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Review

Polar Ice as an Unconventional Water Resource: Opportunities and Challenges

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Abstract: Global water resources are under pressure due to increasing population and diminishing conventional water resources caused by global warming. Water scarcity is a daunting global problem which has prompted efforts to find unconventional resources as an appealing substitute for conventional water, particularly in arid and semiarid regions. Ice is one such unconventional water resource, which is available mainly in the Arctic and Antarctic. In this study, opportunities and challenges in iceberg utilization as a source of freshwater were investigated on the basis of a systematic literature review (SLR). A search in three databases (Scopus, Web of Science, and ProQuest) yielded 47 separate studies from 1974 to 2019. The SLR indicated that harvesting iceberg water, one of the purest sources of water, offers benefits ranging from supplying freshwater and creating new jobs to avoiding iceberg damage to offshore structures. Economic considerations and risks associated with iceberg towing were identified as the main limitations to iceberg harvesting, while environmental impacts were identified as the main challenge to exploiting this resource. Assessment of trends in ice sheets in Arctic and Antarctic across different spatiotemporal scales indicated that the main sources of icebergs showed a statistically significant ($p < 0.01$) decreasing trend for all months and seasons during 2005–2019.

Keywords: water scarcity; iceberg water utilization; global map; Mann–Kendall test



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1. Introduction

Water scarcity is one of the largest global risks and is a major challenge to sustainable development and a potential source of conflict within and between countries, especially in arid and semiarid regions [1–4]. Over 60% of the global population lives in areas under water stress, where available water resources cannot meet demand for at least 1 month of the year [5,6]. Therefore, it is crucial to modify water resource management in many societies to mitigate the consequences of water shortages. Approximately 97% of global available water resources are saline, and only 3% occur in the form of freshwater. In addition, available freshwater resources with a potable quality are very limited [7–9]. Over two-thirds of global freshwater resources are stored in the form of ice, of which over 90% is located in the Antarctic. The Antarctic encompasses 27 million km³ of freshwater. Every year, around 2000 km³ of this total volume detaches as icebergs, which can be harvested as an unconventional source of water [10–13]. An iceberg is a large floating of ice mass separated from glaciers in the polar regions and carried to sea.

In addition to conventional water resources, including renewable surface and ground-water resources [14], several unconventional water resources (UWRs) can be considered as secondary resources to meet demand. UWRs are a lucrative opportunity to narrow the water demand supply gap, while acknowledging the importance of demand management strategies. The initial definition of UWRs, by Brewster and Buros [15], included saline water, wastewater, and available water in remote regions. According to a revised definition

by Odendaal [16] and Qadir et al. [17], UWR (1) is a source of water which has not been used in the past to meet normal water demands, (2) has main features which may lead to complications in using it for a specific goal, and (3) is not accessible for public use [18,19]. According to the latter definition, water harvesting from icebergs can be categorized as a UWR, as it provides a unique, pure, and reliable freshwater source that can be towed by vessels to various regions around the globe [20].

Iceberg water transfer and utilization has a long history. James Cook was the first to use an iceberg as a source of freshwater in 1773 [21]. Initial attempts at larger-scale iceberg transport date back to the 1850s, when sailing boats were used to tow small icebergs from Chile to supply ice to the emerging ice market in Peru over 4000 km away [22]. Around the same time, ice was transported from Alaska to California as a commercial commodity [23]. In the 1950s, polar exploration ships were considered the most practical vehicle for iceberg transportation. In the late 1950s, Isaac was the first to come up with the idea of transporting icebergs to arid regions of the globe [24,25]. A few years later, the feasibility of using icebergs to supply freshwater in the northern hemisphere was assessed [23,26]. In 1977, Prince Faisal of Saudi Arabia asked the French explorer Victor to tow an iceberg from Antarctica to Saudi Arabia [24].

The first international conference on iceberg use as a freshwater supply was held in Ames, Iowa, USA, in 1977 [27]. Premier efforts at commercial iceberg utilization for the production of bottled freshwater were made in Canada in 1986. In 1995, vodka production using iceberg water started in Newfoundland, Canada [28]. Recently, some industries have established factories to use icebergs as the primary material to produce beer, vodka, cosmetics, and luxurious bottled water [29].

This study aimed to assess opportunities and challenges in iceberg water utilization, as well as the feasibility of icebergs as an alternative source of freshwater supply. To this end, the use of icebergs across the globe was explored on the basis of a literature review of relevant publications in three databases (Scopus, Web of Science, and ProQuest). Furthermore, since climate change can cause long-term losses in ice sheet availability, this study also analyzed monthly, seasonal, and annual trends of ice sheets in the Arctic and Antarctic using Mann–Kendall (MK) and Sen’s slope tests. This informs whether or not investment in iceberg-harvesting infrastructure can be a long-term and reliable approach to supply water.

2. Materials and Methods

2.1. Data Sources and Search Criteria

The literature search was conducted in September 2020 in Scopus using all fields, in Web of Science using all databases, and in ProQuest under the “topic” domain. The search was performed identically in the three databases, using the following search terms: “iceberg towing”, “iceberg harvesting”, “iceberg water harvesting”, “iceberg water”, and “iceberg utilization”. This study exemplifies important worldwide iceberg water utilization over the last few decades. However, it is not within the scope of this study to list all projects relevant to iceberg water utilization, as the existing information and databases are too incomplete. Therefore, the global distribution of recorded iceberg water utilization was created by searching for reports and publications on the basis of available data.

2.2. Trend Analysis Using Mann–Kendall (MK) Test

Many researchers have applied parametric and nonparametric tests to identify statistically significant trends in timeseries across various spatiotemporal scales [30]. In the current study, monthly, seasonal, and annual trends were examined for the ice sheets in the Arctic and Antarctic over the period 2005–2019, using Mann–Kendall and Sen’s slope statistical tests. These tests were applied to the data obtained from the US National Snow and Ice Data Center (NSIDC). As a nonparametric method, the Mann–Kendall (MK) test is commonly used to identify statistical significance of trends in climatic variables. MK, as a

distribution-free method with minimal assumptions, was applied here. The MK trend is assessed by the Z statistic, according to the following equation:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i), \quad (1)$$

where x_i and x_j are values in time intervals of i and j , respectively, and n is the dataset length. Sgn represents the sign function as follows:

$$\text{sgn}(\theta) = \begin{cases} +1 & \theta > 0 \\ 0 & \theta = 0 \\ -1 & \theta < 0 \end{cases}. \quad (2)$$

If the sample size exceeds 10, the statistic S is approximately normally distributed. The variance of the statistic S ($\text{Var}(S)$) is then considered as

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)}{18}, \quad (3)$$

where t is the extent of a given time, and Σ is the summation of the times. The values of S and $\text{Var}(S)$ are used in calculating the test statistic, Z , as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & \text{if } S < 0 \end{cases}. \quad (4)$$

The presence of a statistically significant trend is assessed with the Z -value. A positive value of Z shows an upward or increasing condition with time, and a negative value of Z indicates a downward or decreasing condition with time. The null hypothesis with the MK test is that there is no monotonic trend in the data. If $Z \geq Z_{1-\alpha}$ (or alternatively $Z \leq -Z_{1-\alpha}$; α is the significance level), the null hypothesis is rejected, and the alternative hypothesis that there is a monotonic increasing (decreasing) trend is accepted.

2.3. Systematic Literature Review

A systematic literature review (SLR) was conducted to evaluate the status of icebergs as an unconventional resource for freshwater supply. An SLR provides a reliable assessment of the existing literature by clearly defining search and inclusion/exclusion criteria [31]. In the present study, the SLR process started with the identification of data sources and the definition of search criteria for use in three databases (Scopus, Web of Science, and ProQuest). Published studies identified in the searches were then included or excluded from the final set of papers deemed relevant to the purpose of the study (iceberg utilization as a UWR). Finally, relevant published studies were analyzed, and the results were summarized.

2.4. Inclusion and Exclusion Criteria

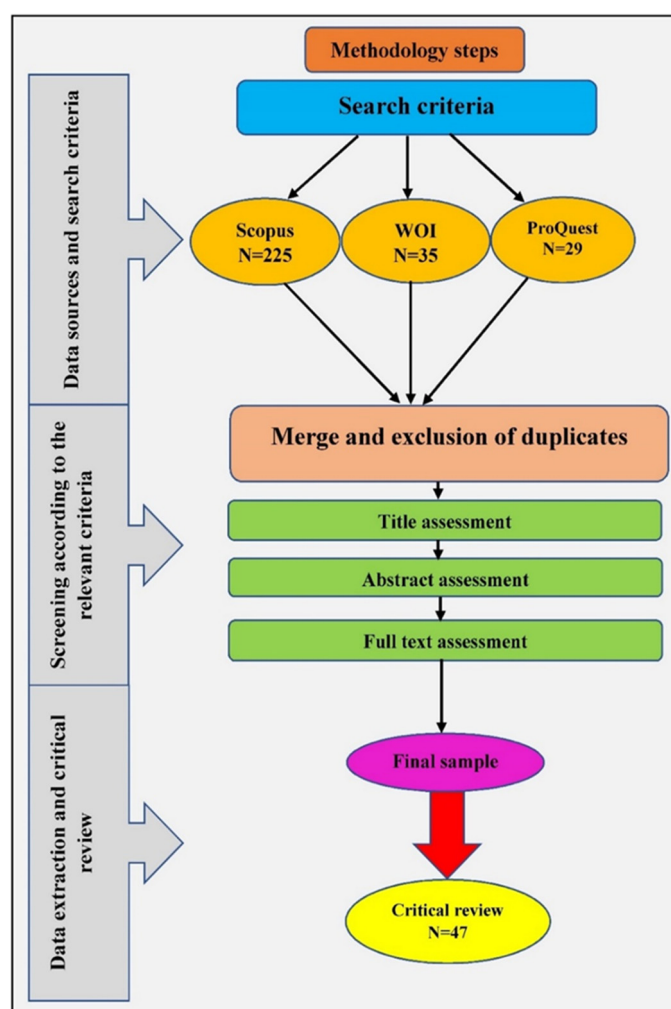
The inclusion and exclusion of published studies was performed at three different levels: (i) title and keywords, (ii) abstract, and (iii) full text, according to the main criterion that ‘the research must assess the use of icebergs for the supply of fresh water’.

In the initial search, a total of 289 published studies were located in the different databases under different search terms (iceberg towing, iceberg harvesting, iceberg water harvesting, iceberg water, and iceberg utilization) (Table 1). The search term ‘iceberg utilization’ yielded the greatest number of publications ($N = 120$), followed by ‘iceberg towing’ ($N = 107$) and ‘iceberg water’ ($N = 54$). After screening all publications in the three databases, 47 were found to be relevant to the topic of icebergs as a source of freshwater.

Table 1. Number of publications located in the three search engines using different search terms.

Keyword	Scopus	Web of Science	ProQuest	Total
Iceberg towing	80	20	7	107
Iceberg harvesting	2	0	4	6
Iceberg water harvesting	1	1	0	2
Iceberg water	35	8	11	54
Iceberg utilization	107	6	7	120
Total	225	35	29	289

The systematic procedure applied in the literature review is shown in Figure 1. Following the search, in the second step, screening was carried out according to the relevant criterion (iceberg utilization as a UWR), by title, abstract, and full-text assessment. In the third step, 47 final publications relating to the iceberg utilization as a UWR and freshwater supply were identified.

**Figure 1.** Flowchart of the systematic literature review; N = number of publications.

3. Results

3.1. Origin Country of Publications

The global distribution and trends in publications on iceberg utilization as a UWR and freshwater supply are presented in Figure 2. The 47 papers that fit the topic were published between January 1973 and September 2019. The number of papers published fluctuated annually over this period and was highest (nine publications) in 1979 (Figure 2).

The publications originated from 12 countries, with the top three countries (76.59% of total publications) to publish on this topic being USA, Canada, and Australia. USA had by far the largest number of publications (27 publications), followed by Canada (five publications) and Australia (four publications) (Figure 2). The trend in publications did not change considerably over the period, except for a drop in the 1980s.

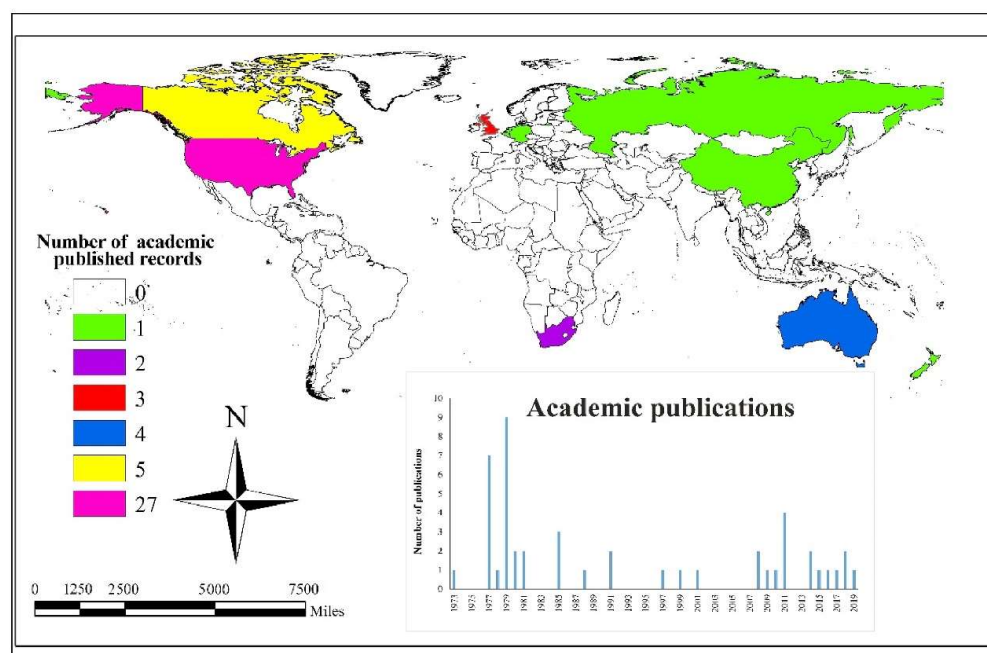


Figure 2. Global distribution and number of publications (1973–2019) on iceberg utilization as an unconventional water resource.

A brief overview of the outcome and the purpose of the 47 papers focusing on iceberg utilization for freshwater supply is presented in Table 2. Aims of these studies included the possibility of obtaining freshwater from icebergs, modeling iceberg towing, international law related to iceberg harvesting, cost analysis of iceberg harvesting, iceberg towing to water-limited areas, opportunities and challenges in iceberg water harvesting, and energy consumption in iceberg melting. Most studies (Table 2) mentioned that iceberg transport to water-deficient regions can be a solution to supply freshwater and must be considered as a solution to water scarcity in some regions. Some studies highlighted economic conditions and risks associated with iceberg towing to be major limitations in iceberg utilization (Table 2). Overall, the SLR showed that environmental impact assessment of iceberg harvesting has not received the attention it deserves in the literature.

In a complementary analysis, global trends were assessed in sea-ice sheets, to provide background information on the change in availability of icebergs at monthly, seasonal, and annual scales from 2005–2019. This information is needed to assess whether or not future investment in iceberg harvesting can be a long-term solution to water scarcity in some regions.

Table 2. Summary of results of the systematic literature review.

Authors	Study Purpose	Outcomes
[31–34]	Mathematical modeling of optimum iceberg towing and freshwater transport by sea	Low cost of iceberg transport by sea Importance of the freshwater from icebergs.
[10,35]	Possibility of freshwater supply using bags of iceberg	Freshwater obtained from icebergs would reduce water stress
[36–39]	International law related to the iceberg harvesting	Feasibility of iceberg utilization by oceanographers, meteorologists, and glaciologists
[40–43]	Cost assessment of iceberg water utilization	Iceberg harvesting has high costs and risks associated with iceberg towing
[15,28,44–54]	Towing icebergs as unconventional water resource to arid areas in terms of technical aspects	Technical and economic comparisons should be considered
[28,55–60]	Opportunities and challenges of iceberg water harvesting	Icebergs have never been considered a main source of drinking water
[23,61–65]	Investigating the requirements of iceberg water harvesting and sustainability of iceberg water	Practical utilization of icebergs depends on political and economic factors
[66–69]	Measurement of thermal conduction to the iceberg for melting	Using temperature gradients in seawater and ice, together with regression rates, an energy balance was calculated for regressing ice/water interface
All studies were conducted considering iceberg water utilization as a water supply.		

3.2. Global Trends in Ice Sheet Area

The nonparametric Mann–Kendall (MK) trend test [70–72] is commonly used to identify significant and nonsignificant trends in climatic variables [73–75]. In this study, the MK test was employed to assess trends in ice sheet area over the Antarctic and Arctic. Polar ice sheets are significant indicators of climate change, as they respond to raised temperatures with increased melt, enhanced mobility, and increased iceberg calving [76]. The MK test and Sen’s slope estimator results, using data obtained from the NSIDC, indicated that ice sheet area significantly decreased in the Arctic region across all months during 2005–2019. Ice sheet area over the Antarctic region did not show a significant decreasing or increasing trend during February, June, July, August, September, October, and December between 2005 and 2019 (Figure 3; Table 3). The MK test results for seasonal scale showed that all seasons (spring, summer, autumn, and winter) experienced significant decreasing trends in ice sheet area in the Arctic region. However, over the Antarctic region, the results indicated that significant changes (decreasing trend) only occurred in spring, summer, and autumn (winter had a nonsignificant decreasing trend) during 2005–2019 (Table 3).

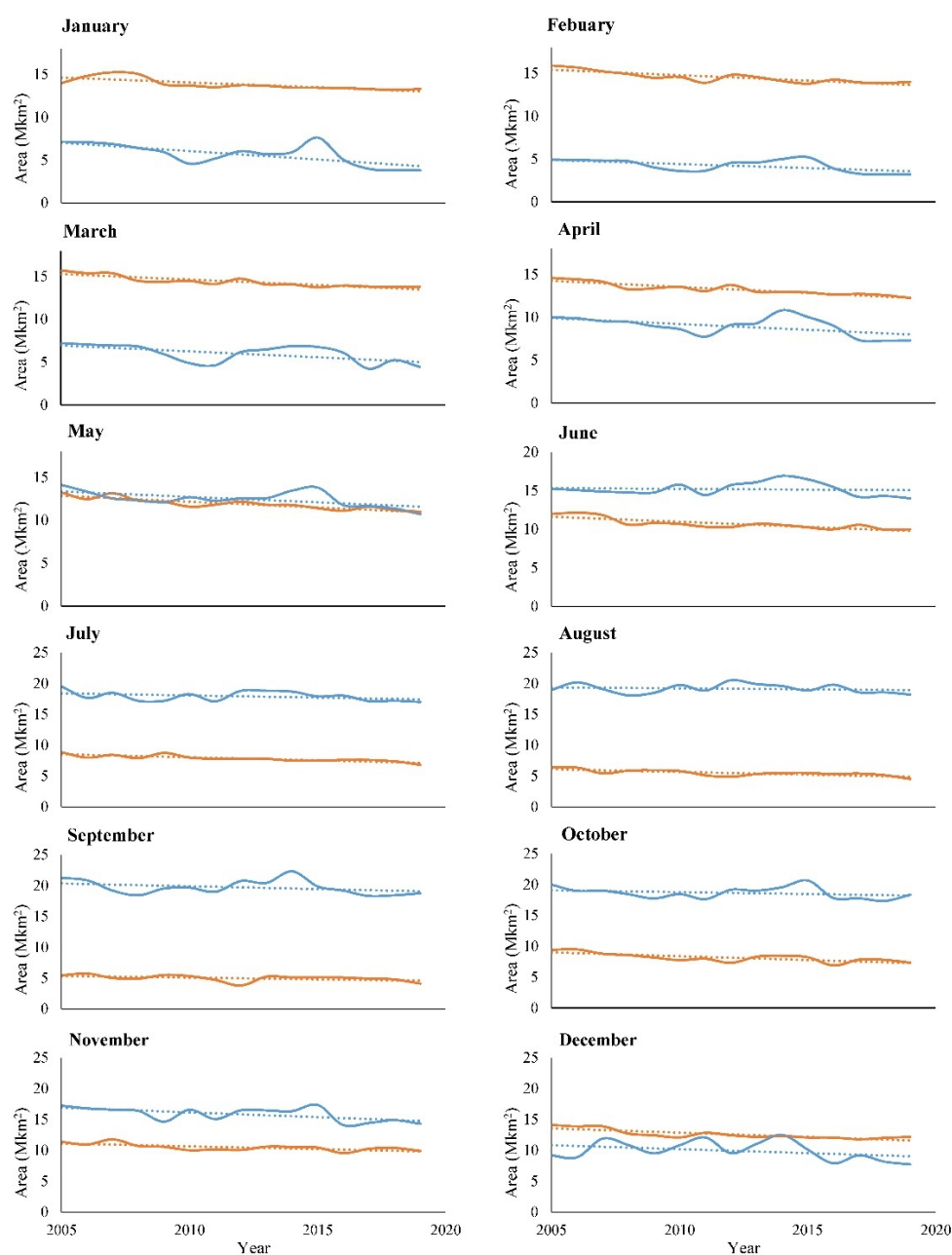


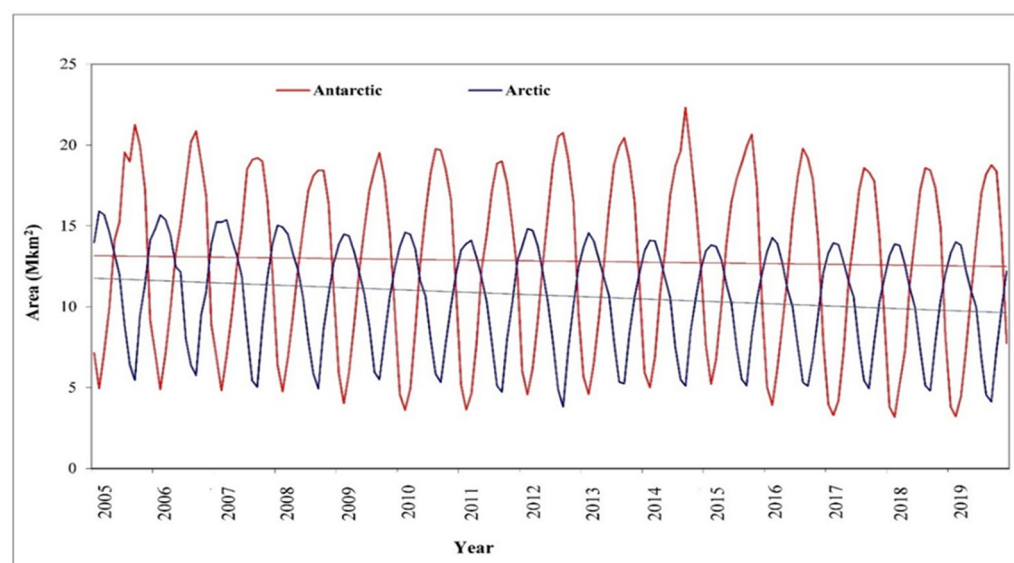
Figure 3. Monthly changes in ice sheet area over the — Arctic and — Antarctic regions during the 2005–2019 period.

Significant decreasing trends in ice sheet area at the annual scale were observed for both regions during 2005–2019 (Table 3, Figure 4).

Overall, the results indicated a decreasing trend in ice sheet area that has been more prominent in the Arctic than in the Antarctic. The annual rate of change in iceberg area was 0.113 and 0.122 million km² per year for the Antarctic and Arctic regions, respectively. From a seasonal point of view, the rate of decrease in ice sheet area in winter was not significant, while warmer seasons, especially summer, showed a significant rate of decrease, especially in the Antarctic. This could be due to the considerable impact of global warming in warmer seasons [77]. A recent study on the impact of climate change on icebergs reported that global warming has increased the melting rate of icebergs in both the Arctic and Antarctic regions [78]. Overall, our analysis indicated a higher iceberg melting rate in the Arctic than in the Antarctic region.

Table 3. Mann–Kendall (SK) test and Sen’s slope estimator (Sen) results for the significance of trends in monthly and seasonal ice sheet area in the Arctic and Antarctic from 2005–2019.

Arctic				Antarctic			
Timeseries	MK	<i>p</i> -Value	Sen	Timeseries	MK	<i>p</i> -Value	Sen
January	−4.2064	0.0000	−0.0774 **	January	−3.2167	0.0013	−0.2016 **
February	−3.5136	0.0004	−0.1347 **	February	−2.2269	0.0260	−0.0830 **
March	−4.1074	0.0000	−0.1094 **	March	−2.7218	0.0065	−0.1446 **
April	−4.3054	0.0000	−0.1441 **	April	−2.3259	0.0200	−0.1657 *
May	−4.1074	0.0000	−0.1307 **	May	−2.2269	0.0260	−0.1450 *
June	−3.6126	0.0003	−0.1180 **	June	−0.8413	0.4002	−0.0551
July	−4.0629	0.0000	−0.0940 **	July	−1.4864	0.1372	−0.0666
August	−3.0187	0.0025	−0.0889 **	August	−0.8413	0.4002	−0.0391
September	−2.3259	0.0200	−0.0656 **	September	−1.5341	0.1250	−0.1016
October	−2.9197	0.0035	−0.1325 **	October	−1.0392	0.2987	−0.0768
November	−2.8208	0.0048	−0.0921 **	November	−2.6228	0.0087	−0.1511 **
December	−3.6126	0.0003	−0.1304 **	December	−1.1382	0.2550	−0.1425
Winter	−4.1074	0.0000	−0.1210 **	Winter	−0.9403	0.3471	−0.0290
Autumn	−4.4044	0.0000	−0.1286 **	Autumn	−2.6228	0.0087	−0.1568 **
Spring	−3.9095	0.0001	−0.1091 **	Spring	−2.0290	0.0420	−0.1020 *
Summer	−3.4146	0.0006	−0.0889 **	Summer	−2.0290	0.0425	−0.1015 *
Yearly	−4.5033	0.0000	−0.1135 **	Yearly	−2.3259	0.0200	−0.1221 *

Statistical significance: * $p < 0.05$, ** $p < 0.01$ **Figure 4.** Annual changes in ice sheet area over the Arctic and Antarctic regions during the 2005–2019 period.

3.3. Opportunities and Challenges

The practical advantage of iceberg water utilization lies in the supply of freshwater to water-deficient regions by iceberg towing or through bagged melted iceberg water [79]. The main environmental advantage of iceberg utilization as a freshwater resource lies in its limited environment impacts and potential mitigation of the environmental problems at or near the ice source area and the destination [80,81]. Another benefit of iceberg utilization is creating new jobs, such as working in factories related to iceberg harvesting or as crew on ships towing icebergs [82]. Additionally, harvesting icebergs from regions near or at coastal areas can help reduce the risks of icebergs colliding with offshore structures [83]. Some studies indicated that water harvesting from icebergs can help reduce the rate of

sea-level rise due to global warming by utilizing the water before it melts into the ocean, although the magnitude of this effect is small in relation to sea-level rise [84,85].

On the other hand, the greatest challenge of iceberg utilization lies in the transport of a large iceberg over the ocean. Icebergs are a tremendous hazard to naval transportation [86], and their transport is associated with other disadvantages, including water and air temperature disturbances [87,88]. There are also possible direct impacts on the fauna and flora in habitats on the iceberg transport path [89,90]. The presence of icebergs has implications for the design of offshore and onshore structures, and it is most important to determine the iceberg intrusion probability into offshore oilfields [91,92]. It is also important to consider changes in ocean current velocity and rising sea-ice volume [93,94]. Grounding and scouring of drifting ice can disturb both shallow and deep polar seafloor habitats [31,95,96].

Icebergs cannot be considered a main source of drinking water since the provision of freshwater from icebergs is associated with high costs and transportation risks [59]. At source, icebergs are a renewable supply of high-quality water that is available in large quantities, but their transport exposes them to pollution, requiring treatment before direct use [47,97].

4. Discussion

This study reviewed the use of icebergs as a freshwater resource. A number of studies and reports identified in the SLR ($N = 47$) assessed the feasibility of icebergs as an alternative source of freshwater supply [64,79,98–100]. Some studies warned that towing an iceberg from the Arctic or Antarctic to a water-deficient region may not be a practical solution to global water deficiencies [10], while others pointed out that it may even worsen the problem by artificially increasing water demands [101,102].

Iceberg towing not only requires processing facilities but should also be carefully analyzed in terms of its economic justifiability, considering aspects such as locating a suitable source through remote sensing, computing the towing power requirements, and accounting for the melting rate during the transport to the destination [10,92].

Our literature review of studies published between 1973–2019 showed that scientific publications on iceberg harvesting decreased after 1980s. This might imply that scientists could not rely on iceberg water as a complementary resource for freshwater supply. In the first conference on iceberg utilization [25], it was pointed out that iceberg transportation projects are expensive, and some are not economically justifiable. However, the economic feasibility of iceberg water harvesting depends on the cost and location of the icebergs and the climate at the source and target locations [10,83]. For example, in some regions, including in Newfoundland (Canada), iceberg water harvesting is the main occupation for local people, due to its geographical position with high potential for iceberg occurrence along coastlines [43]. The pristine water from melted icebergs is bottled in high-quality designer bottles and sold as a luxury product. An example of water used as a luxury commodity is Svalbarði iceberg water [103].

Lastly, the results of this present demonstrated a decreasing trend in ice sheet area from 2005–2019 and showed that the trend has been more significant in the Arctic than in the Antarctic region. Therefore, global warming has not only significantly increased water stress and reduced water availability, but also impacted secondary sources of freshwater such as icebergs in the Arctic and Antarctic. It is noteworthy that a massive volume of freshwater enters the saline seas each year as a result of iceberg melting due to global warming. Spandonide [48] estimated that the amount of iceberg water that drains into the sea annually is 3000 km^3 , which is close to the world's annual consumption of freshwater (3300 km^3). Screen and Simmonds [104] concluded that the Arctic region has experienced greater warming than the Antarctic region. The warming in both regions has caused increased water temperatures and severe sea-ice loss [105,106].

5. Conclusions

The concept of iceberg water utilization as a freshwater resource may have a long history, but it has not yet been comprehensively investigated. This study analyzed variations in sea-ice area over the Arctic and Antarctic in recent decades and assessed challenges and opportunities in iceberg utilization, as well as the feasibility of iceberg harvesting as an unconventional water resource. Novel contributions of this study are (i) a systematic literature review (SLR) showing that the use of icebergs as a source of freshwater has been tested since 1773 and studied scientifically since at least 1973, (ii) an analysis of 47 published studies investigating iceberg water utilization as a UWR across the globe, (iii) a summary of challenges and opportunities associated with iceberg utilization, showing that costs and risks of iceberg towing to coastlines may be too high even for rich countries, (iv) evidence that the United States, Canada, and Australia are the main sources of scientific publications on iceberg harvesting, (v) identification of economic conditions and risks associated with iceberg towing as the main limitation of iceberg utilization, and (vi) identification of a lack of research on environmental impacts of iceberg water utilization. For the direction of future studies, providing methods to prepare quantitative information about iceberg water utilization can help inform adaptation to a warming climate and mitigate some of water shortage problems.

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Abbreviations

Unconventional water resource	UWR
Web of Science	WOS
National Snow and Ice Data Center	NSIDC
Mann–Kendall	MK
Systematic literature review	SLR

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