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Concept Paper

Sustainable Ice-Jam Flood Management for Socio-Economic and Socio-Ecological Systems

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Abstract: Ice jams are critical components of the hydraulic regimes of rivers in cold regions. In addition to contributing to the maintenance of wetland ecology, including aquatic animals and waterfowl, ice jams provide essential moisture and nutrient replenishment to perched lakes and ponds in northern inland deltas. However, river ice-jam flooding can have detrimental impacts on in-stream aquatic ecosystems, cause damage to property and infrastructure, and present hazards to riverside communities. In order to maintain sustainable communities and ecosystems, ice-jam flooding must be both mitigated and promoted. This study reviews various flood management strategies used worldwide, and points to the knowledge gaps in these strategies. The main objective of the paper is to provide a framework for a sustainable ice-jam flood management strategy in order to better protect riverine socio-economic and socio-ecological systems. Sustainable flood management must be a carefully adopted and integrated strategy that includes both economic and ecological perspectives in order to mitigate ice-jam flooding in riverside socio-economic systems, while at the same time promoting ice-jam flooding of riverine socio-ecological systems such as inland deltas.

Keywords: ice jam flooding; sustainable flood management; socio-economic system; socio-ecological system

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1. Introduction

Ice jams are a natural phenomenon in the rivers of cold regions that usually occur during spring ice cover breakup and in mid-winter in temperate regions. An ice jam forms when incoming ice floes along a reach are arrested by an obstacle (for example, existing ice blocks or river meanders), which constricts the channel, rendering it incapable of transporting the ice downstream. Hence, an ice jam resists the incoming river flow, raising water levels and overflowing the river banks [1]. Ice jams can be several metres thick and can extend for many kilometres along a river, often creating floods that are more severe than open water floods. Due to the high water levels, unusual velocities, and complex formation mechanisms of ice-induced floods, damage, injuries, and deaths to humans occur more frequently in these types of floods than in open-water floods. Ice-jam flood events are common in northern Canada, and have been documented around the world, such as for instance in the United States (US) [2,3], Finland [4], Iceland [5,6] Norway [7], Germany [8], Sweden [9], Russia [10,11], Japan [12], and China [13,14]. Most of these studies have focussed on the effects of ice-jam floods on riverine socio-economic systems; other studies have specifically investigated the impact of ice-induced floods on socio-ecological systems [15–21]. These latter studies show that the ice-induced flood is an important hydrological factor in maintaining sustainability in riverine socio-ecological systems in Canada.

Ice jams play a critical role in riverine communities and ecosystems in cold regions, as ice jam-related flooding can provide essential replenishment to perched lakes and ponds in inland deltas [15,22]. River ice jams can also cause devastating flood events, leading to detrimental impacts on aquatic ecosystems (for example, reduced fish habitat), property, and infrastructure (for example, damage to homes, bridges, roads, and businesses), and the loss of human life [23,24]. A previous study suggested that flow regulation and climatic variations increase the risk of extreme flood events to riverside communities [23], while at the same time reducing the frequency of ice jam-related flooding in inland deltas [15,25–28]. Hence, inland deltas have experienced prolonged dry periods and a reduction in wetland areas [16,17]. Therefore, ice-induced flood management requires the consideration of two measures: (1) the mitigation of ice-jam flooding in riverside urban communities, and (2) the promotion of ice-jam flooding in riverine ecosystems (for example, inland deltas), especially rivers, where both socio-economic and socio-ecological systems need to be equally maintained. A socio-economic system is a network of social and economic services that provides society with development, business, education, and homes, whereas a socio-ecological system is a network of interrelated processes that provide society with ecological services such as food, energy, water, and biodiversity. Determining an ice-jam flood management strategy could prove to be beneficial should the paucity of future ice-jam flooding or increases in prolonged drying in northern inland deltas occur due to climate change and regulation. The main objectives of this study are to: (a) provide a critical review of the current state of knowledge of the role of ice-jam flooding in sustaining river socio-economic and socio-ecological systems; (b) provide a framework for a sustainable ice-jam flood management strategy; and (c) identify challenges and knowledge gaps for sustainable ice-jam flood management strategies in cold regions.

2. The Role of Ice Jam Flooding in Systems

2.1. The Socio-Economic System

Ice-jam flooding is a considerable socio-economic concern for the communities, engineers, insurance companies, authorities, and government agencies in cold regions. Ice-jam floods are characterised by a quick increase in water levels and high flow velocities. As well as causing injury and death, these conditions often increase the size or height of river embankments, cause road erosion, damage infrastructure, and harm riverine ecosystems. A study indicated that the average annual damage in the United States from ice-jam formation is $120 M (USD) [2]. Ice-jam flooding interrupts the development of various river structures such as dikes, bridges, pipeline crossings, and pump stations [1]. These structures must be designed to manage the flow characteristics associated with ice-jam formation. Bridges and pipelines crossing a cold region's rivers are often designed to withstand more than the expected maximum ice-jam water levels. It is interesting to note that the dikes at Peace River in Alberta, Canada have been developed and upgraded several times to meet the maximum protection from ice-jam flood events [23]. The high flow velocities generated by the release of ice jams can also damage a river's navigation systems and gauge stations, and can pose a major risk to shipping and hydrological data losses. Another consequence of ice-jam formations along a river is economic losses from hydroelectric dam operations. Over 30% of the annual economic losses of hydro dams in Canada are due to ice-jam interference in hydropower operations [1].

2.2. The Socio-Ecological System

Floods play a key role in the physical, chemical, and biological processes of river ecosystems, and ice-induced floods can have significantly different impacts from open water floods on similar ecosystems [29]. Ice-induced flooding can create extremely high water levels that are capable of inundating elevated portions of a floodplain [15]. High water flows maintain the hydrological connectivity between the main channel and the perched channels, converting the diversion channel to the principal channel or creating a new channel [30]. Scientists have found that many of the deltas in northern Canada (for example, the Peace–Athabasca Delta and Slave River Delta) are drying up because ice-jam flooding has declined during the spring ice-cover breakup [17]. In these deltas, open water flooding is unable to flood perched lakes, while the ice jams can produce much higher water levels compared to open water floods and replenish the perched lakes. In these delta environments, many riparian vegetation are completely dependent on regular flood events for their reproduction, and regular flooding may also be necessary to maintain water balances [19]. Therefore, to prevent further problems, the deltaic environment must be maintained through regular flood events and a certain level of floodwater depth. Although ice-jam flooding is beneficial in many ways for river ecosystems, a large flood can adversely impact stream environments. High river flows and unusually high velocities can increase fish mortality and hydrological disturbances in the aquatic environment. During flood events, suspended sediments change the geomorphology of the channel, affecting aquatic organisms such as fish and invertebrates [31]. Suspended sediments change the chemical composition of the water column (for example, temperature, dissolved oxygen, and pH), and impede the oxygen process of fish habitats [29,32]. Therefore, consideration of an ecosystem's flow requirement is one of the essential tasks in any ice-jam flood management strategy and a moderate flood with a shorter return period should be maintained in order to avoid a major disturbance in the aquatic system [19].

3. Toward Sustainable Flood Risk Management

Sustainable flood management is a strategic approach that provides guidelines for maximum flood protection of the socio-economic and socio-ecological systems. According to the Flooding Issues Advisory Committee (FIAC) of Scotland, sustainable flood management is a strategy that "provides the maximum possible social and economic resilience against flooding, by protecting and working with the environment, in a way which is fair and affordable both now and in the future" [33]. According to this definition, the main objective of sustainable flood management is to incorporate strategies that benefit communities, reduce economic damage, protect environments, and meet the needs of future generations.

The key goal of sustainable flood risk management is to integrate all of the levels of actors and institutions into flood risk management processes, and ensure the maximum resilience of socio-economic and socio-ecological systems, both now and in the future. Therefore, a sustainable ice-jam flood risk management strategy should ensure maximum flood protection to the socio-economic systems and sustainable flow to the socio-ecological systems [34]. Maximum flood protection means that there is a minimal risk to any properties, infrastructure, and human beings exposed to any flood event. A sustainable amount of ecological flow to the socio-ecological systems refers to the maximum flow necessary for maintaining ecological integrity. However, human intervention (for example, flow regulation) and climatic conditions affect these systems, resulting in increasing flood damage and environmental deterioration around the world.

In recent decades, flood risk management experts have adopted new methods, tools, and technologies in an effort to transform policies and better manage and mitigate flood damage. Geographical information systems, remote sensing, and numerical modelling techniques have been widely introduced to map floodplains, quantify potential damages, and analyse flood risks [35]. Many countries have started to shift from flood damage and risk reduction strategies to damage and risk-management strategies. For example, in 2006, the US government integrated all of the flood management administrative authorities and federal and local agencies to form a national flood risk management program [36]. More recently, Emergency Preparedness Canada and the Institute Bureau of Canada identified a set of cultures in current flood-management approaches that contribute to the trend of increasing flood damage, and suggested policy changes in current flood management [37].

Despite all these efforts and the technological advancements in current flood management strategies, two main problems remain: first, national and regional flood management agencies do not collaborate as much as they could, and, second, environmental factors are not well-integrated into flood risk management approaches. To address these challenges and achieve sustainable flood management approaches, new strategies need to be adopted. These include the following: the engagement of all levels of stakeholders, communities, and institutions [38,39]; community or participatory-based flood management strategies [40,41]; non-structural measures and adaptation strategies [42]; and ecosystem-based flood management systems [19,43]. The development of such integrated strategies will require a transdisciplinary approach that combines the perspectives and individuals (e.g., scientists and stakeholders) from different disciplines related to water management (e.g., hydrology and ecology).

4. Ice-Jam Flood Management Strategies

Current ice-jam flood risk management strategies include structural and non-structural measures and flood risk assessment to reduce flood risk. Structural and non-structural measures are usually used to mitigate ice-jam formation and reduce damages during floods.

4.1. Structural Measures

Structural measures involve the construction of various types of physical structures such as dams, reservoirs, dikes, and channel modification to control the floodwater and ice-jam formation along a river. Structural measures prevent the overflow of the rivers to floodplain areas in many ways. For example, reservoirs can control water levels, while dams and levees confine the flow within the main channel, and floodways divert the excess flow. A study in northern Canada showed that an effective flow regulation by a reservoir can reduce the chances of ice-jam formation in ice-jam prone areas [44], and a certain level of flows can create favourable conditions for ice-jam flooding in an environment where seasonal ice-jam flooding is needed [25]. For example, in the winter of 1994–1995, an artificial ice jam was constructed using spray-ice techniques to cause the overtopping of remnants of the original rock-filled weir along a channel in the Peace-Athabasca Delta Although the project was partially successful—which was only because of low flow conditions along the channel [45]—it demonstrated the potential of the structural measures to replenish some of the perched basin. Structural measures are usually effective and suitable for controlling a large volume of ice and protecting the floodplain area from high water stages. In a river, a jam can extend for several kilometres, and a large volume of ice accumulated from upstream can create high shear forces and high-water stages. In this situation, a dyke system is very effective at keeping floodwaters and ice out of the flood prone area. However, structural measures are very costly, and may have long-term adverse environmental effects. Although the variability in ice-jam flood frequency along the Peace River has been shown to be statistically insignificant, and the evidence of the impact of dam operations on altering the ice-jam flood frequency is sparse [30], some previous studies have suggested that dam operations have a certain level of impact by altering the ice regime and reducing the ice-jam flood frequency downstream along the river, resulting in the reduction of wetlands that provide habitats for the aquatic environment [19,20,24]. Consequently, an environment friendly structural design or proper operational conditions for dams and reservoirs are necessary for the better protection of socio-economic systems, in order to avoid the long-term adverse impact of the measure on socio-ecological systems.

4.2. Non-Structural Measures

Non-structural measures can be categorised into two groups: (i) prevention and emergency measures, both of which involve spatial planning (for example, zoning regulation), public awareness programs, education, and research, and the provision of information and communication resources (e.g., flood forecast and early warning); and (ii) financial supports or penalties with respect to floodplain development [46]. Besides these measures, non-structural measures also include ice cutting, drilling, and blasting for emergency mechanical ice-jam breaking, and weakening winter ice covers. The main advantage of non-structural measures is that they are cost effective, environmentally friendly, and sustainable over time. For example, in the spring of 1996, a non-structural measure was employed along the PAD. Although a natural ice-jam was formed in the delta channel, a certain flow release from the reservoir assisted potential flooding with a 20-year return period [18]. Although non-structural measures reduced the catastrophic impacts of residual risks, they are unable to completely mitigate ice-jam flooding. Therefore, a combination of both structural and non-structural measures can be an effective way to optimally reduce the risks of flooding and better protect riverine ecosystems.

4.3. Flood Hazard Mapping

A flood-frequency or stage-probability curve is used to estimate the probability of ice-jam floods and produce the flood hazard map for a specific floodplain [23]. This curve is usually used to quantify the water level for ice-jam flood events. A long-term historical record of ice-jam stages and various statistical methods are traditionally applied to develop this curve. If historical data is inadequate, synthetic flood-frequency relationships are developed. This is an indirect approach to a stage-frequency curve using observation data or applying statistical analyses [47]. Additionally, various hydraulic one-dimensional (1D) and two-dimensional (2D) numerical modelling approaches are also widely used to synthesise ice-jam stages in northern regions [1,48]. Geographic information system (GIS) tools are usually used to develop event-based flood hazard maps and estimate the corresponding flood damage. A digital elevation model (DEM) is used to produce a flood hazard and risk map. A flood hazard map delineates the flood extent areas and provides information on flood characteristics (for example, depth and velocity). A flood risk map provides the information about the potential consequences of a flood event, including the number of inhabitants or infrastructures vulnerable to flooding and the potential economic damage for that specific event [49].

4.4. Flood Risk Assessment

Flood risk is defined as the probability of a flood event combined with the potential adverse impact of such an event on communities, the environment, and economic conditions [50]. Much research has already been conducted on ice-jam flood risk assessment [6,11,23,35,47,51,52], where the flood risks were assessed based on the potential for socio-economic and socio-ecological flood damage. An appropriate flood risk management strategy is adopted based on economic assessments. Such economic assessments incorporate only the direct flood damages, such as property and infrastructure damage, associated with a flood's stages. However, in many cases, indirect damages such as industrial production loss, emergency costs, and most importantly, damage to ecosystem services (which are used for livelihood, recreational, or spiritual purposes) are ignored in flood risk estimation [35]. Therefore, a sustainable flood management method should be introduced that can incorporate both direct and indirect flood damages in flood risk assessment processes.

5. Challenges

Ice-jam flood risk assessment is a challenging task compared to assessments of open water floods. Estimating water levels for ice-jam flood events is complex because ice-jam formation is site specific, and most often, historical data are unavailable [1]. Additionally, the freezing properties and high velocities of the flood water damage properties and structures. This damage is difficult to predict and evaluate during the assessment process.

Although a number of ice-jam prediction models have been developed to date, these models are very site specific, rely on adequate historical data input, and are unable to consider the full effect of climate change and flow regulations on ice-jam formation [47,53]. Research on the effects of climate change on ice regimes is sparse; therefore, little information is available on the impact of climate change on the frequency and the severity of ice jams.

Likewise, very little is known about how to incorporate environmental factors and conditions in flood management strategies [19]. Previous studies mainly considered the economic aspects of determining the flood risk because ecological damage is difficult to quantify in monetary terms. Therefore, future research should also concentrate on how to incorporate environmental damage into flood risk maps and management strategies.

Despite the advancements in scientific technologies of all aspects of ice-jam flood management strategies, national and international collaboration in this field is still very limited [54]. New sustainable ice-jam flood-management strategies should be more regional, integrated, and proactive.

6. Framework for Achieving Sustainable Ice-Jam Flood Risk Management

Sustainable ice-jam flood risk management strategies should deal with current and future influences of hydro-climatic and human interventions on river ice-jam formations, as well as with optimal flood risk reduction. The key idea of sustainable ice-jam management is to engage all kinds of people and organisations, such as governments, businesses, private organisations, scientists, and individuals, into flood risk assessment processes [38]. Some different ways of achieving the goal of sustainable ice-jam flood risk management are discussed below:

6.1. Integrating Structural and Non-Structural Measures

A sustainable ice-jam flood management strategy can be achieved by integrating structural components with non-structural components [55]. Many scientists argue that the construction of structural measures tends to increase flood risk, because perceptions of flood-risk reduction further increase development activities in floodplain areas [55,56]. However, integrating non-structural measures with structural measures can add floodplain development regulations that reduce the flood risk and subsequently increases economic and ecological sustainability in society. The main advantage of this measure is that it can simultaneously control river flows and riverine ecosystems by constructing eco-friendly flood control structures and adding necessary regulations to floodplain areas. For example, an artificial ice dam (structural measurement) with a certain discharge from the dam (non-structural measurement) along the Peace River can lead to favourable conditions for ice-jam flooding along the Peace–Athabasca Delta.

6.2. A Transdisciplinary Approach

A transdisciplinary approach to ice-jam flood management integrates all levels of individuals, such as stakeholders, practitioners, and indigenous peoples into flood management decision-making processes [56]. Such an approach connects practitioners from different disciplines and backgrounds, ranging from officials in public administration, to scholars in the social sciences, to experts in hydrology and river engineering. These practitioners share their own perceptions, as well as the common goal of developing a sustainable flood management strategy. The key objective of this approach is cooperative investigation among all of the disciplines to understand the effect of human activities and climate change on ice-jam formation, and their relation to flood hazards. For example, hydrologists and ecologists should investigate how the annual hydrological cycle and the functions of ecosystems are driven by human activities and hydro-climatic conditions, while institutions dealing with flooding should emphasise the need to better understand the consequences of these impacts on both the economy and the environment.

A transdisciplinary approach is an integrated management approach that can play a vital role in sustainable ice-jam flood management. The main objective of this approach is to ensure the participation of the general public, stakeholders' representatives, community groups, and local authorities in the decision-making processes. A suitable flood management strategy requires the incorporation of water resources, land use, and environmental strategies with flood management [56]. Therefore, incorporating these multi-sectoral strategies into flood management requires active participation from the community, stakeholders, government, local non-government organisations (NGOs), and politicians. They can influence decision-making processes because many decisions are vested completely in community and other participatory groups.

6.3. Incorporating Ecological Perspective in Ice-Jam Flood Management

The main sustainable goal is to preserve and protect natural resources. Riverine ecosystems provide natural resources such as water, energy, and habitats for aquatic communities. However, human activities and climate change are changing ice-jam flood regimes in cold regions, and potentially impacting the delta ecosystems [28,57]. Therefore, a sustainable ice-jam flood management strategy should add ecological perspectives to conventional flood management strategies [19]. To mitigate the impact of ice-jam flooding on riverine ecosystems, an environmental framework can be added to sustainable ice-jam flood management goals. This framework would then include an environmentally sensitive structural design, an environmental assessment in any flood management decision-making process, an environmentally sensitive economic analysis, and a regular monitoring program [56].

An environmentally sensitive structural measure can be designed by clearly understanding the morphology and ecology of a river, and how the river's floodplain and physical characteristics are driven by the flow regime. Environmental assessment is a tool to determine whether there is any significant environmental impact of a proposed flood protection measure or the existing flood protection scheme of a system. The economic value of losing ecosystem services due to any flood measures can also be incorporated in a flood management strategy to determine the feasibility of applying measures or finding alternatives. Continuous monitoring and evaluation of the environmental health and existing flood measures is necessary in flood management, because it helps to determine whether there is any long-term environmental effect of a current flood measure or if it is necessary to adopt any additional measures.

7. Summary and Conclusions

The preceding sections describe the various aspects of ice-jam flood management strategies, their limitations, and a framework for achieving sustainable ice-jam flood management strategies. To select an appropriate flood management strategy, a good understanding of ice-jam formation, growth, and release is critical. As the nature and characteristics of ice-jam formations vary from site to site and region to region, a detailed understanding of hydro-climatic conditions of the mitigation site is needed. To develop a stage-frequency curve requires adequate historical data or a synthetic approach to produce a stage-discharge relationship using numerical modelling tools. Structural measures are usually effective in extensive flood-prone areas, or where a hydropower operation is interrupted by an ice-jam formation; however, the initial investment and maintenance cost of structural measures is much higher than those of non-structural measures. To reduce the flood risk in the areas vulnerable to flood damage, both measures can be combined in a sustainable flood management strategy. Ice-jams impacting riverine ecosystems are widely visible, and much research has investigated the connection between ecology and ice jamming. Incorporating ecological perspectives in ice-jam flood management strategies is a pressing need. Such integration will enable scientists to better manage important natural resources and sustainability in riverine ecosystems.

A sustainable flood management approach should be able to simultaneously protect people and socio-economic activities, as well as secure natural ecosystems functioning through disturbances created by floods. Incorporating both structural and non-structural measures can help ensure maximum flood protection and mitigation, as well as the promotion of flooding in deltaic environments. However, combining both measures is not always an easy task, and requires comprehensive study to determine the feasibility of both measures working simultaneously. Scientists and other individuals working together on such an approach would enhance multi-perspective analyses with consideration of the impact of flooding on both society and on the environment. Ecological perspectives are key to a transdisciplinary approach to ice-jam flood management strategies, as they optimise the resiliency of riverine ecosystems (Figure 1). The ecological perspective can be used as a flood management tool in decision-making processes, policies, and flood mitigation and promotion measures.

Finally, to apply the required flood management measures, a clear understanding of ice-jam processes in the geographic area under study is vital, because river ice processes vary from site to site depending on local climatic conditions. In addition to this, measures must be carefully balanced in order to mitigate ice-jam flooding in riverside socio-economic systems, and at the same time, promote ice-jam flooding in riverine socio-ecological systems such as inland deltas.

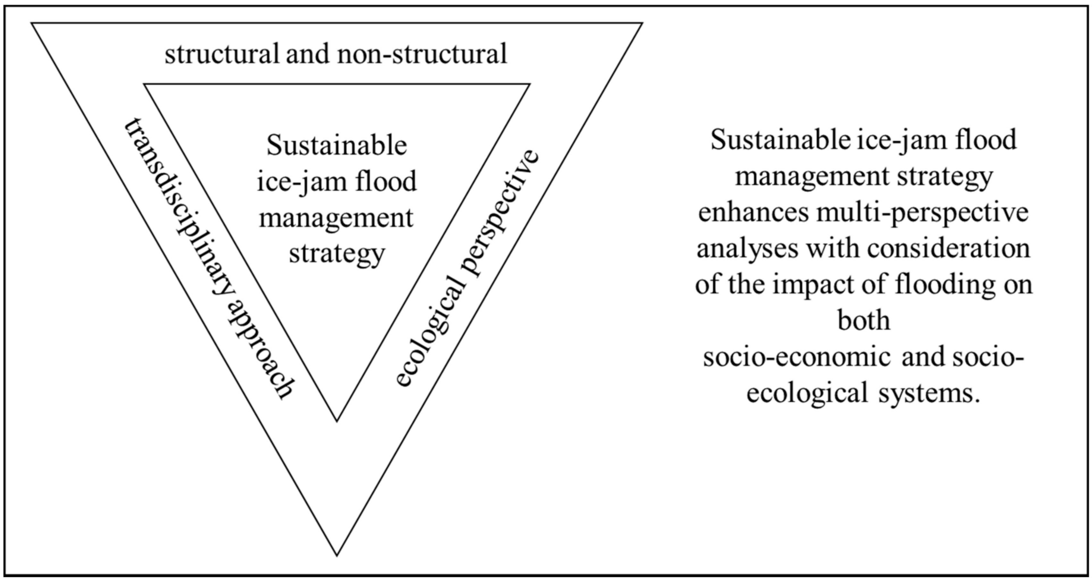

Figure 1. The summary of the sustainable ice-jam flood management strategy.

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