# Chapter 3

## IMPACTS ON INFRASTRUCTURE IN ALASKA AND THE CIRCUMPOLAR NORTH

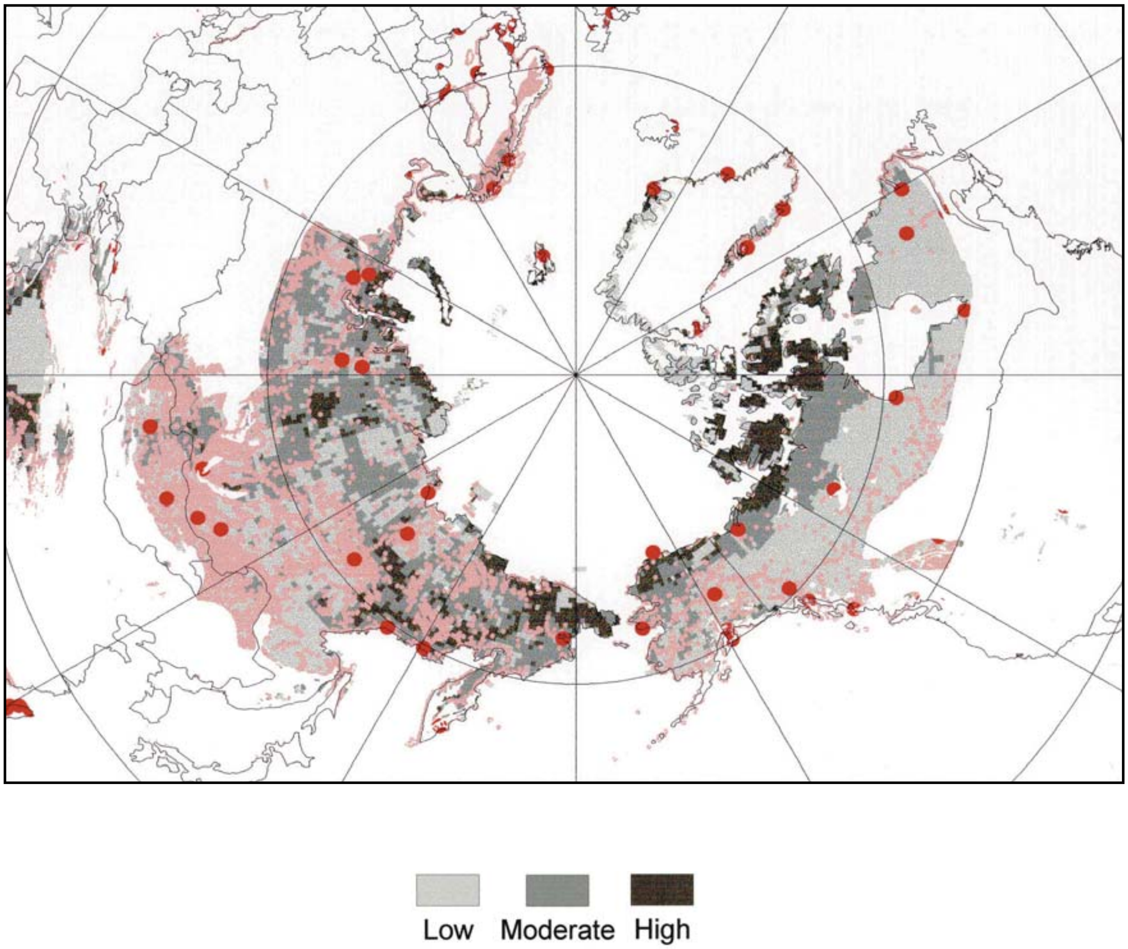
### 3.1 Introduction

Evidence presented in the preceding chapters documents widespread warming of permafrost, which in some cases is showing very clear evidence of thawing. Warming and thawing of permafrost will have significant effects on infrastructure (Instanes, 2003). Local sources of anthropogenic heat and surface modifications associated with urban land uses may exacerbate problems related to thaw and settlement (Hinkel et al., 2003b; Klene et al., 2003). After presenting a general overview of the possible effects of climate warming on permafrost in the Northern Hemisphere, this chapter discusses the existing infrastructure in Alaska with special reference to its relation with permafrost.

### 3.2 Northern Hemisphere Hazards

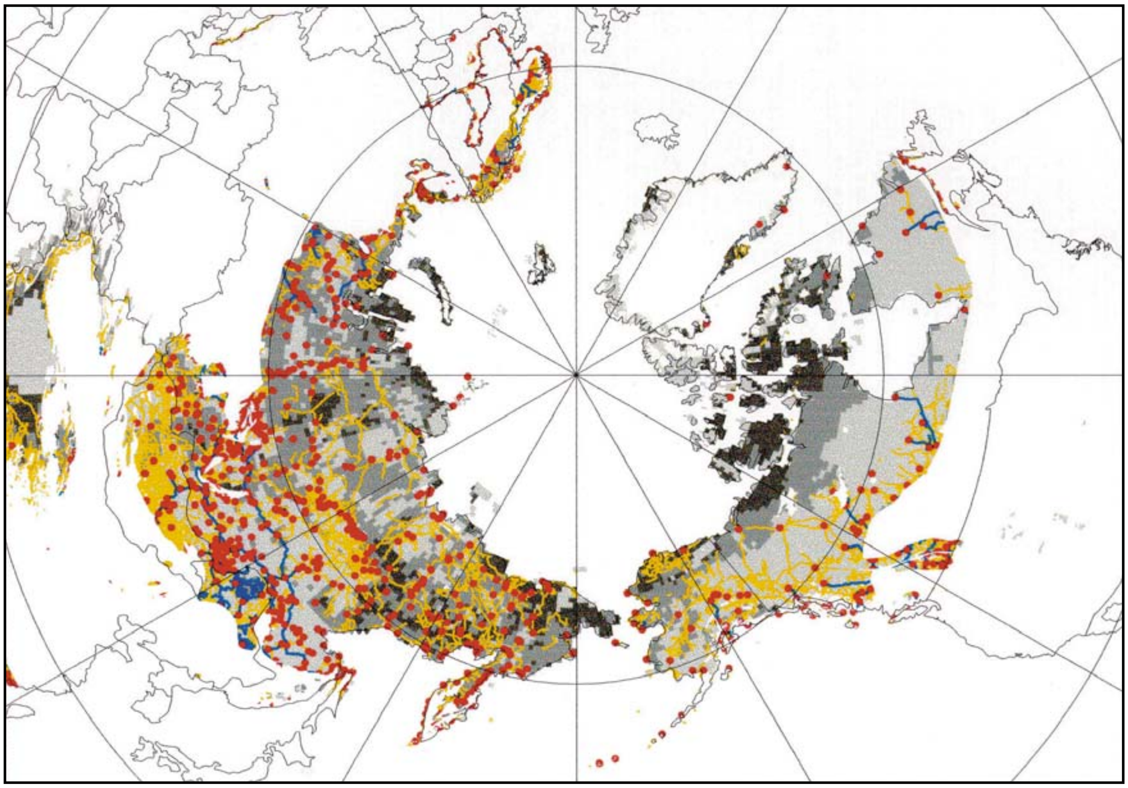
Nelson et al. (2001, 2002) used output from three transient-mode general circulation models (GCMs), in conjunction with a digital version of the International Permafrost Association's *Circum-Arctic Map of Permafrost and Ground Ice Conditions* (Brown et al., 1997, 1998; Brown and Haggerty, 1998), to map the hazard potential associated with thawing permafrost under conditions of global warming. The maps were created using a simple, dimensionless thaw-settlement index, computed using the relative increase in active layer thickness and the volumetric proportion of near-surface soil occupied by ground ice. Computational details are provided in Nelson et al. (2002). The resulting maps depict areas of low, moderate, and high hazard potential. In Figure 13 the location of existing infrastructure has been superimposed on the hazard map, providing a general assessment of the susceptibility of engineered works to thaw-induced damage under the UKTR climate-change scenario. Figure 13a indicates the risk to infrastructure in northern Canada, Alaska, and Russia. Russia has more population centers and infrastructure in the higher risk areas, but Alaska and Canada also have population centers, pipelines, and roads in areas of moderate and high hazard potential. Major settlements are located in areas of moderate or high hazard potential in central and northern Alaska (e.g., Nome and Barrow), northwestern Canada (Inuvik), western Siberia (Vorkuta), and the Sakha Republic in Siberia (Yukutsk). The potential for severe thaw-induced disruptions to engineered works has been reported from each of these areas, and problems are likely to intensify under conditions of global warming.

Figure 13b shows the risk to transportation facilities. The network of seismic trails in northern Alaska, the Dalton Highway between the Yukon River and Prudhoe Bay in Alaska, the Dempster Highway between Dawson and Inuvik in western Canada, and the extensive road and trail system in central Siberia all traverse areas of high hazard potential. Numerous airfields occupy ice-rich terrain in Siberia, and the Trans-Siberian, Baikal-Amur Mainline, Hudson Bay, and Alaska Railroads span regions of lesser hazard potential, although they extend into areas in which localized problems have been reported. A dense network of secondary roads and trails occupies areas of moderate risk in Mongolia, and northeastern China has an

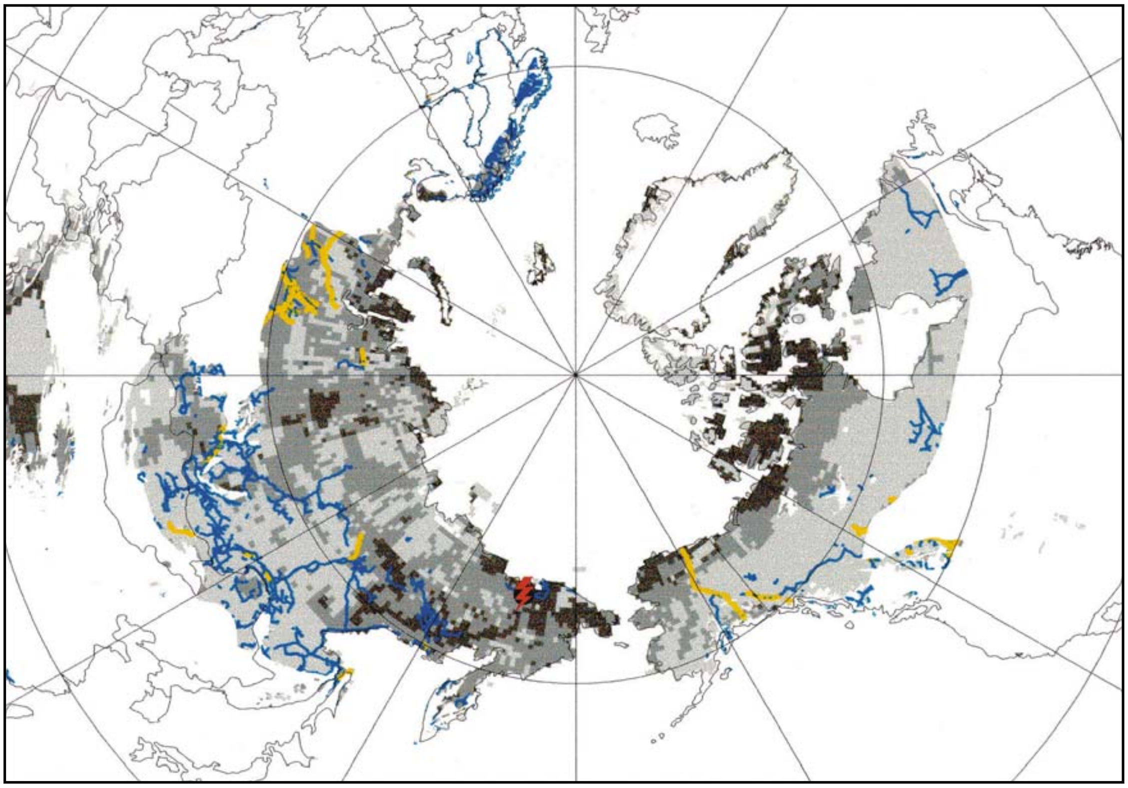


*a. Risk to infrastructure. The red dots indicate population centers; the pink shading indicates areas of human settlement.*

*Figure 13. Areas at risk for infrastructure damage as a result of thawing of permafrost.*



*b. Risk to transportation facilities. The yellow lines indicate winter trails, the blue lines indicate railroads, and the red dots indicate airfields.*



*c. Risk to major electrical transmission lines and pipelines. The blue lines indicate electrical transmission lines, the yellow lines indicate pipelines (yellow), and the black dot with red lightning is the location of the Bilibino nuclear powerplant in Russia.*

extensive railway system developed in areas underlain by permafrost.

The risk to major electrical transmission lines and pipelines is shown in Figure 13c. Most electrical facilities, including the extensive networks in northern Scandinavia and south-central Siberia, are located in areas of moderate risk. The Bilibino nuclear station and its grid, extending from Cherskiy on the Kolyma River to Pevek on the East Siberian Sea, occupy an area in which increased thaw depth and abundant ice-rich permafrost combine to produce high hazard potential. The Trans-Alaska Pipeline System spans two areas of moderate hazard potential. The network of pipelines associated with the West Siberia oil and gas fields is of particular concern because it is located in the ice-rich West Siberian Plain and is vulnerable to freeze–thaw processes (Seligman, 2000).

Figure 13 provides a generalized delineation of regions in the Northern Hemisphere to which high priority should be assigned for monitoring permafrost conditions. At the circum-arctic scale, maps such as these are useful for developing strategies to mitigate detrimental impacts of warming and adaptation of the economy and social life to the changing environment of northern lands. Maps at such scales cannot, of course, resolve the local factors involved in the development of thermokarst. Rather, they point to geographic areas where hazard scientists, policy analysts, and engineers should focus attention and prepare more detailed maps at local and regional scales.

## 3.3 Geocryological Hazards in Alaska

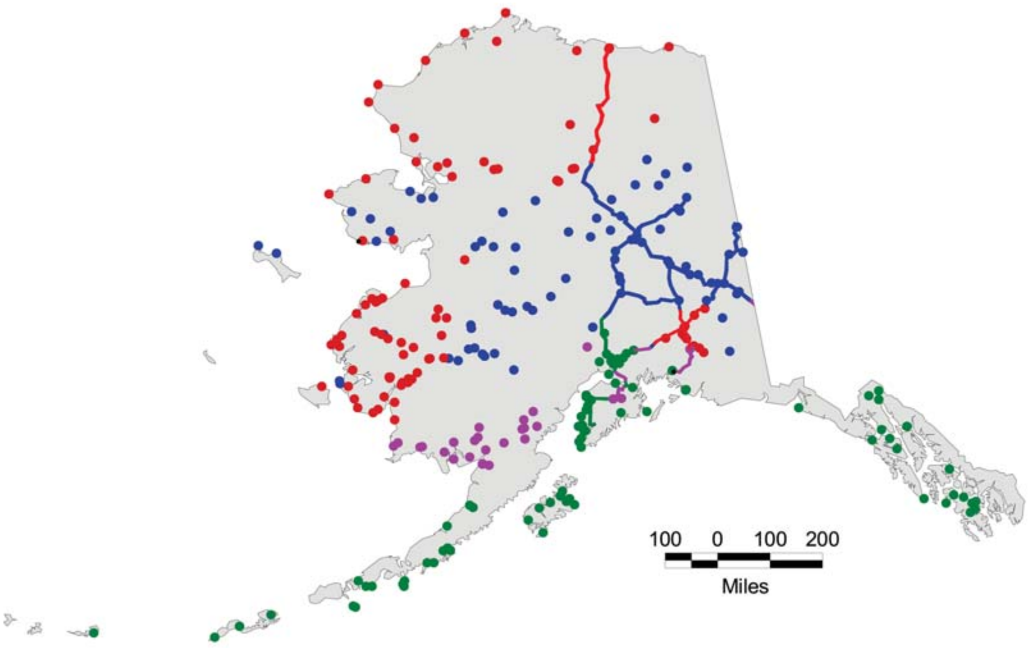
Figure 14 shows the population centers and major roads in areas of Alaska that are presently affected by permafrost. Although a majority of the population resides in permafrost-free areas of the state, sizeable towns and settlements are located in areas that are susceptible to permafrost degradation; nearly 100,000 Alaskans live in areas vulnerable to permafrost degradation (Fig. 14). Moreover, many of the state's highways traverse areas underlain by permafrost. The remainder of this chapter updates earlier reviews by Muller (1947), Ferrians et al. (1969), and Péwé (1954, 1983b) by considering how warming permafrost may affect transportation, the Trans-Alaska Pipeline, and community infrastructure.

### *3.3.1 Transportation Network*

The State of Alaska agency primarily responsible for transportation infrastructure is the Department of Transportation and Public Facilities (ADOT&PF). The ADOT&PF discusses the history, present status, and plans for road, rail, air, and marine transportation infrastructure in its *Vision 2020 Update, Statewide Transportation Plan* (ADOT&PF, 2002). With respect to the present status of roads, this report notes that "…Alaska is twice the size of Texas, but its population and road mileage compare more closely with Vermont…." The state has approximately 12,700 miles of roads, about 30% (less than 4,000 miles) of which are paved. Gravel and dirt roads are by far the most common design. The majority of the state's roads are in the south-central region, where permafrost is discontinuous and sparse. Roads in the interior, particularly north of Fairbanks (i.e., the gravel Dalton Highway), traverse areas underlain by ice-rich permafrost and may require substantial rehabilitation or relocation if thaw occurs.

The Alaska Railroad extends from Seward to Fairbanks, crosses permafrost terrain, and has been affected by differential frost heave and thaw settlement in places (Ferrians et al., 1969). The railroad does not extend northward into the zone of continuous permafrost. Thaw of ice-rich permafrost will increase railway maintenance costs but should not require major relocations of the existing track. Plans to extend the track to Canada across the interior will involve routing through permafrost areas. Selecting a route that avoids ice-rich permafrost foundations will increase the track mileage and construction cost.

Alaska has 84 commercial airports and more than 3,000 airstrips. The state has 285 publicly owned airports, 261 of which are owned by the state government, including 67 paved airstrips, 177 gravel airstrips, and 41 seaplane ports. Many of the state's rural communities depend exclu-



Summary of Alaska Highways Susceptible to Permafrost

| Permafrost Extent | Road Distance (mi) |
|---|---|
| Continuous (90 – 100%) | 456 |
| Discontinuous (50 – 90%) | 1,211 |
| Sporadic (10 – 50%) | 189 |
| Less than 10% | 281 |

Summary of Alaska Communities Susceptible to Permafrost

| Permafrost Extent | Total Communities | Population |
|---|---|---|
| Continuous (90 – 100%) | 87 | 40,811 |
| Discontinuous (50 – 90%) | 79 | 47,140 |
| Sporadic (10 – 50%) | 26 | 5,235 |
| Less than 10% | 129 | 396,821 |

*Figure 14. Exposure of communities and major roads in Alaska to permafrost. (Source data: U.S. Geological Survey, International Permafrost Association, and Alaska Department of Natural Resources GIS database.*

sively on a local airstrip for transporting passengers and freight, including heating fuel. A significant number of airstrips in communities of southwest, northwest, and interior Alaska are built on permafrost and will require major repairs or complete relocation if their foundations thaw.

The vulnerability of Alaska's network of transportation infrastructure to thawing of permafrost can and should be assessed systematically. Roads, railways, and airstrips placed on ice-rich continuous permafrost will generally require relocation to well-drained natural foundations or replacement with substantially different construction methods. Roads through discontinuous permafrost will require this reinvestment for reaches built on ice-rich permafrost. Roads and airstrips built on permafrost with a lower volume of ice will require rehabilitation, but perhaps not relocation, as the foundation thaws.

Site-specific information is most desirable for this purpose, but the information contained on permafrost maps can be applied to compute an expected value of road miles over each category of permafrost. Figure 14 shows the major road routes of the state and the locations of communities, shaded to indicate whether they are situated in areas of continuous, discontinuous, or sporadic permafrost. Thawing of various types of permafrost is predictable by analyses based on knowledge of soil conditions and air temperature warming projections. A timeline for serious permafrost-related problems could be derived from projections of general circulation models in a manner similar to that of Nelson et al. (2001). Expected values of relocation and rehabilitation can be developed, given estimates of per-mile design and construction costs. A master plan of climate-change-induced major relocation and rehabilitation projects can be formed with this information. The information can also be applied efficiently to locate stations to monitor permafrost warming where it matters most. This effort could best be accomplished comprehensively through the combined resources and efforts of the state and federal governments.

### *3.3.2 Community Infrastructure*

Community infrastructure includes facilities in urban and rural communities that are not associated with the transportation network or the Trans-Alaska Pipeline. Examples of community infrastructure include private and public buildings, landfills, sewer and water facilities, solid waste facilities, electrical generating facilities, towers, antennas, and fuel storage tanks. Figure 14 shows the locations of settlements in Alaska with regard to permafrost susceptibility. Although the major population center in the Anchorage area is largely free of permafrost, over 160 communities lie in areas of continuous or discontinuous permafrost. Alaska has four large military bases, two of which must contend with discontinuous permafrost. Alaska also has 600 former defense sites. Russia has an even greater problem, with a significant number of population centers, industrial complexes (including one nuclear power plant), and military bases in permafrost areas (Ershov et al., 2003). The continuous permafrost in the far north forces essentially all facilities to be constructed on permafrost. Farther south, in areas of discontinuous permafrost, land ownership and needs often force facilities to be developed on permafrost.

The permafrost underlying most of the state is the key reason why Alaskan infrastructure will be affected by a warming climate far greater than any other region of the U.S. Thawing permafrost poses several types of risks to community infrastructure. Most are associated with the thawing of ice-rich permafrost, which, when thawed, loses strength and volume. The most basic risk is caused by the loss of mechanical strength and eventually thaw settlement or subsidence. Thaw settlement causes the failure of foundations and pilings, affecting all types of community infrastructure. Bond strengths between permafrost and piles are greatly reduced by rising temperatures. Increases in the thickness of the active layer can cause frost heaving of pilings and structures. Warming will also accelerate the erosion of shorelines and riverbanks, threatening the infrastructure located on eroding shorelines. Thawing of permafrost or increasing the thickness of the active layer can also mobilize pollutants and contaminants that are presently confined (Snape et al., 2003).

Thawing permafrost and changes in the active layer across Alaska will bring potentially adverse impacts to building foundations and support structures. The past is replete with examples of public and private facilities that have failed due to warming and subsidence of the underlying permafrost because of improper siting, design, and construction methods. Thaw subsidence has resulted in numerous cases of expensive fixes or abandoned facilities. During new construction, if ice-rich permafrost cannot be avoided, it can be addressed with proper design and construction techniques. Methods include digging out the permafrost if it is relatively shallow and thin, raising the structure on piles, or otherwise assuring that the substrate remains frozen through active or passive refrigeration. Mitigating existing problems is difficult and expensive, requiring reconstruction of the building support system, as well as repairing the damage to the structure. Warming creates further problems, however. If mean annual air temperatures rise above the freezing point, it will be impossible to maintain permafrost over the long term without expensive artificial refrigeration. The largest problem will be for those areas where the upper permafrost layers are already near the freezing point, primarily in regions of discontinuous permafrost. Larger facilities, such as schools and tank farms, will be affected first. Continued warming will cause problems even for those facilities that were properly designed to maintain the underlying permafrost in its frozen state. New approaches for maintaining existing structures and building new structures on permafrost must be developed to account for increases in soil temperatures.

Thaw subsidence is also a problem for utility distribution networks and communications facilities. These facilities are usually based on foundations or pilings. Frost heaving of piles can result from increased active-layer thickness. One of the major effects of thawing ice-rich permafrost is the development of thermokarst terrain. Uneven surfaces created by differential thaw settlement will cause problems with above-ground power lines, water, sewer, and fuel piped systems. Piped systems are especially susceptible to settlement and subsequent leakage (Williams, 1986).

In many arctic communities, modern sewer and water facilities are non-existent. Many villages still use “honeybucket” (storage and haul) systems in which human waste is emptied into a pit or lagoon in or near the town. Many of the towns with more modern facilities also have lagoons where waste is dumped or piped. Sewage disposal systems that are designed for subsurface discharge may benefit from less extensive permafrost, increased water table depth, and increased groundwater flow rates. For systems that discharge into streams or rivers, increased stream flow and reduced ice cover will help aerate and dilute the effluent. Landfills containing solid waste pose problems in that contaminants confined by the frozen ground may be released and transported as the permafrost thaws. The problem is amplified because there is often far more than solid waste in landfills and at many other locations near villages. Past practice throughout the north has ignored proper disposal of contaminants because of the associated expense and the perception that permafrost acts as an impermeable barrier.

Some villages or facilities located on riverbanks or exposed coastlines are facing major problems with erosion (Walker and Arnborg, 1966; USACE, 1999; Walker, 2001). Warming has contributed to longer ice-free seasons in arctic areas. Riverbank erosion has destroyed homes and public infrastructure in some villages (USACE, 1999). Increased storminess and higher waves are eroding arctic coasts at greater rates than in the past (Brown et al., 2003). The combination of increased wave action and warming permafrost especially threatens low-lying coastal villages (Walker, 2001). Several villages in Alaska have lost buildings to the sea (Callaway et al., 1999). In some cases, entire villages may have to be relocated. Abandoning and rebuilding communities will have the secondary effect of generating large amounts of solid waste.

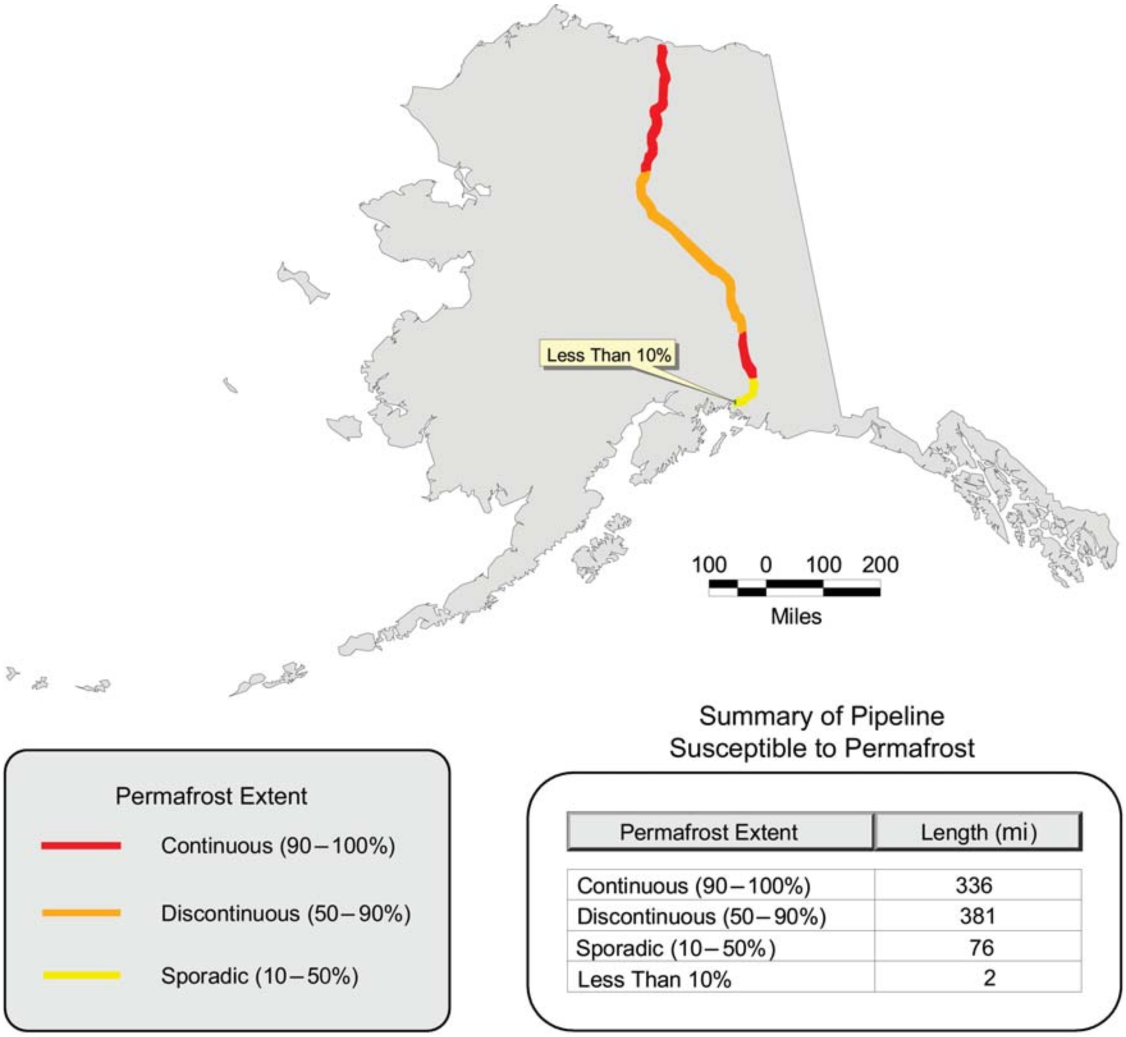
The costs associated with rehabilitating or abandoning community infrastructure damaged by thawing permafrost will be high. Even buildings that have been designed for ice-rich permafrost will not survive unscathed if the temperature rises to the point that systems designed to maintain permafrost in its frozen state no longer function adequately. Electrical distribution systems and pipe and utilidor systems will be subject to failure from subsidence or frost heaving. Contaminants could be released from landfills and other contaminant storage sites once thought to be safe. Huge costs will be associated with villages that must be relocated. In one case study by the Corps of Engineers in 1998, the costs of moving the village of Kivalina, Alaska, to a nearby site were estimated at $54,000,000

(USACE, 1998). Other coastal and river villages can be expected to have problems with warming permafrost and may require additional relocations.

The military has extensive facilities in Alaska. Two of its largest bases and a major training facility are located in areas of discontinuous permafrost, and they must constantly cope with problems caused by thawing permafrost (Cole, 2002). There are also 600 formerly used defense sites in Alaska. Alaska is also used extensively for training, requiring access by military vehicles and live firing of munitions. The development of thermokarst terrain would make some training lands unusable. Additional precautions will be necessary for contaminants generated by the military, some of which are associated with the use of live munitions. Permafrost must be considered in Department of Defense plans for new facilities, including the National Missile Defense sites being contemplated for Alaska.

### *3.3.3 The Trans-Alaska Pipeline*

The Trans-Alaska Pipeline System (TAPS), the only large-diameter hot-oil pipeline to traverse environmentally sensitive permafrost terrain (Fig. 15), has been called an engineering marvel.



Summary of Pipeline Susceptible to Permafrost

| Permafrost Extent | Length (mi) |
|---|---|
| Continuous (90 – 100%) | 336 |
| Discontinuous (50 – 90%) | 381 |
| Sporadic (10 – 50%) | 76 |
| Less Than 10% | 2 |

*Figure 15. Exposure of the Trans-Alaska Pipeline to permafrost. (Source data: U.S. Geological Survey, International Permafrost Association, and Alaska Department of Natural Resources GIS database.*

The TAPS encounters a wide variety of permafrost soil and temperature conditions (Kreig and Reger, 1983). To avoid permafrost degradation, soil liquefaction, and subsidence, pipeline along 434 of the 800 miles of the TAPS was elevated on vertical support members (VSMs) (Fig. 16). The VSMs represented a new approach to engineering when they were designed in the early 1970s. Design standards were based on the permafrost and climate conditions of the period 1950–1970. The objectives of the design were to eliminate thawing of permafrost soils and maintain soil stability (Williams, 1986, Chapter 4).

About 61,000 of the 78,000 VSMs are equipped with pairs of thermosyphons (heat pipes), which were installed to remove heat from the permafrost by releasing it to the atmosphere. They are designed to operate between a range of temperatures in summer and winter and were installed mainly in areas of warm permafrost. Alyeska Pipeline Service Company's *Environmental and Technical Stipulation Compliance Assessment Document* provided the geotechnical justification for the design mode for each of the 1000 individual design segments in the 800-mile pipeline. The pipeline includes 200 elevated segments, where the thermosyphon function is particularly important because local soils have high liquefaction potential. An assessment of the long-term performance of the TAPS heat pipes is provided by Sorensen et al. (2003).

The Federal/State Joint Pipeline Office (JPO) has identified 22,000 VSMs as having possible problems caused by climate change along the pipeline route (JPO, 2001). It has also identified more than 50,000 of the heat pipes that have experienced some malfunction or blockage over the 25-year life of the TAPS. Some VSMs have required replacement. A thawing south-facing slope first identified in 1990 at the Squirrel Creek crossing resulted in one VSM tilting seven degrees by 1993. VSMs at this site were replaced in 2000. Other VSMs are being evaluated for replacement (Golder Associates, 2000). Proper functioning of the VSMs is critical to the future reliability of the TAPS.

At present, neither Alyeska Pipeline Service Company nor the JPO regard permafrost degradation as a problem. This interpretation is based, however, on the present permafrost and climate conditions and does not consider the Arctic Climate Impact Assessment predictions for the next 30 years. It is important to note that the 20-year period used to determine design standards was one of the coldest periods in recent Alaskan history.

The TAPS right-of-way leases from the federal and state governments terminate in 2004, and the owner companies plan to ask for a 30-year renewal. The original VSM design represented a coordinated effort by the Alyeska owners with strong oversight by the TAPS Federal Inspectors Office. That office relied

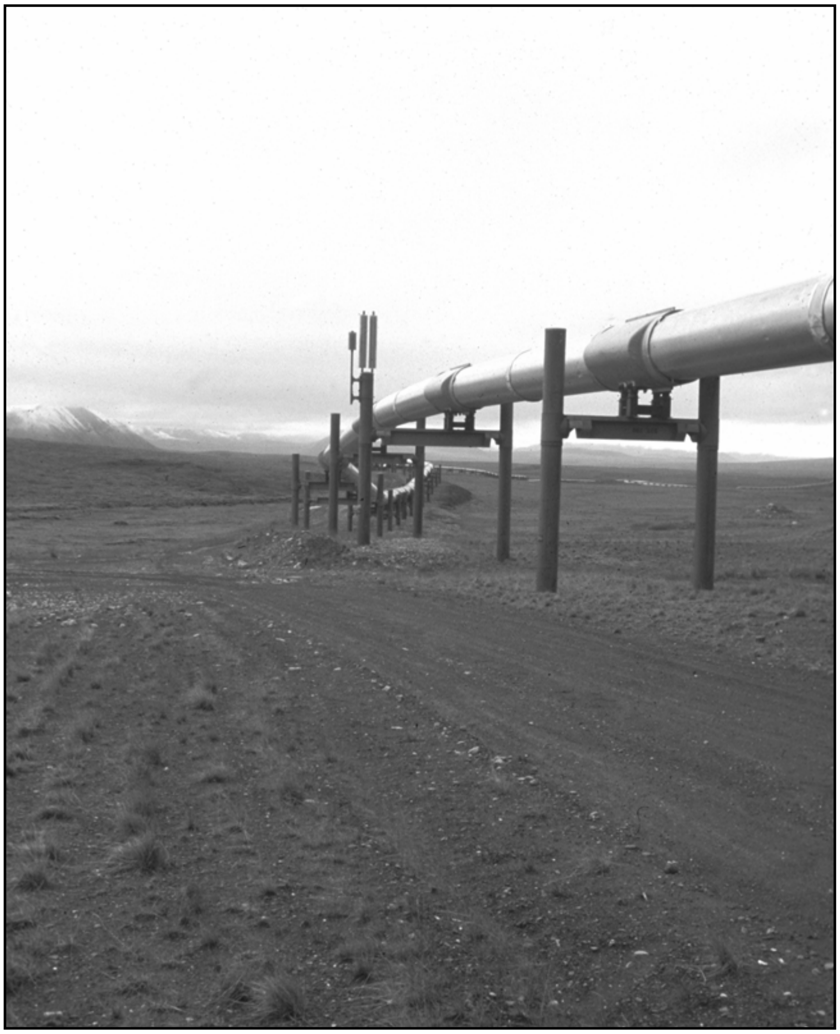


*Figure 16. Vertical support members (VSMs) along the Trans-Alaska Pipeline System.*

upon the expertise of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and the USGS for identification of soil and permafrost problems; continuing operations should incorporate similar cooperative efforts.

In addition to the TAPS segments elevated on VSMs, soil stability in non-permafrost areas where the pipeline is buried may be affected. While there was no permafrost located immediately adjacent to the buried pipeline, changes in freeze–thaw depth, water table location, and soil bearing capacity may cause degradation in downslope areas, river crossings, and other areas.

The TAPS cannot be discussed without mentioning the large infrastructure on the North Slope, which provides the oil to the pipeline. Literally tens of billions of dollars of construction is responsible for drilling pads, production installations, injection plants, pump stations, and hundreds of miles of feeder pipelines. Although these facilities are located on the colder permafrost north of the Brooks Range, which may not be as susceptible to thawing as is the warmer permafrost, their impacts have been substantial (Walker et al., 1987; Committee on Cumulative Environmental Effects, 2003, Chapter 6) and close monitoring is critical.

## 3.4 Summary

A significant proportion of Alaska's population and infrastructure is located in areas of permafrost, much of which may become unstable under conditions of global warming. Although much of this infrastructure was designed for permafrost, substantial retrofitting to accommodate warming conditions may be necessary. In many instances designs are clearly inadequate, and infrastructure could be severely damaged by differential thaw settlement.

The problems presented by climate warming in Alaska, although substantial, are not insurmountable. To achieve maximum effectiveness in an era of declining oil revenues and limited financial resources for both industry and government at all levels, a prevenient, well-informed, and coordinated response to the effects of global warming on permafrost is essential. The last chapter of this report provides a general prescription for the roles governmental agencies can and should play in permafrost research.