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Editorial

Cold Region Ice/Snow Actions in Hydrology, Ecology and Engineering

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Citation: Li, Z.; Li, F.; Tavakoli, S.; Liu, X.; Dai, C. Cold Region Ice/Snow Actions in Hydrology, Ecology and Engineering. *Water* **2024**, *16*, 689. https://doi.org/10.3390/w16050689

Received: 1 February 2024
Accepted: 19 February 2024
Published: 27 February 2024

1. Introduction

In the Earth's hydrosphere, 96.50% of the total mass is composed of seawater, while the remaining 3.50% is freshwater. Much of the sea water freezes into sea ice, either seasonally as first-year ice, or over the long term as multi-year ice. Among fresh water, 77.44% exists in the form of ice/snow at the polar regions [1]; comparatively little ice/snow is found in other inland cold regions. Throughout the course of human development, the ice/snow from the Quaternary glacial period has played an essential role in changing and evolving human life, involving handling and accommodating with ice/snow via multiple means. Some scholars consider the climatic changes at the end of the Quaternary ice age as essential prerequisites for the development of Homo sapiens civilization [2]. Scholars have also connected the fluctuations in grain production caused by modern climate variations with dynastic changes [3]. This is because ice/snow is an integral part of human activities, closely linked to water sources, food, transportation, entertainment, and eventually human development [4]. With the progress of science and technology, human understanding of nature and the ability to handle ice/snow has improved, prompting research into the various phenomena and essence of ice/snow that serve human activities. These indicate that ice and snow research has been standing as a critical frontier in the context of hydrology, ecology, and engineering.

According to IPCC WGI AR4 (2007), the main components of the cryosphere are snow, river and lake ice, sea ice, glaciers and ice caps, ice shelves, ice sheets, and frozen ground, which are all changing under global warming [5]. As the freezing point of ice/snow (−12.8–0 °C) falls into the variation range of atmospheric temperature, phase changes happen along with the temperature varying between minus and plus degrees Celsius, exhibiting sensitivity to temperature. During recent years, as global warming continues, challenges have emerged regarding frozen landscapes following the change in snow/ice. Currently, global warming profoundly alters ice and snow dynamics worldwide, accelerating the melting of glaciers, diminishing polar ice caps, and reducing snow cover. Ice in the polar region becomes more dynamic and more multiyear ice drifts to lower altitude due to melting. The ice cover in the cold regions becomes warmer and its mechanical properties significantly change [6].

In the past, humans primarily used glaciers for agriculture, domestic water supply, and, as an exclusive form of luxury consumption, for tourism and exploration. As human activities extended to Greenland and the Antarctic interior, the role of glaciers have become further elevated, connected to records of climate change. Notably, ice core research has become a crucial aspect of this [7]. These polar expeditions and studies require ice structures, roads, airports, and other logistical support closely related to supply chains [8]. The instability of ice caps caused by climate warming has motivated scientists to link ice caps, ice shelves, and icebergs to ocean circulation, forming a larger-scale atmosphere–ice–water system. Atmospheric circulation, ocean circulation, biological migration, and more are all encompassed within this system. Scientifically subdividing the atmosphere–ice–water system into different scales has given rise to emerging fields such as ice meteorology, oceanography, and sea ice science. Meanwhile, humanity's desire to rationally utilize fisheries, mining, and transportation in ice-covered regions has sparked enthusiasm for ice engineering. New research topics, such as offshore wind power generation and solar panels in ice-covered areas, have emerged in addition to traditional navigation and drilling in ice. Moreover, the ocean, covering two-thirds of the Earth, is considered a crucial carbon sink, resulting in great potential in polar fishery.

The extensive expansion of human activities and resource utilization needs has reached more ice/snow areas. Scientific understanding and technology development are necessary to cope with the challenges posed by ice/snow. Engineers working on projects ranging from buildings and bridges to power lines and transportation systems must stand with the mechanical properties of ice, ensuring structures are resilient in the face of evolving climates. The ice cover above polar waters exerts a profound influence on the underwater ecosystem, shaping the conditions for marine life. Climate change-induced alterations to ice cover disrupt these dynamics, affecting species' behavior, migration patterns, and overall ecosystem health. The delicate balance between ice cover and the underwater environment underscores the vulnerability of polar ecosystems in the face of global climate change. The threat of ice flood disasters is big in regions prone to freezing conditions. Understanding the triggers and patterns of ice-related flooding is crucial for engineering effective preventive measures and emergency response strategies. Balancing the need for sustainable development with the risks posed by changing ice dynamics requires a holistic approach that integrates climate science, ecology, and cutting-edge engineering solutions.

To understand the implications of climate change to our ecosystem to maintain sustainability, and its effect on the engineering world to guarantee safety and mitigate risks, it is important to understand the change in the physical, thermal, mechanical, optical, and electrical properties of crystal ice/snow and the melting water from ice/snow, as well as permafrost. After our previous Special Issue, "Sea, River, Lake Ice Properties and Their Applications in Practice" [9], this Special Issue, entitled "Cold Regions Ice/Snow Actions in Hydrology, Ecology and Engineering", intends to continue research under this context. It invites researchers from different fields to investigate ice/snow-related problems in hydrology, ecology and engineering and publish their results. In this Special Issue, we focus on the physical and mechanical properties of ice and snow, as well as their impact on hydrology, ecology, and engineering. This Special Issue can guide future ice science and engineering in polar regions under climate change. The scope also includes theoretical studies and practical applications of various snow/ice properties in remote sensing, investigation, experiments, and numerical modeling in cold region snow/ice formation and melting processes in water bodies and permafrost, its contributions to the ecosystem, and behaviors in engineering and entertainment.

2. List and Summaries of the Contributions

This Special Issue received 15 manuscripts and all of them were subject to the rigorous *Water* review process. In total, 12 papers were finally accepted for publication and inclusion in this Special Issue. The contributions are listed in List of Contribution.

As shown in Table 1, the contributions covered wide perspectives concerned with ice. The contents of these published papers are snow and ice identification, snow and ice growth, the mechanical properties of ice and snow, the thermal diffusivity of ice, ice condition monitoring, ice flood disaster, and ecosystems under ice.

Table 1. Analysis of the published contributions in the Special Issue.

Number of Contribution	Research Area	Focus	Research Methods	Potential Applications
1	River ice characteristics	Real-time monitoring of river surface ice dynamics	Image processing	Hydrology
2	Sea ice characteristics	Polar objects, e.g., ice floe, identification from remote sensing and onboard images	Image processing	Sea ice engineering
3	Snow characteristics	Cloud removal to recover snow coverage by machine learning from remote sensing image	Image processing	Remote sensing and new technology
4	Snow formation	Snow Crystal Necks and the Effect on Hardness	Experiment	Snow engineering
5	Sea ice formation	Temperature and ice growth	Data collection and statistics	Sea ice engineering
6	Ice thermal properties	Review of research on thermal diffusivity of ice	Literature review	Ice engineering
7	Model ice mechanical properties	Mechanical property of model ice	Experiment and simulation	Ice engineering
8	Snow mechanical properties	Mechanical property of snow	Experiment	Snow engineering
9	Snow/ice mechanical properties	Property and topology of brash ice and its effect on mechanics	Experiment	Ice engineering
10	River ice engineering conditions	Risks of ice flood disaster	Catastrophe theory	River ice engineering
11	Sea ice engineering design conditions	Change of ice characteristics in the Bohai Bay	Data statistics	Sea ice engineering
12	Ecosystem under ice	Productivity of the ecosystem under ice cover	Simulation	Ecological service in cold regions

3. An Overview of Published Articles

As listed in Section 2, research topics related to ice/snow in the field of hydrology, ecology and engineering are all covered by the published articles. An overview of these articles is provided here.

Ice/snow engineering problems are often investigated through experimental or numerical modeling methods, e.g., [10,11], which usually assume an idealized ice field. To support engineering applications, it is of equal importance to identify and understand complex ice/snow fields in nature. Image technology has been developed a lot over recent years for real ice/snow conditions [12]. In-depth understanding of measurement data, in addition to theoretical analysis, has seen a rise in artificial intelligence (AI) and machine learning as new technologies. AI and machine learning are now widely applied to analyze the patterns, mechanisms, and trends in various natural phenomena with a certain level of randomness. As temperature-sensitive materials, ice/snow can benefit from AI and machine learning to assist in extracting valuable insights from available data resources, exploring the relationships between ice behavior and the main controlling factors, as well as numerous secondary controlling factors [13]. Three papers were published on the topic of snow and ice identification using machine learning or artificial intelligence. Yang et al. (Contribution 1) presented a comprehensive approach to the real-time monitoring of river surface ice dynamics using deep learning methods and camera imagery. Focusing on the Nenjiang River in China, the study introduces a four-step methodology. First, image preprocessing involves calibrating camera images to real-world coordinates. Subsequently, a lightweight semantic segmentation network is employed to identify ice and water pixels, facilitating the calculation of ice concentration and area. The motion detection process is enhanced using the segmentation results, and the particle video tracking algorithm is adapted for ice velocity measurement through a novel tracking point generation strategy. The research, encapsulated in the IPC_RI_IDS dataset, contributes to our understanding of ice break-up processes. The goal is to support real-time short-term forecasts of ice floods by analyzing surface ice data and predicting the stages of the ice break-up process. The innovation of this approach is to address previous limitations in tracking river ice velocity, providing valuable insights for mitigating risks associated with ice blockages in water routes. In addressing the safety concerns of ship navigation in polar regions, Ding et al. (Contribution 2) emphasize the need for the prompt detection of sea ice, icebergs, and passing ships. Recognizing the limitations of individual data sources, they construct a comprehensive polar multi-target local-scale dataset with categories such as sea ice, icebergs, ice melt ponds, icebreakers, and inter-ice channels. Using a single-shot detector (SSD), they achieved a final mean average precision (mAP) value of 70.19%. The study further presents a remote sensing sea ice dataset with 15,948 labels, enhancing the You Only Look Once (YOLOv5) model with advanced features. Through ablation experiments, the improved YOLOv5 demonstrated notable enhancements, surpassing other models like YOLOv3 in performance. This facilitates the detection of multiple targets on various scales in polar regions, promoting data fusion and providing valuable support for polar ship path planning. Zhu et al. (Contribution 3) presented a novel approach for fine-spatiotemporal-resolution snow monitoring at the watershed scale, crucial for effective snow water resource management. They proposed a cloud removal algorithm based on snow grain size (SGS) gap-filling using a space–time extra tree. This addresses the limitation of cloud occlusion in long-time-series snow products, enhancing coverage and time resolution. The study focused on the Kaidu River Basin (KRB) and incorporated spatiotemporal information into dimensional data to characterize geomorphic features and snow duration. By training a spatiotemporal extreme tree model, the nonlinear mapping relationship between multidimensional inputs and SGS was simulated. This method demonstrated effectiveness, particularly when cloud cover was below 70%, achieving satisfactory SGS estimation and successful snow cover reconstruction. Compared to traditional methods, the proposed approach exhibited superior detail characterization and performance in complex mountainous environments, resulting in a significant reduction in cloud coverage and an increase in snow coverage from 2000 to 2020. This advancement in cloud removal significantly improved the time resolution of snow cover data without compromising accuracy.

The growth of ice/snow is an important topic relating meteorology to engineering. Ice/snow is a product of a cold environment. Its formation is closely related to hydrological and meteorological conditions. New research results have continuously emerged on the freezing processes of different types of water bodies in different environments, and even beyond natural environmental conditions [14,15]. This Special Issue published two relevant articles, focusing on the current natural environmental conditions of snow morphology and the processes of ice formation and melting. Two papers focus on the topic of snow and ice growth. Wei et al. (Contribution 4) conducted a constant-density (200 $\mathrm{kg/m^3}$) snow metamorphism experiment to investigate the snow microstructure at different metamorphism times and isolate the snow neck area. Their findings highlighted the significant influence of temperature, solar radiation, snow density, and specific humidity on the neck region, with wind speed having a minimal effect. In response to atmospheric forcing, the authors developed a multiple linear regression equation, "$S = 288T + 2E + 189\rho + 12{,}194V - 20{,}443RH - 42{,}729$", where solar radiation (E), temperature (T), snow density (ρ), specific humidity (RH), and wind speed (V) collectively explained 84% of the neck area variability. Notably, the correlation between snow hardness and the neck area reached 71%, potentially rising to 91% in later metamorphic stages. A predictive model for hardness based on the neck area, "$H = 0.002764S + 67.922837$", was established. This study provides insights into the growth variations in the metamorphic snow cover's neck region, illustrating how external factors impact both microstructure and macroscopic physical characteristics. During the winters of 2009/2010 and 2020/2021, Ma et al. (Contribution 5) conducted observations at an eastern port of Liaodong Bay to investigate variations in sea ice thickness and atmospheric conditions. Two main observation items, daily ice thickness (DIT) and cumulative ice thickness (CIT), were studied. For DIT, sea ice thickness gradually decreased with rising temperatures, with a freezing rate of $1.48\ \mathrm{cm/(°C \cdot d)^{1/2}}$. Concerning CIT, at −12 °C, the maximum growth rate decreased from 3.5 cm/d to 1.5 cm/d as ice thickness increased from 0 to 20 cm. The study applied the residual method to calculate oceanic heat flux, a crucial parameter in ice modeling. Both analytic (Stefan's law) and numerical models (high-resolution thermodynamic snow-and-ice model) were employed. Results indicated a high simulation accuracy with a growth coefficient in the analytic model. The numerical model, with an oceanic heat flux of $2\ \mathrm{W \cdot m^{-2}}$, showed a maximum error of 60% in 2010 and 3.7% in 2021. Using the calculated oceanic heat flux, errors were significantly reduced to 4.2% in the winter of 2009/2010 and 1.5% in 2020/2021. Furthermore, the oceanic heat flux in Liaodong Bay exhibited a decreasing trend with increasing ice thickness and air temperature.

In ice/snow engineering, the mechanical properties and response of materials form the basis of engineering mechanics. The thermodynamics of ice are the first factor determining its mechanical properties. As a material formed through natural process, the mechanical properties of ice and snow have long been a challenging problem yet to be solved. Exploring the properties and behaviors of multiphase ice/snow with phase transitions is crucial, especially under the influence of climate change, particularly in the case of global warming [6]. Thorough research on the thermodynamics and mechanical behaviors of ice/snow in these contexts is still necessary [16]. Ongoing studies in this area continue to explore and advance our understanding. In this Special Issue, one paper focuses on the physical properties of ice, specifically the thermal conductivity, and three papers relate to the mechanical properties of snow and ice. Li et al. (Contribution 6) presented a review of ice thermal parameters, essential for accurately simulating ice phenology, distribution, and thickness—a facet considered a "vulnerable group" in ice research. Despite the perceived technical simplicity, the authors emphasized the complexity of obtaining accurate ice thermal property parameters, necessitating a rigorous research process. While progress in understanding the thermal conductivity of ice in China stagnated after explorations in the 1980s, the current century introduced mathematical methods. In this study, inversion identification and analysis utilized time-series data from in situ testing of vertical temperature profiles in ice layers to derive thermal diffusivities for different natural ices. Cross-validation demonstrated variations in thermal diffusivity due to impurities within unfrozen water among ice crystals. The paper highlighted the importance of parameterizing thermal diffusivity in the phase transition zone of ice under the influence of global warming trends. Future research directions were envisioned, encompassing the physical mechanisms, application value, and parameterization schemes for the thermal diffusivity of natural ice. Tian et al. (Contribution 7) presented a study on the flexural strength of columnar saline model ice, crucial for designing structures in ice-infested waters. Conducted at the China Ship Scientific Research Center, circular plate center loading tests explored varied loading rates and ice temperatures. Using FEM and LS-DYNA, a numerical model validated and compared the results, unveiling crack propagation, stress distribution, and failure modes. The model ice exhibited typical brittle failure, with flexural strength linearly linked to temperature and no significant correlation with loading rate. Porosity influenced load response and failure time, but not the failure mode. Specifically, 7% porosity resulted in a 7.8% reduction in load response compared to nonporous ice. This research establishes a method for analyzing model ice flexural strength, laying a foundation for the further exploration of structure–ice sheet interactions. Han et al. (Contribution 8) addressed the limited understanding of snow's mechanical properties, crucial for polar infrastructure construction. Uniaxial compression tests under step loading were conducted to investigate snow behavior in cold regions. Using the Maxwell model, constitutive equations were developed, incorporating different temperatures, densities, and loading rates. Findings revealed that loading rates had no significant impact on snow's elastic modulus and viscosity coefficient. Both parameters exhibited an exponential relationship with density, increasing with higher density. As temperature decreased, the elastic modulus and viscosity coefficient initially declined and then increased, though no specific functional relationship was identified. Notably, a novel constitutive equation, accounting for snow density, was derived based on the Maxwell model, contributing to a more comprehensive understanding of snow mechanics in polar environments. Zhaka et al. (Contribution 9) conducted a comprehensive study to address the critical differences between brash ice and surrounding level ice, crucial for understanding full-scale brash ice channel development. This research, spanning the winters of 2020–2021, 2021–2022, and 2023, focused on channels near the Bay of Bothnia, Luleå, Sweden. Measurements included snow, slush, and total ice thickness, along with analyses of ice microstructure and strength. Notably, this is the first paper reporting on the influence of snow in brash ice channels. The study revealed that snow covered the channels between ship passages, submerging and forming slush-filled voids after each passage. These voids then transformed into snow ice (SI) clusters frozen with columnar ice. Image analyses estimated SI content in brash ice, highlighting varying percentages in different locations, providing valuable insights into the complex dynamics of brash ice channels.

To cope with the impact of ice and snow on human activities, structural or non-structural measures have been adopted. This is the common practice in ice and snow engineering. Many research outcomes have been achieved for various engineering types, covering aspects related to both ice and snow and the use of structures, such as ice navigation, offshore wind farms, ports, reservoir dams, and more [17–19]. These studies encompass research on both ice conditions and the types of structures involved. This Special Issue published two articles with a specific focus on ice conditions. In the field of hydrology, one research article focuses on the ice flood disaster. Li et al. (Contribution 10) established a risk evaluation system for ice flood disasters, prevalent in frigid high-latitude and high-altitude regions, posing threats to personal and property safety through ice dam or ice jam flooding. Utilizing catastrophe theory and the Pearson correlation coefficient, the study aims to provide a comprehensive and necessary risk assessment for preventing ice flood disasters. The system incorporates hierarchical cluster analysis to simplify indicators and select typical years based on correlations. Results reveal catastrophe membership values in the Mohe, Tahe, and Huma regions from 2000 to 2020 ranging from 0.86 to 0.93. The evaluation system, coupled with actual disaster situations, yielded a four-level classification of risk ratings. A comparison with the fuzzy comprehensive evaluation method demonstrates similar risk levels, affirming the effectiveness and practicality of applying catastrophe theory to ice flood risk evaluation. This study introduces a novel method for studying and understanding ice floods. One research article focuses on the change in ice characteristics in the Bohai Bay. Li et al. (Contribution 11) investigated the safety of winter activities in the Bohai Sea, emphasizing the need for more detailed information on ice characteristics and a refined ice zone division. Utilizing a $1/12^{\circ}$-resolution sea ice characteristic dataset derived from the NEMO-LIM2 ice-ocean coupling model, which assimilated MODIS satellite sea ice observations spanning 2005 to 2022, new sea ice hindcasting data was obtained. These data facilitated the analysis of ice period, thickness, concentration, temperature, salinity, and design ice thickness for various return periods in a $1/4^{\circ}$-resolution refined zoning. The findings, compared with the previous 21-ice-zone standard, revealed a significant reduction in ice conditions along the west coast of the Bohai Sea, emphasizing the importance of updated information for enhancing safety measures in winter maritime activities.

Under meteorological conditions, especially driven by solar radiation flux penetrating through the ice, understanding how the ecological environment under ice responds and how changes in the ice cover, influenced by climate change, correlate with the water ecological environment under ice has become an important issue in the context of recent climate change [20,21]. This has received lots of attention, and this Special Issue also published a relevant article. In the field of ecology, one research article focuses on the ecosystem under ice cover. Zhang et al. (Contribution 12) employed a Vertically Generalized Production Model (VGPM) suitable for ice-covered periods to investigate the complete change process of primary productivity in a temperate lake, shedding light on the connection between ice physical characteristics and biological production. Despite the significance of primary productivity in understanding the impact of global warming on temperate lake ecosystems, few studies have delved into the entire change process during the ice-covered period. The study focused on Hanzhang Lake, revealing a substantial primary productivity level (189.1 ± 112.6 mg $C \cdot m^{-2} \cdot d^{-1}$) under the ice. Contrary to common assumptions, phytoplankton production under the ice was not severely restricted by light; instead, water temperature emerged as a more crucial factor influencing primary productivity changes compared to light conditions. The research provided insights into the variability of primary productivity throughout the entire ice-covered age, enhancing understanding of how warmer temperatures affect the aquatic environment of lakes in seasonal ice-covered areas.

Author Contributions: Writing—original draft preparation, Z.L.; writing—review and editing, F.L., S.T., X.L. and C.D. All authors have read and agreed to the published version of the manuscript.

Funding: This organization of this Special Issue was supported by different projects from National Natural Science Foundation of China (grant numbers U23A2012, 52301331, 42207088, 51979024).

Conflicts of Interest: The authors declare no conflicts of interest.

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