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Current Status of Permafrost Degradation

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Abstract: Permafrost, the permanently frozen ground is defined as any type of ground-from soil to sediment to rock- that remains at or below 0° C for at least two consecutive years. At present, permafrost occurs on one quarter of the exposed land surfaces of the earth, but the permafrost extent and its estimate have been changing rapidly. Under warming climate permafrost has been degrading extensively, persistently and rapidly. This degradation of permafrost has resulted in profound hydrological, ecological and socio-economic consequences. To sustainably develop resources in the cold regions while prudently protect the permafrost environment under constantly changing climate, we need to design and manage our environmental and engineering projects by creative and innovative thinking and with rapidly improving technologies. The paper mainly focuses on understanding the meaning and the extent of permafrost, the changing permafrost environment, the impacts of thawing permafrost and proactively adapting to and effective management of these rapidly changing cold regions environment with the latest technologies.
Keywords: permafrost, frozen ground, thawing, hydrological, ecological, socio-economic impacts, effective management

I. INTRODUCTION

A. Introduction to Permafrost

Permafrost, the permanently frozen ground, is defined as any type of ground-from soilto sediment to rock-that remains at or below 0° C for at least two consecutive years (8,9). Any location with annual average year temperatures below freezing can potentially form permafrost. Permafrost includes the content of the ground before it was frozen such as bedrock, gravel, silt and organic material. Permafrost often contains large lenses, layers and wedges of pure ice that grow over many years as a result of annual freezing and thawing of the surface soil layer [11]. It is present extensively in polar, high plateau, alpine and mountainous regions with the model estimated total extent of permafrost regions at 22.79 million square kilometers [3, 5]. Thus, it constitutes one of the most widespread components of the cryosphere. However, geomorphic evidences of past permafrost condition shows that the area affected by the frozen ground during Quarternary old stages such as the Last Glaciation was much larger than today [10].

B. Formation of Permafrost

Most of the current permafrost formed during or since the last ice age over the last 100 thousand years. Some relatively shallow permafrost on land typically extending only to the depth of 30 to 70 M formed during the last 6000 years. Very shall permafrost with depth from a few to 20 m formed during the Little Ice Age in the 16th and 19th century along the southern permafrost boundary in sporadic and discontinuous permafrost zones. Subsea permafrost in the east Siberian sea and elsewhere along the Arctic coastline was formed when these regions were above sea level but were inundated after the last ice age ended more than 15,000 years ago [11,12].

Table 1.1: Time taken for permafrost to reach depth (Source: International PermafrostAssociation)

Time (yrs)	Permafrost Depth (m)
1	4.44
350	79.9
3500	219.3
35000	461.4
100000	567.8
225000	626.5
775000	687.7

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C. Occurrence of Permafrost

Permafrost does not occur everywhere, so permafrost regions are classified into zonesbased on the fraction of land area that contains permafrost. Continuous permafrost zones havepermafrost underlying 90 to 100% of land area; discontinuous zone having 50 to 90% and sporadic permafrost 10 to 50%. Isolated patches refer to regions where permafrost underlies less than 10% of the land area [11].

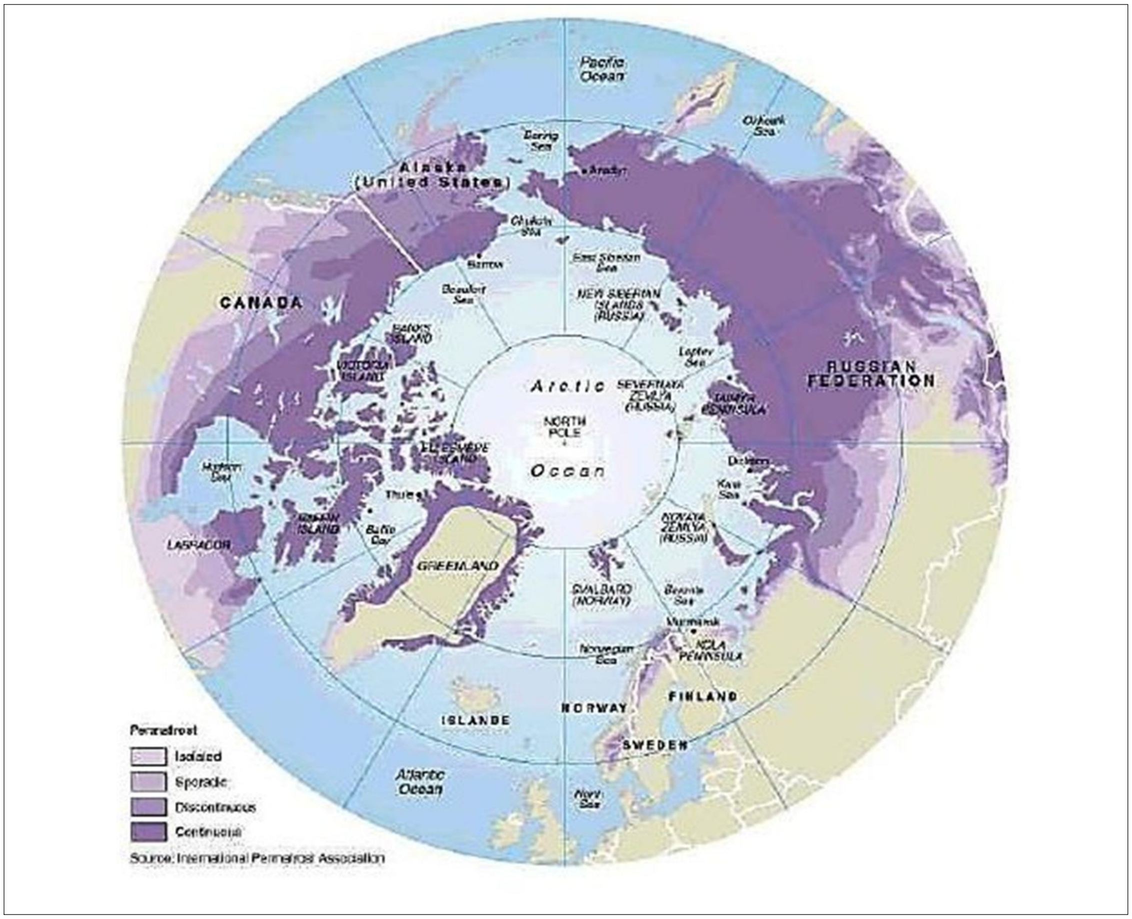

Figure 1.1: Different zones of Permafrost in the northern hemisphere land surface

About a quarter of the entire Northern hemisphere is permafrost where the ground is frozen year round. In the Northern hemisphere, it covers an estimated 9 million square miles -nearly the size of United States, China and Canada combined. It's widespread in the Arctic regions of Siberia, Canada, Greenland and Alaska where nearly 85% of the state sits atop a layer of Permafrost. It is also found on the Tibetan plateau, in high altitude regions like the Rocky mountains and on the floor of the Arctic Ocean as undersea permafrost. In the southern hemisphere, where there's far less ground to freeze, permafrost is found in mountainous regions such as the South American Andes and New Zealand's Southern Alps,as well as below Antarctica [8].

D. Structure of Permafrost

Permafrost is bounded on the top by the permafrost table and on the bottom by the permafrost base. The depth to the permafrost base depends on a balance between freezing from the surface and warming from the earth's interior. Permafrost temperature at deeper depth reflects variability in climate conditions at longer times scales because heat diffuses slowly through permafrost. Seasonal variability in ground temperature reflects variability in air temperature but becomes increasingly muted with depth. Figure shows the vertical structure of permafrost as determined by the soil temperature. The depth of zero annual amplitude varies from a few meters in discontinuous permafrost to 20 meters or more in continuous or in bedrock [11, 13]. Temperatures at the depth of zero annual amplitude reflect climate conditions at the end of 20th century but temperatures at 400 to 800 M depth reflect the climatic conditions at the Holocene optimum around 8000 years ago, just after the end of the last ice age [11].

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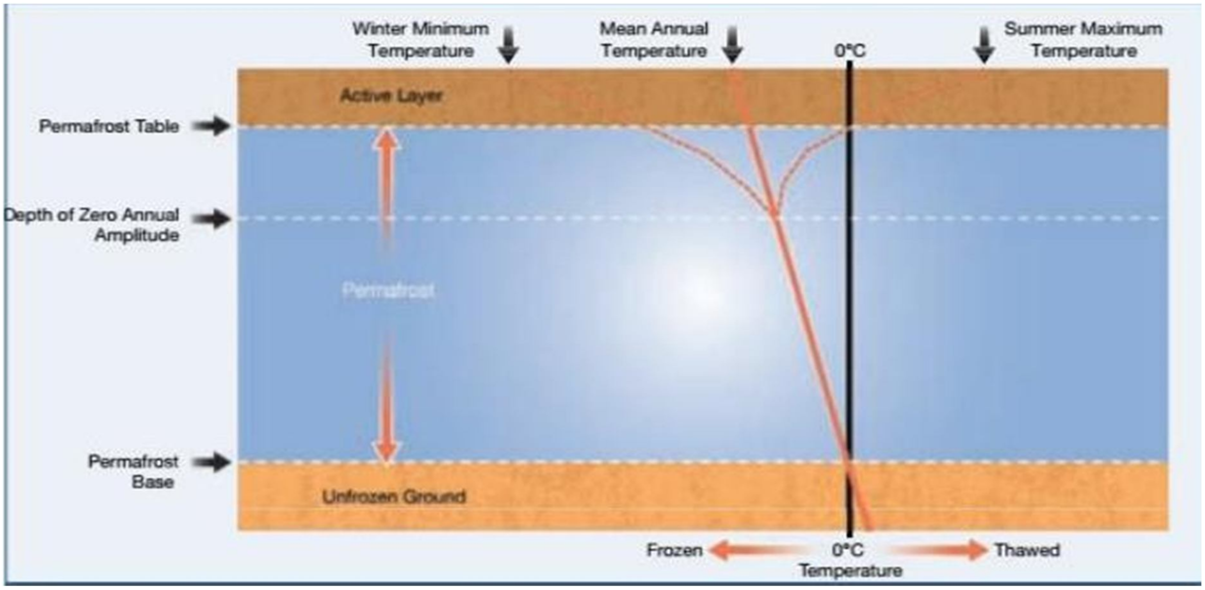

Figure 1.2: The vertical structure of permafrost as defined by temperature

II. THAWING OF PERMAFROST

In permafrost regions, natural and anthropogenic systems are undergoing unprecedented changes with rapidly thawing permafrost as one of the most striking impacts and also drivers. Thawing of permafrost means the melting of ice in the permafrost leaving behind soil and water. Under a warming climate permafrost has been degrading as evidenced by shrinking areal extent, rising temperatures, reducing thickness, melting ground ice and extensive thermokarst development, ground surface subsidence and thaw settlement [5].

A. Causes of Thawing Permafrost

As a product of cold climate, permafrost is extremely sensitive to climate change [20].Snow is an effective insulator and modulates the effect of air temperature resulting in permafrost temperatures up to 6° C higher than the local mean annual air temperature [11]. Climate warming over passed decades has caused degradation in permafrost widely and quickly [20]. While global warming is upping the temperature around the World, the Arctic iswarming twice as fast as anywhere else and faster than it has in the past 3 million years. And when surface air temperatures rise below ground temperatures do, too thawing permafrost along the way [8].

B. The Active Layer

Active layer is the surface layer of soil that thaws each summer and refreezes each winter. The active layer starts thawing in spring after the snow melts and continue to thaw until fall, reaching a maximum depth in late summers. Active layer thickness is the annual maximum thaw depth at the end of summers. It ranges from less than 30 cm in continuous permafrost along the Arctic coast to 2 meter or more in discontinuous permafrost of Southern Siberia and several meters in the European Alps and Qinghai- Tibetan plateau. Active layer thickness has increased in the Russian European North but not in West Siberia [6, 11, 19].

Fig 2.1: Active layer of permafrost

C. Current State of Permafrost

Recent warming in the Arctic and mountainous regions has resulted in warm permafrost and deeper active layers. Permafrost temperature has risen over the last several decades in Alaska. Permafrost in the Alaskan interior warmed in the 1980s and 1990s, but has generally stabilized during the last 10 years. Northern Russia and Northwest Canada show increases in permafrost temperature similar in magnitude to those in Alaska during the last 30 to 35 years [11]. Scientists estimate there is now 10% less Frozen ground in the Northern hemisphere than there was in the early 1900s. One recent study suggests that with every additional 1 degree Celsius of warming an additional 1.5 million square miles of permafrost could eventually disappear. Even if we meet the climate target laid out during the 2015 Paris climate talk the world may still lose more than 2.5 million square miles of frozen turf [8].

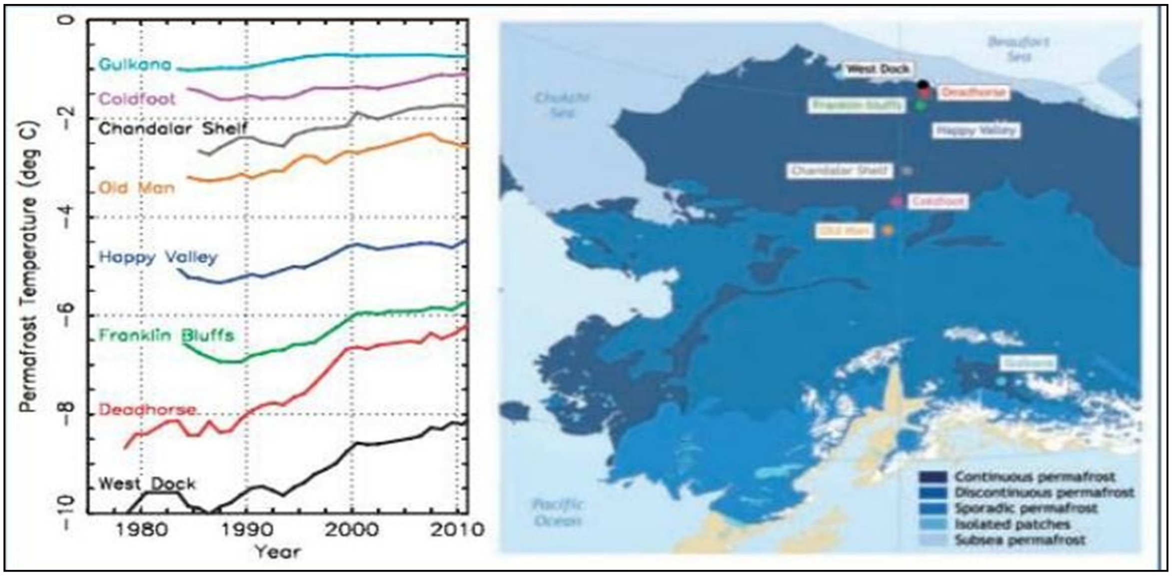

Fig 2.2: Permafrost temperatures at 20 meters depth have risen over the past 30 years,observations from a north-south transect of TSP sites in Alaska

D. Permafrost in the Future

Arctic and alpine air temperatures are expected to increase at roughly twice the global rate and climate projections indicate substantial loss of Permafrost by 2100. The Intergovernmental Panel on Climate Change IPCC 2007 reported that by 2099 the increase inaverage surface area temperature in the Arctic are expected to range between 5 and 6 degree Celsius nearly double the global average of 3 degree Celsius based on the multimodel mean from the IPCC 4th assessment report. Also, by 2099 precipitation is expected to increase by 30% in the Arctic and decrease in the temperate zone based on the multimodel mean from theIPCC 4th assessment report [11].

Projections of future permafrost degradation indicate that active layer thickness will increase and the aerial extent of near surface permafrost will decrease [11]. Depending on the rates of warming the area occupied by permafrost near the surface (3.5 M depth) might be reduced by between 37% and 81% and thus retreats to higher latitude and higher elevation are expected [4, 10]. Consequently, most high latitude environment conditioned nowadays by the presence of permafrost will be affected by the changing climate that will make it disappear or lead to a deepening of the active layer along with higher subsurface temperature.Table below shows projected decrease in the aerial extent of near surface permafrost and the increases in active layer. For areas that retain permafrost when there is moderate reduction in anthropogenic greenhouse gas emission [1, 10].

III. IMPACTS OF THAWING PERMAFROST

Under warming climate permafrost has been degrading extensively, persistently, and rapidly [5]. Permafrost degradation poses serious impacts such as changes in topographic and hydrologic conditions, challenges to the infrastructure, food security and sustainability of northern communities, and increases hazard potential in periglacial mountain regions as permafrost thaw and temperature increases have decreased slope stability, among others [16]. These consequences could be broadly categorized into ecological, hydrological, engineering and socio-economic impacts.

A. Ecological Impacts

Permafrost degradation is a phenomenon which affects the environment and ecology to a large extent adversely. It completely disturbs the ecological balance

1) Loss of Greenhouse Gas Stores

The permafrost region contains a massive frozen store of ancient organic carbon, totaling approximately twice the amount of carbon as is in Earth's atmosphere. This carbon accumulated over tens of thousands of years when cold and frozen conditions protected the carbon rich organic material (derived from dead plants and animals) from microbial decomposition. However, warming and thawing of permafrost promotes decomposition of this once frozen organic matter, releasing CO2 and methane into the atmosphere and thus threatening to turn the Arctic carbon sink into a net source of greenhouse gases to the atmosphere [7, 15].

Permafrost is one of Earth's great stores of global warming gases. Indeed permafrost in the Arctic alone is estimated to hold nearly twice as much carbon as exist in the atmosphere now as well as a sizable amount of methane- a powerful greenhouse gas that traps 80 times more heat on the planet than carbon does. But our warming world may jeopardize these stores. Estimates on how much carbon and methane will be released by thawing permafrost vary, but according to one study, as much as 92 billion tons of carbon could be emitted between now and 2100. For perspective, that's equal to nearly 20% of all global carbon emissions since the start of the industrial revolution. Carbon and methane are'ntthe only pollutants trapped in permafrost. Recent study found that active permafrost is a massive repository of natural mercury-a potent neurotoxin. Indeed, it's estimated that some 15 million gallons of Mercury or nearly twice the amount of Mercury found in the ocean, atmosphere and all other soils combined are locked in permafrost soil. Once released, however, that Mercury can spread through water or air into ecosystems and potentially even food supplies [8]. The release of CO2 and methane from thawing permafrost will amplify the rate of global warming due to anthropogenic greenhouse gas emissions and further accelerate permafrost degradation. This amplification of surface warming due to CO2 and methane emissions from thawing permafrost is called the permafrost carbon feedback [11]. Extreme weather such as the recent Siberian heat wave experienced in the summers of 2020 can trigger catastrophic thaw events which ultimately can release a disproportionate amount of permafrost carbon into the atmosphere [7, 17]. This global climate feedback is being intensified by the increasing frequency and severity of Arctic and boreal wildfires that emit large amount of carbon both directly from combustion and indirectly by accelerating permafrost thaw. Fire induced permafrost thaw and the subsequent decomposition of previously frozen organic matter may be a dominant source of active carbon emissions duringthe coming decades [7].

2) Altered landscapes

Thawing permafrost alters the natural landscapes in many ways. It can create thermokarsts, area of sagging ground and shallow ponds that are often characterised by "drunken forest" of askew trees. It can make soil once frozen solid more vulnerable to landslides and erosion particularly along coasts. As this softened soil erodes, it can introduce new sediments to waterways, which may alter the flow of rivers and streams, degrade water quality (including by the introduction of carbon) and impact aquatic wildlife [8]. Climate change in the Arctic is expected to increase erosion rates along the Arctic coastline, lake shores and river beds. Coastal erosion has increased during the past few decades because reduced sea ice and rising sea levels have resulted in larger waves during storms in the open water season from June to October [11].

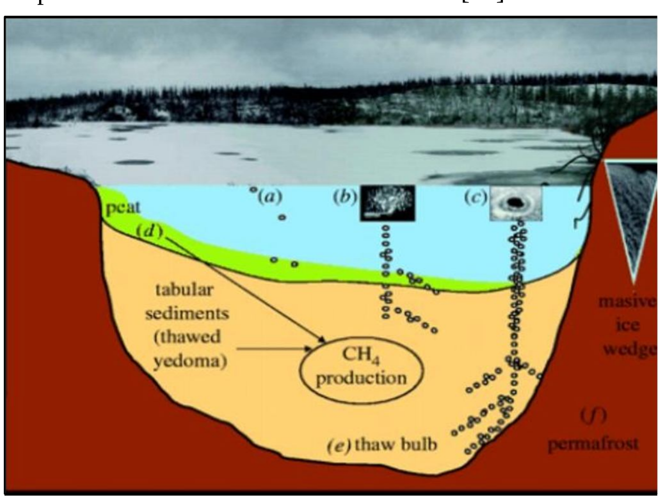

Fig 3.1: Thermokarst lake formation

Fig 3.2: Erosion of coastline

3) Changes in Ecosystem

Permafrost degradation is also expected to accelerate the effects on the natural dynamics of terrestrial ecosystems by affecting geomorphic processes, hydrological dynamicsof rivers, ponds and lakes as well as altering biodiversity in many areas [10]. There is increased evidence that marine ecosystems will also be affected by the degradation of both terrestrial and subsea permafrost as well as the permafrost collapse in Arctic coastal environment [2,10]. Permafrost degradation has the potential to significantly change soil moisture content, alter soil nutrients availability and influence on species composition. In lowland ecosystems, the loss of ice rich permafrost has caused the conversion of terrestrial ecosystem to aquatic ecosystem or wetland. In upland ecosystem, permafrost thaw has resulted in replacement of hygrophilous community by xeromorphic community or shrub. Permafrost degradation can result in losses of some boreal forests, shifts in plant composition and productivity, and changes in vegetation communities through changing ecological and hydrological dynamics, soil nutrients, and soil biogeochemistry in an environment of deepening active layer and/or lowering permafrost and groundwater table and in newly developed taliks [20].

B. Hydrological Impacts

Degrading permafrost has remarkable impacts on water systems in cold regions. Due to its minimal hydraulic conductivity, permafrost strongly affects water dynamics; at the same time water flows also exert strong influences on formation, distribution and evolution ofpermafrost and talik mainly by heat advection along preferential flow paths. This interplay, inaddition to feedbacks from physical, chemical and biogeochemical processes create complex permafrost-groundwater interaction [5].

C. Engineering Impacts

Rapid and accelerating permafrost degradation has induced thermokarst, thaw slumping, detachment failures and many other permafrost related hazards, altering the freeze- thaw cycles, weakening the bearing capacities of engineered foundation soils in permafrost regions and impacting the stability and vulnerability of engineered infrastructures. Thawing near surface permafrost has resulted in the changed serviceability of many basic infrastructures. The rockfalls, debris flows and landslides as results of thawing permafrost and subsequently accelerating mass wasting would severely impact the basic engineering infrastructures such as those along the China-Pakistan and China-Nepal Highways, China- Mongolia-Russia engineering corridor and the proposed high speed rail-link between Beijing and Moscow. In particular, the design, building and safe operation of Beijing-Moscow High- speed Rail-link has prompted the demand for engineering safety and stability in discontinuous permafrost zones and greater challenges are laid out for engineers regarding the construction and controlling techniques to sustain the thermal stability of soils in road foundations [5]. Roads, houses, pipelines even military facilities and other infrastructures are collapsing or starting to become unstable due to the melting of the frozen ground below the surface. Thawing permafrost is also causing fuel storage units to collapse and the landfills that had once been in dry areas are now leaking waste and toxic materials such as Mercury into lagoons and rivers [18]. In Northern Russia, city buildings are crumbling. In Alaska, roads are turning into roller coasters. When water turns into ice underground it expands and the ground swells. When water thaws, the ground contracts which can make the earth crack or cave-in as exemplified by potholes that form in the spring. About 35 million people live in a permafrost zone, in towns and cities built on top of what was once considered permanently frozen ground. But as that solid ground softens, the infrastructure, these communities rely on grows increasingly unstable [18]

Fig 3.3: Crumbling infrastructure due to thawing of permafrost

D. Socio-economic Impacts

Most of studies on the impact from degrading permafrost and climate warming have highlighted the probable adverse aspects such as diminishing usable water, declining agriculture and husbandry production, more and severe droughts and wildfires, spreading contagious diseases, remobilization of viable microorganisms and permafrost hazard troubledinfrastructures, among others [5].

Just as permafrost locks in carbon and other greenhouse gases, it can also trap and preserve ancient microbes. It's believed that some bacteria and viruses can lie dormant for thousands of years in permafrost's cold, dark confines before waking up when the ground warms. As scary as the notion of zombie pathogens sound, however, question remain about how great risk these ancient microbes pose. A 2016 anthrax outbreak in Siberia linked to a decades old reindeer carcass infected with the bacteria and exposed by thawed permafrost demonstrated the potential threat. But when it comes to other diseases such as smallpox and the 1918 Spanish flu known to exist in the frozen tundra in the mass graves of those killed by the disease, scientists are still uncertain how likely these pathogens are to cause outbreak.

What is certain, however, is that developing the Arctic and extracting millions of tons of permafrostto mine for precious metals and petroleum metals will increase human contact with thawed, ancient and possibly zombie pathogens [8].

Many Northern villages such as Tuktoyaktuk are built on permafrost which when frozen is harder than concrete. But as the planet rapidly warms, the Arctic warms at least twice as fast as other regions, the thawing ground erodes and can trigger landslides. Moreover, the reduction and change of sea ice leave coastal villages more vulnerable to stormsurges. Some of the communities who lived right in the tundra above the beach have already been forced to move in land.

At some places people are literally having to prop up and raise the houses (off the collapsing ground). This is something they might have done in the past maybe once a year and now they are doing it 5 times a year because the houses are tilting (13). Another problem is that many communities move across the land in the winter using frozen rivers and lakes that are not freezing enough anymore. This is not only a health risk, but it is also impacting people's accessibility to food [18].

In Canada, disappearing permafrost is estimated to cause tens of millions of dollars in damage to public infrastructure across North Western territories each year. And in Alaska, one study puts the cost of repairing public infrastructure such as roads, train lines, buildings and airports damaged by thawing permafrost and other climate related factors at as much as $5.5 billion by the end of the century [8]. Meanwhile in Canada, in September 2021 Tuktoyaktuk residents were told that protecting their town from climate change would cost at least $ 42 million and that any such protective measures could only be guaranteed to last until2052 [18].

IV. MITIGATIVE MEASURES AND ADAPTIVE STRATEGIES

Back in 2019, the United Nations Environmental Programme (UNEP) called the thawing of permafrost one of the top 10 emerging issues of environmental concern. At that time, the southern permafrost boundaries in the Artic had receded northwards by 30 to 80 kms, a significant loss in coverage [18].

Experts say that while we can't now reverse permafrost thaw – because it has already started – ambition is key to avoid the worst of it. Even under our most ambitious scenarios (for reducing global carbon emissions and subsequent warming), we're going to lose, probably 25 per cent of surface permafrost, and then some of the carbon that's in there will goto the atmosphere. But this is much better than less ambitious scenarios which could take usto 75 per cent thaw. Permafrost is a climate change multiplier and so it needs to be an ambition multiplier [18]. The following mitigative measures and adaptive strategies would help us achieve the ambition.

A. Stop Rapid Climate Change

In order to curtail climate change and save the permafrost, it is indispensable that global CO_2 emissions be reduced by 45% over the next decade, and that they fall to zero after 2050.

To mitigate climate change, there is a need to take a global collective action. If one country cuts its emissions, that is going to be of little use if the others do not follow suit. The expert explains that by reducing emissions and rates of warming we are also reducing meltingand sea level rise and giving people time and methods to adapt

B. Slow Down Erosion:

The scientific journal Nature suggested building a 100-metre-long dam in front of the Jakobshavn glacier (Greenland), the worst affected by Arctic melting, to contain its erosion.

C. Combine Artificial Icebergs

Indonesian architect has won an award for his project Refreeze the Arctic, which consists of collecting water from melted glaciers, desalinating it and refreezing it to create large hexagonal ice blocks. Thanks to their shape, these icebergs could then be combined to create frozen masses.

D. Increase Their Thickness

Some researchers propose a solution to manufacture more ice. Their proposal consists of collecting ice from below the glacier through pumps driven by wind power to spread it over the upper ice caps, so that it will freeze, thus strengthening the consistency.

E. Change in Technologies

To sustainably develop resources in the cold region while prudently protect the permafrost environment under a constantly changing climate, we need to design and manage our environmental and engineering projects by creative and innovative thinking and with rapidly improving technologies. In an effort towards adaptation, engineers have undertaken different options to protect the coastline, one of them, putting down layers of styrofoam insulation and Geotextile to protect the permafrost from rising temperature [18].

F. People's Awareness

The tundra and the permafrost beneath it may seem far away, but no matter where we live, the everyday choices we make contribute to climate change. By reducing our carbon footprint, investing in energy-efficient products, and supporting climate-friendly businesses, legislation, and policies, we can help preserve the world's permafrost and avert a vicious cycle of an ever-warming planet [8].

G. International Consideration

Every country needs to move climate change, global warming to the top of our foreign policy agenda. This is a critical move we need to make and the sooner we do it, the greater is the benefit that we will draw from our own climate actions. A comprehensive understanding of the impacts of the various pathways on permafrost carbon emissions including from abrupt thaw and wildfire induced thaw and the implications for global emission budget is urgently needed in order to motivate and guide mitigation decisions that will impact the state of the Arctic and the planet [7].

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V. CONCLUSIONS

Permafrost, or perennially frozen ground, is a critical component of the cryosphere and the Arctic system. It occupies approximately 24% of the terrestrial surface of the northern hemisphere; further the distribution of subsea permafrost in the Arctic Ocean is not well known but new occurrences continue to be found. The effects of climatic warming on permafrost and the seasonally thawed layer above it (the active layer) can severely disrupt ecosystems and human infrastructure such as roads, bridges, buildings, utilities, pipelines and airstrips [11, 14]. Widespread permafrost degradation will permanently change local hydrology increasing the frequency of fire and erosion disturbance. This will impact the critical habitat particularly for migratory birds. Risks associated with Rock falls and erosion will increase particularly in cold mountain areas. Damage to critical infrastructure such as buildings and road will incur significant social and economic costs [9, 11]. Permafrost contains approximately 1672 Gigatonnes of carbon in the form of frozen organic matter. If the permafrost thaws, so will the organic matter, which will then decay, potentially releasing large amount of carbon dioxide and methane into the atmosphere. Emissions from thawing permafrost could start within the next few decades and continue for several centuries, influencing both short term climate and long term climate [11, 14].

Thus, to ensure the sustainable development of cold regions under warming climate, we need to design and manage our environmental and engineering projects scientifically, prudently and adaptively. Meanwhile, we also need to do research and communication on the cutting edge of science, technology and engineering practices.

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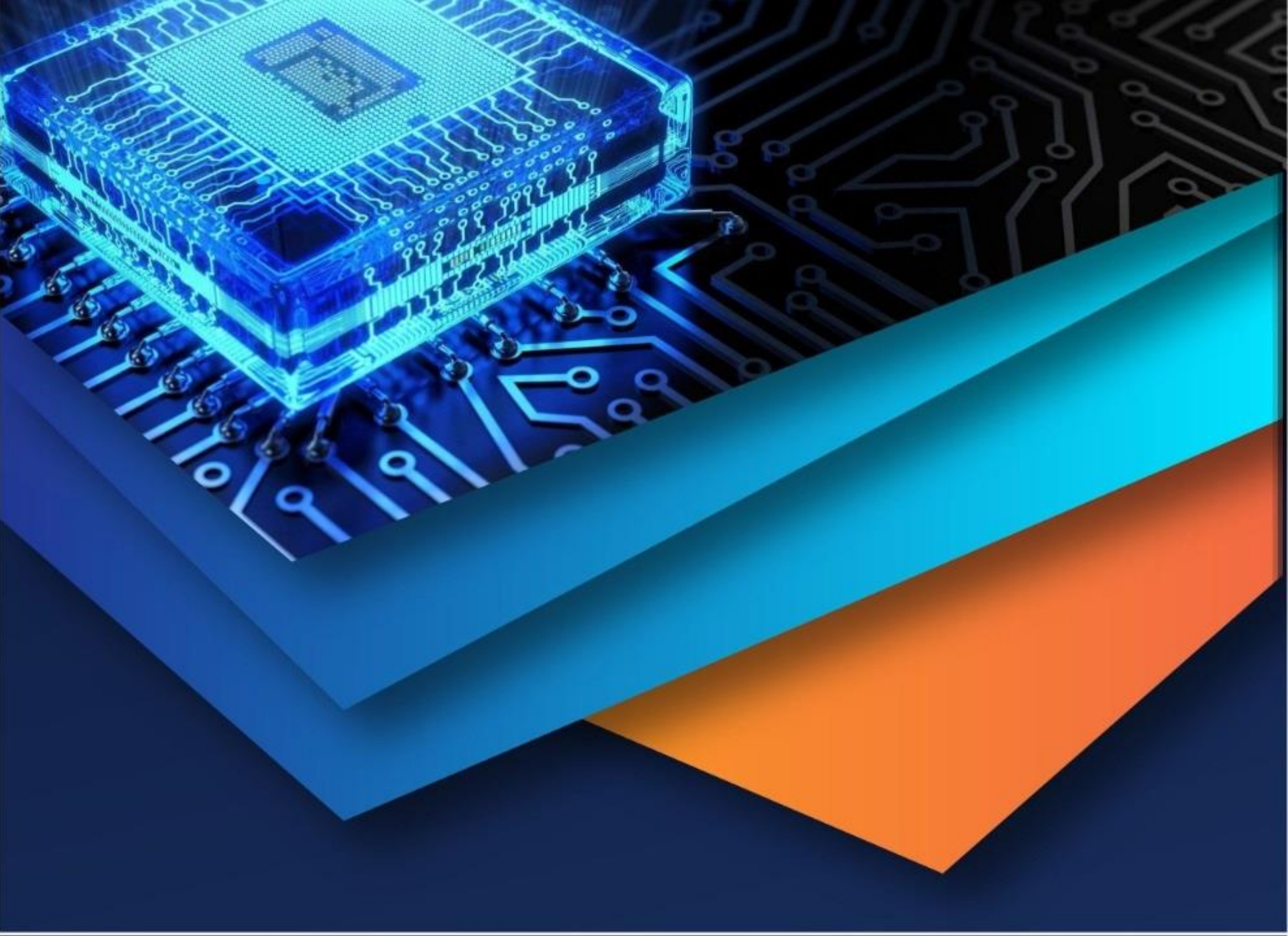

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