Design Requirements and Technical Standards Vuntut Gwitchin Government – Old Crow Zoning Bylaw #02-2014.
Collection of baseline information about site conditions (vegetation)	Yukon Revegetation Manual
Site Preparation	
Avoids unnecessary ground disturbance during tree removal	Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation
Preservation and/or stockpiling of soils and vegetation including careful consideration for the vegetative mat	
Avoids cutting into active zone or permafrost	
Considers optimal timing for site prep and excavations	
Foundation	
Design and drawings stamped by a qualified geotechnical engineer	National Building Code of Canada 2015
Incorporates thermistors	Government of Yukon, Design Requirements and Technical Standards
Optimizes thickness of gravel pad to preserve permafrost	Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation
Considers optimal timing for construction of foundations ▪ placement of engineered fill (gravel pad)	Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation

Item to Consider	Reference
▪ including allowing time for equilibration ▪ deep foundations piling	Good Building Practice for Northern Facilities Technical Guide: Design and construction considerations for foundations in permafrost regions
Includes levelling such as screw jacks or wedges for shallow foundations	Government of Yukon, Design Requirements and Technical Standards Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation
Incorporates drainage considerations and means to prevent water ingress into shallow foundations	Government of Yukon, Design Requirements and Technical Standards Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation Good Building Practice for Northern Facilities Moderating the effects of permafrost degradation on existing building foundations
Includes inspection and maintenance schedule (for thermistors, and for equipment such as thermosyphons)	Thermosyphon Foundations for Buildings in Permafrost Regions
Roadway Design	
Incorporates low-albedo materials	-
Avoids cuts into native ground	Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation
Incorporates appropriate drainage	Community Drainage System Planning, Design, and Maintenance in Northern Communities
Considers impact of embankment thickening and the need for insulation	Guzman et al., 2019; Calmels et al.,2016; Doré et al., 2020.
Design and drawings signed and stamped by a qualified civil engineer/Engineer of Record	Vuntut Gwitchin Government – Old Crow Zoning Bylaw #02-2014
Drainage Design	
Existing drainage patterns should be maintained; stream and creek crossings by infrastructure should be minimized	Good Building Practice for Northern Facilities Developing and Managing Transportation Infrastructure in Permafrost Regions (a Primer)
Where possible, surface water should be directed to natural drainage paths such as streams	Good Building Practice for Northern Facilities Developing and Managing Transportation Infrastructure in Permafrost Regions (a Primer)
Drainage should be designed to convey water away from community sites to a point down gradient, to avoid ponding	Good Building Practice for Northern Facilities

Item to Consider	Reference
Eavestroughs and building drainage features appropriately designed	Moderating the effects of permafrost degradation on existing building foundations
All roofs must be designed to shed snow and water away from entrance doors and adjacent pedestrian walkways and roadways	Government of Yukon, Design Requirements and Technical Standards
Building envelopes designed to control surface and groundwater	National Building Code of Canada 2015
Inlets and outlets of drainage features are designed to resist erosion (riprap, etc.)	Good Building Practice for Northern Facilities
Spring runoff accounted for during construction	Good Building Practice for Northern Facilities
Drainage systems should be designed to minimize surface disturbance in permafrost areas (e.g., armored berms or shallow swales rather than ditches)	Community Drainage System Planning, Design, and Maintenance in Northern Communities
Grading and drainage system designed by a qualified civil engineer/Engineer of Record	Government of Yukon, Design Requirements and Technical Standards
Culverts only used when necessary. Culvert design (materials, cover depth, inlet/outlet structure) is suitable considering permafrost and protects existing permafrost	Community Drainage System Planning, Design, and Maintenance in Northern Communities
Site Revegetation/Reclamation	
Collection of site-specific baseline data (slope, aspect, moisture, level of surface disturbance, sediment structure, drainage etc.)	Yukon Revegetation Manual
Recreate the insulative and protective cover, as quickly as possible, where disturbed or removed	
Utilize active or passive revegetation methods, as guided by vegetation specialist	
Any plant material added to the site must be hardy, suitable for the locality and require little or no maintenance	
Monitoring	
Monitoring for permafrost related distress is incorporated into existing annual inspections for buildings and areas listed	-
Thermistors inspected	Thermosyphon Foundations for Buildings in Permafrost Regions
Thermosyphons and the like are inspected	Thermosyphon Foundations for Buildings in Permafrost Regions

Item to Consider	Reference
Community drainage systems regularly inspected (e.g., in spring for blockages by ice or snow	Community Drainage System Planning, Design, and Maintenance in Northern Communities
Mitigation/Restoration recommendations are acted upon	-

10. RECOMMENDATIONS FOR VGFN

The intent of this document is to support future projects, rather than to provide specific, immediate actions related to permafrost. During discussions with VGFN, however, there was an interest expressed in identifying permafrost-specific actions that the community can pursue. This section provides three such actions, for consideration by the community.

1. Develop a community drainage plan

   Of the effects on permafrost resulting from surface disturbances in Old Crow, surface drainage was identified as the area with the greatest potential for improved permafrost management inside the community. CSA S503:20 *Community Drainage Planning, Design and Maintenance in Northern Communities* (available at no cost) provides a framework for developing a community drainage plan, along with extensive technical knowledge.

2. Establish a local monitoring network.

   It is clear that a large quantity of historical and modern data has been collected in Old Crow, however there is not presently a centralised repository for this knowledge. As part of VGFN's response to climate change, a long-term monitoring program could pull together much of this work. The scope of this would be for the community to decide, but it should include both traditional knowledge and scientific data. Whilst this Plan is focussed on the community of Old Crow as a town, such a monitoring plan is likely to be more valuable if it includes a wider area given the significance of the relationship between Vuntut Gwitchin people and the lands they live amongst.

   Fortunately, existing long-term climate and hydrological records are available. Other subjects of monitoring could include but are not limited to:

   - Ground temperatures (already many thermistors in Old Crow)
   - Vegetation and wildlife
   - Geography (landslides and slumps, inundation of dry areas or draining of lakes)
   - Frequency of relevelling of structures

3. Study projected changes in the natural environment.

   One of the key questions from VGG was what future changes to expect in the natural environment, in particular the permafrost environment, as a result of climate change. Given the ongoing changes in the climate, it is important to think about how the land may change in the future. One technique that may help in visualizing future changes is to identify a community whose present climate is similar to the projected future climate in Old Crow. Such a community would be a present-day "analogy" for a future Old Crow. Dawson, Yukon is too far south to be a good candidate but prospects are good of finding a match at one of the communities along the Mackenzie River, NWT.

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The objectives of this guidance document were determined through early discussion with Mr. Edwards, Ms. Heath, and Mr. Josie. Development of this guidance document is the result of gathering information from written sources and databases, and knowledgeable people, review of pertinent and readily available background information, a desktop preliminary site reconnaissance, and on-site inspections of existing infrastructure in Old Crow.

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CARTOGRAPHIC

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Figure 1: Scale 1:31,100. Data Layers: Geomatics Yukon: Contours (2016), and Roads (2014). Service Layer Credits: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community.

Figure 2: Scale 1:18,000. Data Layers: Geomatics Yukon: Cut Lines – 50k (2017), Trails – 50k (2019), Watercourses (2019); Vuntut Gwitchin Government (VGG): Old Crow Zoning Bylaw. Bylaw #02-2014 Schedule 'B'. Service Layer Credits: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community.

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Figure 4: Scale 1:10,111,020. Data Layers: Geomatics Yukon: Watercourses (2019); Kennedy, K.E., 2016: Surficial geology, Old Crow, Yukon; parts of NTS 116O/12. Yukon Geological Survey, Energy, Mines and Resources, Government of Yukon, Open File 2016-16, 1:10 000 scale. Service Layer Credits: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community.

APPENDIX A: Assessment of Existing Structures and Areas Affected in Old Crow

1. ASSESSMENT OF EXISTING STRUCTURES AND AREAS AFFECTED

1.1 General Indicators of Permafrost Related Distress

Surface infrastructure such as roads, airstrips, buildings, and sewage lagoons, often rely on the frozen state of permafrost for stability. These structures, along with other forms of infrastructure such as roadways, utility poles, ditches and culverts etc., may be vulnerable to distress or damage as a result of permafrost thaw and thickening of the active layer. An increase in temperature of frozen soil, even while remaining below 0°C, may deteriorate soil strength and impact any dependent infrastructure. Signs of permafrost related distress can often be detected through visible inspection of infrastructure and of disturbed landscapes/land surfaces. Appropriate mitigation efforts can then be explored and put in place to prevent further distress, where required.

As climate change continues, the interactions between permafrost, community infrastructure, and the changing climate will be better understood and so will the inherent risks and mitigation methods.

1.1.1 Infrastructure

Distress or damage to existing infrastructure such as buildings, due to permafrost degradation may be linked to climatic changes or other factors such as: the actual site conditions being different to the assumed design conditions for the lifetime of the structure; deviation in use from the original expectations during design; disregard for construction specifications/instructions; or, departure from the planned maintenance program for the structure (Instanes, 2003). Additionally, at the time of construction for some existing infrastructure, infrastructure design standards and engineering methods were not as developed, and permafrost not as well understood, as they are today, resulting in unintended consequences to permafrost stability.

Indicators of potential permafrost degradation beneath a structure includes (CSA Group, 2015):

- Interior (and/or exterior) cosmetic damage, such as cracks in drywall.
- Doors and/or windows sticking or not sealing.
- Damage to other visible structural components (e.g., piping systems, utilities etc.).
- Cracks and deformations in the foundation structure.
- Ground surface settlement or heave.
- Out-of-true building lines (e.g., tilted floors or roof lines).

Indicators of permafrost related distress may actually be a result of seasonal frost related issues within the active layer, rather than a result of permafrost degradation. Frost heave is a result of water in the active layer freezing, expanding, and pushing things such as the foundation up, and is typically cyclical (e.g., opening and closing of cracks) but may be progressive. Problems related to permafrost thaw are often detected in the summer and progressively worsen over time. Where possible, signs of infrastructure distress should be characterized as stemming from one or the other, as methods for mitigation may vary.

1.1.2 Landscapes

Landscapes, either disturbed by the clearing of organic cover or changes in surface or subsurface drainage, or essentially untouched by human activity, may display signs of permafrost related distress due to changes in the soil thermal regime, including:

- Areas with disturbed vegetation or an increase in abundance of shrubs and tall grass-like plants, due to greater thaw depths and wetter and warmer soils, possibly related to trapped snow increasing insulation in wintertime.
- Drunken forests (askew trees) or stunted trees with a “bent knee”, in part due to permafrost marking the limit of rooting and changing permafrost conditions causing displacement from normal to vertical alignment.
- Areas of sagging ground and/or hummocky ground and shallow ponding (thaw ponds).
- Active layer detachments and/or thaw slumps, particularly with slumping and erosion along rivers and lakeshores.

1.2 Previous Assessments of YG Buildings on Permafrost

During the late fall of 2017 and spring of 2018, Tetra Tech Canada completed a survey of Yukon Government buildings on permafrost. A total of 140 buildings were assessed and 20 of them were considered to be directly affected by permafrost thaw. This work was carried out partially in response to an Auditor General report, and as part of the Yukon Government’s continuing building maintenance program.

A total of 25 Yukon Government buildings were assessed in Old Crow as part of the study. The permafrost thaw risk for within Old Crow was listed as moderate and 3 of the assessed buildings were identified as impacted by permafrost thaw, as summarized in Table 1.

Table 1: Summary of 2017 Building Performance Observations for Old Crow (Tetra Tech, 2018).

Building Name and Number	Foundation Type	Observations	Recommendations Made
Warehouse (2646)	Shallow foundation.	Flexible wooden log structure	None.
School (2648)	Adfreeze Steel Pipe Piles.	Generally, in good shape – south entrance canopy has settled, crack in kindergarten bathroom and outside shop area, large cracks around column added in library. Thermistor cables present under school.	Read thermistor cables under school, install solar shield on ground surface along south wall of school to protect the south line of foundation piles, and the south exterior entrance.
Storage Sheds (2655, 2656)	Shallow foundation.	Airport storage sheds by grader station, potentially at the time slotted for demolition.	None.

Building Name and Number	Foundation Type	Observations	Recommendations Made
Three Bay Garage/Firehall (2659)	Mechanically chilled slab (dismantled).	Some slab settlement at back of building.	None.
Grader Station (2660)	Force air ventilated slab.	Floor slab looked good, some maintenance issues with overhead door operation.	None.
Airside Storage Sheds (2672,2673)	Shallow foundation.	No issues.	None.
Air Terminal Building (2675)	Pad footings on permafrost.	Some foundation issues since construction. Contractor did not follow specifications and opened up entire excavation – have had freezeback and surface water ponding issues in the crawlspace ever since. Thermistor strings present.	Read thermistor cables under the building, add fill and re-grade around the building so that water does not pond under the building.
EMR Storage Building (2677)	Pad footings on gravel pad.	New building at the time of inspection, no issues noted.	None.
Nursing Station/Health Centre (2934)	Pad footings on gravel pad.	Hoarded in airspace around the building. Centre was lower than perimeter. Building was noted in relatively good shape for its age.	None.

1.3 Inspection of Structures and Sites

1.3.1 Inspection Methods

The follow-up inspections completed in 2021 were limited to visual observations only and were completed in general accordance with the Canadian Standards Association (CSA) standard CAN/CSA-S501:21 Moderating the effects of permafrost degradation on existing building foundations (CSA Group, 2021) and with consideration for CAN/CSA-S503-15: Community drainage system planning, design, and maintenance in northern communities (CSA Group, 2015). However, due to COVID-19 pandemic related limitations, interior building inspections could not be completed.

No site-specific subsurface data was collected through any subsurface investigations (geotechnical, lithological etc.) as part this study. In future, more targeted, site-specific studies, if warranted, may include completion of a site-specific geotechnical investigation to ground truth the soil lithology, depth to permafrost, ground temperatures, and the ground ice content, and to collect soil samples for laboratory testing.

The Site Inspection Checklist/Form was utilized, and all sites inspected for general indicators of permafrost related distress as described in Sections 1.1.1 and 1.1.2. Site inspections also included inspection and documentation of the following:

- Visible damage to any water supply/distribution or sewage system that could lead to permafrost degradation (e.g., leaking water tanks or sewage tanks or piping).
- Ground settlement and surface drainage characteristics around the site, including ice damming, pooling, faulty eavestroughs, or water dripping or spilling from the structure.
- Conditions of adjacent developments/sites, vegetation, or similar conditions around the site.
- Existing in-situ instrumentation present on site to monitor ground temperatures or permafrost condition.

1.3.2 Inspection Results and Site-Specific Recommendations

Yukon Government Buildings/Sites		
Building Name: Grader Station	**YG and (VGFN) Building Number:** 2660 (130)	
	**Foundation Type**	Forced air ventilated concrete slab.
	Observations	- Single storey building with metal sheeting exterior, double garage. It is not clear if the forced air slab cooling is operational. Concrete slab with gravel pad (approx.) 1 m thick. - No guttering on roof, drains to the north and south sides of building. Positive drainage on-site on all sides, with minor ponding observed at the north side of property. - No subsidence or leaning building lines observed. - Two (2) thermistors present, on the southeast side and northwest corners of property. - No vegetation or shaded areas observed. - Road drainage between pad and runway may be poor.
	Recommendations	The forced air ventilation system should be confirmed to be in working condition. Otherwise, the site and building appear in good condition.
Building Name: Air Terminal	**YG and (VGFN) Building Number:** 2675 (145)	
	**Foundation Type**	Deep foundation - building appears to be on piles.
	Observations	- Raised, singles storey, heated building. Wood siding, shingle roof with gutters but no downspouts. Gravel on all sides, no shade or significant vegetation. - Crawlspace below building is approximately 1 metre, with slatted siding and wire allowing airflow. Water and sewer tanks and other stored items in crawlspace. Vertical shift evident in conduit joints within crawlspace, below building. - Building appears level and site drainage appears to be ok. No ponding visible. - There appears to be a surrounding monitoring network for water and temperature. - Existing records indicate thermistor strings were installed under the building and that there have been some foundation issues since construction. The contractor opened entire excavation resulting in freezeback and surface water ponding issues in crawlspace since (Tetra Tech, 2018).
	Recommendations	Check on thermistors under building. If operational, data should be downloaded and compared to historical data (if possible) to see if there are any warming trends. If ponding within the crawlspace is an issue, the area around the building should be regraded to promote drainage away from the building. Additionally, gutters (where not already present) and downspouts to splash pads can be installed to promote drainage away from the building and reduce potential for ponding within the crawlspace.

Yukon Government Buildings/Sites

Building Name: Storage Sheds (By Grader Station) | **YG and (VGFN) Building Number:** 2655, 2656

Foundation Type	Shallow foundations. 2655 has cribbing on gravel. 2656 has concrete slab, and some cribbing on gravel under small building addition.
Observations	- Single storey buildings, with metal sheeting exterior and/or wood. - No guttering and drainage between buildings appears to catch roof run-off. Positive drainage with sloping away of ground on all sides. No ponding observed. - 2655 is not completely level and appears to be due to building age and some disturbed/uneven cribbing on southeast corner of building. - No vegetation or shaded areas observed. - Monitoring wells and/or thermistors installed within vicinity of property.
Recommendations	Disturbed cribbing could be righted. Otherwise, the site and buildings appear in adequate condition.

Building Name: Airside Storage Shed | **YG and (VGFN) Building Number:** 2673

Foundation Type	Shallow foundation - small wooden structure with metal siding. Wooden sill foundation on gravel pad.
Observations	- Building appears to be for fuel pump. - Drainage appears to be good. - Three above ground storage tanks nearby building. - Monitoring wells and/or thermistors installed within vicinity of property.
Recommendations	None. The site and buildings appear in good condition.

Yukon Government Buildings/Sites

Building Name: Storage Shed	**YG and (VGFN) Building Number:** 2653

Foundation Type	Shallow foundation - building directly on gravel.
Observations	- Single storey buildings, with metal sheeting exterior and/or wood. - No guttering and drainage between buildings appears to catch roof run-off. Positive drainage with sloping away of ground on all sides. No ponding observed. - Building appears level. - No vegetation or shaded areas observed. - Monitoring wells and/or thermistors installed within vicinity of property.
Recommendations	None. The site and buildings appear in servicable condition.

Building Name: Firehall/3 Bay Garage	**YG and (VGFN) Building Number:** 2659

Foundation Type	Mechanically chilled slab (dismantled) (Tetra Tech, 2018). Concrete slab is on gravel, above grade by approx. 5 m.
Observations	- Triple bay wooden frame garage. Heated building. - There may be some slight slab settlement at the back of the building, consistent with Tetra Tech (2018). - Roof is slanted for drainage, with drainage to the southwest and northeast. No gutters. Swale is present by garage. Site drainage appears to be away from the building. - Garage vent fans are raised 4 m above grade. - Some low-lying vegetation (grasses) around building, and a few trees. - Some small puddles observed nearby entrance at roadway.
Recommendations	Site should be monitored for any further slab settlement at the back of the building. Otherwise, site and building appear to be in good condition.

Yukon Government Buildings/Sites

Building Name: Icehouse/Storage & Storage Shed	**YG and (VGFN) Building Number:** 2651 (Icehouse), 2658	
	**Foundation Type**	Shallow foundations. Wood directly on ground or possibly on wooden footings (limited visibility).
	Observations	- Single storey buildings made of wood. Buildings do not appear to be heated. - As the buildings are mostly made of wood, they appear to be somewhat flexible, and the building lines are not perfectly level. Both seem to be low on the river side (south side). The icehouse is also slightly lower on the northwest corner. - No guttering or eavestrough. Roof is slanted for drainage. The icehouse roof is bowed. Roadside swales drain to boat launch area to the south. Drainage is good. - The building is surrounded by vegetation (grass and shrubs). No shaded areas observed.
	Recommendations	Low lying shrubbery around the building could be removed to not promote snow accumulation (and insulation to permafrost) during winter months.

Building Name: Water Treatment & Truck Fill Plant	**YG and (VGFN) Building Number:** 2681	
	**Foundation Type**	Deep foundation - steel building on piles, 4 feet above grade.
	Observations	- Roof is sloped with gutters and downspouts. Downspouts include short (0.5 m) drain away from building. - Splash pad present under truck filling area. - Crawlspace under building is open for airflow with chain link fencing, no stored items. - Gravel pad and concrete splashpad present at truck fill point. This area was wet at the time of inspection. - No subsidence observed and building is level. - No vegetation or shade. - Few small puddles observed on-site. - Swale present between water plant and health centre for drainage towards the river. - Portable thermistor ports installed on-site related to Health Centre monitoring, but not operational.
	Recommendations	Overfill of the water truck can result in ponding water or water infiltration next to the building. Although the quantity may be negligible the frequency of the filling and spillage may have a cumulative impact on permafrost below. Otherwise, the site and building appear in good condition.

Yukon Government Buildings/Sites

Building Name: Health Centre/Nursing Station	**YG and (VGFN) Building Number:** 2934 (205)

Foundation Type	Appears to be post and wooden beam with gravel pad.
Observations	- Two-storey wooden building with complex gable roof. Building raised 1 m above grade. - Some building edges have gutters and downspouts but not all. There is a drainage extension at front of building to side garden. Some gutters are in poor condition. - Skirted crawlspace beneath building on all sides, except for below front entrance stairway. Each skirted side had one small vent. Some signs of settling below decking at southwest side of building. - Grass present to the south and west of building, exposed gravel to the north and east. - Extensive on-site monitoring network. Above ground fuel tank on-site on concrete slab. Concrete slab may be slightly unlevel. - Ditch present along east side of property draining towards the river. Site drainage is ok, some areas likely to puddle within driveway (due to pitting). Trees along south boundary of the property (by river) likely provide some shade on-site. - Multiple sheds on-site for storage. Shed at northeast corner not completely level.
Recommendations	Any damaged gutters or downspouts could be repaired to promote drainage way from the building to prevent any ponding. Otherwise, the Health Centre building appears to be in good condition.

Building Name: John Tizya Centre (Visitor Center)	**YG and (VGFN) Building Number:** 2943

Foundation Type	Deep foundation - steel frame on piles with gravel pad.
Observations	- Building raised 1 m above gravel pad, and gravel pad is approximately 1 m thick. Building is single storey with metal siding and is level. - Sloped roof with drainage to northeast corner with extended gutter past roof edge which drains into a garden/cobble pit. - Crawlspace is open and only stores sewage and water tanks. Fuel tank to east of building. - Some vegetation (shrubs and grasses) present around building on gravel pad. - Site grading is good with drainage way from building on all sides. Northwest of the raised gravel pad may be prone to ponding. No signs of subsidence.
Recommendations	Based on ERT data by (Benkert et al., 2016), there may be a talik present beneath this building. However, the site and building appeared to be in good condition. Therefore, there are no recommendations.

Yukon Government Buildings/Sites

<table>
<tr><td colspan="2">Building Name: Chief Zzeh Gittlit School</td><td colspan="2">YG and (VGFN) Building Number: 2648 (999)</td></tr>
<tr><td rowspan="3" colspan="2"></td><td>Foundation Type</td><td>Deep foundation - adfreeze steel pipe piles.</td></tr>
<tr><td>Observations</td><td>- Single storey building. Raised from grade by 0.5 m at perimeter. There is a larger vault under the building centre where tanks are stored and separated from the ground.
- Crawlspace is skirted with wire mesh to allow airflow.
- Above ground fuel tank present at northeast side of building.
- Roof slopes in all directions with a few flat sections. Gutter only over entrance.
- Site is well drained.
- Building lines appear to be good with exception of east entrance where deck support beam experienced frost jacking.
- No interior inspection could be completed. Tetra Tech (2018) previously reported cracking in kindergarten bathroom and outside shop area, and large cracks around a column in the library. Tetra Tech (2018) identified that the south entrance canopy has settled and recommended that a solar shield be installed on ground surface along south wall of school to protect foundation piles and south entrance. No solar shield was observed on-site.</td></tr>
<tr><td>Recommendations</td><td>Check on thermistors under building. If operational, data should be downloaded and compared to historical data to see if there are any warming trends. To reduce further settling at the south entrance area of the school, snow management methods could be implemented, including installation of snow sheds or clearing of snow from around the building and crawlspace through the winter to allow frost penetration and cooling during winter. Additionally, as suggested by Tetra Tech (2018) a sunscreen or solar shield could be installed or a surface treatment applied to increase albedo.</td></tr>
<tr><td colspan="2">Building Name: Teacherages</td><td colspan="2">YG and (VGFN) Building Number: XXXX (898/899, 895/897)</td></tr>
<tr><td rowspan="2" colspan="2"></td><td>Foundation Type</td><td>Shallow foundations - space frames on low gravel pad.</td></tr>
<tr><td>Observations</td><td>- Wooden footings under entrance decking.
- Multi-storey residences with metal siding.
- Some gutters with downspouts are installed over entrances. Rooves are slanted. Downspouts point to ground at building perimeter.
- Some low spots likely prone to ponding on gravel driveway.
- Outside of gravel pad area is surrounded by native vegetation.
- Above ground fuel storage tanks on cement pads.
- No signs of settling.</td></tr>
</table>

<table>
<tr><th colspan="3">Yukon Government Buildings/Sites</th></tr>
<tr><td></td><td>Recommendations</td><td>None. The site and building appear in good condition.</td></tr>
<tr><td>Structure: Sewage Lagoons</td><td colspan="2">YG and (VGFN) Building Number: Not applicable. Located northwest of runway.</td></tr>
<tr><td rowspan="3"></td><td>Foundation Type</td><td>Gravel pad.</td></tr>
<tr><td>Observations</td><td>- Sewage Lagoons have recently been significantly upgraded.
- No evidence of subsidence or ponding water on-site.</td></tr>
<tr><td>Recommendations</td><td>None. The site and structures appear to be in good condition.</td></tr>
<tr><th colspan="3">VGG Buildings/Sites</th></tr>
<tr><td>Building Name: Community Hall (prior to construction of new Hall in 2020-2021)</td><td colspan="2">VGFN Building Number: 600</td></tr>
<tr><td></td><td>Foundation Type</td><td>Shallow foundation. Wood building on wooden footings.</td></tr>
</table>

Yukon Government Buildings/Sites		
	**Observations**	- Single storey wooden building on gravel pad. - Positive drainage on all sides of building with grading and/or swales/ditches. - No gutters or downspouts, but roof is sloped. - Grassy vegetation surrounds building. Drainage appears to be slightly south, towards the roadway and river. - Good building lines. - Above ground fuel tank located at north end of building. - No signs of settling.
	Recommendations	None. The site and building appear in good condition.
Building Name: Chief Peter Moses Centennial Hall	**VGFN Building Number:** 570	
	**Foundation Type**	Shallow foundation. Wood building on wooden footings.
	Observations	- Single storey wooden building on gravel pad. - Positive drainage on all sides of building with grading and/or swales/ditches. - No gutters or downspouts, but roof is sloped. - Grassy vegetation surrounds building. - There appears to have been some shifting of wooden logs on western side of building.
	Recommendations	None. The site and building appear in good condition.
Building Name: Sarah Abel Chitze Building (Administration Building)	**VGFN Building Number:** 775	
	Foundation Type	Suspected as deep foundation with steel piles.

Yukon Government Buildings/Sites		
	**Observations**	- Single storey building with wood and some metal siding. - Roof appears flat in some spots. No observed gutters or downspouts. - Building is on gravel pad that is slightly elevated compared to adjacent roadway. - Some vegetation around building. - Building is raised approx. 0.3 m above ground. Crawlspace has slatted wooding skirting with some restriction of air flow. - Building lines look good.
	Recommendations	None. The site and building appear in good condition.

Yukon Government Buildings/Sites

Building Name: Community Youth Centre & Radio Station	**VGFN Building Number:** 700	
	**Foundation Type**	Shallow foundation – cribbing on gravel.
	Observations	- Multi-storey wooden building. Building raised approx. 0.5 above ground. Crawlspace is unrestricted to airflow. - No gutters. Slanted roof. No ponding observed. - Building lines look good. - Some storage of items within crawlspace beneath building. - Appears to have positive drainage on all sides of building with ditching to the west and south.
	Recommendations	None. The site and building appear in good condition.
Building Name: St. Luke's Anglican Church	**VGFN Building Number:** 490	
	**Foundation Type**	Shallow foundation. Wood directly on ground or possibly on wooden footings (limited visibility).
	Observations	- Single storey wooden building. - No gutters or downspouts, but roof is sloped. - Grassy vegetation surrounds building. Drainage appears to be slightly south, towards the roadway and river. - Building lines look good considering the age of the building. - Above ground fuel tank located at north end of building. - No signs of settling. No ponding.
	Recommendations	None. The site and building appear in good condition.

Yukon Government Buildings/Sites		
Building Name: Alice Frost Community Campus	**VGFN Building Number:** 460	
	**Foundation Type**	Shallow foundation – cribbing on gravel.
	Observations	- Single storey wooden building. Building raised approx. 0.35 above ground. Crawlspace is unrestricted to airflow. - Gutters only above entranceway. - Building lines look good. - No ponding observed. Site drainage looks ok.
	Recommendations	None. The site and building appear in good condition.
Building Name: Archdeacon McDonald Memorial Church	**VGFN Building Number: 495**	
	**Foundation Type**	Shallow foundation. Wood directly on ground.
	Observations	- Single storey wooden building. - No gutters or downspouts, but roof is sloped. - Grassy vegetation surrounds building. Drainage appears to be slightly south, towards the roadway and river. - Building lines are off which is consistent with building age and wooden structure.
	Recommendations	None. Building is a historical building, and it is understood that it is not in use and not heated.

Yukon Government Buildings/Sites		
Additional Areas Inspected		
Area: Airport Runway Area		
	**Observations**	Perimeter fencing around airport runway was observed to be frost jacked in some locations.
	Recommendations	None. Not likely related to permafrost.
Area: North Road		
 	**Observations**	- Eastern portion of airport runway area and North Road appears to drain to the north via ditches and culverts to Lakes. - Western portion of airport runway area and North Road appears to drain to the two small lakes nearby, and to a westward flowing stream adjacent to the roadway which appears to drain westward to the Porcupine River. - Drainage in the area of North Road and the Airport Runway appears to be good. - Young willows and other shrubbery were observed growing on both sides of North Road, which may promote snow drifting and accumulation resulting in an insulating impact along the gravel roadway.
	Recommendations	Roadside shrubbery should be removed to prevent snow accumulation along the edges and ditches of the gravel roadways.

Yukon Government Buildings/Sites		
Area: North of North Road, east of Sewage Lagoons		
	**Observations**	- Low lying area at the toe of a colluvial apron/fan. Likely subject to flooding. - Transected by a number of ski trails and accessible by Ski Chalet to the northeast. - Characterized by forest of black spruce, some birch, and many large shrubs, grasses, and thick hummocky ground cover. - Ice content in active layer and permafrost is high and likely quite susceptible to warming and subsidence. - There may be ephemeral streams in this area, present or flowing during or shortly after snow melt or rainfall events. Ponding may be an issue in this area.
	Recommendations	The presence of water at ground surface can have significant impact on ground temperature, especially where drainage is limited. Additionally, high ground ice contents can be susceptible to thaw and significant subsidence. Careful consideration should be taken for any future development plans (if any) for this area.
Area: Roadways in community core (not including North Road or Crow Mountain Road)		
	**Observations**	- Ponding of water was observed in low lying areas along gravel roadways within the community core.
	Recommendations	Pooling of water along roadways and roadsides in Old Crow has been observed in the autumn and is likely a more prevalent issue in the spring with the spring melt or shortly after and rainfall events. Ponding water may be due to poor grading or due to a lack of a defined drainage system. Areas with ponding due to poor grading should be regraded to promote positive drainage. An inspection could be completed in the spring to identify areas with significant ponding that could benefit from the installation of additional drainage systems.

1.3.3 Priority List of Areas Requiring Mitigative or Restorative Efforts

Areas or structures requiring mitigative or restorative efforts as identified in the former result and recommendations table, are listed below in order of priority:

1. Roadways with ponding water
2. North Road
3. Chief Zzeh Gittlit School
4. Airport Terminal
5. Truck Fill Plant (minor recommendations)
6. Health Centre (minor recommendations)

1.3.4 Areas Requiring Protection

Previously disturbed and abandoned sites should be protected or carefully considered for future redevelopment activities. This would include the abandoned houses and/or lots located to the east of the Tank Farm. This area is believed to have a deep seasonal thaw, or a supra-permafrost talik which is linked to the structural damage previously observed in the log homes (Benkert et al., 2016). Previously disturbed and abandoned sites may continue to be affected by thaw that was triggered by the former site structures or activities.

Gravel surfaces, including pads and roads, are often built to protect permafrost and if abandoned, should be left in place, if possible, to avoid any further disturbance. Revegetation options could be considered for reclamation of abandoned gravel surfaces; however, such surfaces are difficult to revegetate due to their inherent conditions (general absence of organic layers, little moisture holding capacity, low nutrients, high compaction etc.) (Johnson 1987, Jorgenson and Joyce 1994) as elaborated on further in Section 8.5.

Low-lying areas that are prone to flooding and poor drainage, paired with high ground ice content, such as the area located to the north of North Road and east of Sewage Lagoons (with many ski trails), should be protected, or careful consideration and planning efforts (including permafrost protection measures) should be taken for any future development in the area.

1.4 Establishing a Monitoring Program

All sites should include in their annual general maintenance inspections, visual assessments (of interior and exterior) for any general indicators of permafrost related distress, as outlined in Section 6.1, of the Guideline. The Site Inspection Checklist/Form utilized for this study (and provided at the end of Appendix A) can be provided for this purpose. Any new signs of distress or changes in conditions could be noted and reported to the proper YG authority for action.

Sites with ground temperature monitoring infrastructure, such as the Air Terminal or the Chief Zzeh Gittlit School should be maintained and utilized periodically for continued monitoring of ground temperatures to identify any warming trends in the permafrost.

APPENDIX B: Best Practices for the Protection of Existing Vegetation

1. BEST PRACTICES FOR THE PROTECTION OF EXISTING VEGETATION

Permafrost requires an insulating surface cover, consisting of accumulated organic matter and living plants to remain cool and stable. Without vegetative cover, the permafrost may melt quickly and result in melted ground, ground saturation, and then slumping and erosion (Matheus and Ontzigt, 2012). For development projects, existing vegetation on site should be protected and maintained as much as possible. Vegetation is a natural asset in the Yukon and takes a long time to grow. Preserving vegetation also helps to minimize erosion and can reduce revegetation costs following construction.

General best practices for the protection of existing, includes the following:

- Leave surface organic mat in-place (where possible) and reduce the disturbance of the mat to the greatest extent practical. Often infrastructure projects require a base layer of granular fill to either level the surface of the site or act as an engineered pad on which to construct a structure. Even in a compressed state, the organic mat will to some degree insulate the permafrost soils below, while separating them from the imported fill above (CSA Group, 2019a).
- Clearing and grubbing operations should be staged to preserve existing vegetation.
- Protection zones should be developed during site design. Potential sources of injury include soil compaction during grading or due to construction traffic. Direct equipment-related injury such as scraping or ripping up of the vegetative mat or tree branch breakage, surface grading and trenching, and soil cut and fill. In order to minimize damage that may lead to immediate or later death of vegetation, protection zones should be developed during site design, implemented at the beginning of a construction project, and continued during construction.
- Construction fencing should be installed around protection zones. The temporary fencing should be at least 1 meter tall. For protection areas that contain trees, ensure the protection zone includes enough space from the trunk to protect the root zone from soil compaction and mechanical damage. The roots of a tree can extend from the trunk to approximately 2-3 times the distance of the dripline.
- On-site personnel/subcontractors should be informed of and instructed to honor protective fencing and carry out protective measures.
- Only clear and blade to bare mineral soil when and where it is absolutely necessary. Instead, consider cutting trees and shrubs off at ground level and leaving the root mass in the ground. Willows in particular are very hardy and will regrow after being cut off and driven on, as long as most of the roots are kept intact. When blading to bare mineral soil must be done, stockpile and cover the scraped vegetation and organic soil and leave it in the immediate vicinity. It can be re-applied after work is complete, or applied elsewhere as needed (YG, 2019).