Increases in highway maintenance costs in a permafrost environment undergoing climate change, Yukon, Canada

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Abstract

Assessment of infrastructure vulnerability to climate change in permafrost environments has emphasized increases in ground temperature, deepening of the active layer, and differential settlement. Hydrological factors are less emphasized. Yukon's Transportation Maintenance Database records expenses for 61 activities on the 21 maintenance sections of the territorial highway network. The costs associated with snow clearing, icing control, washout repair, and landslide removal have been examined from April 1994 to March 2022. These are directly related to climate and are primarily associated with hydrologic processes. For Yukon's entire highway network, climate-related maintenance expenditures have increased by $169,000 per year (in constant 2021 CA$) since 1994. Topography, surficial deposits, permafrost, and climate create specific sub-regional financial responses to a changing environment. For example, snow clearing expenditures are greatest for highways in the Coast Mountains region (now over $600,000 per year), icing control expenditures dominate on the Silver Trail in the discontinuous permafrost zone (over $250,000 annually), while intermittent clearing of landslides and repair of washouts are greatest for the Ogilvie section of the Dempster Highway in steeply sloping terrain and continuous permafrost ($825,000 in 2013). This paper presents expenditure profiles for seven representative maintenance camps in distinct physiographic and permafrost environments within the highway network.

1 Introduction

In Canada, Yukon and Mackenzie Valley have experienced the greatest recent increases in air temperatures (Vincent et al. 2015). Long-term trends in precipitation are not as clear, but rain is replacing snowfall in the shoulder seasons (Vincent et al. 2015). These changes will likely continue for the next several decades, at least (Bush and Lemmen 2019).

Road infrastructure may destabilize permafrost and induce its thaw. In turn, degradation of near-surface permafrost affects the road, reducing its bearing capacity and causing differential subsidence. For example, in western sections of the Alaska Highway in Yukon (Figure 1), the road is undulating, necessitating repeated rehabilitation and local reductions in operating speeds (Oldenborger et al. 2015). Such damage, treated by resurfacing sealed sections and grading of gravel roads, increases in both intensity and magnitude with climate change.

Less consideration is typically given to the hydrological aspects of climate change affecting infrastructure. Nevertheless, in permafrost environments characterized by limited infiltration, road hazards are closely associated with local precipitation and surface hydrology (Michel and van Everdingen 1994). These hazards include the development of icings (aufeis), washouts, and landslides. Such hazards may disrupt vital routes which facilitate the distribution of resources, and private and business travel connecting northern communities to the south.

Yukon's highway network encompasses both primary and secondary routes linking most communities throughout the territory (Figure 1). The network is entirely operated and maintained by Highways and Public Works, Yukon. A total of 21 maintenance camps are distributed around the network, each responsible for distinct highway sections (Figure 1).

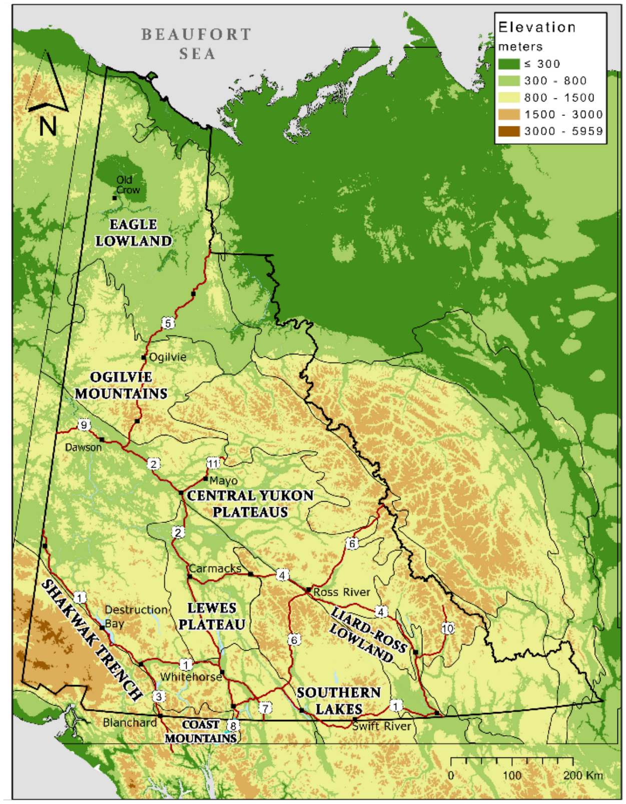

Figure 1. Highway network in Yukon, with locations of maintenance camps discussed in the paper. Physiographic regions are identified. The highway numbers are displayed in Table 1. Elevation data retrieved from ArcticDEM (Porter et al. 2018).

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Detailed accounts of maintenance expenditures are recorded daily at each camp and archived in a generalized database. In this paper, we present a retrospective analysis of highway maintenance expenditures associated with climate conditions from 1994 to 2022. The analysis examines variations in expenditures due to climate and physiographic conditions and underlying permafrost in seven distinct regions. Three climate-related maintenance activities were selected for examination here, and annual totals for seven highway maintenance sections in Yukon are presented. The three sets of costs are for snow removal, icing (locally called "glacier") control, and repairs after landslides and washouts. The research helps evaluate the changing magnitude of public costs associated with climate and provides insight on records of consequence for infrastructure management. The information will be valuable for planning ongoing maintenance of Yukon's highways in order to maintain functional integrity throughout their service life.

2 Climate Change in Yukon

2.1 Air Temperature

Since about 1970, the climate in Canada has changed throughout the country (Bush and Lemmen 2019). The change has been particularly pronounced at higher latitudes where increases in temperature since 1979 have been recorded at rates up to four times the planetary average (Rantanen et al. 2022). In Yukon, mean annual air temperatures increased by 2.5 °C between 1948 and 2021, or more than double the global average (Perrin and Jolkowski 2022). The warming has been prominent in winter, with mean air temperatures increasing by 4.3 °C between 1972 and 2012 (Vincent et al. 2015). Temperature records in 1971–2020 for southern (Whitehorse) and central (Dawson) Yukon indicate that annual warming has been at rates of 0.43 and 0.48 °C per decade, respectively, while winter warming has been faster at 0.97 and 1.15 °C per decade (Figure 2; Schetselaar et al. 2023).

2.2 Precipitation

Although precipitation records between stations in Yukon are poorly correlated (Schetselaar et al. 2023), Perrin and Jolkowski (2022) detected an increase of 3% in total annual precipitation for 1966–2015 in the territory. Increases in the precipitation record are not statistically significant, due to high interannual variability, but the regime is expected to shift with increasing temperatures, especially to rain in autumn (Bintanja and Andry 2017). Early detection of this shift may be evident in the frequency distribution of August and September rainfall at Mayo presented for 1961–2020 as a normal probability plot (Figure 3). If events were evenly distributed, each 20-year interval would contribute six or seven events to the upper, middle, and lower thirds of the distribution. However, the most recent 20-year interval (2001–20) is overrepresented in the upper third of the distribution, indicating that rainfall has increased in this season.

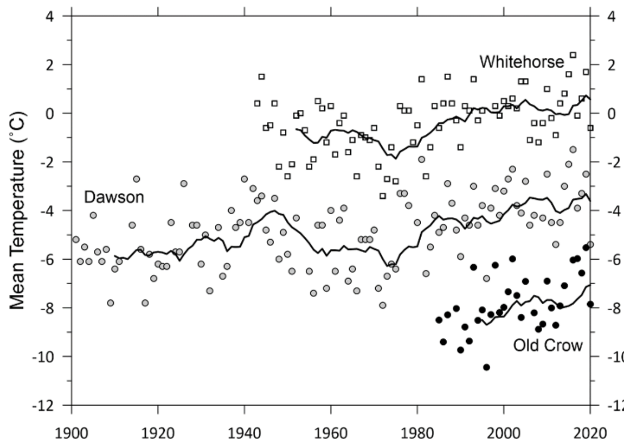

Figure 2. Annual mean temperature record for southern (Whitehorse), central (Dawson), and northern (Old Crow) Yukon. The lines show the running mean for the previous ten years of data. Data retrieved from Environment and Climate Change Canada (ECCC 2020).

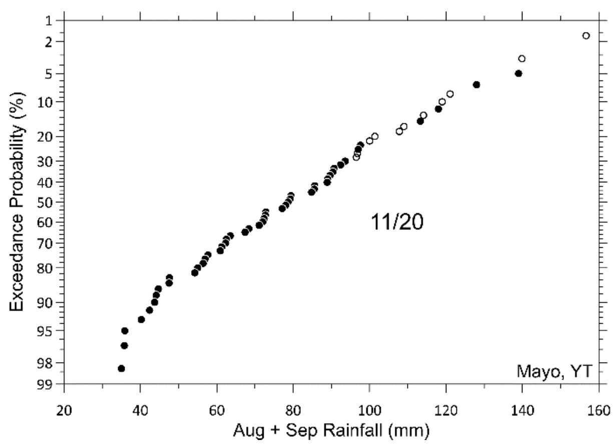

Figure 3. Exceedance probability distribution for August and September rainfall at Mayo, YT, for 1961–2020. Open circles are years from 2001–2020 in the upper third of the distribution and are listed as a fraction of the 20 upper years. Data from Environment and Climate Change Canada (ECCC 2020).

3 Physiography of Yukon

We divided the highway network into seven distinct physiographic regions following Bostock (1948) and Matthews (1986). Here we present physiographic information for each region (Figure 1). The highway responsibility of a representative maintenance camp for each region is presented in Table 1.

Table 1. Summary of Yukon's highway network, maintenance camps investigated in this paper, and lengths of highway for each camp. Highway number is marked in Figure 1.

Physiographic Region	Camp	Highway (#)	Length (km)	Kilometer Post
Shakwak Trench	Destruction Bay	Alaska Highway (1)	133.8	Km 1636.6 -1770.4
Coast Mountains	Blanchard	Haines Road (3)	121.3	Km 71.3 - 192.6
Southern Lakes	Swift River	Alaska Highway (1)	131.2	Km 1062.8 - 1194.0
Liard-Ross Lowland	Ross River	Robert Campbell Highway (4)	184.6	Km 230.0 - 414.6
Lewes Plateau	Carmacks	Klondike Highway (2)	174.6	Km 256.2 - 430.8
Central Yukon Plateaus	Mayo	Silver Trail (11)	110.4	Km 0 - 110.4
Ogilvie Mountain-Eagle Lowland	Ogilvie	Dempster Highway (5)	146.8	Km 139.2 - 286.0

3.1 Shakwak Trench

The northwestern section of the Alaska Highway, from near Haines Junction to Beaver Creek, is mainly in the Shakwak Trench, a 4–8 km wide fault between Yukon Plateaus and St. Elias Mountains (Figure 1). The climate is influenced by St. Elias Mountains, which separate the maritime Pacific coast from drier interior conditions (Yukon Ecoregions Working Group 2004). The terrain is mainly composed of glacial and colluvial materials. Over 80% of the highway section is underlain by permafrost (Rampton et al.1983).

3.2 Coast Mountains

The Klondike Highway, south of km 146, and the Haines Road traverse units of Coast Mountains characterized by rugged terrain with glaciated peaks up to 2400 m a.s.l. (Yukon Ecoregions Working Group 2004; Figure 1). Valleys dissecting this terrain channel maritime air ascending from the Pacific coast, resulting in high levels of precipitation. Permafrost is rarely found beneath both roads.

3.3 Southern Lakes

The Alaska Highway, from km 1468 west of Whitehorse to Watson Lake, is situated within physiographic units of Teslin, Nisutlin, and Dease plateaus. The region features wide valleys, rounded peaks, and numerous lakes associated with deglaciation of the McConnell (Late Wisconsinan) ice sheet. There is sporadic discontinuous permafrost. The climate of this region is generally dry due to the rain shadow of Coast Mountains (Yukon Ecoregions Working Group 2004).

3.4 Liard-Ross Lowlands

The Robert Campbell Highway from Watson Lake to km 528 traverses broad flats and rounded hills surrounded by mountains and plateaus. In Pelly Mountains, west of Ross River, areas with steep terrain are prone to landslides, rock falls, and avalanches (Yukon Ecoregions Working Group 2004). The region has moderate precipitation, with most falling as rain (ECCC 2020).

3.5 Lewes Plateau

The Klondike Highway from Whitehorse north to Minto, and the Robert Campbell Highway from Carmacks to km 528 are in glaciated terrain characterized by rounded, rolling hills with broad valleys (Figure 1). Dry and coarse surficial materials in the region are generally free of ground ice whereas glaciolacustrine deposits in valleys are ice-rich (Yukon Ecoregions Working Group 2004). Precipitation is relatively low.

3.6 Central Yukon Plateaus

The Klondike Highway from km 432 to Dawson City and the Silver Trail traverse units of the central Yukon plateaus. These include Tintina Trench, a 450 km ancient fault trace, Klondike Plateau, displaying distinct rounded ridges dissected by deep valleys characteristic of unglaciated Beringia, and Stewart Plateau featuring tablelands interspersed with broad valleys (Figure 1). Surficial deposits include thick till deposits in glaciated areas and coarse-grained glacial outwash in unglaciated zones (Yukon Ecoregions Working Group 2004). This region experiences strong seasonal variability, with severe inversions in winter trapping cold air in valleys.

3.7 Ogilvie Mountains-Eagle Lowland

The Dempster Highway is a 736 km route, of which 465 km is in Yukon, connecting the Klondike Highway, 40 km east of Dawson City, to Inuvik, NT. The highway lies in deep valleys of southern Ogilvie Mountains and on rolling hills of Eagle Lowland (Yukon Ecoregions Working Group 2004). Valleys between km 75 and km 129 were glaciated while the remainder of the route is in unglaciated Beringia (Burn et al. 2015). Permafrost is ubiquitous. Ground and surface water in the mountains cause frequent icings at the base of hillslopes (Burn et al. 2015). The climate of this region is influenced by the topographic relief of the terrain. Valley bottoms are extremely cold in winter due to cold air pooling and topographic shading (Burn et al. 2015).

4 Permafrost Road Hazards

Yukon supports all categories of permafrost due to its climatic and physiographic conditions, but generally the proportion of the ground underlain by permafrost and its thickness increase northward (Figure 4).

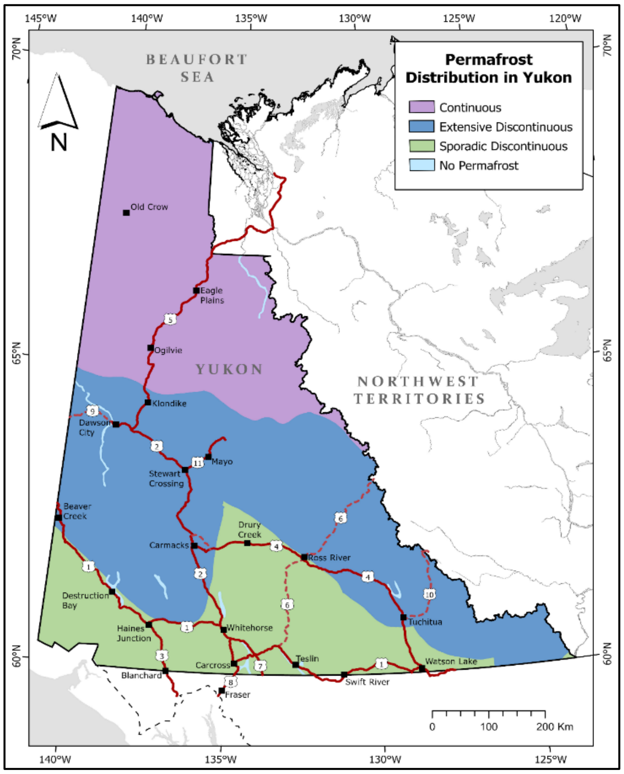

Figure 4. Distribution of permafrost relative to the highway network in Yukon. Permafrost limits from Heginbottom et al. (1995).

4.1 Hydrologic processes

Permafrost acts as an impermeable layer restricting groundwater movement to the active layer and taliks. Water flow in the active layer is closely associated with local precipitation and surface hydrology. Icings commonly develop adjacent to roads, may reach the driving surface, overflow, and create hazardous conditions (Figure 5). Icings may also block culverts leading to washouts during freshet. These hazards most commonly form in discontinuous permafrost at the foot of slopes (Turcotte et al. 2023). Low infiltration in permafrost regions, particularly in the continuous zone creates rapid hydrographic response to precipitation. Such events may erode road embankments adjacent to river channels. Washouts may be initiated by heavy rainfall or unserviceable culverts and occur during freshet or following rainstorms (Figure 6; Burn et al. 2015). Embankments in valley floors of rugged terrain and near rivers are particularly susceptible to this process.

Figure 5. Surface icing adjacent and covering the Dempster Highway at km 20, November 2022. Photo by kind permission of L.P. Roy.

Figure 6. Road washout at km 237 on the Dempster Highway, May 2023. Photo by O. Didier.

4.2 Slope processes

Mass movements in permafrost terrain include gradual phenomena like solifluction and immediate movements such as landslides, particularly, active-layer detachments and retrogressive thaw slumps (Figure 7). In Yukon, hillslopes with permafrost are susceptible to downslope mass movements (Burn et al. 2015). Active-later detachments occur in ice-rich ground on mid-to-upper slopes during late summer after heavy rain and following forest fires (Lewkowicz 1992). As infrastructure is predominantly constructed in valley floors with little room for alternate routes, mass movement events may disrupt traffic flow throughout the territory.

Figure 7. Landslides adjacent to Dempster Highway at km 244, July 2018. Photo by C.R. Burn.

5 HIGHWAY MAINTENANCE DATABASE

Financial data were retrieved from an internal database of Highways and Public Works, Yukon. Each expenditure is recorded with a 21-digit identifier code by camp, highway, activity, and program. Monthly expenditures were examined over 28 years from April 1994 to March 2022. Maintenance costs were converted to constant 2021 Canadian dollar values using the Consumer Price Index for Whitehorse as a measure of inflation (Statistics Canada 2023).

Three maintenance activities were identified as directly related to climate. First, snow removal, including drift control and sanding (Figure 8), is predominantly carried out from October to April. Second, icing control includes both physical removal of aufeis from road surfaces and maintaining flow inside culverts to prevent overflow (Figure 5). This activity is primarily carried out between freeze-up and freshet. Third, clearing of landslides and repair of embankments after washouts. Landslides may be triggered by late summer rainfall or following forest fires. Washouts are common after rapid runoff events during spring freshet and after heavy rainfall. These events occur on an intermittent basis (Figures 6 and 7).

Annual totals for snow removal, icing control, and the repair of landslides and washouts were tabulated for seven maintenance camps (Table 1). The sum of these individual activities was determined to define total climate-related expenditures. Five-year means were calculated by camp for the beginning (1994/1995–1998/1999) and end of the series (2017/2018–2021/2022) for each individual climate-related activity, and total operation and maintenance expenditures.

6 HIGHWAY MAINTENANCE EXPENDITURES

6.1 Total operation and maintenance

The operation and maintenance (O&M) for the entire highway network in Yukon covers all activities and camp overhead expenditures by fiscal year. Camp overheads are indirect expenses necessary for overall operation and management of highways and include expenses for activities such as field supervision, freight, road inspection, stockpiling, transport, and building and ground maintenance. In 1994–2022, the total O&M expenditures, adjusted for inflation, varied between $32M and $43M. Total expenditures, adjusted for inflation, have slightly decreased over time, although there has been substantial interannual variation (Figure 9). However, the proportion of the total cost devoted to camp overheads has increased from 24% to 31% (Figure 10). As a result, the resources available for maintenance operations declined from $28.4M/yr in 1994–99 to $25M/yr in 2017–22.

6.2 Climate-related maintenance

Mean annual climate-related maintenance expenditures, increased, in constant dollars, from $6.6M in 1994–1999 to $10.2M in 2017–2022. The rate of increase was $169,000/yr (Figure 11). Climate-related costs rose from 24% of total maintenance, excluding overheads, to 43% (Figure 12). The greatest increase in cost was for snow removal, with an 18% increase of the total between 1994–1999 and 2017–2022; the repair of slides and washouts increased from 1% to 3%; and icing control remained at the same percentage of the total.

Figure 8. Snow removal in Hurricane Alley, Dempster Highway, YT. December 2021. Photo by kind permission of C. Brais (2021).

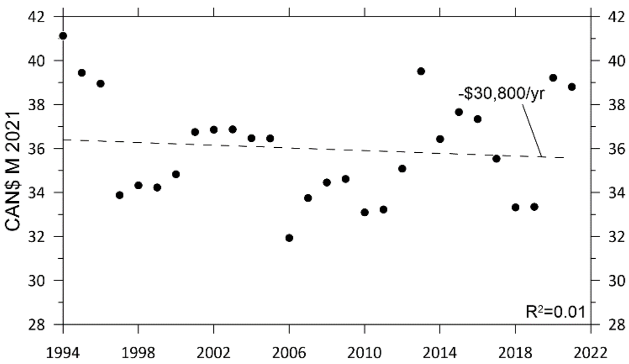

Figure 9. Total operation and maintenance costs (including camp overheads) for Yukon highways in 1994–2022.

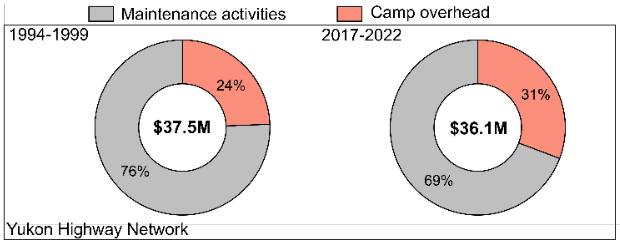

Figure 10. Proportion of annual camp overheads in 1994–1999 and 2017–2021.

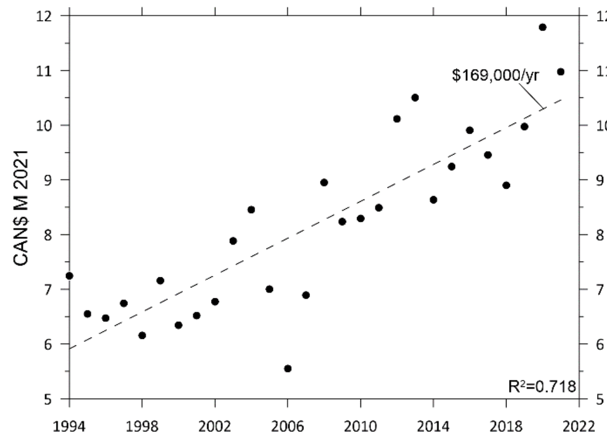

Figure 11. Annual climate-related maintenance expenditures for Yukon highways in 1994–2022.

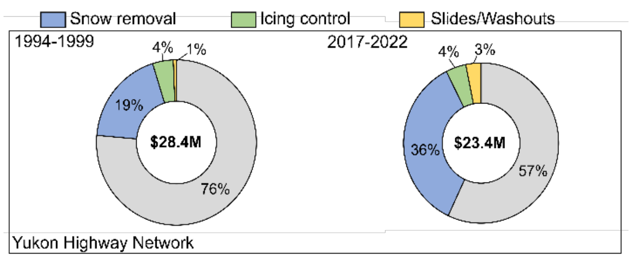

Figure 12. Break-down of annual mean climate-related maintenance costs for snow removal, icing control, and slides/washouts in 1994–1999 and 2017–2022 for Yukon's entire highway network. All other maintenance activities are indicated in gray shading. Camp overheads have been excluded from this figure.

6.3 Effects of physiography

Snow removal expenses dominate operation and maintenance costs at each camp, but they vary throughout the network (Figure 13). Blanchard, located in the Coast Mountain region, stands out with the highest proportion of these expenditures, reaching up to 71% in 2017–2022. This can be attributed to high snowfall in the region due to its elevation and proximity to the Pacific Ocean, which is a recurrent source of moisture-laden air masses. Additionally, blowing snow and accumulation of snow drifts are common occurrences above treeline in these high-altitude regions.

Mayo, in the central Yukon plateaus region, and Ross River, in Liard-Ross Lowland, have notably high expenses for icing control (Figure 13). Most recently, the proportion of such expense at Ross River rose to 14% and to 23% at Mayo. These regions are within extensive discontinuous permafrost with groundwater flow concentrated in creek taliks. Groundwater discharge and successive overflow lead to frequent icing formation. Sites vulnerable to icings are also typically found at the foot of slopes, where groundwater is forced to the surface (Turcotte et al. 2023).

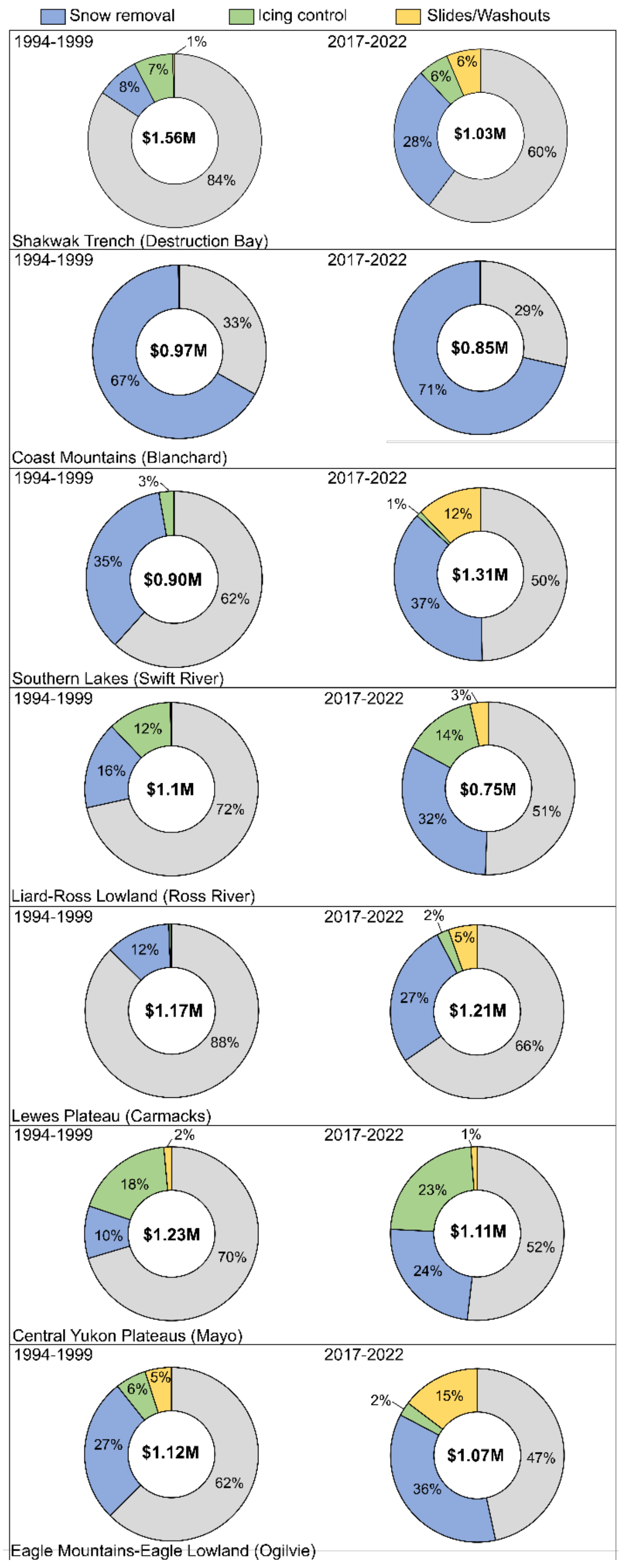

Figure 13. Break-down of annual mean climate-related maintenance costs for a representative camp in each physiographic region in 1994–1999 and 2017–2022. All other maintenance activities indicated by gray shading. Camp overheads have been excluded from this figure.

For instance, the Ross River highway section is situated near the slopes of Pelly Mountains and the Silver Trail (Mayo) traverses slopes on the edge of Stewart Plateau.

Huscroft et al. (2004) describe a close association between the occurrence of landslides and presence of unconsolidated material on steep slopes, river erosion, and degradation of ice-rich permafrost. Expenses for slides and washouts at Swift River, in the Southern Lakes region, increased to 12% in 2017–2022 (Figure 13), and are associated with proximity to waterbodies and steep slopes. In the Ogilvie Mountains-Eagle Lowland, expenses for the Ogilvie camp rose from 5% to 15% (Figure 13) due to a combination of proximity to steep slopes, degradation of permafrost, and proximity to the Ogilvie River in a narrow valley (Figure 6). Highway repairs after washouts may also incur costs allocated to capital budgets. These costs are not included in this analysis and therefore the full cost of these events is underestimated in the maintenance budgets.

6.4 Expenditures by permafrost zone

Maintenance activities discussed here are influenced by permafrost occurrence and primarily driven by hydrologic processes. However, permafrost distribution indirectly affects activities such as icing control and occurrence of slides and washouts. Washouts are primarily associated with the limited infiltration in frozen ground during rainstorms or snow melt as surface water accumulates and subsequent rapid runoff occurs. Landslides in permafrost environments are often caused by elevated pore water pressure as permafrost thaws, reducing its shear strength, and with rainfall saturating the active layer (Harris et al. 2009). Icings occur due to emergence of groundwater which subsequently freezes at the surface (van Everdingen 1982).

An overlay analysis was conducted for the highway network and a high-resolution permafrost distribution model (Bonnaventure et al. 2012). The model, with a pixel resolution of 30 x 30 m, divides the study area into four distinct zones of permafrost. It only extends to about 65°N, but farther north the Dempster Highway is assumed to lie in the zone of continuous permafrost (Heginbottom et al. 1995). Maintenance expenditures are recorded on a section basis and therefore each section was classified by permafrost zone. Highway sections situated in two zones are assumed to be in the zone where majority of the highway length is situated (i.e., > 50%). The Whitehorse section was excluded due to higher level of service required with greater traffic flows. According to this model and assumptions, roughly half of the network, excluding the Whitehorse section, lies in extensive discontinuous permafrost, 34% in sporadic discontinuous permafrost, 13% in continuous permafrost, and 9% in isolated patches (Table 2).

Maintenance costs associated with the presence of permafrost have been highest in the extensive discontinuous permafrost zone, with total costs reaching over $16,000/km in 1994–2022 (Table 2). Relatively high costs were also observed for highway sections underlain by continuous permafrost. On a per kilometer basis, maintenance costs for highways situated in zones where more than half of the terrain is underlain by permafrost (i.e., extensive discontinuous and continuous permafrost) are more than 50% higher than in sections with lower permafrost presence.

Some of the costs associated with the northern permafrost zones may be elevated because of the steep, mountainous terrain, limited availability of construction materials, and the remote locations of the maintenance sections.

Table 2. Highway length, proportion of network, and total maintenance expenditures for icing control and the repair of slides and washouts (1994–2022) in each permafrost zone. Expenditures for Whitehorse are excluded.

Permafrost Zone	**Length (km)**	**Proportion of network (%)**	**Cost ($/km)**
Continuous (>90%)	461	13	11,400
Extensive discontinuous (50-90%)	1553	44	16,600
Sporadic discontinuous (10-50%)	1185	34	7200
Isolated patches (0-10%)	325	9	4700

7 CONCLUSIONS

The examination of historical maintenance costs associated with climate change in Yukon leads to the following five key results:

1. Although the total operation and maintenance budget, adjusted for inflation, remained relatively stable, climate-related maintenance expenditures increased in 1994–2022.
2. Across all maintenance camps, the most substantial increases have been observed in snow removal expenditures.
3. Icing control expenditures are greatest for highway sections situated near hillslopes in extensive discontinuous permafrost.
4. Landslides and washout expenditures increased at all representative camps, except in Coast Mountains, where there is little permafrost.
5. On a per kilometer basis, maintenance expenditures influenced by the presence of permafrost (i.e., icing control and the repair of slides and washouts) are 50% greater for highways in the extensive discontinuous and continuous permafrost zones than in areas of sporadic discontinuous permafrost or isolated patches of permafrost.

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