Chapter 1

Glaciers as an Important Element of the World Glacier Monitoring Implemented in Svalbard

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Abstract

Glaciers are not only contributors to the sea level rise but also important players in the circulation of pollutants. Over a billion people apply glacial waters for domestic purposes; hence, both the quality and quantity of this water should be monitored. In this chapter, we concentrate on the archipelago Svalbard in the Arctic, a typical target area for xenobiotics from long range atmospheric transport (LRAT), holding an important share of the Arctic glacial ice cover. Literature review has been conducted over both the cryospheric metrics and the achievements of analytical chemistry in the environmental monitoring. Svalbard is a relatively well-monitored part of the Arctic, with 17 glaciers regularly monitored for mass balance. In the chemical records of glaciers, a variety of substances have been determined, e.g., ions, heavy metals, or persistent organic pollutants (POPs), with the use of precise analytical techniques. However, knowledge gaps persist, preventing a formation of a reliable chemical inventory of Svalbard glaciers. Moreover, detailed studies on the deposition and transport of pollutants, rather than focusing on their presence only, are crucial future research recommendations.

Keywords: glacial catchments, anthropogenic pollutants, glacier mass balance, polar ecosystems, environmental contamination

1. Introduction

Glaciers are not only contributors to the sea level rise but can also accumulate and release pollutants [1, 2], as well as transform the chemical composition of water that originates or flows through them. Since glacial water is used by over a billion people for domestic purposes [3], both the quality and quantity of this water should be monitored. Indeed, such studies can be a vast source of knowledge on the processes in the otherwise unavailable subglacial environment. In this chapter, we concentrate on the archipelago Svalbard in the Arctic, a typical target area for xenobiotics from long range atmospheric transport (LRAT), holding an important share of the Arctic glacial ice cover. We show the ways the glaciers of Svalbard are monitored for water losses and quality changes, alongside some benefits already acquired through such studies. A new direction in the research is needed that would deepen the interpretation of the obtained monitoring data.

2. Glacier monitoring and projects implemented in the Arctic

2.1. Cryosphere

Cryosphere refers to "*the part of the Earth's crust and atmosphere subject to temperatures below 0°C for at least part of each year*" [4]. The snow, ice, and frozen ground all constitute the cryosphere, considered a source of climatic diagnosis due to its sensitivity to air temperature and precipitation changes. The most recent intergovernmental panel on climate change (IPCC) assessment [5] emphasizes also the importance of cryosphere in the Earth's ecosystem as a reservoir of solidified water. Glaciers and the great ice sheets of Greenland or Antarctica are only part of the cryosphere, as shown in **Figure 1**.

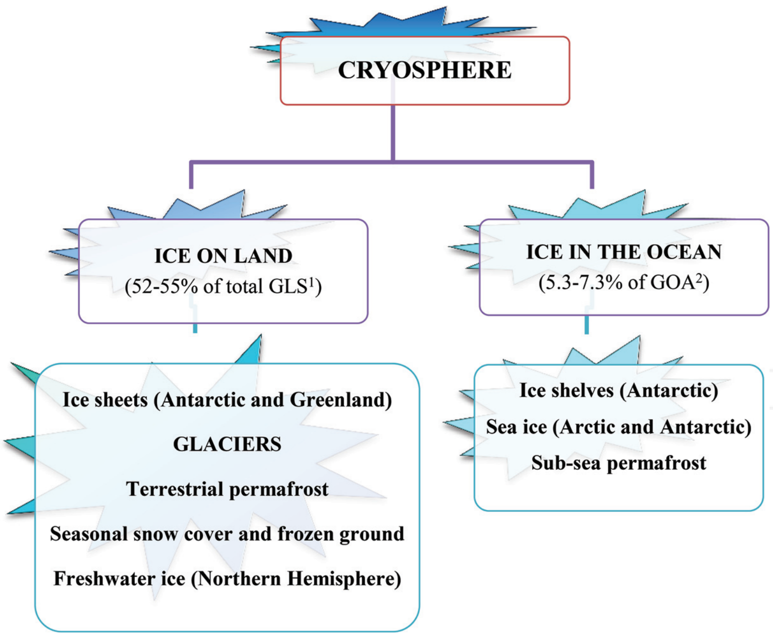

Figure 1. Division of the cryosphere and its components: [1]Global land surface: 147.6 Mkm^2, [2]Global ocean area: 362.5 Mkm^2 [5].

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The global land surface covered by glaciers (0.5%) is the least abundant cryosphere component. It is referred to as "ice on land." Nevertheless, the general significance of glaciers for the sea level equivalent (0.41 m a.s.l.) is the highest among the components, except for ice sheets (Antarctic: 58.3 m, Greenland: 7.36 m). Glaciers are long-term components of the cryosphere, with a lifespan exceeding freshwater ice on rivers and lakes (seasonal) and sea ice (several years in the Arctic), but shorter than ice sheets and permafrost, surviving even millions of years [5] (**Table 1**).

Considering their contribution to the sea-level rise and the lifespan of particular components of the cryosphere, glaciers are of extreme significance for the environment as an indicator of climate change in the context of global warming.

2.2. Glacial system

Glaciers occupy 10% of the Earth's surface. As natural water reservoirs, they represent 75% of freshwater on Earth. The vast majority of the water (99.5%) is stored in the Greenland and Antarctic ice sheets. Ref. [3] has emphasized the great significance of glaciers as a source of freshwater widely used by over a billion people. Glacial waters are not only used for domestic purposes, but also for electricity production and crops irrigation (e.g., in the Alps, Himalayas). However, it is the small glaciers and ice caps of the High Arctic that have been rapidly responding to climate changes in the recent years, and therefore have contributed the most to the sea level rise [4–8].

Although the high latitude regions of the Arctic are distinguished by limited human impact and low emission from local sources, they cannot be considered free from the presence of pollutants. For example in Svalbard, the long range transport of atmospheric pollutants transmitted from Eurasian industrialized and urbanized areas may substantially affect the quality of Arctic waters, since the atmospheric deposition is one of the main factors (next to rock-water interaction) controlling water chemistry in this polar region [9–13].

Due to glacial drainage and the processes by which glaciers are formed, they are an important element in the global water cycle. The accumulation of water as snow and its gradual release in the liquid form determine the importance of glacial controls upon the drainage characteristics of partly glaciated catchments [6].

Element of the cryosphere	Lifespan
Snow	A day to several months
River and lake ice	Several days to several months
Sea ice	Several days to almost a year
Glaciers and ice caps	Months to a century
Frozen grounds	A day to a millennium
Ice sheets, ice shelves	Days to a millennium

Table 1. Lifespan of selected elements of the cryosphere.

Glaciers develop when snow accumulates over a period of several years, and then gradually transforms into firn (at least 1 year old snow) to finally turn into ice. The ice flows downward due to the force of gravity. Snow accumulation predominantly depends on the climate conditions and topographic characteristics [4, 5, 14, 15]. When the accumulation process (snowfall) prevails over the ablation processes (iceberg calving, surface melting, and runoff, melting under floating ice shelves), glaciers gain mass [4, 5, 14, 15].

An important typical feature of glaciers is the circulation of mass, i.e., ice, snow, water, and mineral matter, as well as the circulation (exchange) of energy manifested in accumulation, the glacier movement, and ablation. The processes are determined by external factors. They also substantially affect the environment, making the glacier a dynamic, open system [16]. The glacier system is fed by and releases various forms of energy and mass, which are subject to further movement and/or transformation inside it. **Figure 2** shows the relations between the entry and exit elements.

The mass movement is determined by the force of gravitation. Energy transformations and movement are accompanied by complex processes within the glacier. As a result of differences in the mass balance, the uniform glacial system is divided into two spatial subsystems, namely the accumulation and ablation system, separated by the equilibrium line [16, 17]. Maintaining balance within the glacial system is only possible when the balance elements (entry and exit elements of the system) are equal, and the mass flow through the equilibrium line is even. Any disturbance in the balance causes a response of the system in the form of feedback loops. An example of such a process is an increase in accumulation, which causes an increased flow of ice

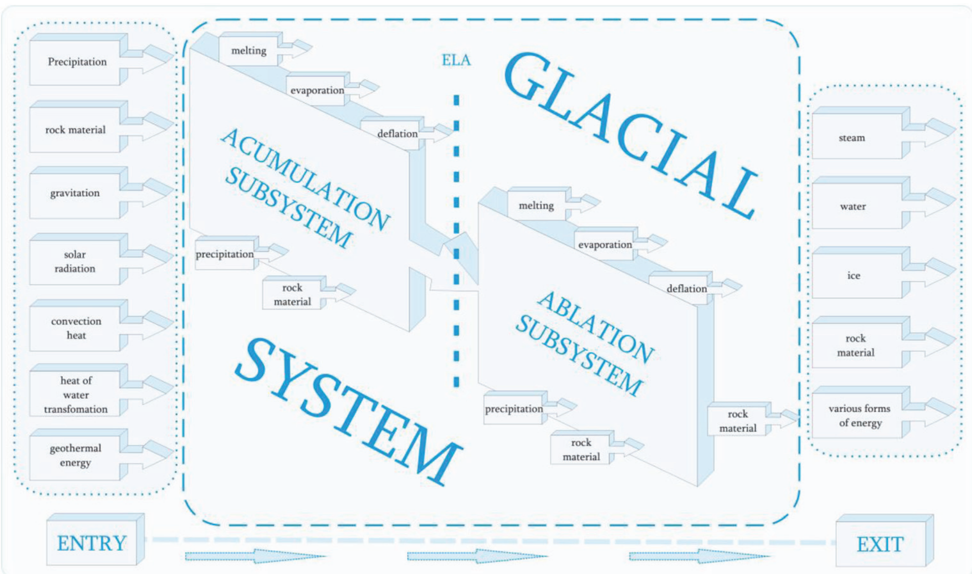

Figure 2. Schematic model of the glacial system.

mass through the equilibrium line, contributing to the advance of the glacier terminus, an increase in ablation, and reduction in the lower part of the glacial system.

The dynamic open glacial systems substantially affect climate at the global scale. They are also excellent indicators of climate fluctuations. The response of glaciers to climatic changes varies depending on their morphological features and internal thermal structure [14, 16].

Polythermal glaciers, i.e., glaciers with a complex thermal structure, are particularly good indicators due to their response to changing climate characteristics, as they are developed not only as a result of varied air temperature, but also by variable amount and structure of precipitation. In contrast to glaciers with cold thermal regime, the internal hydrothermal structure of polythermal glaciers is determined not only by solid, but also by liquid precipitation [18].

2.3. The beginning of world glacier monitoring

Glacier monitoring has a history dating back to the nineteenth century (**Figure 3**). The father of glacier monitoring was François-Alphonse Forel, the first scientist to observe changes in Alpine glaciers. The first international initiative emerged during the sixth International

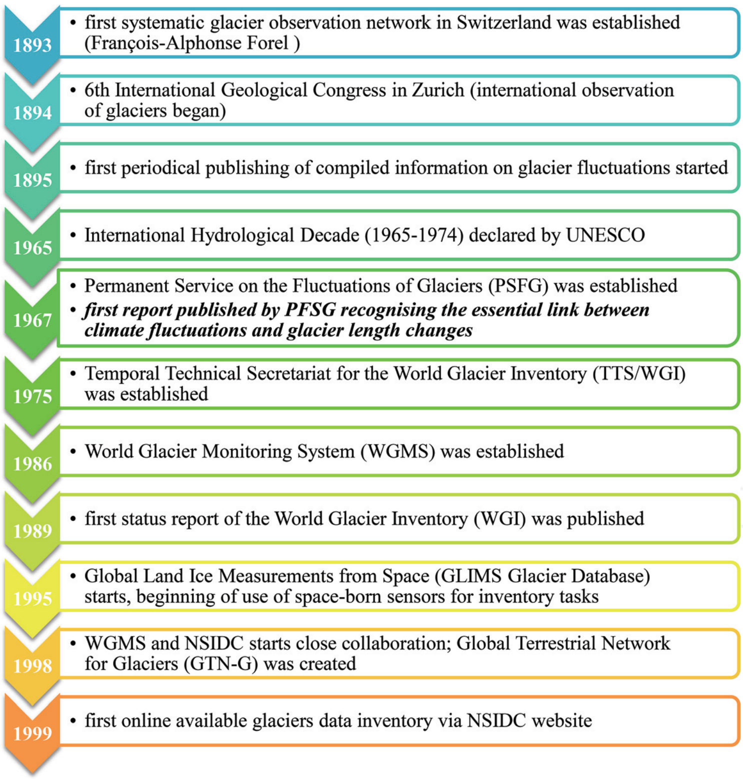

Figure 3. Most important dates in the early history of glacier monitoring.

Geological Congress in Zurich. Since then, scientists have been collecting information on changes in selected glaciers and performing detailed surveys of their tongues on a regular basis. The data were enriched by the indigenous knowledge on earlier glacier stages, provided by the mountain people. At the early stages of the research, it focused on glacier fluctuations, therefore only data on front variations were published. Since 1940, information regarding mass balance has been included in publications. The need for a worldwide inventory of the existing ice and snow masses was recognized just after the declaration of the International Hydrological Decade (1965–1974) by the United Nations Educational, Scientific, and Cultural Organization (UNESCO). This resulted in the establishment, under the auspices of UNESCO, of the first international network called the Permanent Service on the Fluctuations of Glaciers (PSFG). Worldwide glacier monitoring has been rapidly evolving since then, and in 1975, the Temporal Technical Secretariat for the World Glacier Inventory (TTS/WGI) was established. Its role was to collect and periodically publish glacier inventory and fluctuation data. The tasks of TTS/WGI and PSFG were taken over by the World Glacier Monitoring Service (WGMS), established in 1986. The first status report of glaciers inventory, published in 1989, includes information on their geographic location, area, length, orientation, elevation, and classification of morphological type and moraines. The data were mainly based on aerial photographs, maps, and satellite images. Since 1995, when project Global Land Ice Measurements from Space (GLIMS) was launched, the data have also been collected from optical satellite instruments such as the Advanced Spaceborne Thermal Emission and reflection Radiometer (ASTER) [19–21]. The collaboration of WGMS with the US National Snow and Ice Data Center, initiated in 1998, resulted in the first data inventory available online via the website of the National Snow and Ice Data Center (NSIDC) already a year later [20, 22, 23]. The most important dates and events in the early history of worldwide glacier monitoring are provided in **Figure 3**.

2.4. The organization of the glacier monitoring system

The establishment of the Global Terrestrial Observing System (GTOS) in 1996 was a consequence of the Second World Climate Conference held in 1990. The conference called for the establishment of a coordinated monitoring system (**Figure 5**). The Terrestrial Observation Panel for Climate (TOPC) was established within GTOS. The global observing strategy was subsequently designed. It permits introducing all variables essential for the climate (e.g., river discharge, groundwater, lakes, glaciers, and ice caps) related to monitoring systems to the Global Terrestrial Network (GTN). As a result, the Global Terrestrial Network for Glaciers (GTN-G) was established in 1998. GTN-G is responsible for collecting standardized data on the current state of glaciers. Since its establishment, it has been run by WGMS with the assistance of NSIDC and GLIMS. The monitoring system is under the supervision of several worldwide organizations presented in **Figure 4** [22, 24].

2.5. Glacier research projects in Svalbard

Due to the strong response of glaciers to climate change, their great importance for sea-level rise, and impact on the environment, many international research programs and projects have been conducted in the Arctic, including Svalbard. Research projects, unlike monitoring, include innovative testing of new methods and techniques and have a typical duration from

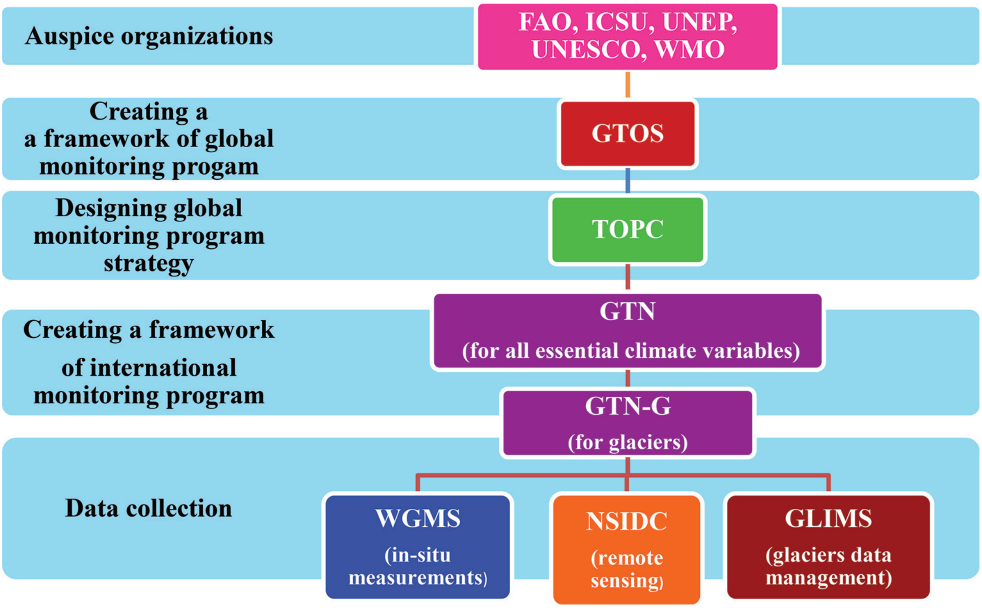

Figure 4. Major international organizations and their role in glacier monitoring.

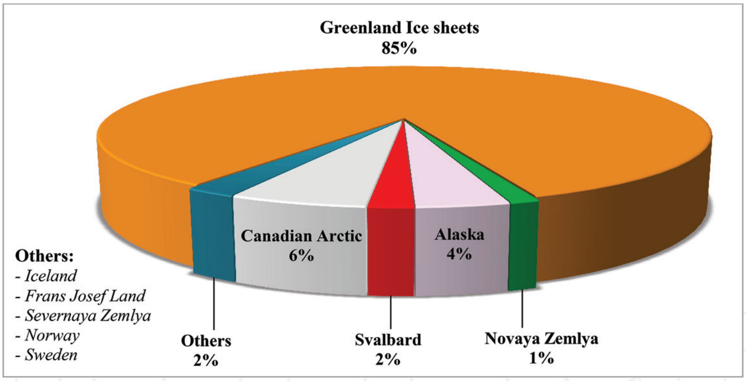

Figure 5. Percent contribution of 10 Arctic regions covered by extensive glaciation [4].

3 to 6 years, and are funded from different sources. Examples of such research projects regarding Svalbard glaciers are listed in **Table 2** [25–28]. A great number of projects is interdisciplinary, concerning both glaciology and glacial hydrology. Some are also related to meteorology (e.g., CRYOMET) and seismology (e.g., SEISMOGLAC). The vast majority of research projects is associated with the response of the cryosphere to global warming and climate change.

Project (years of implementation)	Scope of research	Source of funding
"GLACIODYN" The dynamic response of Arctic glaciers to global warming (2007–2010)	**1.** Current mass budget of each glacier (including calving); **2.** Subglacial processes (hydrology and sliding interactions); **3.** New models of calving processes (numerical models including functions of sliding and calving); **4.** Prediction of glacier response to climate change scenarios.	RCN
"SvalGlac" Sensitivity of Svalbard glaciers to climate change	**1.** Measurements of mass budget, glacier flow velocity, glacier thickness and hydrothermal structure, weather; **2.** Studies on actual glacier topography and shallow ice cores (for the past climate reconstruction).	ESF
"Ice2sea" Estimating the future contribution of continental ice to the sea-level rise (2009–2013)	**1.** Studies of key processes in longer-lived elements of the cryosphere (mountain glacier systems, ice caps, ice sheets); **2.** Improvement of satellite determinations of current changes in continental ice masses; **3.** Development of a detailed forecast of the contribution of continental ice to the sea-level rise over the next 200 years by means of ice-sheet/glacier models.	ERC
"ICEMASS"ERC advanced grant global glacier mass continuity	**1.** Data collection and analysis regarding glacier thickness changes, and converting the data to a global glacier mass budget; **2.** Estimation of the current sea-level contribution from glaciers; **3.** Studies on glacier mass changes reflecting climate change patterns; **4.** Examination of the impact of glacier imbalance on river run-off.	ERC
"CRYOMET" Bridging models for the terrestrial cryosphere and the atmosphere (2012–2015)	**1.** Validation of the polar weather research and forecasting model (WRF) land surface scheme; **2.** Collection of cryosphere data sets constituting variables with Polar WRF; **3.** Studies on further probabilistic downscaling of snow cover by means of snow distribution models; **4.** Tests of upscaling schemes for the surface energy balance in polar WRF (cryosphere-atmosphere feedbacks).	RCN
"SEISMOGLAC"-Seismic monitoring of glacier activity on Svalbard (2012–2015)	**1.** Studies on the relation between glacial process and seismicity; **2.** Finding the source location of ice quakes; **3.** Use of automatic pattern recognition methods to classify their signals.	RCN
Abbreviations: RCN: Research Council of Norway, ESF: European Science Foundation, ERC: European Research Council.		

Table 2. International research projects in Svalbard within the framework of which glaciers are studied.

3. Svalbard glaciers and climate warming

Part of the cryosphere of the northern hemisphere categorized as "ice on land" is distributed irregularly in the Arctic. Therefore, glaciers and ice caps are subject to different climatic conditions. In Ref. [5], 10 regions of the Arctic are specified as covered by extensive glaciation. Together they occupy an area of 1,972,600 km^2. The percent contribution of each of them is shown in **Figure 5**.

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Svalbard archipelago is the most glaciated region of the European Arctic. The area of its glaciation (approximately 36.6 km^2) is substantially higher than that of Norway and Sweden (approximately 3.1 km^2), Iceland (approximately 10.9 km^2), Franz Josef Land (approximately 13.7 km^2), and Novaya Zemlya (approximately 23.6 km^2).

The response of the Greenland ice sheet to climate change is slower, because more than a half of its surface experiences temperatures well below the freezing point during the entire year. Changes in temperature or precipitation cause a more rapid response in smaller glaciers and ice caps, which are more sensitive [4]. Throughout the Arctic, except for Russian Arctic, the mass balance (difference between annual mass gain and annual mass loss) is only monitored on 27 glaciers. Four of them are located on Svalbard (Midre Lovenbreen, Austre Broggerbreen, Kongsvegen, and Hansbreen) [29].

The Svalbard archipelago includes four main islands (Spitsbergen, Nordautslandet, Edgeøya, and Barentsøya) and occupies an area of 62,248 km^2. Approximately, 60% of the Svalbard archipelago is covered with ice. The glacier inventory of Svalbard amounts to 1615 glaciers and ice caps, of which 17 are under permanent or periodic mass balance research.

Sixty percent of Svalbard glaciers are terminating in the sea at calving ice-cliffs. Ref. [7] has emphasized that due to calving, the annual specific mass loss of Svalbard glaciers is much higher than from the Greenland ice sheet and seems to be the highest in the Arctic. Each of the main islands of the archipelago represents a different type of landscape (more detailed information is provided in **Table 3**). On Spitsbergen, the largest island of the archipelago, 90% of glaciers are considered polythermal (subpolar) [8, 30, 31].

Although the dominant component of Spitsbergen landscapes is rugged mountains with glaciers, its eastern part is covered with several large ice caps. Together with ice caps from three other islands, also calving into the sea, they all develop a calving ice front with a total length of approximately 1000 km. The total volume of the ice masses of Svalbard is estimated at 7000 km^3 [7, 32].

3.1. Role of glaciers in the Svalbard environment

Glaciers occur in places where climatic and topographic conditions favour snow accumulation. Their role may be considered both at the global scale and at the regional scale, as shown in **Figure 6**.

Islands	Landscape	Area of glaciation
Spitsbergen	Steep, rugged mountains	~22,000 km^2 of glaciers ~14,600 km^2 of ice caps
Nordautslandet	Two largest single ice bodies within Svalbard	~2450 km^2 (Vestfonna ice cap) ~8000 km^2 (Austfonna ice cap)
Edgeøya and Barentsøya	Plateau-type terrain	~2800 km^2 of low altitude ice caps

Table 3. Dominant types of landscapes and extent of glaciation of the main Svalbard archipelago islands [8, 32].

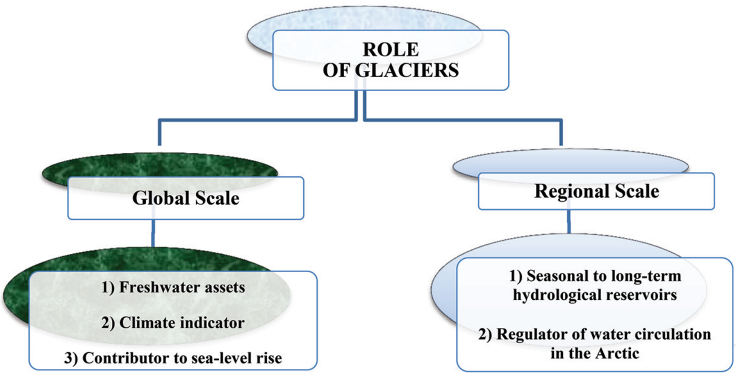

Figure 6. The role of glaciers in the environment [5, 32].

Glaciers adjust their size in response to changes in climate, e.g. in temperature and precipitation. Therefore, they are considered very sensitive climate indicators. Changes in their size or shape may be observed over several decades or even several years. Svalbard glaciers also have a contribution in the sea level rise, estimated at 4% of the total contribution of smaller glaciers and ice caps. The contribution of the archipelago corresponds to the ratio between the glaciated area of Svalbard and the global surface covered by glaciers and ice caps [4, 8].

For the Arctic environment, with a fragile homeostasis, the regional role of glaciers is significant [10, 32]. Glaciers are the most visible component of the Svalbard environment. Due to this, they can also be considered a major geomorphological factor of the entire archipelago [32]. They respond the fastest and strongest to climate changes among all environmental components, and are a major regulator of water circulation in the Arctic [33]. Ref. [32] has emphasised the role of glacier runoff in Svalbard, a factor affecting not only the hydrology of rivers, but also circulation in the neighbouring seas and fjords, due to changes in stratification within the water column. Local climate and biota may also be influenced by changes in the glacial runoff, affecting the sea ice conditions of the archipelago. Even deep-water production close to the shelf of Svalbard may be influenced by a rapid discharge of freshwater from glaciers [32].

4. Glacier water chemistry and the origin of chemical additions

The chemical composition of glacial meltwaters in Svalbard has been subject to increased interest in recent years [34–37]. Waters originating from glaciers affect the quantity and quality of water delivered to the environment in glaciated catchments, which also plays an important role in ice mass dynamics [13]. Furthermore, glaciated catchments regulate the biogeochemical circulation of nutrients, and influence the cryosphere-atmosphere interactions [38].

Although the high latitude regions of the Arctic experience very limited human impact and low emission of local origin, they cannot be considered free from pollutants any more. The long-range atmospheric transport from the regions of Eurasia with higher emissions may influence the Arctic water quality, making atmospheric deposition one of the main factors (alongside rock-water interactions) controlling water chemistry of the polar regions. Due to high rates of chemical weathering and minimal human impact in glaciated areas, they constitute an environment almost ideal for studying water-rock interactions [11–13]. Hydrochemical data on proglacial waters provide explanation of water drainage pathways through glaciers and estimations of chemical weathering rates [34, 39].

Ref. [12] has emphasized the specific conditions of the Arctic environment, such as: *"(1) relatively short water-rock contact time, (2) cold temperatures, (3) thin soils, and (4) lack of vegetation,"* which reduce the activity of geochemical processes, including chemical weathering. However, the contact of water with eroded glacial debris and the abundance of soluble rocks such as carbonates and sulphides tend to considerably enhance such activity. In addition to the chemical weathering of rocks and the atmospheric deposition, other factors potentially influence dissolved solute concentrations, these are *"(1) discharge conditions at the time of sampling, (2) inputs and outputs from the soil exchange pool, (3) uptake of organic nutrients by biomass, and local variations in non-living organic material (humus), and (4) changes in the topography and soil development"* [12, 13].

The ionic composition of glacial meltwater varies due to different types of its transit through the glacial system, and the duration of chemical weathering reactions supplying solutes to such waters. The variety of glacial processes, and consequently chemical weathering, is strongly influenced by the thermal regime of glaciers. Meltwater in contact with the bedrock is present in temperate and subpolar glaciers. The acquisition of solute derived from chemical weathering occurs at the glacier bed during the transit of meltwater through two types of drainage systems: distributed and channelised. The distributed drainage involves linked cavities or porous flow through permeable subglacial sediments, and is mainly fed by snowmelt or slow transit of meltwater. This system of drainage is characterised by high water pressure and long residence time. The rock-water contact area is high. The channelised drainage system is fed by ice melt, mixed with waters from the distributed system to produce bulk meltwater. This system rapidly drains high volumes of water from beneath the glacier. The chemical reactions occurring on the water-rock interface in the glacial system depend on the type of drainage and their changeability during the ablation season [13, 40].

The most important mechanism of chemical rock weathering is acid hydrolysis. Ref. [13] has emphasized that dissolved anion signature of the meltwater indicates the source of protons necessary to drive acid hydrolysis reactions. Furthermore, Ref. [13] has listed the sources of protons such as (1) dissociation of atmospheric CO_2 [Eq. (1)], (2) sulphide oxidation [Eq. (2)], and (3) oxidation of pyrite [Eq. (3)]. The latter is often coupled with carbonate dissolution.

$$\mathrm{CaCO_3(s) + H_2CO_3(aq) \leftrightarrow Ca^{2+}(aq) + 2HCO_3{}^{-}(aq)} \tag{1}$$

$$\mathrm{4FeS_2(s) + 14H_2O(l) + 15O_2(aq) \leftrightarrow 16H^{+}(aq) + 8SO_4{}^{2-}(aq) + 4Fe(OH)_3(s)} \tag{2}$$

$$\begin{aligned}&\mathrm{4FeS_2(s) + 16CaCO_3(s) + 14H_2O(l) + 15O_2(aq) \leftrightarrow 4Fe(OH)_3(s) + 8SO_4{}^{2-}(aq)}\\&\mathrm{+16Ca^{2+}(aq) + 16HCO_3{}^{-}(aq)}\end{aligned} \tag{3}$$

The relative proportions of HCO_3^- and SO_4^{2-} in the bulk outflow reflect the dominance of the major sources of aqueous protons driving subglacial weathering reactions. Ref. [13] has assumed that, when using the C-ratio $[HCO_3^-/(HCO_3^-+SO_4^{2-})]$, a value of 1 signifies weathering by carbonation reactions, while a value of 0.5 reflects coupled sulphide oxidation and carbonate dissolution.

4.1. Pollutants examined in the catchments of Svalbard glaciers

Next to the natural chemicals from rock-water contact, human activity also contributes chemicals to Arctic waters, despite the distance of thousands of kilometres between the Arctic and the industrial and agricultural areas. During the last two decades, pollutants continued arriving into the Arctic, and despite their decreasing or steady atmospheric levels [41], their negative impact on the polar environment remains an important concern [42–49].

The Svalbard archipelago is different from the other Arctic regions. Due to its geographical location and specific climate conditions, it is particularly exposed to the accumulation of a wide range of chemical substances recognised as pollutants [9, 10]. Its relatively short distance from continental Europe, the location of the archipelago in the gap between the continents surrounding the Arctic Basin, and its landscape dominated by rugged mountains with glaciers, make it conducive to the accumulation of pollutants on its glaciers. Moreover, ocean and wind currents contribute to the transport of pollutants from lower geographic latitudes. In combination with low temperatures, this results in Svalbard and its glaciers becoming a sink for xenobiotics [50–54]. Although the levels of multiple pollutants such as heavy metals and many POPs contained in various elements of the living and inanimate environment are well known [10], knowledge on the fate of pollutants in Svalbard glaciers is still scarce.

Many scientific studies discuss the issue of the contamination of the Arctic environment. A vast number of publications concern the content of xenobiotics detected both in the living organisms (e.g. [46, 55–59]) and in the inanimate environment [60–64]. In Ref. [10], levels of pollutants present in samples collected in the Svalbard archipelago are discussed in detail. This paper focuses on the literature directly related to the presence of a wide range of chemicals recognized as pollutants in glacial catchments. The majority of research on the chemistry of glacier catchments is performed on Spitsbergen, the largest island of the archipelago (**Figure 7**).

The research site locations are directly related to the occurrence of the warm West Spitsbergen Current, considerably affecting the climate of the western coast of Spitsbergen. The warm waters limit the sea-ice development, which makes this area easier available for research activities. This is evident in the contribution of individual fjords, with the only representant of the eastern side of the island being Woodfjorden. Moreover, due to the cold East Spitsbergen Current, the east coast is dominated by several large ice caps [7, 10, 32].

Three main types of glacial catchments on Svalbard may be distinguished. The first two types involve the glacier terminus ending in the sea. In the first case, the glacier basin covers the coastal valley, and in the second case, the basin reaches into the centre of the island, covering large glaciated valleys. The third type of a glacial catchment is distinguished by the glacier terminus ending on land [78]. The glacier moraine is located in front of the glacier terminus, at

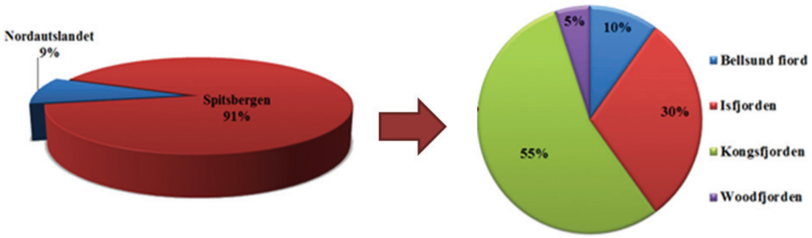

Figure 7. Places of conducting chemical research in glacial catchments in Svalbard, including the contribution of particular fjords of the Spitsbergen island [12, 34, 35, 38, 40, 49, 55, 65–77].

a certain distance from the seashore. Ablation water leaving the glacier flows through the glacier moraine and into the fjord via a number of channels developing a river system between the glacier and the fjord. Various types of surface water samples can be collected and examined depending on the type of catchment. According to the literature, glaciers representing the latter type of glacial catchments are subject to most frequent research activities (**Figure 8**). The evaluation was based on selected scientific articles, cited in **Tables 4**, **5** and **6**.

A vast majority of publications [12, 34, 40, 49, 75–77] focused on water from glaciers (proglacial, supraglacial, subglacial, and cryoconite waters). However, some include also direct

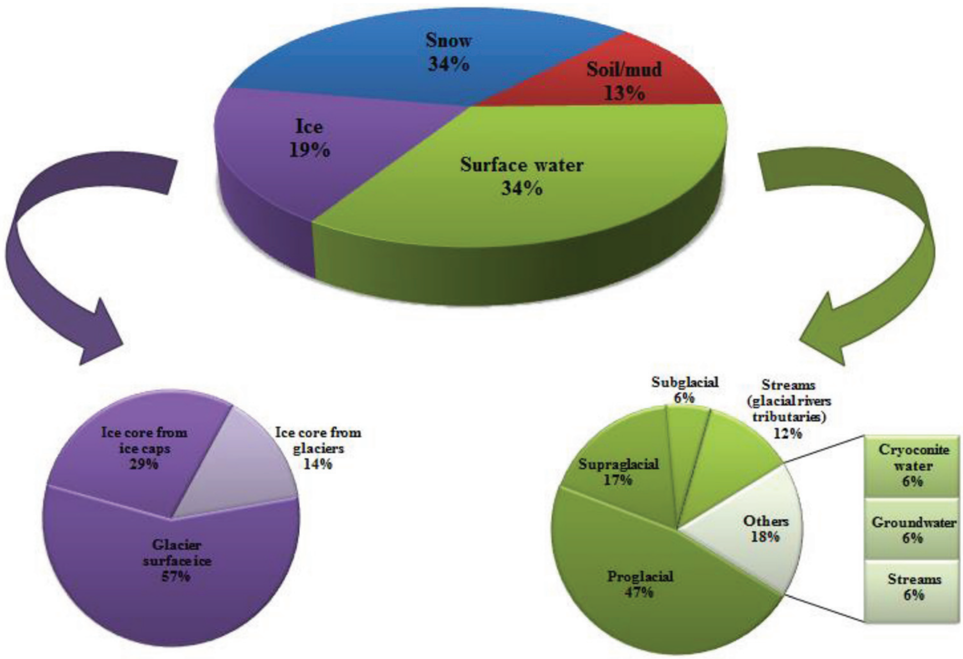

Figure 8. Contribution of different type of samples examined on the Svalbard archipelago [12, 34, 35, 38, 40, 49, 55, 65–77].

tributaries of glacial rivers [12, 76], as well as other streams and groundwaters functioning in glacier basins [12, 38]. A smaller number of studies involves the analysis of ice samples. In prevalence, the examined ice was collected from the surface of glaciers rather than from drilled ice cores, and this sampling strategy may be driven by the predominance of polythermal regime among Spitsbergen glaciers (90%). The percolation of water and chemical substances in this thermal regime disturbs the original depositional sequence of chemical composition, making it difficult to analyze their accumulation in glaciers over time. Therefore, the examined Svalbard ice cores originate usually from ice caps. Only in Ref. [49], authors analyze pollutants in ice cores collected from the polythermal glacier of Longyearbreen. Snow samples for analysis are collected from the surface of glaciers and their surroundings in nearly equal proportion. Substantially, more sediment samples from cryoconite holes [72, 77, 79] on glaciers are subject to research than soil samples collected in glacier catchments.

Projects listed in **Table 2** mainly focus on glaciological investigations [80–84]. Some of them are associated with the impact of climate change on cryosphere components and the modelling of possible cryosphere-climate interactions [8, 85]. Many scientific works also focus on the presence of pollutants such as heavy metals or POPs in biotic samples [50, 55, 61, 86, 87]. The majority of the research is related to biochemistry, and refers to the processes of bioaccumulation and biomagnification of pollutants within the marine or terrestrial food webs. Publications concerning abiotic samples collected from glacier catchments of Svalbard focus on types of research presented in **Figure 9**. The evaluation was based on selected scientific articles cited in **Tables 4**, **5** and **6**.

According to the literature review, the majority of conducted research concerns the fate and transport of pollutants in the abiotic environment. These publications mostly refer to levels of selected metals (e.g., Al, Hg) or POPs (e.g., PCN, PCBs, PFOA, PFOS, DDD, DDE, DDT) in snow [49, 67, 69–71] and ice samples [49, 55, 73, 74]. Ref. [49] discusses the effect of pollutants

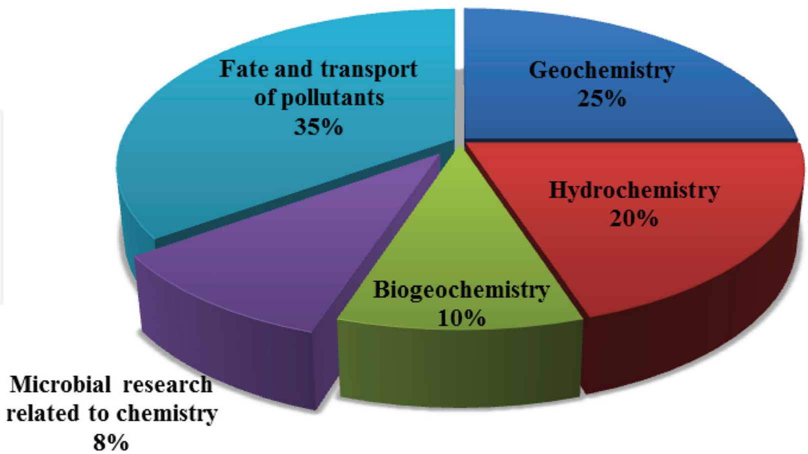

Figure 9. Types of research performed on inanimate samples collected in the Svalbard archipelago [12, 34, 35, 38, 40, 49, 55, 65–77].

present in snow, ice, and surface water samples (i.e., supraglacial lake or river and sea water) collected throughout the glacial catchment, starting from the top of the glacier and ending in the fjord waters. This is the only work providing an insight into the transport of anthropogenic pollutants through almost all of the elements of the glacial catchment. A considerable number of publications focus on the chemical weathering process [12, 34, 35, 38, 75]. Others concern seasonal changes in hydrochemistry [68, 76], or compare the hydrochemistry of inanimate samples collected in different parts of the environment [66, 72]. Such works mainly present results of analysis of inorganic ions (e.g., K^+, Na^{2+}, Mg^{2+}, F^-, Cl^-, NO_3^-, NO_2^-). A smaller number of studies concerns biogeochemistry [40, 65] or microbiology related to the fixation of nitrogen on glaciers or carbon cycle [77, 79].

Since data from long-term chemical monitoring of glaciers are scarce and rarely published in full, we collected here an inventory of shorter published measurement series or important datasets that can be treated as a proxy of the current state of the glacial chemical monitoring in Svalbard. First, we present an overview of the techniques and equipment used for the determination of a wide range of analytes studied in the environmental samples from glacial catchments of the Svalbard Archipelago. We have divided the data into three categories: snow (**Table 4a**), ice (**Table 4b**) and surface water (**Table 4c**). According to the literature review, ion chromatography (IC) is the analytical method that is used most frequently for the determination of not only inorganic ions, but also other pollutants (e.g., methyl-sulfonic acid and glutaric acid). The determination of the concentration of metals in the environment usually involves the methods of flow injection analysis (FIA) or atomic absorption spectroscopy (AAS). The determination of organic pollutants, which are highly detrimental for Arctic biota, is performed by means of gas chromatography (GC), usually coupled with mass spectrometry (MS) in different resolution modes (low resolution, high resolution). Inorganic ions and metals are the most frequently determined analytes in almost all of the elements of glacial catchments (snow, ice, water, soil, and cryoconite). Research involving the determination of persistent organic pollutants (e.g., DDD, DDT, PCBs, PCNs, HCH, HCB) is conducted very rarely in the glacier catchments. These dangerous chemical compounds are usually determined in snow and ice samples (ice cores and surface ice) collected in the glacial catchment, where they reflect contribution of long-range atmospheric transport and their history of accumulation.

Except water samples, other abiotic material has also been investigated in the glacial catchments of Svalbard, especially rock material of different types. For example, cryoconite sediment has been analysed for its nutrient content (for DIN, TIN and TN, using Bran and Luebbe Autoanalyzer 3, [77]) or heavy metal concentration (Fe, Mn, Zn, Pb, Cu, Cd; by voltamperometric and spectrophotometric method, [72]). Similar parameters to water samples were established in soils, especially pH [34, 65], inorganic anions (Cl^-, NO_3^-, SO_4^{2-}, HCO_3^-) and cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) [34, 65], SiO_2 concentration [34], and organic carbon and nitrogen [65]. The methods used in the mentioned studies matched those used for snow, with the exception of the Fisons NCS analyser application for organic carbon and nitrogen.

In **Tables 5a**, **5b** and **5c**, we present the published chemical concentration data from the samples described in **Tables 4a**, **4b** and **4c**, respectively. Most studies concerned watercourses, and there the highest variability of chemical parameters was found. Ice samples have shown

Determined compound(s)/parameters	Analytical method/apparatus		References
pH			[65]
	pH meter		[66]
	Heito pH meter (Paris)		[67]
	Orion SA 250 portable meter with Ross combination electrode		[34]
	Orion 290a portable pH meter with Ross combination electrode		[68]
EC	conductivity meter		[66]
Anions (Cl^-, Br^-, NO_3^-, SO_4^{2-})	IC	Dionex ion chromatography	[65]
		DionexR 2100	[66]
		Dionex DX100	[40]
		IC, colorimetric method	[38]
		Dionex ICS 3000	[67]
		Dionex 4000i	[34, 68]
		Dionex ICS-1100	[49]
HCO_3^-	Titration (0.01 M HCl)		[68]
	Titration (1 mmol HCl)		[34]
	Titration (10^{-3} mol/L H_2SO_4)		[65]
Cations (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+})	AAS		[34, 38, 65]
	ICP-OES		[66]
	FIA		[40]
	IC	Dionex ICS-3000	[67]
		Dionex 4000i	[68]
		ICS-1100 Dionex	[49]
Metals	Al_{total}	AAS	[65]
	Hg_{total}	CVAFS	[67]
		ICP-SFMS	[69]
	$Hg_{reactive}$	ICP-QMS	[69]
	MMHg (monomethylmercury)	AFS	[67]
S	ICP-OES		[66]
Si-$Si(OH)_4$	FIA		[65]
SiO_2			[34]
Si			[68]
MSA(methyl-sulfonic acid), Glut (glutaric acid)	IC (Dionex ICS 3000)		[67]
	GC-MS-EI-SIM		[70]

Determined compound(s)/parameters	Analytical method/apparatus	References
∑PCB9, α-HCH, γ-HCH, ∑DDT, HCB, chlordane (cis- or trans-)		
∑PCN, ∑PCB	HRGC-LRMS	[71]
PFOA, PFOS	LC-MS/MS	[49]

Table 4a. Literature data on the analytical techniques and equipment used for the determination of a wide range of compounds in the snow samples (snowfall, surface snow, snowpack) collected in the glacial catchments of the Svalbard archipelago.

Determined compound(s)/parameters	Analytical method/apparatus		References
pH/EC	pH/conductometer CPC-411 by Elmetron		[88]
Anions (Cl^-, NO_3^-, SO_4^{2-})	IC, colorimetric method		[38]
	IC (ICS-1100 Dionex) IC (ICS-3000Dionex)		[49, 88]
Cations (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+})	AAS		[38]
	IC (ICS-1100 Dionex) IC (ICS-3000Dionex)		[49, 88]
Metals		AAS	[55]
	Zn, Mn, Cu, Fe, Ni, Cr, Pb, Cd, Co	Voltamperometric and spectrophotometric method	[72]
	Li, Be, B, Al, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Cd, Cs, Ba, La, Ir, Pb, Th, U	ICP-MS	[88]
PFOA, PFOS	LC-MS/MS		[49]
Aldrin, Dieldrin, α-HCH, Heptachlor, Heptachlor epoxide, Methoxychlor, Chlorpyrifos, Dacthal, Methyl-parathion	GC-LRMS-EI GC-ECD		[73] [74]
γ-HCH, α Endosulfan, β Endosulfan, Diazinon, Dimethoate, Disulfoton, Imidan, Terbufos, Alachlor, Pendamethalin, Desethyl atrazine	GC-LRMS-EI GC-LRMS-ECNI		[73] [74]
Endrin-aldehyde	GC-LRMS-EI		[73]
Endrin, Endrin-ketone, Cis-nonachlor, Trans-nonachlor, o.p'-DDD, p.p'-DDT (L), p.p'-DDE, γ-chlordane, α-chlordane,	GC-ECD		[74]
Endosulfan sulphate, Metolachlor, Trifluralin, Metribuzin	GC-LRMS-ECNI		[74]
DOC	TOC analyser (Shimadzu)		[88]

For acronyms see list in the beginning of the article.

Table 4b. Literature data on the analytical techniques and equipment used for the determination of a wide range of compounds in the ice samples (glacier surface, ice cores from glaciers and ice caps) collected on the glaciers of Svalbard.

Determined compound(s)/parameters	Analytical method/apparatus		References
pH			[37, 38, 65]
	Orion SA 250 portable meter with a Ross combination electrode		[34]
	Jenco pH-meter		[35]
	Orion (Thermo Scientific), WPA (Cambridge, UK) or VWR pH meter		[36]
EC	CC-317 conductivity meter		[35]
Anions (Cl^-, NO_3^-, PO_4^{3-}, SO_4^{2-})	IC	Dionex 4000i	[75]
		Dionex Ion Chromatography	[65]
		Dionex DX100	[40, 36]
		IC, colorimetric method	[38]
		Dionex 4000i	[34]
		Metrohm Compact IC 761	[35, 37]
		Dionex DX-120	[12]
		Dionex ICS-90	[76, 36]
HCO_3^-	IC	Dionex 4000i	[75]
		Dionex DX-120	[12]
	Titration (10^{-3} molc/L H_2SO_4)		[65]
	Colorimetric titration		[38]
	Titration (1 mmol HCl)		[34]
	Titration (10 mmol HCl)		[36]
	Titration (0.02 M HCl)		[35]
	Titration (Metrohm 702 SM Titrino)		[37]
N-NO_2^-	IC	Dionex DX-120	[12]
N-NO_3^-		Dionex Ion Chromatography	[65]
		Dionex DX-120	[12]
N-NH_4^+		Dionex DX-120	[12]
	FIA		[65]
Cations (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+})	IC	Dionex 4000i	[75]
		Dionex ICS-90	[76, 36]
		Metrohm Compact IC 761	[37]
	AAS		[12, 34–36, 38]
	FIA		[40]
Metals (Al_{total}, Fe, Mn, Zn, Pb, Cu, Cd)	AAS		[65]
	FIA		[34]
	Voltamperometric method, spectrophotometric method		[72]
Si	Colorimetric method (Skalar Autoanalyser)		[76]

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Determined compound(s)/parameters	Analytical method/apparatus	References
Si-Si(OH)$_4$	FIA	[65]
SiO$_2$		[34]
	Spectrometry using the method of reduction to molybdenum-blue	[35, 36]
	Perkin Elmer ICP-OES Plasm 40 spectrometer	[37]
DOC	LABTOC Carbon Autoanalyser	[65]
DOC, DON	Shimadzu Total Organic Carbon (TOC)/Total organic nitrogen (TON)-V analyzer	[38]
DIN	Bran and Luebbe Autoanalyzer	[77]
DIC	Estimated from charge balances	[76]
PFOA, PFOS	LC-MS/MS	[49]

For acronyms see list in the beginning of the article.

Table 4c. Literature review of the analytical techniques and equipment used for the determination of chemical parameters in the surface water samples (glacial waters, streams, springs, cryoconite water) from glacial catchments of Svalbard.

Determined compound(s)/parameters		Identified level/range			References
pH		4–6.82			[34, 65–68]
EC		[μS cm^{-3}] 6.1–80.4			[66]
Anions		[μmol L^{-1}]	[mg L^{-1}]	[μEq L^{-1}]	
	Cl^-	0.9–553	0.2–20.7	<LOD-2400	[34, 38, 40, 49, 65–68]
	Br^-	<LOD-0.90	–	–	[67]
	NO_3^-	0.1–3.9	0.01–0.162	<LOD-7	[34, 38, 40, 49, 66–68]
	SO_4^{2-}	0.4–34.5	<LOD-2.82	<LOD-240	[34, 38, 40, 49, 66–68]
	HCO_3^-	[μmol L^{-1}]		[μEq L^{-1}]	
		57.1–195		11–900	[34, 65, 68]
	N-NO_3^-	[mg L^{-1}]			
		0.01–0.02			[65]
Cations	N-NH_4^+	0.06–0.77			
		[μmol L^{-1}]	[mg L^{-1}]	[μEq L^{-1}]	
	Na^+	0.8–486	0.12–9.76	2–2000	[34, 38, 65–68]
	NH_4^+	0.4–5.4	<LOD-0.11	–	[38, 40, 49, 67]
	K^+	0.03–11.5	<LOD-5.56	<LOD-96	[34, 38, 49, 65–68]
	Mg^{2+}	0.3–47.9	<LOD-1.378	<LOD-200	[34, 38, 49, 65–68]
	Ca^{2+}	0.6–15.2	0.04–2.17	<LOD-110	[34, 38, 49, 65–68]

Determined compound(s)/parameters		Identified level/range	References
Si-$Si(OH)_4$		[mg L^{-1}]	
		0.03–0.13	[65]
SiO_2		0.0	[34]
Si		<LOD-1.5 [μmol L^{-1}]	[68]
Metals	Al_{total}	3.78-117 [μg L^{-1}]	[65]
	Hg_{total}	[ng L^{-1}]	
		<LOD-59.9	[67, 69]
	$Hg_{reactive}$	2.2–45.3	[69]
	MMHg	3–43 [pg L^{-1}]	[67]
S		0.17–0.88 [mg L^{-1}]	[66]
MSA (methyl-sulfonic acid)		[μmol L^{-1}]	
		<LOD-1.56	[67]
Glut (glutaric acid)		<LOD-0.07	
$\sum PCB_9$		[pg L^{-1}]	
		116–2000	[70, 71]
α-HCH		<LOD-47.6	
γ-HCH		186–3090	
∑DDT		0.391–59.5	
HCB		3.10–35.3	
∑PCN		59.0–1100	[71]
PFOA		89.5–590.8	[49]
PFOS		18.6–133.2	

Table 5a. Literature data on snow samples collected in the glacial catchments of Svalbard.

the pHs closest to neutral and lowest electrical conductivities, and also in terms of inorganic ions their concentration range was smaller than experienced in snow samples (**Table 5b** and **5a**). This reflects the effects of snow accumulation on inorganic chemicals, which are readily removed in meltwater (**Table 5c**) and therefore less of them remains in glacial ice. Conversely, the POPs found in ice were usually occurring at higher concentration than in snow, showing their historical deposition was higher, but also perhaps the ability of the accumulating snowpack to retain them better. An environmental concern are also the concentrations of heavy metals experienced in glacial ice (**Table 5b**), which additionally demonstrate the possibility that glaciers store pollutants of various types.

In **Table 6** we additionally provide the data on other abiotic media except frozen and liquid water, i.e. soil and cryoconite sediment. For cryoconite, it is noteworthy that it may contain

Determined compound(s)/parameters		Identified level/range		References
pH [⁻]		5.65–7.03		[88]
SEC [μS cm^{-1}]		4.50–21.2		
Anions		[μmol L^{-1}]	[mg L^{-1}]	
	Cl^-	328	<LOD-1.12	[38, 49]
	NO_3^-	1.5	<LOD-0.10	
	SO_4^{2-}	19.8	<LOD-0.27	
∑anions	F^-, Cl^-, NO_2^-, Br^-, NO_3^-, PO_4^{3-}, SO_4^{2-}	[meq L^{-1}]		
		0.022–0.236		[88]
Cations		[μmol L^{-1}]	[mg L^{-1}]	
	Na^+	199	<LOD-0.7	[38, 49]
	NH_4^+	0.4	<LOD-0.08	
	K^+	7.6	<LOD-0.09	
	Mg^{2+}	26.2	<LOD-0.19	
	Ca^{2+}	28.5	0.03–0.75	
∑cations	Na^+, NH_4^+, Li^+, K^+, Mg^{2+}, Ca^{2+}	[meq L^{-1}]		[88]
		0.015–0.279		
Metals		[μg kg^{-1}]	[μg L^{-1}]	[55, 72, 88]
	Zn	43.75	1–40.91	[55, 72, 88]
	Mn	42.75	0.22–5.20	
	Cu	11.25	0.27–3.25	
	Fe	2552.50	0.10–17.20	
	Ni	7.25	0.13–2.34	
	Cr	19.25	<LOD-0.16	
	Pb	16.75	0.02–0.45	
	Cd	4.50	<LOD-0.10	
	Co	1.50	<LOD	
	Be	–	<LOD-0.02	
	B	–	<LOD-2.31	
	Al	–	<LOD-2.85	
	Se	–	<LOD-0.15	
	Rb	–	<LOD-0.30	
	Sr	–	0.51–3.89	
	Ba	–	0.30–3.14	
	U	–	<LOD-0.02	
PFOA		[pg L^{-1}]		[49]
		13.5–45.9		

Determined compound(s)/parameters		Identified level/range		References
PFOS		<LOQ-13.5		
DOC		[mg L^{-1}]		[88]
		<LOD-0.566		
Pesticides		[pg L^{-1}]	[pg cm^{-2} yr^{-1}]	[73, 74]
	Aldrin	69,000	30,000	
	Dieldrin	7500	54.7	
	Endosulfan (α, β)	10,700–19,700	2.8–6.8	
	Endrin	–	16.3	
	Endrin-aldehyde	13,600	–	
	Endrin-ketone	–	13.6	
	Heptachlor	6500	470	
	Heptachlor epoxide	32,800	1580	
	HCH (α, γ)	1100–7700	295–369	
	Methoxychlor	4700	19.6	
	Chlorpyrifos	16,200	809	
	Dacthal	300	12.7	
	Diazinon	20,500	1410	
	Dimethoate	87000	598	
	Disulfoton	6500	447	
	Imidan	44,100	3030	
	Methylparathion	7400	357	
	Terbufos	11,100	530	
	Alachlor	1200	57	
	Desethyl-atrazine	2100	144	
	Metolachlor	9300	450	
	Pendimethalin	18,600	890	
	Chlordane (α, γ)	–	13.39–18.3	
	DDD(o.p')	–	11.5	
	DDE (p.p')	–	1.14	
	DDT (L) (p.p')	–	2.93	
	Endosulfan sulphate	–	2.81	
	Metribuzin	–	1.05	
	Nonachlor (trans, cis)	–	2.28–5.03	
	Trifluralin	–	2.32	

Table 5b. Literature data on chemical concentrations in ice samples from Svalbard glaciers.

Determined compound(s)/parameters		Identified level/range			References
pH		4.95–9.74			[34–38, 65]
EC		[μS cm^{-3}] 84.00–188.5			[35]
Anions	Cl^-	[μmol L^{-1}]	[mg L^{-1}]	[μEq L^{-1}]	[12, 34, 35, 37, 38, 65, 76]
		58–464	0.41–36	4–991	
	NO_3^-	0.1–34.7	0.4–2.2	0.56–9.0	[34, 35, 38, 40, 76]
	PO_4^{3-}	–	<LOD-1.0	–	[12]
	SO_4^{2-}	12–217.8	0.73–920.0	1–27,400	[12, 34–38, 65, 75, 76]
HCO_3^-		[μmol L^{-1}]	[μEq L^{-1}]		[12, 34–38, 65, 75]
		4.65–3198	<LOD-7600		
N-NO_2^-		[mg L^{-1}]			[12]
		<LOD-4.90			
N-NO_3^-		0.01–50.70			[12, 65]
N-NH_4^+		<LOD-19.50			[12, 65]
Cations	Na^+	[μmol L^{-1}]	[mg L^{-1}]	[μEq L^{-1}]	[12, 34–38, 65, 76]
		79–513	0.39–35.1	4–833	
	NH_4^+	0.1–6	–	–	[38, 40]
	K^+	8–26	0.22–5.5	<LOD-37	[12, 34, 35, 37, 38, 65, 76]
	Mg^{2+}	92–633	0.18–75.3	<LOD-12,300	[12, 34–38, 65, 75, 76]
	Ca^{2+}	249–1072	0.54–33,300	9–18,700	[12, 34–38, 65, 75, 76]
Metals	Al_{total}	[mg L^{-1}]			[65, 72]
		1.9–275.0			
	Fe	<0.010–0.300			
	Mn	<0.050			
	Zn	<0.001–0.010			
	Pb	<0.001–0.010			
	Cu	<0.001			
	Cd	<0.001			
Si		[mg L^{-1}]			[76]
		0.46–2.31			
Si-Si$(OH)_4$		0.01–0.63			[65]
SiO_2		[μmol L^{-1}]	[mg L^{-1}]	[μEq L^{-1}]	[34–37]
		2-22	0.120–0.780	2–34	
DIC		15.3–851.3			[76]
DOC		0.31–2.17			[38, 65]
		[μmol L^{-1}]			

Determined compound(s)/parameters	Identified level/range	References
	165–426	
DON	<7–27	[38]
DIN	<LOD-132.5 [μg N L^{-1}]	[77]
PFOA	[pg L^{-1}]	[49]
	95.7–639	
PFOS	<LOQ-967	
	–	
TIN	<LOD-18.2	
TN	2200–3800	

Table 5c. Literature overview of chemical concentrations in surface water samples from the glacial catchments of Svalbard.

marked amounts of both harmful heavy metals and life-supporting nutrients. In respect to soils, it can be highlighted that their ionic components may be at lower concentrations than those encountered in the riverine waters flowing out of glacial catchments, especially the fast-flowing, sediment-rich proglacial rivers (**Table 5c**).

Type of abiotic sample	Determined compound(s)/parameters		Identified level/range		References
Soil	pH		7.38–8.79		[34, 65]
	Anions	Cl^-	[μEq L^{-1}]		[34]
			120		
		NO_3^-	19		
		SO_4^{2-}	240		
	HCO_3^-		4100		[34]
	Cations	Na^+	[mmol kg^{-1}]	[μEq L^{-1}]	[34, 65]
			0.12–1.72	180	
		K^+	1.74–4.04	31	
		Mg^{2+}	4.11–23.4	1700	
		Ca^{2+}	63.2–528	2700	
	Organic carbon		[%]	[65]	
			1.28–6.05		
	N		0.04–0.16		[65]
	SiO_2		3.3 [mg L^{-1}]		[34]
Cryoconite (sediment)	Metals	Fe	[g kg^{-1}]		[72]
			31.9		

Type of abiotic sample	Determined compound(s)/parameters	Identified level/range	References
	Mn	0.11	
	Zn	0.08	
	Pb	0.19	
	Cu	–	
	Cd	–	
	DIN	[μg N g^{-1}]	[77]
		–	
	TIN	<LOD-18.2	
	TN	2200–3800	

Table 6. Literature data on sediment samples (soil, cryoconite) collected in the glacial catchments of Svalbard.

5. Summary

The results of research presented in the reviewed literature do not answer all questions arising in the context of the current global warming. The role of glaciers as contributors to the sea level rise is widely discussed by scientists, and extensively described in the latest IPCC report. However, the role of the changing glaciers and glacial waters, particularly for the biota of the polar environment, frequently does not receive enough attention. Considering the presence of contaminants such as POPs in many abiotic elements of the glacial catchment (e.g., snow, ice, surface water), it seems necessary to ask questions about the way and pace of the release of these highly toxic contaminants from the rapidly melting Arctic glaciers, as well as about the potential impact of those on the polar wildlife. Further research should address these questions, in order to help protect the highly sensitive environment of this area. Especially, a more detailed approach to the transport, deposition, and redistribution or transformation of pollutants in the glacial catchments is required, as opposed to the focus on the presence of pollutants in the environment only. However, without a stronger basis in chemical monitoring, there is frequently too little data to draw more global conclusions about the fate of chemicals in Svalbard glaciers.

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List of acronyms

AAS	Atomic Absorption Spectroscopy
ACIA	Arctic Climate Impact Assessment
AFS	Atomic Fluorescence Spectrometry
ASTER	Advanced Spaceborne Thermal Emission and reflection Radiometer
CVAFS	Cold Vapour Atomic Fluorescence Spectroscopy
DDD	Dichlorodiphenyldichloroethane
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
DIC	Dissolved Inorganic Carbon
DIN	Dissolved Inorganic Nitrogen
DOC	Dissolved Organic Carbon
DON	Dissolved Organic Nitrogen
EC	Electrochemical Conductivity
ECV	Essential Climate Variables
ERC	European Research Council
ESF	European Science Foundation
FAO	Food and Agriculture Organization
FIA	Flow Injection Analysis
GC-ECD	Gas Chromatography with Electron Capture Detection
GC-LRMS-ECNI	Gas Chromatography Coupled to Low Resolution Mass Spectrometry in Electron Capture Negative Ionization Mode
GC-LRMS-EI	Gas Chromatography Coupled to Mass Spectrometry with Low Resolution in Electron Ionization Mode
GC-MS-EI-SIM	Gas Chromatography Coupled to Mass Spectrometry in Electronic Ionization Mode with Selected-Ion Monitoring
GLIMS	Global Land Ice Measurements from Space
GLS	Global Land Surface
GOA	Global Ocean Area
GTN	Global Terrestrial Network

GTN-G	Global Terrestrial Network for Glaciers
GTOS	Global Terrestrial Observing System
HCB	Hexachlorobenzene
HCH	Hexachlorocyclohexane
HRGC-LRMS	High-Resolution Gas Chromatography Coupled with Low Resolution Mass Spectrometry
IC	Ion Chromatography
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
ICP-SFMS	Inductively Coupled Plasma-Sector Field Mass Spectrometry
ICP-QMS	Inductively Coupled Plasma-Quadrupole Mass Spectrometry
ICSU	International Council for Science
IPCC	Intergovernmental Panel on Climate Change
LC-MS/MS	Liquid Chromatography with Tandem Mass Spectrometry
LOD	Limit Of Detection
LOQ	Limit Of Quantitation
LRAT	Long Range Atmospheric Transport
NSIDC	National Snow and Ice Data Center
PCB	Polychlorinated Biphenyls
PCN	Polychlorinated Naphthalene
PFOA	Perfluorooctanoate
PFOS	Perfluorooctane sulfonate
POP	Persistent Organic Pollutants
PSFG	Permanent Service on the Fluctuations of Glaciers
RCN	Research Council of Norway
TIN	Total Inorganic Nitrogen
TN	Total Nitrogen;
TOC	Total Organic Carbon;
TON	Total Organic Nitrogen;
TOPC	Terrestrial Observation Panel for Climate;

TTS/WGI	Temporal Technical Secretariat for the World Glacier Inventory;
UNEP	United Nations Environment Programme;
UNESCO	United Nations Educational, Scientific and Cultural Organization;
WGMS	World Glacier Monitoring Service;
WMO	World Meteorological Organization.

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