RISK EVALUATION FOR PERMAFROST-RELATED THREATS: METHODS OF RISK ESTIMATION AND SOURCES OF INFORMATION

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DISCLAIMER

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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ABSTRACT

In our evaluation of permafrost-related threats that affect Alaska communities, we have focused on threats associated with permafrost degradation and thawing ground ice, which can result in significant thaw settlement and cause unacceptable damage to engineered structures. Our evaluation system for permafrost-related threats includes risks of general permafrost degradation and thaw settlement (general and differential). We have evaluated permafrost-related threats for 187 Alaska villages based on available information including scientific publications, maps, satellite imagery and aerial photographs, geotechnical reports, personal communication, community plans and reports, and other sources. Evaluation was based on five criteria: permafrost (PF) occurrence; PF temperature; thaw susceptibility of frozen soils (expected thaw settlement in case of permafrost degradation); massive ice occurrence; and existing PF-related problems. For each of these categories, four risk levels (ranks) were considered. The total (cumulative) risk level was based on the rating score (sum of individual ranks for all five categories). Based on the rating score, each village was assigned one of four risk levels: 0 – no permafrost; 5–8 – low risk level; 9–11 – medium risk level; 12–15 – high risk level. A vulnerability score was developed for each community allowing the identification of communities with the highest risk of damage due to thawing permafrost. Most of communities with the high-risk level (22 villages of 34) are underlain by continuous permafrost, while the low risk level is typical mainly of communities underlain by predominantly unfrozen soils/bedrocks (33 villages of 46), and no high risk levels were detected for this group of villages. Medium risk level is typical mainly of communities underlain by discontinuous and sporadic permafrost (35 villages of 47); some villages of this group are characterized by high and low risk levels (12 and 9, correspondingly). Occurrence of massive-ice bodies (mostly ice wedges) is typical exclusively of communities underlain by continuous and discontinuous permafrost (23 and 20 villages, correspondingly). We presume that at least 20 communities may have extremely ice-rich yedoma deposits with large ice wedges either within villages or in their vicinity. Permafrost conditions in Alaskan communities are very diverse, and in many cases they are extremely variable even within the same community. Detailed studies are required for more precise evaluation of potential permafrost-related threats associated with permafrost degradation and/or thawing of ground ice.

CHAPTER 1. GENERAL APPROACH TO RISK EVALUATION

In this evaluation of permafrost-related threats that affect Alaska communities, we have focused on threats associated with permafrost degradation and thawing ground ice, which can result in significant thaw settlement and cause unacceptable damage to engineered structures. Our general approach to risk evaluation for permafrost-related threats, which includes risks of general permafrost degradation and thaw settlement (general and differential), is illustrated in the flowchart (**Figure 1**).

The first step in the evaluation process includes analysis of the possibility that mean annual ground temperature (MAGT) at the permafrost table will exceed 0°C in the future, causing permafrost degradation. According to Smith et al. (2010) and Romanovsky et al. (2017), the recent climate-related increase in permafrost temperatures has strongly affected areas of continuous permafrost. Under present-day climate conditions, the risk of permafrost degradation is still much higher in areas with isolated, sporadic, and discontinuous permafrost, where MAGTs are already close to 0°C. In most of the continuous permafrost zone, MAGTs are still cold enough to prevent permafrost degradation for several decades. Thawing of permafrost in these cold areas may occur only in the case of thawing saline cryotic soils caused by an increase in MAGT. Depending on the salinity, such thawing may start even if MAGTs are still relatively low. For example, continued thawing may be expected at Utqiaġvik (former Barrow) and Kaktovik where unfrozen saline soils (cryopegs) were encountered recently at several meters below the ground surface.

If the risk of permafrost degradation around a certain community is probable in the near future (in areas with MAGTs >-2°C), two possible scenarios should be considered, depending on the occurrence of thaw-susceptible soils (**Figure 1**, left side of diagram). If soils do not contain significant amounts of excess ground ice, there is no risk of thaw settlement even after complete permafrost degradation. If soils are thaw susceptible, two scenarios are possible, depending on the occurrence of massive ice bodies near the ground surface. When no massive ice is present in the area (particularly ice wedges), no risk of differential thaw settlement caused by melting of massive ice should be expected, and the risk level of general thaw settlement depends on the amount of excess ground ice. The occurrence of massive ice commonly results in differential thaw settlement caused by general permafrost degradation (e.g., differential thaw settlement due to thermokarst and thermal erosion along ice wedges).

If there is no risk of permafrost degradation caused by an increase in MAGT in the near future (in areas with cold permafrost), two possible scenarios should be considered, depending on the occurrence of thaw-susceptible soils (**Figure 1**, right side of diagram). If no thaw-susceptible non-saline soils and/or massive ice bodies are present, significant risk of general permafrost degradation and thaw settlement, both general and differential, should not be expected. The occurrence of massive ice bodies near the surface very often results in differential thaw settlement caused by thermokarst and thermal erosion (commonly along degrading ice wedges), which may not be related to an increase in MAGT. In areas of cold continuous permafrost, this process is usually reversible (Jorgenson et al., 2006, 2015; Kanevskiy et al., 2017), but may cause serious damage to roads and buildings because ice wedges may degrade to significant depths while the central part of polygons remains relatively stable. Under certain conditions, ice-wedge degradation may result in the formation of deep thermokarst ponds and consequent permafrost degradation (and general thaw settlement) if MAGT under the pond exceeds 0°C.

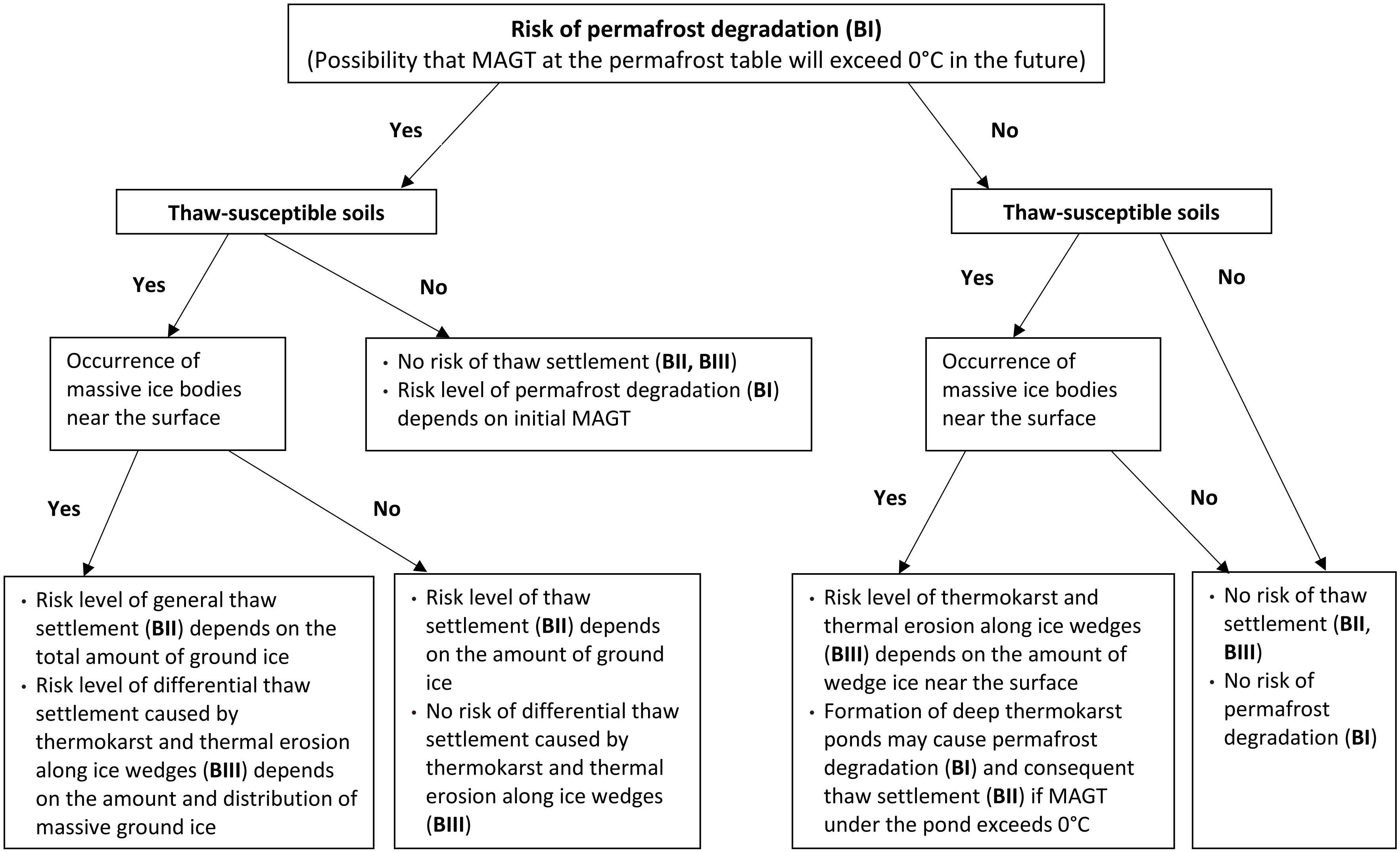


Figure 1. Evaluation of risks of permafrost degradation (BI) and thaw settlement (BII – general, BIII – differential, due to ice-wedge degradation); for explanation of risk categories BI, BII, and BIII, see **Chapter 3**.

CHAPTER 2. DATA REQUIRED FOR RISK EVALUATION AND THEIR SOURCES

To characterize permafrost conditions and evaluate permafrost-related threats that affect Alaska communities, we have collected available data on permafrost occurrence, temperature, thickness, and distribution; soil types and properties (ground-ice content, thaw strain, etc.); occurrence of massive ice bodies (first of all, ice wedges); occurrence of surficial features indicating ground-ice degradation; estimation of potential thaw settlement; and information on existing permafrost-related threats. Data sources included scientific publications, maps, satellite imagery and aerial photographs, geotechnical reports, community plans and reports, authors' field data, and personal communication. A database containing PDFs of publications and reports for Alaska villages was compiled. Obtained data were summarized in a table (examples for several villages are presented in **Table 1**), which contains various categories of information:

1. Permafrost (PF) zone and PF thickness. In Alaska, there are four PF zones defined by permafrost extent: Continuous (>90%), Discontinuous (50–90%), Sporadic (10–50%), and Isolated (<10%). The thickness of PF in Alaska varies from several to >600 m. Data sources: Permafrost map of Alaska (Jorgenson et al., 2008); books (e.g., Ferrians et al., 1969, Williams, 1970; Péwé, 1975, 1993; Yoshikawa, 2013) and journal publications; and geological (USGS, DGGS) and geotechnical (DOT, Golder, Shannon and Wilson, Duane Miller, etc.) reports.

2. Permafrost occurrence and distribution. To characterize PF distribution, we use the following codes: P – near-surface permafrost; L – areas with lowered permafrost table (closed taliks); PL – near-surface permafrost with closed taliks in some areas; T – open or deep (> depth of drilling) taliks; PT/LT/PLT – permafrost (P and/or L) with open or deep taliks; U – unfrozen (no permafrost); C – cryopegs (unfrozen saline soils with temperatures <0°C); PC/LC/PTC/LTC/PLTC – permafrost (P and/or L) with cryopegs (**Figure 2**). This information is important for villages with diverse permafrost conditions. If a village and its vicinities are located within different terrain units with different PF conditions, this information should be specified. For example, a village may be located on unfrozen soils (U), but an airport area is underlain by near-surface permafrost (P). Data sources: geological and geotechnical reports, scientific publications.

3. Permafrost temperature, °C. Information on PF temperature is necessary for evaluation of the risk of permafrost degradation (**Risk Category BI,** see **Figure 1 and Chapter 3**), i.e., risk of gradual lowering of the permafrost table, which starts when MAGT at the permafrost table exceeds 0°C. Sources: data from the Geophysical Institute Permafrost Laboratory (GIPL), University of Alaska Fairbanks (http://permafrost.gi.alaska.edu/sites_map); Romanovsky et al., 2017; Jorgenson et al., 2008; Yoshikawa, 2013; geological and geotechnical reports, etc.

4. Active layer (AL) thickness, cm; and/or PF table, m (the latter should be determined for locations with lowered PF table with codes L, PL, PTL, TL, see **Figure 2**). Sources: CALM database (https://www2.gwu.edu/~calm/data/data-links.html), papers, geological and geotechnical reports, etc.

Table 1. Data required for general assessment of permafrost (PF) conditions in Alaska villages and risk evaluation for PF-related threats (example).

Village	PF zone and PF thickness	PF occurrence[1]	PF temperature (MAGT), °C	Active layer (AL) thickness, cm; PF table, m (for locations with lowered PF table)	Soils, gravimetric moisture contents (GMC), excess ice volume (EIV), salinity, etc.	Thickness of layer with excess ground ice (H), m	Thaw strain (T), unit fraction	Massive ice: Wedge-ice volume (WIV), unit fraction; height of ice wedges (HIW), m	Thaw settlement (TS), m [2] TS = WIV*HIW* (1–T)	PF features detected on satellite imagery [3]	Existing threats: Threat Mitigation Plans; pers. comm., etc.[4]
1	2	3	4	5	6	7	8	9	10	11	12
Kaktovik	Continuous ~400 m	P	-9	AL 30-50cm	Ice-rich peat, sandy silt with ice wedges (2.5 m), sand and gravelly sand with massive ice (7 m), underlain by marine clay	>9	0.3	0.35 (WI + buried glacier ice), H=HIW	4.9	HCP – high surface; LCP – thaw-lake basins; TP, TG; TLB	Houses and other buildings are beginning to settle, with floors and structures now becoming uneven (Kaktovik LHMP, 2005). Survey: Lots of residential settling, utilidor shifting, soil depressions, erosion, etc.
Kaltag	Discontinuous 20 m	PTL	-0.5	AL40-100cm, PF 2-7.5m	Organic silt, silt, sporadically - sand and gravel; GMC of frozen silt up to 40%	5?	<0.05	No massive ice	0.2	Shallow TLB in the forests adjacent to the village	The new town site development area has approximately 14 homes that are experiencing uneven settlement (thawing) or uplift (frost heaves). These incidents are directly related to human-induced thawing and refreezing permafrost conditions. Uneven settling throughout the years within the City has damaged other buildings and roads constructed in permafrost areas (Kaltag HMP, 2010).
Wainwright	Continuous ~300 m (~330-GTNP)	PC	-8	AL 20-50cm	Ice- and org-rich silt (4.5-6 m thick) underlain by sand and gravelly sand	6	0.5	WIV: 0.2 HIW: 4	3.4	HCP – high surface; LCP – thaw-lake basins; TP&TG – rare; TLB	Half of all ice cellars in Wainwright have been lost in the last 30 years; problems with foundations were reported (Wainwright Comprehensive Plan, 2014). Survey: Uneven floors, ponding, settlement, etc., stove oil lines stretching and cutting off supply.

[1] P – near-surface permafrost; L – areas with lowered permafrost table (closed taliks); PL – near-surface permafrost with closed taliks; PT/LT/PLT – permafrost (P and/or L) with open or deep (> depth of drilling) taliks; U – unfrozen (no permafrost).

[2] Thaw settlement: **TS = T*H**, where T – average thaw strain of soils, unit fraction; H – thickness of layer with excess ground ice, m. Average thaw settlement in the areas with ice wedges: **TS = WIV*HIW + T*HIW*(1 – WIV) + T*(H – HIW) = WIV*HIW*(1 – T) + T*H**, where WIV – wedge-ice volume, unit fraction; HIW – height (vertical extent) of ice wedges, m; T – average thaw strain of soils (without taken ice wedges into account), unit fraction; H – thickness of layer with excess ground ice, m. For situation, when H = HIW, **TS = WIV*H + T*H *(1 – WIV).** For situation, when T values are different for a layer containing ice wedges (T^1 for HIW) and a layer with excess ice below ice wedges (T^2 for H – HIW), **TS = WIV*HIW + T^1*HIW*(1 – WIV) + T^2*(H – HIW)** Differential thaw settlement depends mainly on HIW, width of ice wedges, and depth of thawing; commonly we may expect not less than 1-m settlement in areas affected by ice-wedge thermokarst

[3] HCP – high-centered polygons; LCP – low-centered polygons; FCP - flat-centered polygons; TP – thermokarst ponds; TG – thermo-erosional gullies; TLB – thaw-lake basins; RTS – retrogressive thaw slumps

[4] Local or Tribal Hazard Mitigation Plans (LHMP or THMP), which contain some information on critical infrastructure and permafrost-related problems, are available for many villages at: https://www.commerce.alaska.gov/dcra/DCRARepoExt/Pages/CommunityPlansLibrary.aspx.

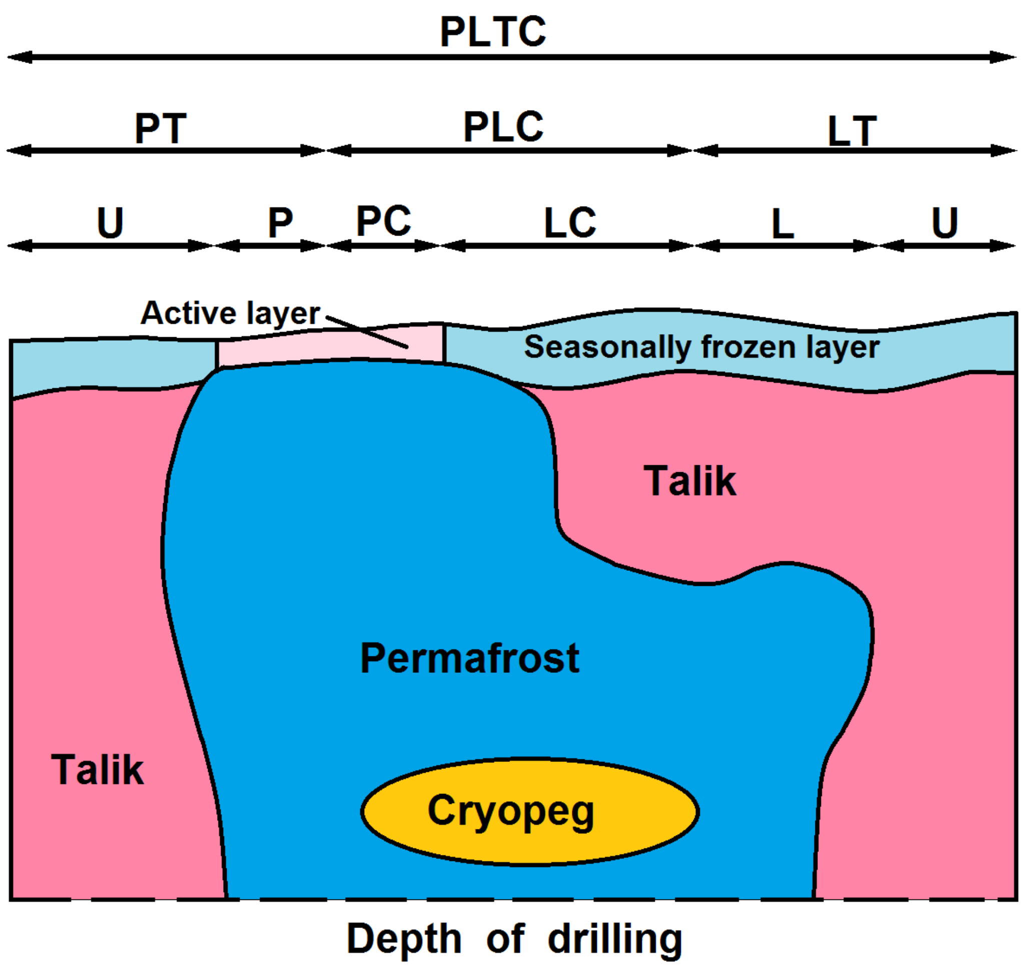


Figure 2. Codes used for descriptions of permafrost occurrence and distribution within Alaska communities: P – near-surface permafrost; L – areas with lowered permafrost table (closed taliks); PL – near-surface permafrost with closed taliks; PT/LT/PLT – permafrost (P and/or L) with open or deep (> depth of drilling) taliks; U – unfrozen ground (no permafrost); C – cryopegs (unfrozen saline soils with temperature <0°C).

5. Soil types and properties, including gravimetric moisture contents (GMC), excess ice volume (EIV), salinity, etc. Information on soil types and properties is necessary for estimation of potential thaw settlement (**Risk Categories BII, BIII**, see **Figure 1 and Chapter 3**). During geotechnical investigations, EIV is commonly estimated as a volume of lenses and inclusions of visible ice in frozen cores. Based on GMC and/or EIV values, thaw settlement may be estimated. Sources: geotechnical reports, journal publications, etc. If a village and its vicinities are located within different terrain units with completely different soil and ground-ice conditions, this information should be specified. For example, a village may be located on thaw-stable soils, while an airport area may be underlain by ice-rich permafrost.

6. Thickness of layer with excess ground ice (H), m. Excess ground ice – the volume of ice in the ground that exceeds the total pore volume that the ground would have under natural unfrozen conditions (van Everdingen, 1998). Excess ground ice includes lenses of segregated ice, massive ice bodies, and partially pore ice (first of all, inclusions of pore ice visible by naked eye). Excess ground ice mostly accumulates in the upper permafrost. For this study we cannot take into account excess ground ice located in deep permafrost horizons that cannot be encountered by drilling during geotechnical investigations. Sources: geotechnical reports, journal publications, etc.

7. Thaw strain (T), unit fraction. Information on thaw strain is essential for evaluation of the risk of thaw settlement (**Risk Category BII**, see **Figure 1 and Chapter 3**). Here we report average value of thaw strain caused only by melting of pore and segregated ice (massive ice bodies are not taken into account). Data on thaw strain of frozen soils in Alaska are very limited but thaw strain may be estimated based on GMC and EIV values obtained from geotechnical reports. For example, thaw strain of organic-rich silts (yedoma) may be estimated based on GMC values according to the diagram shown in **Figure 3**. Similar diagrams were also created by Shur (1988) for silty soils in Siberia. Excess ice volume values, obtained during geotechnical investigations, may be used as a proxy for thaw strain, though visual estimations cannot be precise. In this column, we present T values, which are estimated for free-thawing conditions (without taking external load into account, but these values would be much greater under stress (**Figure 3**).

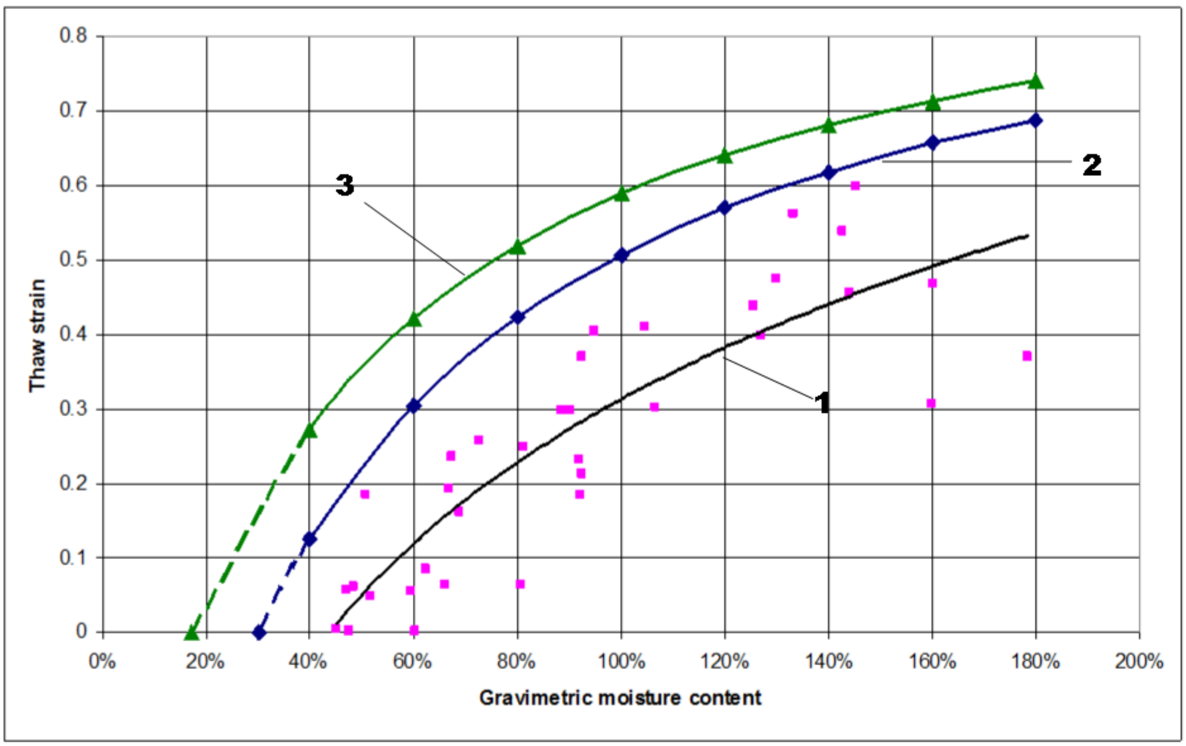


Figure 3. Thaw strain of yedoma silt vs gravimetric moisture content, Dalton Highway, 9-Mile Hill: 1 – without external load; 2 – under the stress 50 kPa (7.5 psi); 3 – under the stress 140 kPa (20 psi) (Shur et al., 2010; Kanevskiy et al., 2012).

8. Massive ice: Wedge-ice volume (WIV), unit fraction; height of ice wedges (HIW), m. Information on massive ice is essential for evaluation of the risk of thaw settlement (**Risk Categories BII** and **BIII**). The main types of massive ground ice are (1) wedge ice (most common); (2) buried glacier ice (we presume it exists in the Kaktovik area; there are many locations with buried glacier ice in the Alaska Range and Brooks Range areas, including in the foothills); (3) intrusive (pingo) ice (relatively rare, easy to detect, usually does not create problems for villages); (4) thermokarst-cave ice (relatively small ice bodies, commonly form along partially degraded ice wedges; no need to consider during risk evaluation). Wedge-ice volume for epigenetic ice wedges (for the layer containing ice wedges, equivalent to HIW) may be estimated according to the diagram (**Figure 4**). The size of ice-wedge polygons may be detected on satellite imagery (**Figure 5**). In many cases, the estimation of ice-wedge width requires additional information, which is not easily available. For syngenetic ice wedges (e.g., wedges in yedoma), WIV usually varies from 0.2 to 0.8; for areas without appropriate information, we assume that the average value of WIV is ~0.5. During our permafrost studies along the Beaufort Sea coast of Alaska (Kanevskiy et al., 2013), we estimated the wedge-ice volume for various terrain units based on the assumption that the cross-section of ice wedges has a shape of an isosceles triangle, which is typical of the epigenetic ice wedges that prevail in the study area, and all polygons are square. Such an approach allows calculation of wedge-ice volume through the volume of truncated pyramids representing the soil block framed by ice wedges. An average size of polygons was estimated from satellite or aerial photographs. To find an average polygon area, we calculated the total number of whole (complete) polygons and one-half of the number of incomplete polygons, located within 100 × 100 m^2 areas (**Figure 5**) adjacent to our field sites. For estimation, the average size of polygons was considered equal to a square root of the average polygon area. An average size of ice wedges for study sites was estimated in the field. Unfortunately, estimation of ice-wedge width using satellite imagery is possible only for areas with well-developed high-centered polygons with wide (>4–5 m) ice wedges. Several other studies have also estimated WIV in polygonal terrain using remotely sensed images (Bode et al., 2008; Morse and Burn, 2013; Skurikhin et al., 2013; Ulrich et al., 2014; Jorgenson et al., 2015).

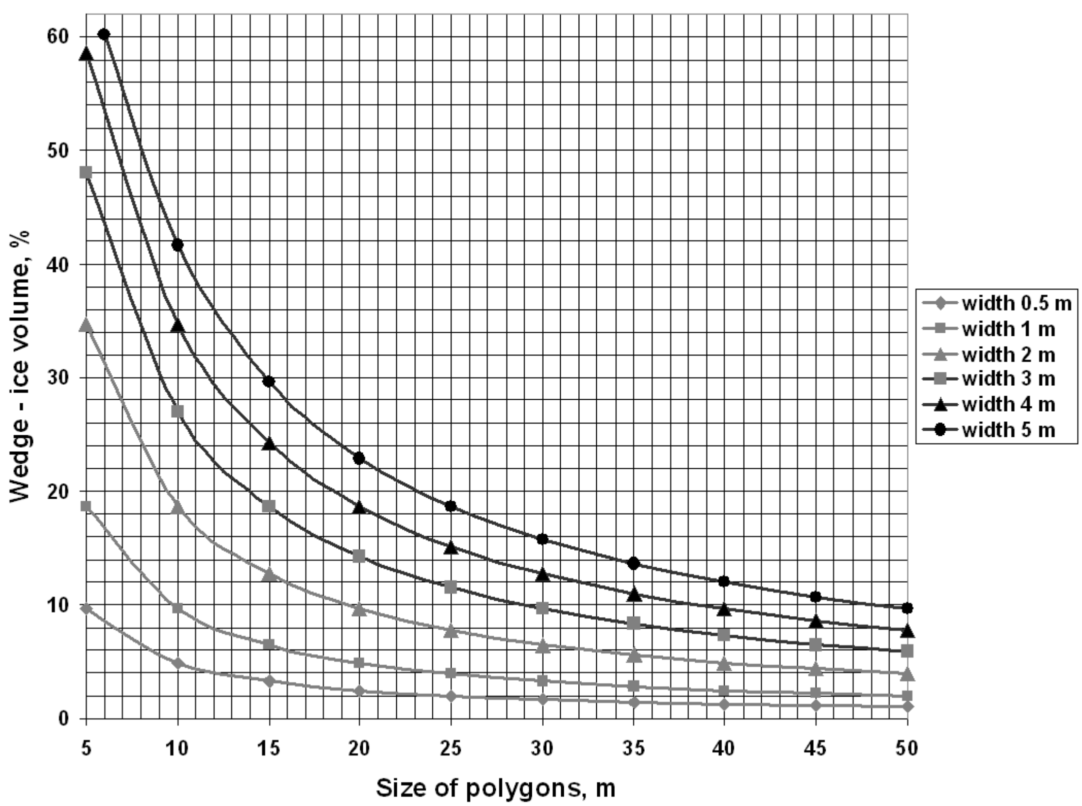
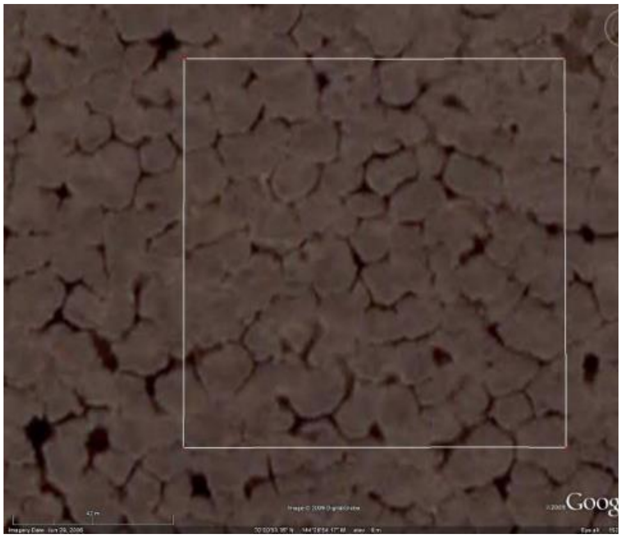
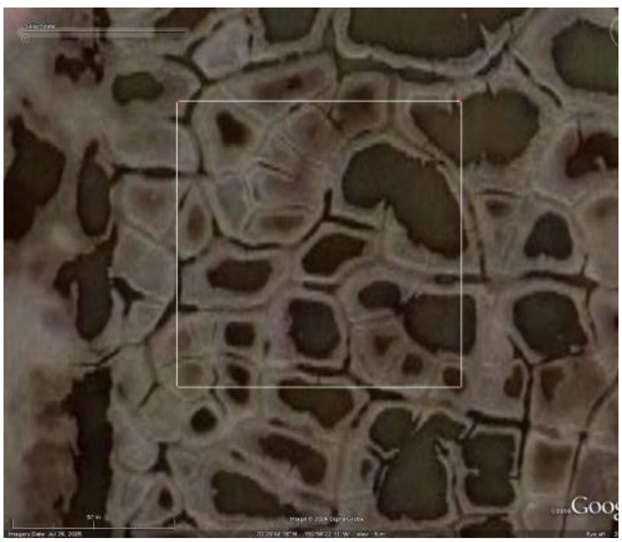


Figure 4. Estimation of wedge ice volume based on size of polygons and width of epigenetic ice wedges (Kanevskiy et al., 2013); size of polygons may be estimated based on aerial or satellite imagery.



A. Site BSC-42 (W=2.0m, P=10m; V=19%)

B. Site BSC-36 (W=2.0m, P=11; V=17%)



C. Site BSC-27 (W=1.3m, P=20; V=7%)

D. Site BSC-25 (W=0.8m, P=15; V=5%)

Figure 5. Examples of ice-wedge polygons typical of various terrain units along the Beaufort Sea coast of Alaska and estimations of wedge-ice volumes (Kanevskiy et al., 2013): A – Primary surface of the coastal plain (high-centered polygons with degrading ice wedges); B – Old drained-lake basins (high-centered polygons with degrading ice wedges); C – Deltas (low-centered polygons); D – Stabilized eolian sand dunes (high-centered polygons). Squares are 100×100 m2 (squares were used for estimation of the polygon size); W – average width of wedges; P – average size of polygons; V – wedge-ice volume.

9. Thaw settlement (TS), m. The thaw settlement value represents average settlement in case of complete degradation of the upper permafrost, which contains excess ground ice. Thaw settlement is estimated based on values of thaw strain of soils due to inclusions of pore ice and lenses of segregated ice, thickness of layer with excess ground ice, wedge-ice volume, and height of ice wedges (**Figure 6**). This value is crucial for estimation of risk of thaw settlement of the ground surface during the anticipated life of the infrastructure (**Risk Category BII**).

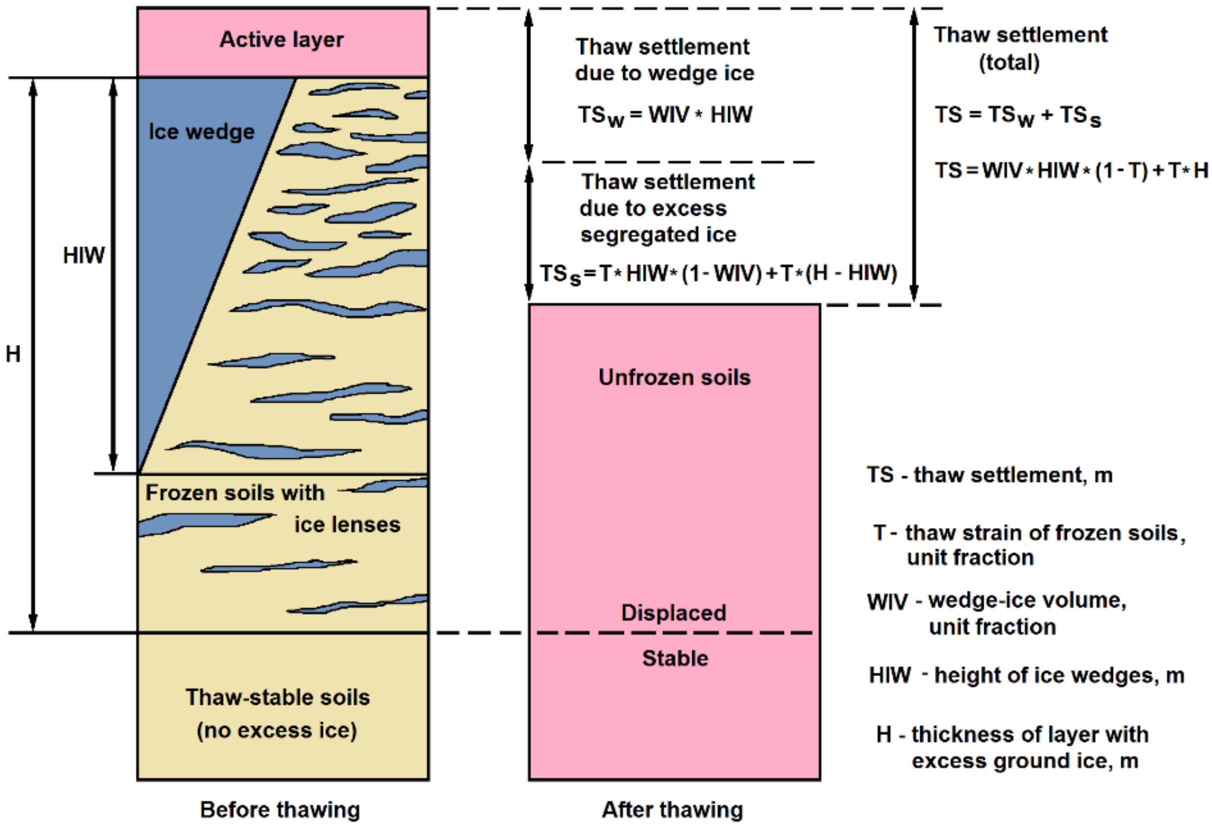


Figure 6. Estimation of total average thaw settlement (TS) based on values of thaw strain of frozen soils, thickness of layer with excess ground ice (H), wedge-ice volume (WIV), and height of ice wedges (HIW).

- For situation when a thickness of layer with excess ground ice is equal to the height of ice wedges (H = HIW), TS = WIV∗H + T∗H ∗(1 – WIV).
- For situation when thaw strain (T) values for a layer containing ice wedges (HIW layer) and a layer with excess ice below ice wedges (H – HIW) are different (T^1 and T^2, correspondingly), TS = WIV∗HIW + T^1∗HIW∗(1 – WIV) + T^2∗(H – HIW).
- For situation when there are no ice wedges, TS = T∗H.

Average thaw settlement in areas without ice wedges: **TS = T∗H**, where T – average thaw strain of soils, unit fraction; H – thickness of layer with excess ground ice, m. In ice-poor soils without excess ice (T = 0), TS = 0; in pure ice (T = 1), TS = H.

Average thaw settlement in areas with ice wedges: **TS = WIV∗HIW + T∗HIW∗(1 – WIV) + T∗(H-HIW)**, where WIV – wedge-ice volume, unit fraction; HIW – height (vertical extent) of ice wedges, m; T – average thaw strain of soils (without taking ice wedges into account), unit fraction; H – thickness of layer with excess ground ice, m.

For a situation when H = HIW, **TS = WIV∗H + T∗H∗(1 – WIV)**

For a situation when T values are different for a layer containing ice wedges (T^1 for the layer corresponding to HIW) and a layer with excess ice below ice wedges (T^2 for the layer corresponding to H – HIW), **TS = WIV∗HIW + T^1∗HIW∗(1 – WIV) + T^2∗(H – HIW)**.

Differential thaw settlement (**Risk Category BIII**) depends mainly on HIW, width of ice wedges, and depth of thawing.

10. PF features detected on satellite imagery. Main features that indicate possible occurrence of ice-rich soils and can be easily detected and include: high-centered polygons (HCP) (**Figure 5A,B,D**); low-centered polygons (LCP) (**Figure 5C**); flat-centered polygons (FCP); baydzherakhs (B) – conical thermokarst mounds that occur mainly in yedoma areas (**Figure 7**); thermokarst ponds (TP) (**Figure 8**); thermal-erosional gullies (TG); thaw-lake basins (TLB) (**Figure 9**); and retrogressive thaw slumps (RTS) (**Figure 10)** Many of these features are related to ice wedges, whose occurrence near the surface determines a high risk of differential thaw settlement (**Risk Category BIII**), which may occur even with MAGT at the PF table much less than 0°C. Depth of differential thaw settlement depends mainly on HIW, width of ice wedges, and depth of thawing; commonly, we may expect not less than 1-m settlement in areas affected by ice-wedge thermokarst. The depth of TLB indicates potential thaw settlement of the adjacent surface that has not been affected by thermokarst. Occurrence of such features as HCP, B, TP, TG, TLB, and RTS indicates recent (or still active) processes of ground-ice degradation (**Risk Category AI**).

11. Existing permafrost-related threats: Hazard Mitigation Plans, Community Plans, environmental and geotechnical reports, personal communication, etc. Information on existing permafrost-related threats is necessary for evaluation of permafrost-related problems (**Risk Category AII**). Sources: Local or Tribal Hazard Mitigation Plans (LHMP or THMP) and other community documents that contain information on critical infrastructure and permafrost-related problems (https://www.commerce.alaska.gov/dcra/DCRARepoExt/Pages/CommunityPlansLibrary.aspx; https://www.commerce.alaska.gov/dcra/DCRARepoExt/Pages/CommunityInfrastructureLibrary.aspx); geotechnical reports; personal communication, etc.

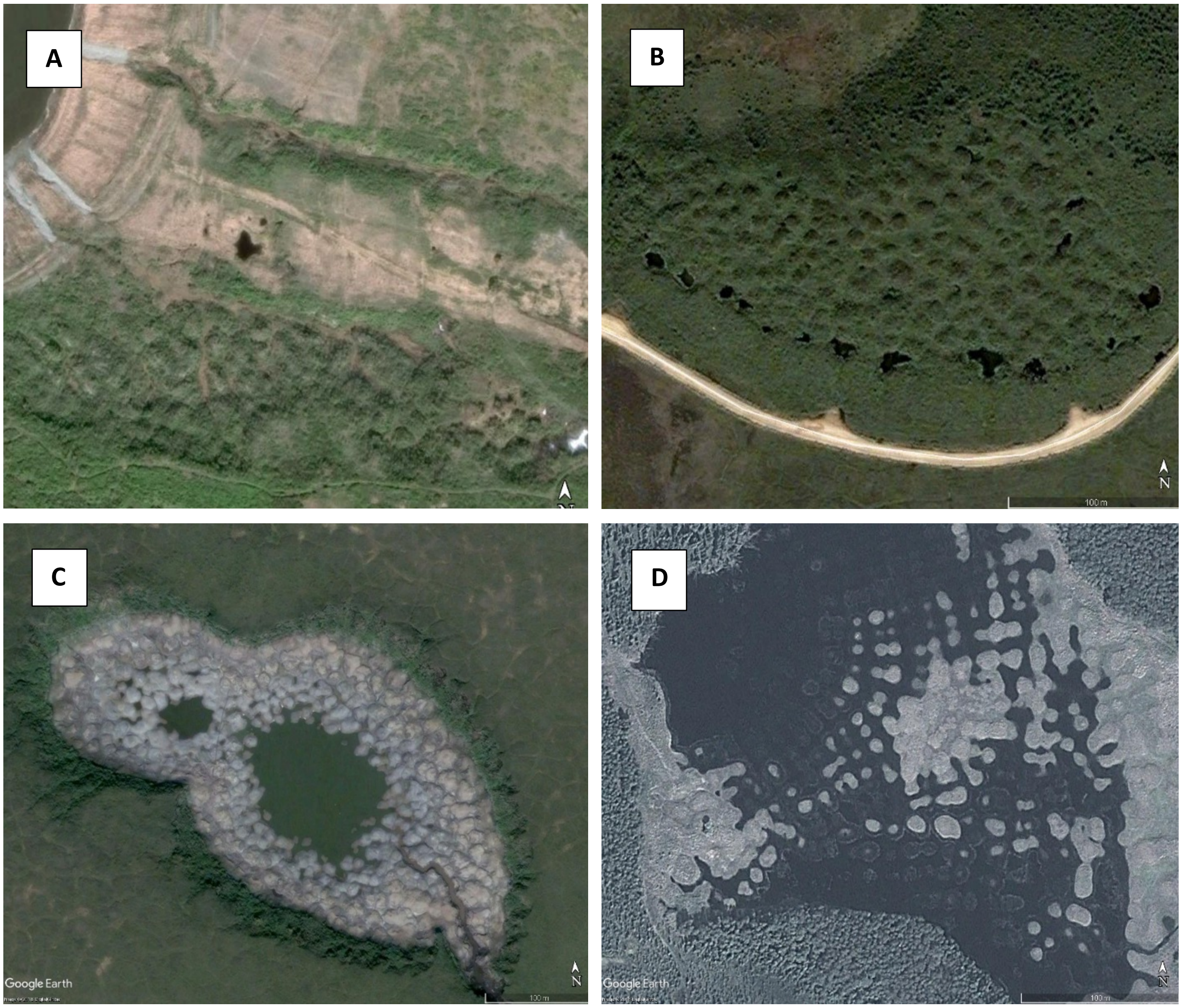


Figure 7. Baydzherakhs (conical thermokarst mounds): A – near Kotzebue airport; B –near Buckland; C – at the bottom of partially drained thaw-lake basin, Seward Peninsula; D –at the bottom of partially drained thaw-lake basin, Horseshoe Lake, Interior Alaska.

Figure 8. Thermokarst ponds developed as a result of ice-wedge degradation caused by (A) accumulation of surface water near embankment (Utqiaġvik airport), and (B) accumulation of snow around snow fences (Kaktovik).

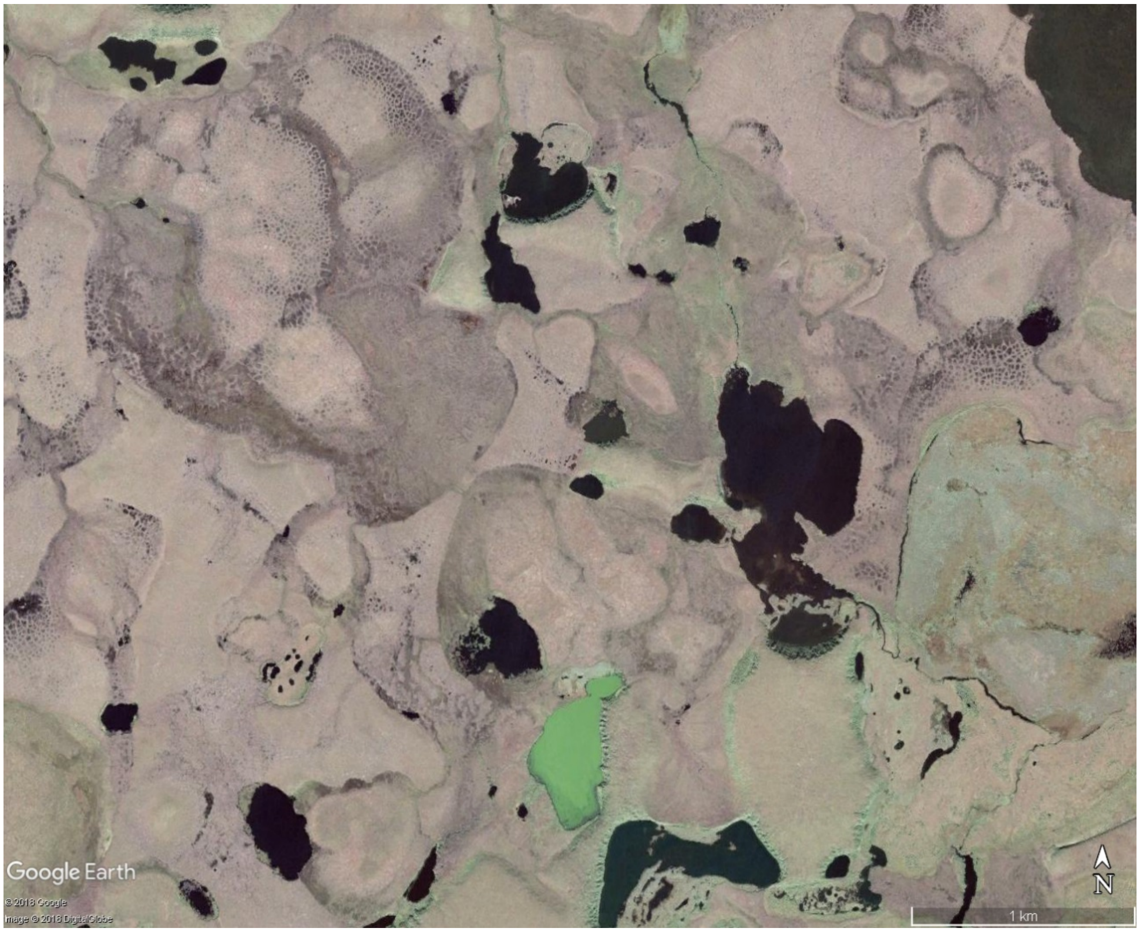


Figure 9. Thermokarst lakes and thaw-lake basins in the yedoma area (northern Seward Peninsula).

Figure 10. Retrogressive thaw slump with numerous baydzherakhs developing at the retreating yedoma bluff located near Shishmaref Inlet, Seward Peninsula.

CHAPTER 3. EVALUATION SYSTEM AND RESULTS OF RISK EVALUATION FOR PERMAFROST-RELATED THREATS FOR ALASKA COMMUNITIES

A risk evaluation system (**Table 2**) was developed for evaluation of permafrost-related threats (levels 0 to 4) for two major threat classes: (A) Existing permafrost-related problems, and (B) Future risks of permafrost degradation and thaw settlement (general and differential). These two classes include five risk categories: AI, AII, BI, BII, and BIII.

AI Risk Category includes thermokarst and thermal-erosional threats, detected based on analysis of aerial photos and satellite imagery. These threats are related to the occurrence of massive ice bodies near the surface and may be activated without general permafrost degradation; i.e., the mean annual ground temperature (MAGT) at the permafrost table may be much less than 0°C. Risk evaluation for this category is based on the estimation of thermokarst activity and thermal erosion (e.g., formation of lakes, ponds, and other thermokarst depressions, thermo-erosional gullies). Thermokarst and thermal erosion may be triggered by climatic changes or human activity. The most common threat within the areas with ice wedges is ice-wedge degradation, which results in differential thaw settlement indicated by active development of high-centered polygons and thermokarst ponds. Risk levels vary from 0 (no permafrost) to 4 (extreme threats: active thaw slumps with exposed ice-rich permafrost, ice-wedge polygons with numerous deep thermokarst ponds above large degrading ice wedges, deep active thermo-erosional gullies).

AII Risk Category includes already existing permafrost-related problems affecting community infrastructure. Risk level is determined by documented distress based on communication with the community and maintenance personnel, and analysis of existing reports and publications. Risk level is estimated separately for different types of structures (**AIIa** – Structures including schools, power plants, water/wastewater treatment plants, clinics; **AIIb** – Utilities including water/wastewater transmission, power transmission, water and fuel storage, lagoons and landfills; **AIIc** – Transportation including roads, streets, and airports). Risk levels vary from 0 (no documented distress) to 4 (major structural damage or distress resulting in loss of service or major repairs).

BI Risk Category includes risk of general permafrost degradation – gradual lowering of the permafrost table, which starts when the MAGT at the permafrost table exceeds 0°C. Risk level is determined based on ground temperatures only. Risk levels: 0 (no permafrost), 1 (low risk, MAGT < -5°C), 2 (moderate risk, MAGT = -5 – -2°C), 3 (high risk, MAGT = -2 – 0°C) and 4 (extremely high: permafrost is currently degrading; MAGT at the permafrost table exceeds 0°C). For many villages located in areas of warm permafrost, risk level would be 3.5 because such villages may be underlain by very warm permafrost (MAGT = -2 – 0°C, risk level 3), but in some parts of these villages with lowered PF table permafrost may be currently degraded (risk level 4). For areas with saline soils, we suggest a different approach to evaluation of risk levels: 0 (no permafrost), 1 (low risk, MAGT < -8°C), 2 (moderate risk, MAGT = -8 – -5°C), 3 (high risk, MAGT = -5 – -3°C) and 4 (extremely high: MAGT >-3°C, at such temperatures, even soils with relatively low salinity are commonly thawing).

Table 2. Evaluation system for permafrost-related threats: categories (AI, AII, BI, BII, and BIII) and levels (0 to 4).

A. Existing Permafrost-Related Problems				B. Risks of Future Permafrost Degradation and Thaw Settlement					
AI. Natural threats: Thermokarst and thermo-erosional processes, detected by analysis of aerial photos and satellite imagery	***AII. Documented distress based on communication with community and maintenance personnel; analysis of existing reports and publications***			***BI. Risk of permafrost degradation (depends on ground temperatures only)***	***BII. Risk of thaw settlement (TS) of the ground surface during anticipated life of infrastructure as a result of permafrost degradation (occurs only if MAGT > 0°C)***				***BIII. Risk of differential TS > 1 m due to ice-wedge thermokarst and thermal erosion not necessarily related to general PF degradation (may occur when MAGT < 0°C)***
	AIIa. Structures including schools, power plants, water / wastewater treatment plants, clinics	**AIIb. Utilities including water / wastewater transmission, power transmission, etc.**	**AIIc. Transportation including roads, streets and airports**		**BIIa. For structures with shallow foundations** **Life = 50 years**	**BIIb. For structures with deep foundations** **Life = 50 years**	**BIIc. For utilities** **Life = 30 years**	**BIId. For roads and airports** **Life = 20 years**	
0. No detected permafrost features	**0. No documented distress**			**0. No risk** No permafrost					**0. No risk** No ice wedges
1. Minor threats No active thermokarst and thermo-erosional features, rare relic inactive features may be detected (e.g., vegetated thermo-erosional gullies, depressions of possibly thermokarst origin)	**1. Cosmetic Damage**	**1. Minor distress to include minor movement with no loss of service**	**1. Minor distress which results in occasional maintenance and loss of service**	**1. Low** MAGT < -5°C (< -8°C for saline soils)	**1. Low** TS < 0.05 m	**1. Low** TS < 0.1 m	**1. Low** TS < 0.05 m	**1. Low** TS < 0.2 m	**1. Low** Inactive ice wedges buried by thaw-stable permanently frozen soils >1 m thick
2. Moderate threats Ice-wedge polygons with rare small thermokarst ponds, rare moderately active thermo-erosional gullies	**2. Fundamental Damage**	**2. Minor damage requiring occasional shoring or minor repairs to restore service repair**	**2. Distress requiring occasional maintenance beyond routine**	**2. Moderate** MAGT = -5 – -2°C (-8– -5°C for saline soils)	**2. Moderate** TS = 0.05 – 0.1 m	**2. Moderate** TS = 0.1 – 0.5 m	**2. Moderate** TS = 0.05 – 0.1 m	**2. Moderate** TS = 0.2 – 1.0 m	**2. Moderate** Small inactive or moderately active ice wedges
3. Major threats Wide-spread ice-wedge polygons with numerous thermokarst ponds above degrading ice wedges, active thermo-erosional gullies	**3. Minor Structural Damage**	**3. Major damage requiring frequent shoring and major repairs to restore service**	**3. Distress requiring frequent maintenance to ensure service**	**3. High** MAGT = -2 – 0°C (-5– -3°C for saline soils)	**3. High** TS = 0.1 – 0.5 m	**3. High** TS = 0.5 – 1.0 m	**3. High** TS = 0.1 – 0.3 m	**3. High** TS = 1.0 – 2.0 m	**3. High** Medium-size moderately active ice wedges
4. Extreme threats Active thaw slumps with exposed ice-rich permafrost, numerous deep thermokarst ponds above large degrading ice wedges, deep active thermo-erosional gullies	**4. Major Structural Damage**	**4. Major damage resulting in prolonged loss of service**	**4. Distress resulting in loss of service and major repairs**	**4. Extremely high** PF is currently degrading; MAGT > 0°C (> -3°C for saline soils)	**4. Extremely high** TS > 0.5 m	**4. Extremely high** TS > 1.0 m	**4. Extremely high** TS > 0.3 m	**4. Extremely high** TS > 2.0 m	**4. Extremely high** Large active ice wedges near the surface

BII Risk Category includes risk of general thaw settlement (TS) of the ground surface during the anticipated life of the infrastructure as a result of permafrost degradation, which occurs when MAGT at the PF table exceeds 0°C. Risk level is estimated separately for different types of structures, which may endure different TS (**BIIa** – structures with shallow foundations, life 50 years; **BIIb** – structures with deep foundations, life 50 years; **BIIc** – utilities, life 30 years; **BIId** – roads and airports, life 20 years). Risk levels are determined based on values of potential TS and vary from 0 (no permafrost) to 4 (extremely high, which varies from >0.5 m for structures with shallow foundations to >2.0 m for roads and airports). The difference between structures with shallow and deep foundations is based on the assumption that after 50 years deep piles may still rest upon permafrost, so in many cases deep foundations may tolerate bigger thaw settlement than shallow foundations. Values of general TS represent average settlement; in real life, high variability in ground-ice content (even in soils that do not contain massive ice bodies) almost always results in differential TS. For areas without ice wedges, we consider potential differential TS to be ~50% of average values of general TS; in areas with ice wedges (see **BIII Risk Category**), under certain conditions it may be close to the HIW value (see Column 9 of **Table 1**).

BIII Risk Category includes risk of significant differential thaw settlement (TS) caused by ice-wedge thermokarst and thermal erosion. Ice-wedge degradation may occur under very cold conditions (at the North Slope MAGT may be as low as –9°C) and is not necessarily related to general TS caused by general PF degradation. Risk evaluation for this category is based on the estimation of risk of ice-wedge thermokarst and/or thermal erosion along ice wedges, which does not depend on MAGT at the permafrost table. Risk of differential TS depends mainly on the amount and distribution of massive ground ice near the surface (width and vertical extent of ice wedges, occurrence of protective layers of frozen soils above ice wedges), and depth of thawing; commonly we may expect not less than 1 m settlement in areas affected by ice-wedge thermokarst, but under certain conditions (e.g., in the case of formation of thermal-erosional gullies along ice wedges) it may be close to the HIW value (see Column 9 of **Table 1**). Risk levels vary from 0 (ice wedges are absent in the area) to 4 (extremely high, areas with large active ice wedges located at the base of the active layer). Risk of differential TS is low (Level 1) when ice wedges are inactive and buried by thaw-stable permanently frozen soils more than 1 m thick.

Our general approach to risk evaluation for the category B, which includes risks of permafrost degradation (**BI**) and thaw settlement (**BII** – General, **BIII** – Differential), is reflected in the flowchart (**Figure 1**).

To estimate the **total (cumulative) risk level (R_{tot})** for permafrost-related threats based on determined risk levels for individual categories (according to **Table 2**), the following equations are suggested:

$$\mathbf{R_{tot} = R_A + R_B}\text{, where } \mathbf{R_A = R_{AI} + (R_{AIIa} + R_{AIIb} + R_{AIIc})/3;}$$
$$\mathbf{R_B = kR_{BI} + (R_{BIIa} + R_{BIIb} + R_{BIIc} + R_{BIId})/4 + R_{BIII}}$$

or

$$\mathbf{R_{tot} = R_{AI} + (R_{AIIa} + R_{AIIb} + R_{AIIc})/3 + kR_{BI} + (R_{BIIa} + R_{BIIb} + R_{BIIc} + R_{BIId})/4 + R_{BIII}}$$

The reason for including already existing threats (**Risk Category A**) in this equation is based on the high probability that these existing problems (thermokarst, thermal erosion, structural damage, etc.) will escalate with time, increasing the risk of thaw settlement in the future. For example, if we compare two villages with similar risk levels for **Category B**, but one of them has much higher risk levels for **Category**

A, it shows us that this village will definitely have problems in the future. For the other village, we cannot be so sure because risk levels for **Category B** are estimated mainly based on geotechnical data, which in many cases are not complete: for example, for many villages we have information for the airport area only, while the permafrost conditions in other areas may be completely different.

If enough information is not available to evaluate all risk levels for **Category AII**, we should calculate an average value only for risk levels we can estimate. For example, if we cannot evaluate $\mathbf{R_{AIIb}}$, the average value for $\mathbf{R_{AII}}$ would be $\mathbf{(R_{AIIa} + R_{AIIc})/2}$. If we do not have any information to evaluate risk levels for **Category AII** at all, we should just use coefficient 2 for $\mathbf{R_A}$ estimation $\mathbf{(R_A = 2\ R_{AI})}$.

We assume that the coefficient **k** should be applied to the risk of general permafrost degradation $\mathbf{R_{BI}}$ (**Risk Category BI**) because this is a major risk, which strongly affects other threats. For example, if a village is located in the area with warm permafrost (risk levels 3 to 4 for $\mathbf{R_{BI}}$) without ice wedges but with thaw-susceptible soils (Village #1), a total risk with **k = 1** would be approximately two times lower than that of a village located in the very cold area (risk level 1 for $\mathbf{R_{BI}}$) with ice-rich permafrost containing large ice wedges (Village #2). In case of permafrost degradation, thaw settlement in the first village would be much smaller (though still intolerable for most structures), but the probability of settlement would be much higher (though ice-wedge degradation may occur without general permafrost degradation under very cold climatic conditions). If we compare the first village with a village located in the very cold area (risk level 1 for $\mathbf{R_{BI}}$) with ice-rich permafrost but without significant risk of ice-wedge thermokarst and thermal erosion (Village #3), with **k = 1** a total risk for this village would be slightly higher than for the first village, which also does not look correct. Comparison of total risk levels for these three villages with different **k** values (**k = 1, 2, and 3**) show that $\mathbf{R_{tot}}$ values with **k = 2** look more reasonable (see examples below):

Village #1, individual risk levels = 0, 1, 3.5, 2, 0; R_{tot} = 6.5 (for k = 1), 10 (k = 2), 13.5 (k = 3)

Village #2, individual risk levels = 3, 3, 1, 3, 3; R_{tot} = 13 (for k = 1), 14 (k = 2), 15 (k = 3)

Village #3, individual risk levels = 1, 2, 1, 3, 1; R_{tot} = 8 (for k = 1), 9 (k = 2), 10 (k = 3)

We don't think it's necessary to apply any coefficients to the risks of thaw settlement $\mathbf{R_{BII}}$ and $\mathbf{R_{BIII}}$: if there are high risks, they are already taken into account by adding the high values of $\mathbf{R_{AI}}$ and $\mathbf{R_{AII}}$ to $\mathbf{R_{tot}}$.

Simplified Risk Evaluation System

In the process of collecting data, we realized that it is not possible to obtain sufficient information on many communities to evaluate PF-related risks based on the system of risk evaluation described above (**Table 2**). Therefore, we developed a simplified system (**Table 3**) based on five criteria: PF occurrence; PF temperature; thaw susceptibility of frozen soils; massive ice occurrence; existing PF-related problems. For each of these categories, four risk levels (ranks) were considered.

For PF occurrence, the ranks are as follows: 0 – no permafrost; 1 – mostly unfrozen soils with isolated patches of PF; 2 – discontinuous permafrost (intermittent distribution of PF and unfrozen soils, numerous open and/or closed taliks); 3 – continuous permafrost (rare taliks exist only under large and deep waterbodies).

Table 3. Simplified evaluation system for permafrost-related threats based on five criteria; numbers (0 to 3) represent rating scores estimated for each criterion independently.

Permafrost Occurrence	Permafrost Temperature	Thaw Susceptibility	Massive Ice	Existing Problems	Risk Level[1]
0. No permafrost	**0.** No permafrost	**0.** No permafrost	**0.** No permafrost	**0.** No permafrost	**No risk (0)**
1. Mostly unfrozen soils with isolated patches of PF	**1.** Mean annual ground temperature (MAGT) < -5°C	**1.** Almost no excess ice, thaw settlement is less than ~0.1 m	**1.** No massive ice	**1.** No PF-related problems (or minor problems)	**Low risk (5–8)**
2. Discontinuous permafrost (intermittent distribution of PF and unfrozen soils, numerous open and/or closed taliks)	**2.** MAGT = -5 – -2°C	**2.** Thaw settlement is 0.1 to 1.0 m	**2.** Sparse small to medium ice wedges (inactive or slightly active), rare occurrence of buried ice	**2.** Moderate problems	**Medium risk (9–11)**
3. Continuous permafrost (rare taliks exist only under large and deep waterbodies)	**3.** MAGT = -2 – >0°C	**3.** Thaw settlement is more than 1 m	**3.** Abundant large ice wedges close to the surface (yedoma and/or active modern wedges)	**3.** Severe problems	**High risk (12–15)**

[1] Cumulative rating scores (numbers in parentheses) are calculated as a sum of individual rating scores estimated for each criterion independently

For PF temperature, the ranks are as follows: 0 – no permafrost; 1 – mean annual ground temperature (MAGT) < -5°C (< -8°C for saline soils); 2 – MAGT = -5 – -2°C (-8– -5°C for saline soils); 3 – MAGT = -2 – >0°C (-5– -3°C for saline soils).

For thaw susceptibility, the ranks are as follows: 0 – no permafrost; 1 – almost no excess ice, thaw settlement is less than ~0.1 m; 2 – thaw settlement is ~0.2–0.7 m; 3 – thaw settlement is more than 1 m.

For massive ice occurrence, the ranks are as follows: 0 – no permafrost; 1 – no massive ice; 2 – sparse small to medium ice wedges (inactive or slightly active) and/or rare occurrence of buried ice; 3 – abundant large ice wedges close to the surface (yedoma and/or active modern wedges) and/or large bodies of buried glacier ice close to the surface. The occurrence of large ice bodies near the surface makes communities extremely vulnerable to PF thawing even in the areas with very low PF temperatures.

For existing PF-related problems, the ranks are as follows: 0 – no permafrost; 1 – no PF-related problems (or minor problems); 2 – Moderate problems; 3 – Severe problems. Estimation is based mainly on available documents (e.g., HMPs) and/or personal communication.

The total (cumulative) risk level is based on the rating score that was calculated as a sum of ranks for five different criteria: PF temperature; thaw susceptibility (potential thaw settlement); occurrence of massive ice; existing PF-related problems. Based on the rating score, each village was assigned one of four risk levels: 0 – no permafrost; 5–8 – low risk level; 9–11 – medium risk level; 12–15 – high risk level.

Results of Risk Evaluation for Permafrost-Related Threats for Alaska Communities

Based on the simplified risk evaluation system (**Table 3**), we have evaluated permafrost-related threats for 187 Alaska communities. Results of this evaluation are presented in **Table 4**, which shows risk levels (ranks) for PF occurrence; PF temperature; thaw susceptibility of frozen soils; massive ice occurrence; existing PF-related problems, and total (cumulative) risk level, which is based on the rating score (sum of individual ranks for these five categories). We also added a special column to **Table 4** showing three confidence levels marked with stars: (*) low – no reports with ground-ice data, no Hazard Mitigation Plans (HMPs) or other information on existing problems; estimation is based on general information on surficial geology and PF occurrence and analysis of available imagery; (**) medium – some information on permafrost conditions is available, including several geotechnical reports, HMPs, etc.); (***) high – comprehensive data are available, including numerous reports with geotechnical information, HMPs, and other sources, or we have sufficient information that there is no PF in the area.

According to our estimation, **31 communities (~17%) are underlain by continuous permafrost** (near-surface permafrost exists within >90% of the area), and 22 of them (71%) are characterized by the high total risk level (**Figure 11**), while only 4 villages are located on thaw-stable soils (or bedrock) and do not have significant permafrost-related problems. Most of these 31 villages are located within the continuous and discontinuous permafrost zones (Jorgenson et al., 2008). Ice wedges occur within 23 communities, and 12 of the communities have abundant large ice wedges located close to the surface and are therefore especially vulnerable to thermokarst and thermal erosion. We presume that at least 11 of 31 villages (Alatna, Buckland, Chevak, Noatak, Noorvik, Point Lay, Koyuk, Marshall, Saint Michael, Rampart, and Shishmaref) may have yedoma deposits either within the villages or in the vicinity. Some of these villages may be located on thaw-stable soils, but the occurrence of ice-rich yedoma in the vicinity may create some problems for such communities. For example, the coastal village of Shishmaref, which is underlain by ice-poor soils, is strongly affected by coastal erosion, but the wide occurrence of yedoma within the adjacent mainland complicates its relocation. We presume that buried glacier ice also may be encountered in several communities (e.g., Arctic Village, Kaktovik).

Fifty-six communities (~30%) are underlain by discontinuous permafrost, which means that numerous open and/or closed taliks exist in these locations, and we presume that permafrost occupies from ~20–30 up to ~80–90% of the area. Unfortunately, no data on real permafrost distribution for Alaska communities (i.e., detailed permafrost maps) are available at the present time, and our estimation of the permafrost distribution cannot be precise. Most of these 56 villages are located within the discontinuous permafrost zone, although some of them belong to zones of continuous, sporadic, and even isolated permafrost. Most of these villages (35, or 63%) are characterized by medium risk level, while for 12 villages (~21%), the risk level is high. Active large ice wedges are not common at these communities, but at least 20 of the communities have either relatively small inactive (or weakly active) ice wedges or buried inactive ice wedges relatively well protected from thawing by a layer of ice-poor soils. We presume that yedoma deposits with large ice wedges occur in the vicinity of at least 9 of 56 villages (Bethel, Eek, Golovin, Kiana, Kotzebue, Upper Kalskag, Kivalina, Kwinhagak, and Unalakleet). There is also a possibility that yedoma exists not only in the vicinity, but also under some of these villages as well (Bethel, Eek, Kiana). Ice wedges in yedoma are mostly inactive (buried), except in some locations within the continuous permafrost zone (e.g., in the vicinity of Kotzebue and Kivalina), where yedoma deposits with near-surface active ice wedges are common. We do not have any reliable data on the occurrence of buried glacier ice within the villages, but we can presume that glacier ice can be encountered in several communities located in the mountain valleys.

Forty communities (~21%) are underlain by predominantly unfrozen soils/bedrock, but within some parts of these villages, isolated patches of permafrost may be encountered (presumably the total area of such patches does not exceed 10–20%). These villages are located within discontinuous, sporadic, and isolated permafrost zones, and most of them do not experience serious permafrost-related problems. Most of these villages (33, or ~83%) are characterized by the low risk level, while for seven villages (~18%), the risk level is medium. To our knowledge, no massive ice has been encountered in these 40 villages, although yedoma deposits with large inactive ice wedges may occur in the vicinity, especially around villages located in Interior Alaska, like Ruby or Minto.

Sixty communities of 187 (~32%), mostly located within Southeast Alaska and the Aleutians, **are underlain by entirely unfrozen soil/bedrock**. Though they may experience some problems associated with seasonal frost heave, no real permafrost-related threats affect these communities.

Table 4. Risk evaluation of permafrost-related threats for 187 Alaska villages.

Village	Confidence[1]	Permafrost Occurrence[2]	Permafrost Temperature[3]	Thaw Susceptibility[4]	Massive Ice[5]	Existing Problems[6]	Rating Score[7]	Risk Level
Akhiok, Native Village of	***	0	0	0	0	0	0	
Akiachak Native Community	**	1	3	2	1	2	9	med
Akiak, Native Community	***	0	0	0	0	0	0	
Akutan, Native Village of	***	0	0	0	0	0	0	
Alakanuk, Village of	**	1	3	2	1	2	9	med
Alatna Village	**	3	3	3	3	2	14	high
Aleknagik, Native Village of	**	0	0	0	0	0	0	
Allakaket Village	*	2	3	2	2	2	11	med
Ambler, Native Village of	*	2	3	1	1	1	8	low
Anaktuvuk Pass, Village of	*	3	1	2	2	2	10	med
Angoon, Community Association of	***	0	0	0	0	0	0	
Aniak	**	1	3	1	1	1	7	low
Anvik Village	**	1	3	1	1	1	7	low
Arctic Village	*	3	2	2	2	2	11	med
Atka, Native Village of	***	0	0	0	0	0	0	
Atmautluak, Village of	**	2	3	2	2	2	11	med
Atqasuk Village (Atkasook)	*	3	1	2	3	3	12	high
Utqiaġvik, Native Village of	***	3	1	3	3	3	13	high
Beaver Village	*	2	3	2	1	2	10	med
Bethel, Orutsararmuit Native Village	**	2	3	2	2	2	11	med
Birch Creek Tribe (formerly listed as Birch Creek Village)	*	2	3	1	1	1	8	low
Brevig Mission, Native Village of	*	3	3	3	2	2	13	high
Buckland, Native Village of	*	3	2	3	3	3	14	high
Cantwell, Native Village of	*	1	3	1	1	1	7	low
Chalkyitsik Village	**	2	3	1	1	1	8	low
Chefornak, Village of	*	3	3	3	1	3	13	high

Village	Confidence[1]	Permafrost Occurrence[2]	Permafrost Temperature[3]	Thaw Susceptibility[4]	Massive Ice[5]	Existing Problems[6]	Rating Score[7]	Risk Level
Chenega Bay, Native Village of	**	0	0	0	0	0	0	
Chevak Native Village	**	3	3	3	3	3	15	high
Chickaloon Native Village	***	0	0	0	0	0	0	
Chignik Bay, Native Village of	***	0	0	0	0	0	0	
Chignik Lagoon, Native Village of	***	0	0	0	0	0	0	
Chignik Lake Village	***	0	0	0	0	0	0	
Chilkat Indian Village (Klukwan)	***	0	0	0	0	0	0	
Chistochina, Native Village of (Cheesh-Na Tribe)	*	1	3	1	1	1	7	low
Chitina, Native Village of	*	2	3	2	1	2	10	med
Chuathbaluk	*	1	3	1	1	1	7	low
Circle Native Community	**	3	3	3	2	2	13	high
Clarks Point, Village of (formerly Village of Clark's Point)	**	0	0	0	0	0	0	
Copper Center, Native Village of Kluti Kaah	*	1	3	1	1	1	7	low
Craig Community Association	***	0	0	0	0	0	0	
Crooked Creek, Village of	*	2	3	2	1	2	10	med
Deering, Native Village of	**	3	3	2	2	2	12	high
Dillingham, Curyung Tribal Council (formerly Native Village of)	***	1	3	1	1	1	7	low
Diomede, Native Village of (aka Inalik)	*	3	2	1	1	1	8	low
Eagle, Native Village of	**	2	2	2	2	2	10	med
Eek, Native Village of	**	2	3	3	2	3	13	high
Egegik Village	*	1	3	1	1	1	7	low
Eklutna Native Village	*	1	3	1	1	1	7	low
Ekwok Village	**	0	0	0	0	0	0	
Elim, Native Village of	*	2	3	1	1	1	8	low
Emmonak Village	**	1	3	2	1	2	9	med

Village	Confidence[1]	Permafrost Occurrence[2]	Permafrost Temperature[3]	Thaw Susceptibility[4]	Massive Ice[5]	Existing Problems[6]	Rating Score[7]	Risk Level
Evansville Village (aka Bettles Field)	*	3	3	2	1	2	11	med
Eyak, Native Village of (Cordova)	***	0	0	0	0	0	0	
False Pass, Native Village of	***	0	0	0	0	0	0	
Fort Yukon, Native Village of	**	2	3	2	1	2	10	med
Gakona, Native Village of	*	1	3	1	1	1	7	low
Galena Village (aka Louden Village)	**	2	3	2	2	1	10	med
Gambell, Native Village of	*	3	3	1	1	2	10	med
Golovin, Chinik Eskimo Community	**	2	3	2	2	2	11	med
Goodnews Bay, Native Village of	*	1	3	1	1	1	7	low
Grayling, Organized Village of (aka Holikachuk)	**	1	3	1	1	1	7	low
Gulkana Village	**	2	3	2	1	2	10	med
Holy Cross Village	*	1	3	2	1	2	9	med
Hoonah Indian Association	***	0	0	0	0	0	0	
Hooper Bay, Native Village of	**	1	3	1	1	1	7	low
Hughes Village	*	1	3	1	1	2	8	low
Huslia Village	**	1	3	1	1	2	8	low
Hydaburg Cooperative Association	***	0	0	0	0	0	0	
Igiugig Village	*	0	0	0	0	0	0	
Iliamna, Village of	*	0	0	0	0	0	0	
Iqurmuit (Russian Mission)	*	2	3	2	1	2	10	med
Kake, Organized Village of	***	0	0	0	0	0	0	
Kaktovik Village (aka Barter Island)	**	3	1	3	3	3	13	high
Kalskag (Lower), Village of	*	2	3	2	1	2	10	med
Kalskag (Upper), Village of	*	2	3	2	1	2	10	med
Kaltag, Village of	**	2	3	2	1	2	10	med
Kasaan, Organized Village of	***	0	0	0	0	0	0	
Kasigluk, Native Village of	*	2	3	2	1	2	10	med

Village	Confidence[1]	Permafrost Occurrence[2]	Permafrost Temperature[3]	Thaw Susceptibility[4]	Massive Ice[5]	Existing Problems[6]	Rating Score[7]	Risk Level
Kiana, Native Village of	*	2	3	3	2	2	12	high
King Cove, Agdaagux Tribe	***	0	0	0	0	0	0	
Kipnuk, Native Village of	**	2	3	2	1	2	10	med
Kivalina, Native Village of	**	2	3	1	1	1	8	low
Klawock Cooperative Association	***	0	0	0	0	0	0	
Kobuk, Native Village of	*	1	3	2	1	2	9	med
Kokhanok Village	***	0	0	0	0	0	0	
Kongiganak, Native Village of	**	3	3	3	2	3	14	high
Kotlik, Village of	*	1	3	2	1	1	8	low
Kotzebue, Native Village of	**	2	3	2	2	2	11	med
Koyuk, Native Village of	**	3	3	2	2	2	12	high
Koyukuk Native Village	*	1	3	1	1	1	7	low
Kwethluk, Organized Village of	*	2	3	2	2	1	10	med
Kwigillingok, Native Village of	**	1	3	2	1	2	9	med
Kwinhagak, Native Village of (aka Quinhagak)	**	2	3	3	1	3	12	high
Larsen Bay, Native Village of	***	0	0	0	0	0	0	
Levelock Village	***	0	0	0	0	0	0	
Lime Village	*	2	3	2	1	2	10	med
Manley Hot Springs Village	*	2	3	2	2	2	11	med
Manokotak Village	***	0	0	0	0	0	0	
Marshall, Native Village of (aka Fortuna Ledge)	**	3	3	2	2	2	12	high
McGrath Native Village	**	1	3	1	1	1	7	low
Mekoryuk, Native Village of	**	2	3	3	1	3	12	high
Mentasta Traditional Council (formerly Mentasta Lake Village)	*	1	3	1	1	1	7	low
Minto, Native Village of	*	1	3	1	1	1	7	low
Mountain Village, Asa'carsarmiut Tribe	*	2	3	2	2	2	11	med

Village	Confidence[1]	Permafrost Occurrence[2]	Permafrost Temperature[3]	Thaw Susceptibility[4]	Massive Ice[5]	Existing Problems[6]	Rating Score[7]	Risk Level
Naknek Native Village (South Naknek?)	*	1	3	1	1	1	7	low
Nanwalek, Native Village of (aka English Bay)	***	0	0	0	0	0	0	
Napakiak, Native Village of	*	1	3	1	1	1	7	low
Napaskiak, Native Village of	*	1	3	1	1	1	7	low
Nelson Lagoon, Native Village of	***	0	0	0	0	0	0	
Nenana Native Association	**	1	3	1	1	1	7	low
New Koliganek Village Council (formerly Koliganek Village)	*	1	3	1	1	1	7	low
New Stuyahok Village	*	2	3	2	2	2	11	med
Newhalen Village	*	0	0	0	0	0	0	
Newtok Village	**	2	3	3	1	3	12	high
Nightmute, Native Village of	**	2	3	3	2	2	12	high
Nikolai Village	*	1	3	1	1	1	7	low
Nikolski, Native Village of	***	0	0	0	0	0	0	
Ninilchik Village	*	0	0	0	0	0	0	
Noatak, Native Village of	*	3	3	3	3	2	14	high
Nome Eskimo Community	*	2	3	3	2	2	12	high
Nondalton Village	*	0	0	0	0	0	0	
Noorvik Native Community	*	3	3	3	3	3	15	high
Northway Village	*	2	3	1	1	1	8	low
Nuiqsut, Native Village of (aka Nooiksut)	*	3	1	3	3	3	13	high
Nulato Village	**	2	3	2	1	3	11	med
Nunakauyarmiut Tribe (formerly Native Village of Toksook Bay)	**	2	3	3	2	2	12	high
Nunapitchuk, Native Village of	*	2	3	3	2	3	13	high
Old Harbor, Village of	***	0	0	0	0	0	0	
Oscarville Traditional Village	*	1	3	1	1	1	7	low

Village	Confidence[1]	Permafrost Occurrence[2]	Permafrost Temperature[3]	Thaw Susceptibility[4]	Massive Ice[5]	Existing Problems[6]	Rating Score[7]	Risk Level
Ouzinkie, Native Village of	***	0	0	0	0	0	0	
Pedro Bay Village	*	0	0	0	0	0	0	
Perryville, Native Village of	***	0	0	0	0	0	0	
Pilot Point, Native Village of	*	0	0	0	0	0	0	
Pilot Station Traditional Village	**	2	3	2	1	2	10	med
Pitka's Point, Native Village of	*	2	3	2	1	2	10	med
Platinum Traditional Village	*	0	0	0	0	0	0	
Point Hope, Native Village of	*	3	2	1	1	1	8	low
Point Lay, Native Village of	**	3	1	3	3	3	13	high
Port Graham, Native Village of	***	0	0	0	0	0	0	
Port Heiden, Native Village of	***	0	0	0	0	0	0	
Port Lions, Native Village of	***	0	0	0	0	0	0	
Rampart Village	*	3	3	2	1	2	11	med
Red Devil, Village of	**	0	0	0	0	0	0	
Ruby, Native Village of	**	1	3	1	1	1	7	low
Saint George Island (See Pribilof Islands Aleut Communities)	***	0	0	0	0	0	0	
Saint Mary's, Algaaciq Native Village & Yupiit of Andreafski	*	2	3	2	1	1	9	med
Saint Michael, Native Village of	**	3	3	3	2	3	14	high
Saint Paul Island (See Pribilof Islands Aleut Communities)	***	0	0	0	0	0	0	
Salamatoff, Village of	***	0	0	0	0	0	0	
Sand Point Village (Qagan Tayagungin Tribe of)	***	0	0	0	0	0	0	
Savoonga, Native Village of	**	3	3	3	2	2	13	high
Saxman, Organized Village of	***	0	0	0	0	0	0	
Scammon Bay, Native Village of	*	1	3	1	1	1	7	low
Selawik, Native Village of	**	3	2	3	3	3	14	high

Village	Confidence[1]	Permafrost Occurrence[2]	Permafrost Temperature[3]	Thaw Susceptibility[4]	Massive Ice[5]	Existing Problems[6]	Rating Score[7]	Risk Level
Seldovia Village Tribe	***	0	0	0	0	0	0	
Shageluk Native Village	*	2	3	2	1	2	10	med
Shaktoolik, Native Village of	*	1	2	1	1	1	6	low
Sheldon's Point, Native Village of (Nunam Iqua)	**	2	3	3	1	3	12	high
Shishmaref, Native Village of	*	3	2	1	1	1	8	low
Shungnak, Native Village of	*	3	3	2	2	2	12	high
Sleetmute, Village of	**	0	0	0	0	0	0	
South Naknek Village	*	1	3	2	1	2	9	med
Stebbins Community Association	*	2	3	2	2	3	12	high
Stevens, Native Village of	*	2	3	2	1	2	10	med
Stony River, Village of	*	0	0	0	0	0	0	
Takotna Village	*	2	3	2	1	2	10	med
Tanacross, Native Village of	*	2	3	2	1	2	10	med
Tanana, Native Village of	*	2	3	2	1	2	10	med
Tatitlek, Native Village of	***	0	0	0	0	0	0	
Tazlina, Native Village of	*	1	3	1	1	1	7	low
Teller, Native Village of	*	2	2	2	2	2	10	med
Tetlin, Native Village of	*	2	3	1	1	1	8	low
Togiak, Traditional Village of	*	0	0	0	0	0	0	
Tuluksak Native Community	**	2	3	1	1	2	9	med
Tuntutuliak, Native Village of	**	2	3	3	2	3	13	high
Tununak, Native Village of	**	2	3	2	1	2	10	med
Twin Hills Village	*	0	0	0	0	0	0	
Tyonek, Native Village of	***	0	0	0	0	0	0	
Ugashik Village	***	0	0	0	0	0	0	
Umkumiute Native Village (Annex of Toksook Bay)	*	1	3	1	1	1	7	low

Village	Confidence[1]	Permafrost Occurrence[2]	Permafrost Temperature[3]	Thaw Susceptibility[4]	Massive Ice[5]	Existing Problems[6]	Rating Score[7]	Risk Level
Unalakleet, Native Village of	**	2	3	1	1	1	8	low
Unalaska, Qawalangin Tribe of	***	0	0	0	0	0	0	
Venetie, Village of (See Native Village of Venetie Tribal Government)	*	2	3	1	1	1	8	low
Wainwright, Village of	**	3	1	3	3	3	13	high
Wales, Native Village of	*	3	2	1	1	1	8	low
White Mountain, Native Village of	*	1	3	1	1	1	7	low
Yakutat Tlingit Tribe	*	0	0	0	0	0	0	

Notes:

[1] Confidence level: * – low (no reports with ground-ice data, no HMPs; estimation is based on general information on surficial geology and PF occurrence and analysis of available imagery); ** – medium (some information on permafrost conditions is available, including several geotechnical reports, HMPs, etc.); *** – high (comprehensive data are available, including numerous reports with geotechnical information, HMPs, and other sources, or we have sufficient information that there is no PF in the area).

[2] PF occurrence: 0 – no permafrost; 1 – mostly unfrozen soils with isolated patches of PF; 2 – discontinuous permafrost (intermittent distribution of PF and unfrozen soils, numerous open and/or closed taliks); 3 – continuous permafrost (rare taliks exist only under large and deep waterbodies).

[3] PF temperature: 0 – no permafrost; 1 – Mean annual ground temperature (MAGT) < -5°C (< -8°C for saline soils); 2 – MAGT = -5 – -2°C (-8– -5°C for saline soils); 3 – MAGT = -2 – 0°C (-5– -3°C for saline soils).

[4] Thaw susceptibility: 0 – no permafrost; 1 – almost no excess ice, thaw settlement is less than ~0.1 m; 2 – thaw settlement is ~0.2-0.7 m; 3 – thaw settlement is more than 1 m.

[5] Massive ice occurrence: 0 – no permafrost; 1 – no massive ice; 2 – sparse small to medium ice wedges (inactive or slightly active) and/or rare occurrence of buried ice; 3 – abundant large ice wedges close to the surface (yedoma and/or active modern wedges) and/or large bodies of buried glacier ice close to the surface. Occurrence of large ice bodies near the surface makes communities extremely vulnerable to PF thawing even in the areas with very low PF temperatures.

[6] Existing PF-related problems: 0 – no permafrost; 1 – no PF-related problems (or minor problems); 2 – Moderate problems; 3 – Severe problems. Estimation is based mainly on available documents (e.g., HMPs) and/or pers.com.

[7] Risk level based on the rating score: 0 – no permafrost; 5-8 – low risk level; 9-11 – medium risk level; 12-15 - high risk level. Rating score (cumulative risk level) is a sum of ranks for five different categories: PF temperature; thaw susceptibility (potential thaw settlement); occurrence of massive ice; existing PF-related problems.

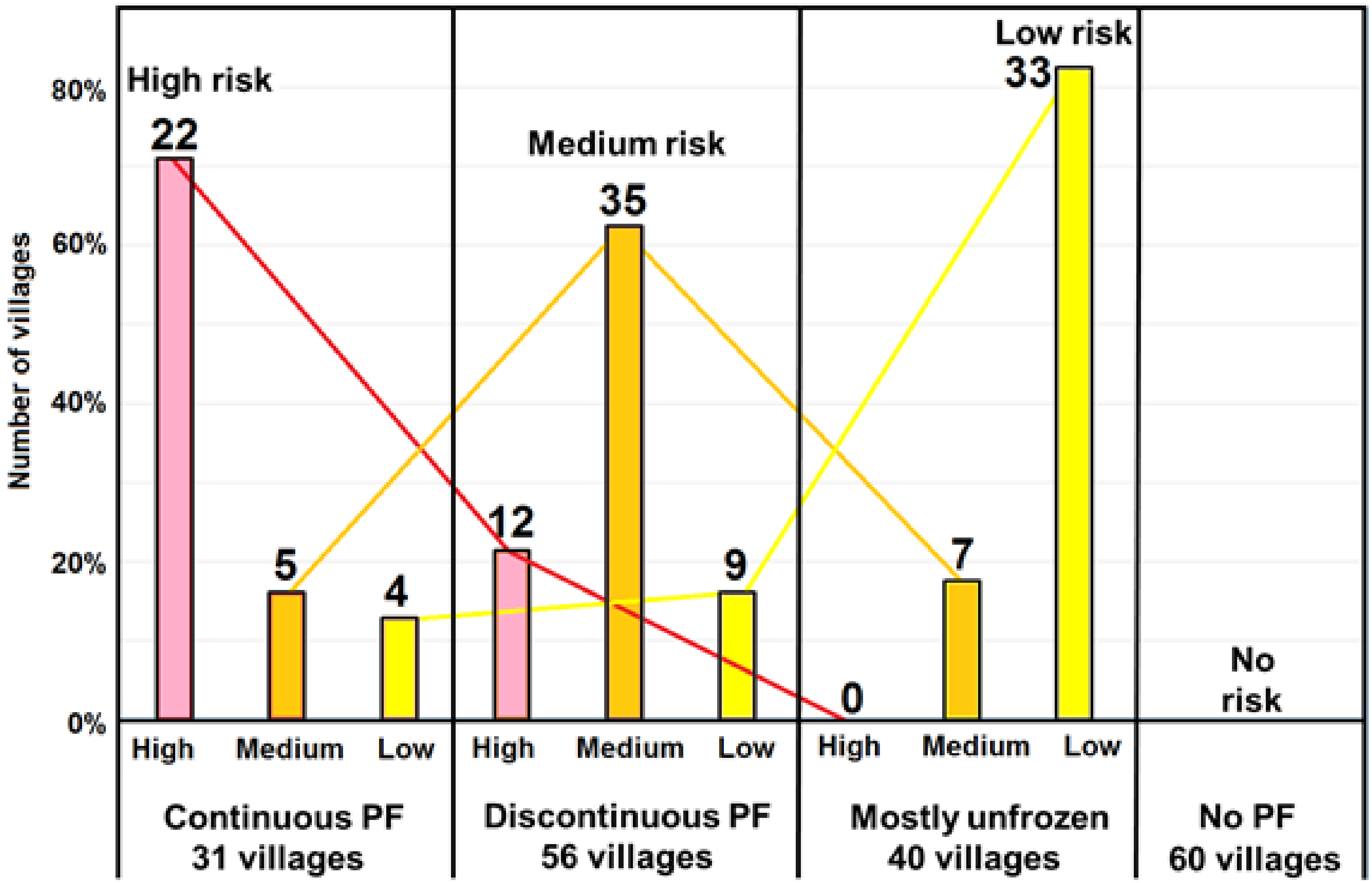


Figure 11. Risk levels for permafrost-related threats estimated for 187 Alaskan communities in the areas with different permafrost extent.

CHAPTER 4. CONCLUSIONS

We have evaluated permafrost-related threats for 187 Alaska villages based on available information including scientific publications, maps, satellite imagery and aerial photographs, geotechnical reports, personal communication, community plans and reports, and other sources. Evaluation was based on five criteria: permafrost (PF) occurrence; PF temperature; thaw susceptibility of frozen soils (expected thaw settlement in case of permafrost degradation); massive ice occurrence; and existing PF-related problems. For each of these categories, four risk levels (ranks) were considered. The total (cumulative) risk level was based on the rating score (sum of individual ranks for all five categories). Based on the rating score, each village was assigned one of four risk levels: 0 – no permafrost; 5–8 – low risk level; 9–11 – medium risk level; 12–15 – high risk level.

According to our estimation,

- 31 communities (~17%) are underlain by continuous permafrost;
- 56 communities (~30%) are underlain by discontinuous permafrost;
- 40 communities (~21%) are underlain by predominantly unfrozen soils/bedrocks with isolated patches of permafrost;
- 60 communities (~32%) are underlain by entirely unfrozen soils/bedrocks.

Total (cumulative) risk levels are distributed among communities as follows:

- 34 communities (~18%) – high risk level;
- 47 communities (~26%) – medium risk level;
- 46 communities (~24%) – low risk level;
- 60 communities (~32%) – no permafrost.

Most communities at the high risk level (22 villages of 34) are underlain by continuous permafrost, while communities at the low risk level are typically underlain by predominantly unfrozen soil/bedrock (33 villages of 46), and no high risk levels were detected for this group of villages. Medium risk level is typical mainly of communities underlain by discontinuous permafrost (35 villages of 47); some villages in this group are characterized by high and low risk levels (12 and 9, correspondingly). The occurrence of massive ice bodies (mostly ice wedges) is typical exclusively of communities underlain by continuous and discontinuous permafrost (23 and 20 villages, correspondingly). We presume that at least 20 communities have extremely ice-rich yedoma deposits with large ice wedges either within the villages or in the vicinity. Some of these villages may be located on thaw-stable soils, but the occurrence of ice-rich yedoma in the vicinity may create problems for such communities. For example, the coastal village of Shishmaref, which is underlain by ice-poor soils, is strongly affected by coastal erosion, but the wide occurrence of yedoma within the adjacent mainland complicates its relocation.

In general, permafrost conditions in Alaska communities are diverse, and detailed studies are required for more precise evaluation of potential permafrost-related threats associated with permafrost degradation and/or thawing of ground ice.

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