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The Sapporo Glacier: a conceptual framework for urban cryosphere engineering and climate-responsive design

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Urban snow management systems are typically treated as logistical operations to remove and dispose of excess snow. However, the *Sapporo Glacier* concept reframes municipal snow management within a cryospheric systems framework, transforming urban snow accumulation into a controlled cryospheric process that interacts with climate and urban energy systems. This paper presents a hypothesis-driven scoping concept, the Sapporo Glacier, as a conceptual framework for Urban Cryosphere Engineering, which seeks to design and control the long-term storage, insulation, and metamorphism of urban snow using bounded, first-order physical reasoning rather than site-calibrated performance prediction to create a glacier possessing glacier ice (as classically defined) and measurable flow. Using Sapporo City's existing snow-depot infrastructure as a reference model, the framework integrates physical modeling (degree-day method and simplified energy-balance considerations), surface control through organic mulch, and seasonal monitoring to delineate feasible design regimes for optimizing the thermal state of accumulated snow. Beyond technical feasibility, it emphasizes socio-environmental integration, envisioning snow storage as both a climate-adaptive infrastructure and a cultural landscape that connects citizens to seasonal cycles. Importantly, meltwater released from such an urban glacier during summer may generate a localized, testable nearshore thermal signal, enabling empirical evaluation of coastal cryosphere–ocean interactions. This hypothesis-driven, conceptual approach aims to establish an interdisciplinary foundation for future empirical studies and design experiments, rather than to deliver predictive site-specific outcomes, toward the realization of urban glaciers as sustainable and ecological elements of city life.

KEYWORDS
climate adaptation infrastructure, climate engagement, climate-responsive design, conceptual framework, controlled glacier formation, controlled snow accumulation, Sapporo Glacier, urban cryosphere

1 Introduction

This study introduces the Sapporo Glacier Project, a documented attempt at an urban scale to create an artificial glacier with the potential for multi-year survival and flow by leveraging a city's snow-depot infrastructure; to the best of my knowledge, no documented case has demonstrated comparable multi-year glacier formation at this scale within an urban snow-depot context.

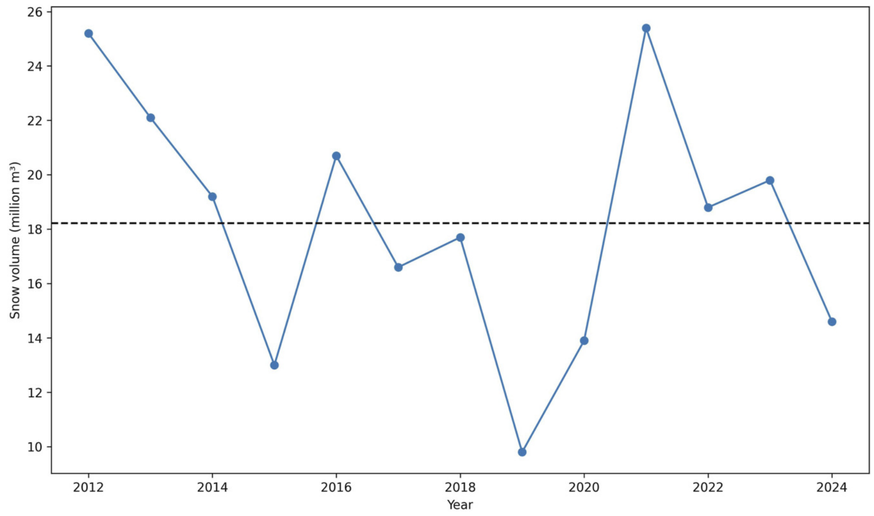

FIGURE 1
Interannual variability in the total volume of snow transported to municipal snow-depot sites in Sapporo City from 2012 to 2024. The horizontal line indicates the 13 year mean (18.2 million m^3). Data digitized from official municipal reports.

In this study, I define a glacier following the classical definition of Armstrong et al. (1973) as a mass of snow and ice that flows continuously or, if afloat, spreads continuously (Armstrong et al., 1973).

I further require evidence for the presence of glacier ice, that is, ice that has densified to values characteristic of glacier ice (≥830 kg m^{-3} (Cuffey and Paterson, 2010)).

An artificial glacier is defined in this manuscript as a glacier whose accumulation is intentionally supported or initiated by human activity, while its internal deformation and flow, if present, arise from natural physical processes.

Cold-climate cities across the globe contend with immense accumulations of snow each winter. While vital to local hydrology and culture, urban snow is typically managed as waste—rapidly collected, transported, and discarded. Yet the scale of this snow management is not trivial. Sapporo, Japan, among the snowiest large cities globally, receives nearly 6 m of snowfall annually and collects around 20 million cubic meters of snow during each winter season, as confirmed by municipal staff (pers. comm.) and reported in official publications (Sapporo City Construction Bureau, 2025a). Based on official municipal records for the period 2012–2024, however, this collected volume varies from year to year, with a mean of 18.2 ± 4.6 million m^3 (mean ± SD) and year-to-year totals ranging from approximately 10–25 million m^3 (Figure 1; (Sapporo City Construction Bureau, 2025a); Supplementary Table S1). Comparable large-scale snow transport and removal infrastructure is also operated in other cold-climate cities, including Montreal, Québec City, and Helsinki, indicating that such urban snow systems are not unique to Sapporo. This volume rivals or exceeds that of many small glaciers (<0.5 km^2) worldwide (Huss and Fischer, 2016; Grunewald and Scheithauer, 2010). However, such cryospheric material has rarely been harnessed for scientific or environmental purposes within the urban context.

Historically, the notion of artificial glacier creation has appeared sporadically in high-altitude regions. The earliest documented reference comes from G. Dainelli, who in 1914 reported second-hand accounts of "glacier-growing" in Baltistan as part of the Italian expedition to Central Asia (published in 1932 (Dainelli, 1932)). Nearly a century later, Tveiten (2007) conducted fieldwork in Baltistan and Gilgit, observing five glacier-growing sites where small volumes of glacial ice (typically 200–400 kg) were placed in shaded talus slopes along with water and insulating organic materials, with the symbolic aim of encouraging glacier growth through the "marriage" of male and female glacier (Tveiten, 2007). Despite these efforts, no case of glacier-growing has ever been documented to produce a flowing glacier—that is, one exhibiting internal deformation, basal movement, or dynamic stratification.

Scientific efforts have also explored the possibility of inducing glacial formation through deliberate intervention. Notably, in the 1970s, Japanese glaciologist Keiji Higuchi conducted field experiments on perennial snow patches in Japan with the explicit aim of transforming them into cirque glaciers. His work focused on controlling snow accumulation and ablation—employing snow fences, avalanche triggering, and insulation using polystyrene foam sheets—to artificially sustain and grow snow masses under unfavorable climatic conditions (Higuchi, 1973). These efforts were conceived as foundational steps toward what Higuchi described as an "artificial glacier." However, the project remained in a preliminary, experimental phase, and never resulted in the development of glacier flow.

Building on this mixed historical and scientific background, the Sapporo Glacier Project proposes a novel, urban-scale reframing: to treat municipal snow not as waste, but as latent glacier material. Unlike traditional glacier-growing rooted in cultural symbolism or past scientific efforts limited to natural alpine sites, this project aims to deliberately convert urban snow—collected, transported, and compacted within the city—into a cryospheric mass capable of evolving toward glacier behavior. The objective is not simply to store snow for seasonal use or cooling, but to observe and eventually induce the genesis of glacier dynamics—layering, firnification, and slow mass flow—within a designed and monitored structure.

As climate change shifts ecological baselines and increases the exposure of urban systems to environmental stress, cities may play an expanding role as testbeds for adaptive infrastructure. In this context, the artificial glacier represents not only a technical implementation but also a publicly observable intervention designed to study long-term responses to climate variability. Situated in one of the snowiest large cities globally, the Sapporo Glacier Project offers an unusual opportunity to observe the potential emergence of a glacier from controlled snow, and to advance research directions in urban cryospheric engineering.

2 Materials and methods

2.1 Conceptual design

The Sapporo Glacier Project envisions the creation of an artificial glacier within the urban periphery of Sapporo, using existing snow removal infrastructure to accumulate and preserve a large mass of snow beyond the melt season. The goal is not only physical glacier formation, but also environmental intervention and long-term ecological utility. This section outlines the conceptual basis, design parameters, and projected interactions with the surrounding environment.

2.2 Accumulation and initial form

Rather than piloting a modest test site, the Sapporo Glacier Project envisions a full-scale implementation using the entirety of Sapporo's seasonal snow waste. Each winter, the city collects on the order of 20 million cubic meters of snow—an amount rivaling many natural glaciers. This proposal calls for redirecting all of that snow to a single, dedicated coastal site, forming a snow body approximately 1 km × 1 km in area.

The chosen site should be flat, unoccupied land adjacent to the sea, such as a coastal plain facing Ishikari Bay that remains largely unused for industrial or residential purposes. At this scale, the snow mound would reach tens of meters in height, forming a low-profile, broad-based structure with a favorable surface-area-to-volume ratio that inherently suppresses melt.

No artificial shaping is required beyond simple logistical placement. Snow would be deposited layer by layer using existing city equipment, and the surface would be covered with a thick blanket of bark chips or similar organic mulch, providing passive insulation. This approach minimizes cost while maximizing thermal control and sets the stage for natural internal transformation into glacier ice. In practice, the annual volume of collected snow in Sapporo exhibits substantial interannual variability, and both transport capacity and storage availability are subject to operational constraints. Accordingly, the assumption of redirecting the totality of collected snow to a single site is treated here as an upper-bound conceptual scenario, rather than as a prescriptive operational plan.

2.3 Melt suppression and glacier formation potential

The snow body would be covered with passive insulating materials—such as wood chips, geotextiles, or reflective films—to minimize heat input. With sufficient mass and seasonal persistence, internal transformation toward glacier ice may gradually occur over multiple years, driven by snow metamorphism, densification, pressure melting, and refreezing. Continued monitoring of internal temperature distributions and mechanical deformation will be essential to determine whether glacier flow dynamics have begun to develop.

I adopted a degree-day method as a simplified temperature-index framework, used here not as a predictive melt model but as a first-order bounding tool to constrain plausible melt-rate magnitudes under idealized conditions. This approach originated from the foundational work of Martinec (1960) and was subsequently developed and extended within the Snowmelt Runoff Model (SRM) framework by Kustas et al.(1994). Its theoretical basis and practical limitations were further examined in a critical review by Rango and Martinec (1995). Together, these studies demonstrate that cumulative positive temperatures (°C·days) can be related empirically to melt depth over appropriate temporal scales, and that the method provides operationally robust estimates when applied with suitable averaging and hydrological context.

The model is typically expressed as:

$$M = DDF \times \Sigma T_{\text{positive}}$$

where M is the melt depth expressed as water equivalent (mm w.e.), DDF is the degree-day factor (mm $^{\circ}\mathrm{C}^{-1}$ days^{-1}), and $\Sigma T_{\text{positive}}$ represents the cumulative sum of daily mean air temperatures above 0 °C, commonly referred to as positive degree-days (PDD; °C·days).

A representative reference value of the degree-day factor (DDF), 4.0 mm $^{\circ}\mathrm{C}^{-1}$ day^{-1}, is cited only to indicate the order of magnitude reported in the literature, rather than as a calibrated site-specific parameter. Recent findings further clarify how the degree-day factor may vary spatially and seasonally due to changes in cloud cover and albedo (Ismail et al., 2023).

For Sapporo, the annual sum of daily mean temperatures above 0 °C is approximately 3,457 °C·days, representing the 10 year mean PDD for the 2015–2024 period, based on ERA5 reanalysis climatology retrieved from the Copernicus Climate Data Store ((Copernicus Climate Change Service C3S, 2024); Supplementary Table S2), resulting in an estimated annual melt depth of 13.8 m w.e. under natural, unprotected conditions. For Montreal, the corresponding figure is approximately 3,513 °C·days ((Copernicus Climate Change Service C3S, 2024); Supplementary Table S3), yielding a melt depth of 14.0 m w.e.

As a regional case study, I considered Bibai City, located near Sapporo in Hokkaido, Japan. For the year 2006, the cumulative total of positive degree-days at this site was 3,082 °C·days ((Copernicus Climate Change Service C3S, 2024); Supplementary Table S4), corresponding to an estimated natural melt depth of approximately 12.3 m w.e. under unprotected conditions. At the same site, Homma et al. (2007) demonstrated that covering a snow body with a 30 cm layer of bark chips reduced the annual melt depth to approximately 1.5 m of snow thickness during the 2006 melt season. This experimentally grounded result provides the primary empirical basis for melt suppression assumptions adopted in the present study.

Comparable use of organic insulation has also been reported in large-scale seasonal snow storage systems developed for district cooling in northern Europe, where wood chips or similar materials are routinely used to preserve snow masses through summer (Skogsberg, 2001). In addition, comparative analyses indicate that organic mulch-based insulation performs on par with, or more robustly than, synthetic or reflective cover materials under midlatitude conditions, particularly when evaluated over large areas and multi-season timescales (Weiss et al., 2019).

In this study, these external findings are not used for direct model calibration, but rather to define a plausible upper bound on melt suppression achievable through organic insulation under comparable climatic conditions. Accordingly, under insulated surface conditions, the effective degree-day factor is not treated as a fixed coefficient. Instead, insulation performance is represented as a constrained range of reduced effective DDF values, reflecting variability in radiative forcing, wind exposure, rainfall, and evolving surface conditions.

Box 1 Feasibility bounds for multi-year urban glacier formation.

To translate the conceptual framework into testable feasibility conditions, this box summarizes governing thermal and geometric bounds using a degree-day approach consistent with snow-storage literature.

For clarity and reproducibility, the governing assumptions and feasibility bounds summarized narratively in Box 1 are consolidated in structured tabular form in Supplementary Table S5.

i. Annual positive degree-days (PDD): Representative annual PDD for cold-climate cities comparable to Sapporo typically falls within 3,000˚C–4,000˚C·days (depending on interannual variability and site exposure).
ii. Degree-day factor (DDF): Reported DDF values for snow and debris/organic-covered ice span 2–6 mm w.e. ˚C^{-1} days^{-1}.
iii. Insulation efficiency (ε): Field studies of bark-chip and organic insulation indicate melt-energy reductions of 50%–90%, depending on layer thickness, moisture content, and maintenance state.
iv. Resulting melt depth and multi-year survival threshold: The effective annual melt depth M can be expressed as $M = PDD \times DDF \times (1 - \varepsilon)$. Across the bounds above, M spans approximately 0.1–0.6 m w.e. yr^{-1}. Consequently, snow–ice bodies with effective thicknesses exceeding ~10–30 m fall within a multi-year survival regime, permitting firnification, internal ice layering, and the potential emergence of measurable glacier flow.

This boxed summary defines a design envelope, not an operational prescription, and clarifies where urban glacier formation is thermodynamically plausible *versus* where perennial snow storage alone is expected.

These findings suggest that effective surface insulation, combined with basic thermal modeling, may enable perennial snow preservation—and possibly artificial glacier development—in cold, snowy cities such as Sapporo. With climate-specific adjustments, the same principles may apply to other cold, snow-rich urban environments including Montreal.

In addition to thermal constraints, quantitative mechanical thresholds and safety considerations must also be addressed.

In flat coastal settings such as the sandy shore of Ishikari Bay, an ice dome inevitably develops gentle surface slopes from its geometry. For a 1 km × 1 km dome with a conservative maximum thickness of $H \approx 40$ m, and a characteristic horizontal scale $R \approx 500$ m, the representative slope of $H/R \approx 0.08$ (≈4.6˚) (dimensionless) yields a driving stress $\tau_d = \rho\ g\ H \sin \alpha \approx 28$ kPa (with $\rho \sim 900$ kg m^{-3} and $g = 9.81$ m s^{-2}). Glen-type creep alone can generate cm yr^{-1} surface velocities under such low stress (e.g., Cuffey and Paterson (2010)). Basal sliding, if it develops, could further increase motion; however, in porous coastal sediments, freeze-on and ice infiltration may instead strengthen basal resistance, shifting the flow partitioning toward deformation-dominated glacier motion (Meyer et al., 2018). This indicates that observable flow is possible even below the canonical 50 kPa driving-stress scale.

In urban contexts, safety must take precedence. On flat, sandy ground, the vertical stress from 40 m of ice ($\sigma_v = \rho\ g\ H \approx 0.35$ MPa) requires site-specific geotechnical investigation to confirm that the allowable bearing capacity meets or exceeds this value, together with adequate drainage to prevent basal overpressure and sliding. In this setting, gentle slopes are recommended, and continuous geodetic and hydrological monitoring is essential for risk management (Haeberli et al., 2016). Under these design conditions, a Sapporo "urban glacier" could evolve toward glacier ice while ensuring structural stability and public safety.

2.4 Urban cryosphere infrastructure

The artificial glacier is intended not only as a scientific experiment, but also as a prototype for climate-adaptive urban design. Like green roofs or urban forests, the Sapporo Glacier functions as an engineered environmental buffer—one that actively stores winter cold and passively offsets summer warming. Its presence could influence local microclimates, urban heat dynamics, and seasonal humidity, offering new forms of cryospheric infrastructure for cities under climate stress.

2.5 Coastal feedback: cooling the Ishikari Bay

In Hokkaido, long-term environmental monitoring indicates that sea surface temperatures in Ishikari Bay have exhibited a gradual warming trend over recent decades, as illustrated in local environmental reports (Shiga, 2025). This warming has increasingly been linked to shifts in fisheries catch composition, particularly along the Pacific coast, where warming trends and marine heatwaves have become more prominent in recent years. For instance, Miyama et al. (2021) reported recurrent summer marine heatwaves between 2010 and 2016 in the Oyashio-influenced region, highlighting the potential for ecological restructuring in subarctic marine environments (Miyama et al., 2021).

The proposed glacier site, located on an underutilized coastal plain directly facing the sea, offers a unique ecological opportunity. As the glacier melts seasonally, its runoff could be directed into the bay via engineered drainage pathways. Sapporo City has long conducted routine snow management operations, and as a result, meltwater has ultimately been discharged into Ishikari Bay, with regular monitoring in place. In this context, the glacier runoff may function as a seasonal thermal buffer for nearshore waters. Although its total thermal mass is modest, this proximity and controlled timing allow it to function as a localized seasonal thermal buffer, with a bounded capacity to moderate nearshore temperature variability, as quantified in the upper-bound heat-budget analysis below.

Regionally reported coastal observations for Ishikari Bay indicate that sea surface temperatures typically range from an annual mean of approximately 11 ˚C–13 ˚C, to seasonal minima of −1 ˚C–1 ˚C, and seasonal maxima of 23 ˚C–27 ˚C (Shiga, 2025).

In estimating the thermal anomaly associated with glacier runoff, I do not assume that meltwater discharge scales linearly with instantaneous melt rates. Glaciological studies have shown that the timing and magnitude of external runoff are strongly modulated by the seasonal development of englacial and subglacial drainage systems, which can temporarily store and redistribute meltwater before release. Accordingly, I adopt a conservative,

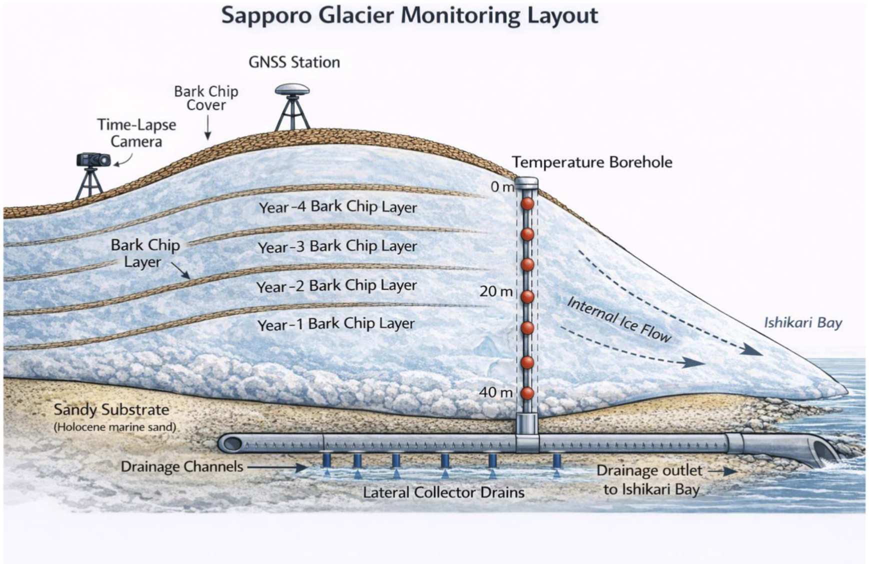

FIGURE 2
Conceptual monitoring layout for the proposed Sapporo Glacier at a flat coastal site adjacent to Ishikari Bay. The schematic cross-section shows annual bark-chip insulation layers (Year –1 to –4). These are shown illustratively to represent repeated seasonal accumulation and multi-year surface re-insulation, rather than a prescriptive 4 year threshold. A surface GNSS station, a time-lapse camera, and a vertical temperature borehole (0–40 m) are installed to monitor internal temperature. Deformation is assessed through geodetic and marker-based observations. Subsurface drainage channels and lateral collector drains route meltwater toward the bay. Dashed arrows indicate potential internal ice flow.

representative melt-season scenario, assuming nearshore seawater temperatures characteristic of late spring to early summer (on the order of several degrees above 0 °C), rather than peak summer conditions. This choice is intended to provide an order-of-magnitude thermal bound without invoking optimally large temperature contrasts.

A complementary way to express scale is to consider the heat budget of the meltwater itself. For a seasonal meltwater volume on the order of 10^6 m^3 at approximately 0 °C entering nearshore waters that are approximately 5 °C–10 °C warmer during the melt season, the associated negative heat anomaly can be expressed as

$$Q \approx \rho\, c_{\mathrm{p}}\, V_{\mathrm{m}}\, \Delta T$$

here, Q denotes the associated heat anomaly, ρ the density of water, c_{p} its specific heat capacity, V_{m} the seasonal meltwater volume, and ΔT the characteristic temperature difference between meltwater and ambient seawater.

Any resulting temperature signal therefore depends primarily on the effective nearshore mixing volume and stratification conditions, and is expected to be localized to the coastal zone and transient in time, rather than climatically meaningful at the scale of Ishikari Bay.

Moreover, locating the glacier at the water's edge ensures that any future glacial movement—if flow develops—would be directed toward the bay, thereby reducing potential risk to urban infrastructure under controlled design conditions. A corresponding conceptual monitoring layout is shown in Figure 2, summarizing the structural configuration and observation framework of the proposed system. This configuration represents a deliberate coupling of urban snow management and coastal environmental response, in which potential nearshore cooling is treated as a secondary, testable co-benefit rather than a primary climate mitigation mechanism.

3 Observation protocol

To evaluate whether an artificial glacier can form and persist under urban conditions, a dedicated observation system is essential. The goal is not only to track melt and retention, but to assess internal structural changes that may indicate glaciological processes such as densification, ice metamorphism, and basal flow. This section outlines a passive, low-cost observational framework suitable for multi-year deployment at an experimental snow accumulation site.

3.1 Core parameters and objectives

The observational system is designed to monitor the following key parameters.

- Surface and internal temperature (diurnal/seasonal gradients)
- Snow and ice mass retention (volume loss or gain over time)
- Internal densification (from snow to firn to ice)
- Meltwater generation and runoff pathways
- Surface albedo and radiative input
- Deformation indicators (e.g., stake tilting or internal displacement)
- Vertical development of crystal grain structure across stratified ice layers
- Three-dimensional displacement of fixed points embedded in and on the ice body

These data will enable the identification of physical thresholds for glacier behavior and provide early indicators of long-term viability.

Additionally, the project includes a focused effort to track the development of internal ice crystal structures, especially in basal zones where pressure-driven recrystallization is expected. This may involve scheduled ice core sampling at designated locations, as well as non-destructive imaging if feasible.

To assess potential glacier flow or deformation, fixed reference points will be embedded both within and atop the ice body. Their positions will be tracked using differential GNSS and, if integrated with borehole markers, may allow for three-dimensional reconstruction of internal displacement (Blake and Clarke, 1992; Gudmundsson et al., 1999).

3.2 Instrumentation and layout

Unlike traditional glacier monitoring in remote or alpine settings, the proposed urban-edge site benefits from immediate access to municipal infrastructure, including routine environmental monitoring of snow accumulation at major snow-depot sites conducted by the City of Sapporo (Sapporo City Construction Bureau, 2025b). This proximity allows for rapid deployment, regular maintenance, and the potential integration of public-facing research facilities—such as field laboratories or glacier museums—in collaboration with universities and research institutes.

A minimal yet effective instrument package is proposed.

- Temperature loggers (e.g., HOBO or iButton sensors) placed at vertical intervals from surface to base
- Snow stakes and marker layers (dye bands, colored fabrics) for measuring melt and densification
- Time-lapse cameras for snow surface monitoring and volume estimation
- Simple surface GNSS stakes or stake tilting sensors for detecting displacement over time
- Surface albedo sensors or light meters, if possible, to correlate with radiation input
- Buried metal markers for non-visual relocation via handheld metal detectors—when accessible
- Sampling zones for periodic ice core extraction to observe vertical crystal grain development over time
- Fixed surface reference points (reinstalled annually) to track horizontal and vertical movement via differential GNSS; potential integration with borehole markers for full 3D displacement mapping

All instruments are designed for low maintenance and can be deployed without access to power or telecommunications infrastructure.

3.3 Observation schedule

Season	Activity
Winter (accumulation)	Initial mound formation, post-compaction installation of external sensors and fixed GPS markers
Spring–Summer (melt season)	Regular (e.g., monthly) site visits to collect temperature and stake data, image downloads, and core sampling
Autumn (pre-snow)	Structural assessment, densification evaluation, maintenance, relocation and alignment of surface reference points

4 Uncertainties, risks, and failure modes

This manuscript presents a conceptual framework rather than an operational plan. Accordingly, I summarize below the key uncertainties and plausible failure modes that could prevent multi-year survival or the emergence of glacier behavior at a candidate coastal site, together with practical mitigation measures. These considerations bound interpretation and clarify conditions under which the intended outcomes would not be expected.

4.1 Climatic anomalies: warm winters and rain-on-snow events

Interannual climate variability is a primary uncertainty. Unusually warm winters, mid-winter thaws, or rain-on-snow events can increase sensible and latent heat inputs, accelerate melt, and inhibit firnification.

4.2 Insulation performance uncertainty and degradation

Organic insulation (e.g., bark chips/wood chips) may compact, redistribute under wind and meltwater, or degrade biologically over time, reducing insulation efficiency and introducing spatial heterogeneity.

4.3 Ground settlement and mechanical stability

Large seasonal-to-perennial snow/ice loads can induce settlement or uneven deformation of the foundation, particularly in reclaimed or unconsolidated coastal areas. Such deformation may alter surface slope, drainage pathways, and internal stress fields.

4.4 Drainage limitations and meltwater management

Poor drainage can cause surface ponding, localized flooding, refreezing hazards, and increased heat transfer to the snow/ice body. Meltwater routing also determines whether cooling effects (if any) remain localized and transient.

4.5 Snow contamination and material heterogeneity

Urban snow can contain debris, road salts, soot, and other contaminants that alter albedo and melt rates, affect internal stratigraphy, and raise environmental or regulatory concerns regarding meltwater quality.

Urban snow quality, including contamination arising from traffic exposure and deicing practices, is recognized as an important contextual constraint in some cold-climate cities, including Sapporo, but is not considered further in this study (Kawajiri et al., 2020; Borris et al., 2021).

4.6 Governance, permitting, and social acceptance

Even if physically feasible, the project may face governance and public-acceptance risks (including permitting, liability, competing land uses, and perceptions of nuisance or environmental impact), which are treated here as contextual constraints rather than determinants of physical feasibility.

The interpretation of the processes described above is further constrained by the practical uncertainties and potential failure modes summarized in this section.

5 Discussion

The Sapporo Glacier Project reframes urban snow not as waste, but as latent glacier material, i.e., cryospheric material already present in sufficient quantity and quality to support artificial glacier formation. With approximately 20 million cubic meters of snow collected annually, the available volume is sufficient for large-scale accumulation. By concentrating this volume at a single coastal site, the city could form a large, slowly deforming ice body comparable in mass and spatial extent to small natural glaciers.

To clarify the range of conditions under which the present framework may be applicable, I briefly summarize the effective constraints already implicit in the analysis. This study considers an ice body with a maximum thickness of approximately 40 m, which is sufficient to generate driving stresses on the order of several tens of kilopascals under the low-slope geometry discussed above. Climatic constraints are expressed here in terms of the effective positive degree-day (PDD) budget after surface insulation, rather than raw atmospheric temperature alone. Based on the degree-day estimates presented for Sapporo and the magnitude of melt suppression achievable through organic insulating cover, multi-year ice preservation corresponds to effective PDD values on the order of several hundred °C·days. These bounds are intended solely to clarify physical applicability and do not constitute prescriptive design or site-selection criteria.

In contrast to conventional engineered snow storage systems designed for short-term cooling or logistical efficiency, this project focuses on the long-term transformation of urban snow into a stable glaciological body. The objective is to observe the development of glacier-relevant processes, including internal ice layering, firnification, and slow flow, within a managed urban setting. The Sapporo Glacier is therefore conceived as a multi-year ice body maintained through controlled melt suppression and repeated seasonal accumulation, rather than as a single-season installation.

Observations from cities such as Montreal indicate that large urban snow bodies can persist through summer and, in some cases, into the following winter in cold, snowy climates. One frequently cited example, referred to by local media as “Montreal’s snow glacier,” involved a snow dump at a repurposed quarry site that survived multiple melt seasons despite the absence of intentional preservation measures (CBC News, 2025; Financial Times, 2024). This so-called “glacier-by-accident” was a media-reported phenomenon that was not designed, monitored, or managed for environmental purposes. Its persistence nonetheless demonstrates that multi-season survival of large urban snow accumulations is physically possible under favorable climatic conditions.

From a broader perspective, the Sapporo Glacier Project situates urban cryospheric management within ongoing discussions of climate adaptation. A large, visible ice body offers a concrete means of engaging with cryospheric processes in an urban context, while remaining grounded in physical feasibility rather than symbolic intent alone.

One promising candidate site is a flat, underutilized coastal plain facing Ishikari Bay. The site, commonly referred to as Otane Beach, Otaru City, lies near the former settlement of Otanai, an Ainu-derived place name preserved in historical records. Otanai is generally interpreted as deriving from *ota* (“sand”) and *nay* (“rivulet”) (Chiri, 1956), though multiple morphological interpretations have been proposed (Honda, 1999). The original toponym Ota-*nai* later evolved into Ota-*ne*, likely reflecting phonological changes during incorporation into Japanese. Because the site is adjacent to the ocean, any future ice movement would be directed seaward, reducing potential risk to urban infrastructure. Meltwater could be conveyed through engineered channels into the bay, where it may provide limited seasonal cooling of nearshore waters.

Figure 3 provides a spatial overview of representative snow-depot sites (●), including the Shin-Kotoni 8-Yoko snow-depot site (★) and the proposed Otanai site (◆). These locations correspond to existing municipal snow-depot sites and illustrate the logistical feasibility of large-scale snow redistribution.

Potential physical effects of the glacier include local microclimatic moderation, seasonal cooling, and contributions to freshwater input and thermal buffering. In addition, the scale of the structure and its accessibility, potentially including access by public transportation, allow it to function as a long-term observation site.

The project also has implications for environmental education and public engagement. A persistent urban ice body could support observational activities by schools, citizen scientists, and researchers, providing a tangible reference for discussions of permafrost, glacier change, and long-term climate processes.

Finally, the project highlights a temporal contrast between urban infrastructure and cryospheric processes. Whereas urban systems typically operate on seasonal or administrative timescales, glacier development occurs over decades. Sustaining such an ice body therefore requires long-term planning and monitoring, aligning urban management with slower cryospheric dynamics.

6 Conclusion

This study outlines the conceptual foundation of the Sapporo Glacier Project, a proposal that treats the city’s full seasonal snow accumulation as a conceptual upper-bound scenario. Rather than treating snow as transient nuisance, the project envisions it as potential glacier-forming material—concentrated, insulated, and cultivated into a mass of ice over years. By directing the collected snow to a dedicated coastal site under a conceptual upper-bound scenario, the city could build a glacier and locally influence nearshore thermal conditions through a controlled cold-based input.

As an adaptation-oriented urban infrastructure, it operates at the interface between climate-related risk management and urban planning practices. Its runoff may help promote localized nearshore cooling; its mass may locally influence seasonal temperature dynamics; its visibility may alter how citizens perceive winter, and seasonal

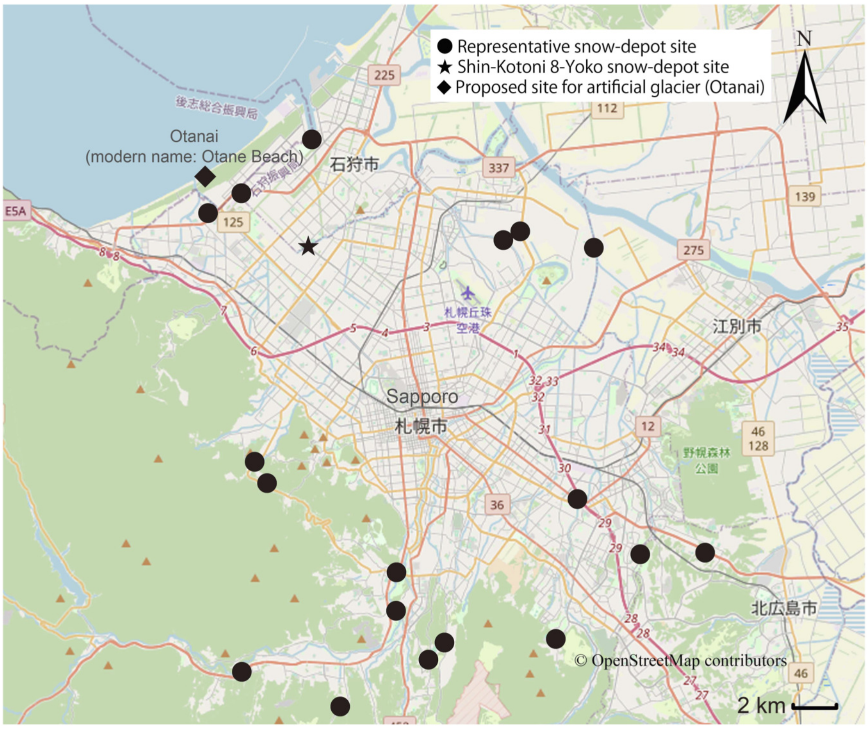

FIGURE 3
Location of municipal snow-depot sites in Sapporo, Japan, including the Shin-Kotoni 8-Yoko snow-depot site shown in Figure 4 (★) and Otanai (◆), a proposed site for artificial glacier development. Approximately 70 snow-depots are operated each year, of which 18 representative sites (●) are shown. Basemap data: © OpenStreetMap contributors (ODbL 1.0).

FIGURE 4
Aerial view of the Shin-Kotoni 8-Yoko snow-depot site in Sapporo, Japan, based on drone footage recorded on May 5, 2022 (M Channel, 2022). Despite active melting efforts, a massive volume of snow lingers well into the melt season. This snow body represents only a fraction of the city's annual snow removal, yet vividly illustrates the latent cryospheric potential embedded in urban snow. The structure spans approximately 300 m across at its base. Reproduced with permission from the rights holder (M Channel); the original watermark is retained in accordance with the licensing terms.

environmental change. It functions not only as a research object but also as a long-term urban-scale infrastructural project that enables publicly observable, long-term observation of urban cryospheric processes. Moreover, its scale and accessibility may offer a unique platform for long-term climate education, citizen observation, and public engagement and education in urban settings.

While practical challenges remain—site engineering, long-term observation, governance coordination—the climatic and physical conditions necessary for sustained multi-year snow retention are present in Sapporo. Implementation depends on systematic design, long-term monitoring, and institutional coordination.

Ultimately, the Sapporo Glacier Project presents an opportunity to reconsider how cities engage with their cryospheric environments—moving beyond mitigation toward intentional, long-term adaptation. Although rooted in the specificity of Sapporo, its framework may prove instructive for other cold-climate cities seeking new forms of symbolic, material, and even artistic resilience.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MT: Software, Funding acquisition, Writing – review and editing, Supervision, Writing – original draft, Investigation, Resources, Data curation, Formal Analysis, Conceptualization, Project administration, Visualization, Methodology, Validation.

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Conflict of interest

The author declares that there are no commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Generative AI was used for language editing and structural refinement of the manuscript. The conceptual framework, data interpretation, calculations, and scientific content were developed and verified solely by the author. The author takes full responsibility for the accuracy and integrity of the work.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2026.1733696/full#supplementary-material

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