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Changing discharge regimes and sediment transport in seasonally ice-covered rivers

Karoliina Lintunen



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CHANGING DISCHARGE REGIMES AND SEDIMENT TRANSPORT IN SEASONALLY ICE-COVERED RIVERS

Karoliina Lintunen

University of Turku

Faculty of Science
Department of Geography and Geology
Physical Geography
Doctoral Programme of Biology, Geography and Geology

Supervised by

Professor Petteri Alho
University of Turku
Turku, Finland

Associate Professor Elina Kasvi
University of Turku
Turku, Finland

Assistant Professor Eliisa Lotsari
Aalto University
Espoo, Finland

Reviewed by

Professor Shawn Clark
University of Manitoba
Winnipeg, Canada

Professor Thomas Buffin-Bélanger
Université du Québec à Rimouski
Rimouski, Canada

Opponent

Professor Rebecca Hodge
Durham University
Durham, UK

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ABSTRACT

Cold-region rivers, many of which are seasonally ice covered, are undergoing rapid hydroclimatic change as rising air temperatures alter precipitation phase, snow accumulation, freeze–thaw cycles, and river-ice regimes. These changes modify discharge seasonality and flow and sediment processes that have traditionally been dominated by spring snowmelt and stable winter ice cover. Despite their importance, flow conditions and sediment transport beneath river ice remain poorly understood, particularly in natural rivers. This thesis examines climate-change-driven alterations in cold-region river systems by integrating watershed-scale analyses of long-term discharge records with reach-scale field observations of under-ice flow and sediment processes. It is based on two long-term time series and applies three complementary approaches: (1) statistical analyses of multi-decadal discharge records from unregulated Finnish rivers, (2) multi-year in situ measurements of near-bed flow and sediment transport beneath ice cover in a subarctic meander bend, and (3) near-bed turbulence analyses to assess hydraulic controls on ice-covered flow processes. Results show that climate change is redistributing river discharge within the hydrological year across Finland. Spring flood peaks are occurring earlier, while winter and autumn flows are increasing, whereas annual total discharges remain largely unchanged. Reach-scale observations demonstrate that the ice-covered period is morphodynamically active, even during the lowest midwinter discharges, with sediment transport occurring year-round. Turbulence analyses reveal that water-column height beneath the ice is the primary regulator of near-bed turbulence and shear stress, with ice thickness, discharge, and channel morphology further modulating bedload transport. Overall, wintertime processes play a key role in cold-region sediment dynamics. As warming continues, flow and sediment transport are likely to become less concentrated during spring floods and increasingly distributed across winter and autumn events. The impacts of their changes must be considered when assessing the effects of climate change in cold-region rivers.

KEYWORDS: cold-region rivers; climate change; river ice cover; discharge regime; sediment transport; near-bed flow; near-bed turbulence; river morphodynamics

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TIIVISTELMÄ

Kylmien alueiden joet, joista monet ovat kausittain jääpeitteisiä, ovat nopean hydroklimaattisen muutoksen kohteena, kun ilmastonmuutoksen muuttaa sateen olomuotoa, lumen kertymistä, jäätymis-sulamissyklejä ja jääolosuhteita. Nämä muutokset vaikuttavat virtaaman vuodenaikaisvaihteluun sekä virtaus- ja sedimenttiprosesseihin, joita ovat aiemmin hallinneet lumen sulaminen keväällä ja pysyvä jääpeite talvella. Merkityksestään huolimatta virtaamaolosuhteet ja sedimentin kulkeutuminen jääpeitteen alla tunnetaan edelleen puutteellisesti, erityisesti luonnontilaisissa joissa. Tässä väitöskirjassa tarkastellaan ilmastonmuutoksen vaikutusta kylmien alueiden joissa yhdistämällä valuma-alueen pitkien virtaama-aikasarjojen tarkastelu kenttähavaintoihin jäänalaisista virtaus- ja sedimenttiprosesseista. Tutkimus perustuu kahteen pitkään aikasarjaan, ja menetelminä käytetään kolmea toisiaan täydentävää lähestymistapaa: (1) sääntelemättömien suomalaisten jokien monikymmenvuotisten virtaama-aineistojen tilastollinen tarkastelu, (2) pohjanläheisen virtauksen ja sedimentin kulkeutumisen monivuotiset kenttämittaukset jääpeitteen alla sekä (3) pohjanläheisen turbulenssin tarkastelu jään alla ja siihen vaikuttavien hydraulisten tekijöiden arviointi. Väitöskirjan tulokset osoittavat, että ilmastonmuutos on muuttanut virtaamarakennetta suomalaisissa joissa. Kevättulvien huiput ajoittuvat aiemmaksi, kun taas talvi- ja syysvirtaamat kasvavat. Vuotuisten kokonaisvirtaamien määrät pysyvät kuitenkin pääosin ennallaan. Tämä viittaa virtaamahuippujen ajankohdan muuttumiseen, ja tulokset osoittavat kevättulvien aikaistuneen ja talvivaarimien kasvaneen. Jokuoman mittakaavan havainnot osoittavat, että jääpeitteinen kausi on morfodynaamisesti aktiivinen myös keskitalven alhaisimpien virtaamien aikana ja sedimentin kulkeutumista tapahtuu ympäri vuoden. Turbulenssianalyysit osoittavat, että jäänalaisen vesipatsaan korkeus on keskeinen pohjanläheisen turbulenssin ja leikkausjännityksen säätelijä ja että jään paksuus, virtaama ja uoman pohjan morfologia muokkaavat edelleen pohjakuljetusta. Kokonaisuutena talviajan jääprosessit ovat keskeisiä kylmien alueiden sedimenttidynamiikassa, ja niiden muutosten vaikutukset tulee huomioida arvioidessa ilmastonmuutoksen vaikutuksia.

ASIASANAT: kylmien alueiden joet; ilmastonmuutos; jääpeite; virtaamat; sedimentin kulkeutuminen; pohjanläheinen virtaus; pohjanläheinen turbulenssi; jokien morfodynamiikka

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Abbreviations

ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
b	Intake opening of Helley-Smith (m)
CS	River cross-section
D_*	Non-dimensional grain size parameter
D_{10}	10th percentile grain size
D_{50}	50th percentile (median) sediment grain size
D_{90}	90th percentile grain size
Dfb	Cold, humid climate with warm summers, Köppen classification
Dfc	Cold, humid climate with cold summers, Köppen classification
FMI	Finnish Meteorological Institute
G	Dry weight of sediment sample (kg)
g	Gravitational acceleration (m/s^2)
HQ	High discharge (m^3/s)
MQ	Mean discharge (m^3/s)
NQ	Low discharge (m^3/s)
P	Precipitation (mm)
Q	Discharge (m^3/s)
SNR	Signal-to-noise ratio
SYKE	Finnish Environmental Institute
s	Specific density, defined as the ratio of sediment density to water density
T	Transport stage parameter or time (min)
T_w	Water temperature
TKE	Turbulent kinetic energy
TKE_{min}	Lower-bound estimate of turbulent kinetic energy
TI	Turbulence intensity
TI_u, TI_v, TI_w	Component-specific turbulence intensities in the streamwise (u), cross-stream (v), and vertical (w) directions, normalised with the corresponding mean velocity components
u	Streamwise velocity component

u_*	Shear velocity
u_{*c}	Critical shear velocity
v	Cross-stream velocity component or kinematic viscosity
w	Upwards velocity component
z	Height above the bed
z_0	Bed roughness length
ρ	mass density of water (g/cm^3)
ρ_s	mass density of sediment (g/cm^3)
τ	Reynolds stress tensor
$\tau_{uv}, \tau_{uw}, \tau_{vw}$	Reynolds shear stress components in the streamwise-cross-stream (uv), streamwise-upwards (uw) and cross-stream-upwards (vw) planes
θ_{cr}	Critical mobility parameter
κ	von Kármán constant

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

- I Lintunen, K., Kasvi, E., Uvo, C. B. & Alho, P. (2024). Changes in the discharge regime of Finnish rivers. *Journal of Hydrology: Regional Studies*, 53: 101749. <https://doi.org/10.1016/j.ejrh.2024.101749>
- II Lotsari, E., Lintunen, K., Kasvi, E., Alho, P. & Blåfield, L. (2022). The impacts of near-bed flow characteristics on river bed sediment transport under ice-covered conditions in 2016–2021. *Journal of Hydrology*, 615: 128610. <https://doi.org/10.1016/j.jhydrol.2022.128610>
- III Lintunen K., Vilhonen, E., Takala, T., Blåfield, L., Kasvi, E., Lotsari, E. & Alho, P. (2026). Near-bed flow turbulence beneath ice cover under varying hydrological conditions: a 9-year field measurement-based analysis from a meander bend. Accepted for publication in *Water Resources Research*.

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1 Introduction

Rivers are fundamental components of the Earth’s hydrological cycle, supplying water resources essential for human societies, ecosystems, agriculture, and energy production. In cold regions, river ice strongly influences hydrological processes, and climate largely controls the magnitude of this influence (Beltaos & Prowse, 2009). Human activities, primarily through the release of greenhouse gases, have been the main driver of global warming, with mean global surface temperatures in 2011–2020 about 1.1 °C higher than in 1850–1900 (IPCC, 2023). Since 1979, the Arctic has warmed almost four times more quickly than the globe (Rantanen et al., 2022). In the northern high latitudes, human-caused global warming (hereafter referred to as “climate change”) is projected to substantially increase the frequency, magnitude, and spatial extent of climate extremes, such as heavy rainfall, flooding, and droughts (Zhou et al., 2023). These intensifying climatic extremes will increasingly affect hydrological systems, particularly on river flow dynamics and seasonal processes, such as discharge and ice formation (Kuusisto & Elo, 2000; Magnuson et al., 2000; Newton & Mullan, 2021; Ruostenoja, 1986; Williams, 1970). River ice has long been a subject of interest to researchers, particularly in engineering disciplines, and flow processes beneath ice have been examined (Ashton, 1986; Beltaos, 1995; Michel, 1971). Modelling studies have been conducted in flumes (Sayre & Song, 1979; Tsai & Ettema, 1994; Urroz & Ettema, 1994; Wuebben, 1986); however, investigations based on field measurements have been comparatively limited and have largely emerged only in recent years (e.g., Demers et al., 2011, 2013; Ghareh Aghaji Zare et al., 2016; Koyuncu & Le, 2022; Lotsari et al., 2017; Lotsari, Tarsa, et al., 2019; Polvi et al., 2020; Sukhodolov et al., 1999).

Understanding how climate change alters river discharge and ice dynamics in natural environments is crucial for predicting future hydrological responses, ecosystem impacts, and water resource availability in high-latitude regions. As societies and ecosystems in cold regions are adapted to predictable seasonal flow and ice regimes, shifts in these regimes’ timing or magnitude can substantially affect flood risk (Beltaos & Prowse, 2009), water security (Barnett et al., 2005), hydropower operations (Prowse et al., 2011), and fluvial ecosystems (Thellman et al., 2021). Therefore, examining the linked changes in river flow and ice regimes

offers key insights into the broader consequences of a warming climate. As climate change accelerates, these systems are undergoing rapid transitions, underscoring the need for research to assess ongoing and past changes and to anticipate future developments.

Globally, streamflow seasonality is governed by precipitation seasonality, snow and ice storage and melt, and evapotranspiration (Dettinger & Diaz, 2000). In high latitude regions, snowmelt-dominated regimes are the primary controls of flow timing. Climate change is leading to a weakened flow seasonality in cold-region regions (H. Wang et al., 2024). This weakening is associated with earlier snowmelt and an increasing proportion of precipitation falling as rain rather than snow (Tan et al., 2011; H. Wang et al., 2024). The loss of a distinct and predictable seasonal flow regime reduces hydrological reliability, shifts the timing of peak runoff, and increases the probability of winter flooding and summer droughts (Barnett et al., 2005; Veijalainen et al., 2010, 2019). Globally, over one third of the land surface is drained by rivers that experience seasonal ice cover (X. Yang et al., 2020). The timing of river-ice freeze up and breakup is closely linked to air temperature fluctuations around 0 °C, reflecting the strong thermal control on river water temperature and on ice dynamics (Beltaos & Prowse, 2009; Bennett & Prowse, 2010). Rising temperatures have already caused thinner ice cover, reduced spatial extent, and shorter ice-covered periods (Beltaos & Prowse, 2009; Lin et al., 2025; Qiu et al., 2025; R.-M. Yang & Zhang, 2022; X. Yang et al., 2020). These alterations modify the physical and ecological characteristics of river systems, influencing sediment transport and human activities dependent on stable ice conditions.

Cold-region rivers are already undergoing a pronounced reorganisation of their discharge regimes driven by climate change (Burn & Whitfield, 2017). Although annual discharge volumes remain unchanged, many cold-region river watersheds are experiencing declining snow storage and earlier melting, resulting in higher winter baseflows and earlier spring onsets (Blåfield, Marttila, et al., 2024; Tan et al., 2011; Thellman et al., 2021). Warming-induced shifts in the rain–snow balance and reductions in snowpack further shorten storage and shift runoff towards winter and early spring. Permafrost thaw and evolving groundwater pathways enhance winter discharge and reduce seasonality whereas declines in river-ice duration and thickness reflect warming and altered snow insulation (Feng et al., 2021; Park et al., 2016). These changes modify freeze up and breakup dynamics, affecting the timing and magnitude of peak flows and sediment transport. These changes in the dynamics increase the probability of damaging ice jam floods and require adaptation of hydraulic structures, such as dams and bridges.

River-ice processes are controlled by winter snow storage and the magnitude and timing of spring flow peaks (Turcotte et al., 2011). High snow accumulation can produce a thinner ice cover due to increased insulation whereas a limited snowpack

may promote thicker ice growth. Consequently, reductions in ice duration or thickness influence the timing and magnitude of flood peaks, the nature of ice breakup (thermal or mechanical), and sediment mobilisation. Rising winter temperatures and increasing winter discharges are also expected to enhance the frequency of midwinter melt events (Beltaos & Prowse, 2009). These events can trigger early ice-cover breakup, leading to midwinter ice jams and flooding at times when communities and infrastructure are adapted to low-flow, ice-covered conditions (Turcotte et al., 2020).

Although the large-scale impacts of climate change on river discharge and ice regimes are increasingly recognised, field-based understanding of under-ice flow processes in natural environments has only recently advanced (Demers et al., 2011, 2013; Kämäri et al., 2015; Koyuncu & Le, 2022; Lotsari et al., 2017, 2020; K. Smith et al., 2023a, 2023b). Despite these developments, our understanding of how ice cover influences flow and sediment processes remains limited. Moreover, even less attention has been paid to investigating flow dynamics during the phases of ice formation and decay although some recent progress has been achieved (Ansari et al., 2017; McFarlane et al., 2017; Pei et al., 2024; Takala et al., 2025). Transitional periods between open-water and ice-covered states play a critical role in river hydraulics and sediment dynamics, with geomorphological activity peaking during these phases (Beltaos & Prowse, 2009). Most research, however, has focused on ice jam dynamics during breakup in large rivers (Burrell et al., 2023; Turcotte & Morse, 2013), resulting in mid-winter conditions, freeze up and other transitional stages receiving considerably less attention (Burrell et al., 2023; Thellman et al., 2021). Therefore, the physical processes governing flow characteristics beneath the ice cover are still poorly understood. Advances in this knowledge are important for improving hydrodynamic models, refining sediment transport predictions, and assessing the impact of climate change on cold-region river systems.

Sediment transport beneath ice cover has often been overlooked although winter and ice breakup processes can significantly impact sediment dynamics and channel morphology (Turcotte et al., 2011). Field and laboratory studies have demonstrated that sediment transport occurs beneath ice during winter (Ettema & Daly, 2004; Muste et al., 2000; Polvi et al., 2020; K. Smith et al., 2023a) and the discharges required to transport sediment may be much lower than the critical discharges necessary for sediment movement under open-water conditions (Turcotte et al., 2011). Ice cover modifies flow structure by increasing hydraulic resistance and shifting maximum velocity toward the midwater column or bed (Ghareh Aghaji Zare et al., 2016; Koyuncu & Le, 2022; F. Wang et al., 2021). These changes alter near-bed shear stress, turbulence, and sediment-entrainment patterns. Shifts in ice timing and flow seasonality also affect nutrient pulses, primary production, habitat

conditions, and oxygen dynamics (Beltaos & Prowse, 2009; Thellman et al., 2021). For society, alterations in river-ice processes increase the risk of ice jams, disrupt winter transportation, and complicate hydropower operations (Fukš, 2023; Turcotte et al., 2011; X. Yang et al., 2020).

In this thesis, the effects of changing hydroclimatic conditions on flow and sediment processes in cold-region rivers are analysed using three approaches: (1) statistical analyses of long-term discharge and flow records, (2) in situ measurements of flow and sediment dynamics, and (3) spatial analyses of flow structure and sediment transport under ice-covered conditions. Through this integrated methodology, detailed insights are obtained in seasonal and interannual variations in discharge and flow seasonality as well as the spatial and temporal patterns of near-bed flow characteristics beneath ice and the dynamics of winter bedload and suspended sediment transport. The term “cold-region rivers” refers to rivers located within the subarctic-hemiboreal climate zone (60° – 70° N latitude), where winters are characterised by seasonal snow and ice cover and strong temperature variations during the hydrological year.

This study is conducted at two spatial scales: the watershed scale and the reach scale of an individual meander bend in a subarctic river. The watershed-scale analysis focuses on Finland, where climate model projections indicate warming that exceeds the global mean, with the most pronounced changes occurring in winter. Mid-century (2040–2069) projections under a moderate-emissions scenario suggest increases of approximately 3.3°C in mean winter temperature and 2.4°C in mean summer temperature, together with increases in winter and summer precipitation of about 12 % and 5 %, respectively, relative to the 1981–2010 baseline (Ruosteenoja & Jylhä, 2021). These projections, together with previous research, indicate that by the end of the century, the hydrological regime of Finnish rivers will change substantially as a result of climate change, with the most pronounced impacts expected in coastal and central Finland (Veijalainen et al., 2010). In northern Finland, climate change is projected to substantially reduce spring peak floods due to decreased snowpack accumulation. However, in the northernmost regions, where the local study site of this thesis, the Pulmanki River, is located, winters are still expected to remain sufficiently cold to allow for substantial snowpack formation and the occurrence of high spring floods. Consequently, it remains essential to study ice-cover-related processes and their effects on flow and sediment dynamics in these regions, as ice cover is not anymore occurring consistently each winter in southern Finland, making its impacts increasingly difficult to quantify there.

The primary objective of the thesis is to advance understanding of river flow and sediment processes beneath ice cover at the reach scale and to quantify long-term changes in discharge regimes at the watershed scale over the available period of

record (Figure 1). The findings provide new insights into the hydrological and geomorphological processes of cold-region rivers, where snow and ice strongly influence river dynamics throughout the year. This thesis integrates statistical analyses, multi-year wintertime field observations, and spatial analysis to quantify and assess the response of cold-region rivers to a changing climate.

The aims of the thesis are

- 1) To quantify long-term changes in regional river discharge regimes and link variations in volume, magnitude, and timing to climatic drivers using multi-decadal discharge records (Paper I).
- 2) To characterise near-bed flow and sediment transport beneath ice by quantifying turbulence parameters and assessing how near-bed flow controls sediment entrainment and bedload transport under varying hydrological conditions, supported by field bedload measurements (Papers II–III)
- 3) To integrate hydrological, hydraulic, and sediment-transport findings to improve the prediction of sediment dynamics and morphodynamic response beneath ice cover under changing climatic conditions (Papers I–III).

In Paper I, daily mean discharge data from 36 unregulated gauging stations across 19 watershed areas in Finland, obtained from the national database of Finnish Environment Institute (SYKE, Hertta database), are analysed to characterise long-term (1911–2021) changes in discharge volumes, magnitudes, timings, and frequencies. The dataset comprises approximately 765000 daily records, with individual station record lengths ranging from 28 to 110 years (mean period of 60 years). Trend analyses are conducted using the non-parametric Mann-Kendall test and Sen's slope estimator to quantify the magnitude and significance of trends. Stations are analysed individually and across three hydrological regions, (A) lake-rich southern/central catchments, (B) coastal catchments, and (C) northern snowmelt-dominated catchments, to assess spatial patterns in the observed changes and to compare with previous studies. The aim is to determine how discharge volumes, extreme-flow magnitudes, event timings, and frequencies have shifted in unregulated Finnish rivers in response to climate change.

In Paper II, stationary cross-sectional acoustic Doppler current profiler (ADCP) and near-bed acoustic Doppler velocimeter (ADV) measurements are gathered through drill holes in the ice, and are used to characterise time-averaged near-bed velocities, ice thickness, and water depth beneath a seasonally ice-covered meander bend. Bedload transport and river bed sediment properties are quantified using pressure difference (i.e. Helley-Smith type sampler: Helley & Smith, 1971) and grab sediment sampling (i.e. Van Veen type sampler), respectively for cross-sectional grain-size distributions. Near-bed velocities are compared with Hjulström thresholds

and converted to shear-velocity estimates using the logarithmic law-of-the-wall (Wilcock), with bed roughness (z_0) represented by the measured D_{50} . Critical shear velocities and transport-stage parameters are calculated using Van Rijn's D_* and θ_{cr} formulations, and the resulting metrics are analysed against water depth, ice thickness, and discharge using Pearson correlations. The aim is to determine how ice cover and hydrological variability influence near-bed flow and sediment transport potential in a subarctic river system. This study is based on multi-year (2016–2021) field observations.

In Paper III, partially overlapping ADCP and ADV datasets used in Paper II are further analysed, complemented by extended time series. In addition, visual information of bedforms is used to characterise near-bed and water column flow beneath river ice. Turbulence metrics were derived from nine years of ADCP and five years of ADV time series and subsequently analysed using Spearman correlations with water column height and ice thickness. These results were also compared with prevailing hydroclimatic conditions before and during the measurement period. This study is intended to investigate how water column height, ice conditions, discharge, and bedform characteristics influence near-bed turbulence beneath ice in a subarctic meander bend. This study is based on multi-year (2016–2024) field observations.

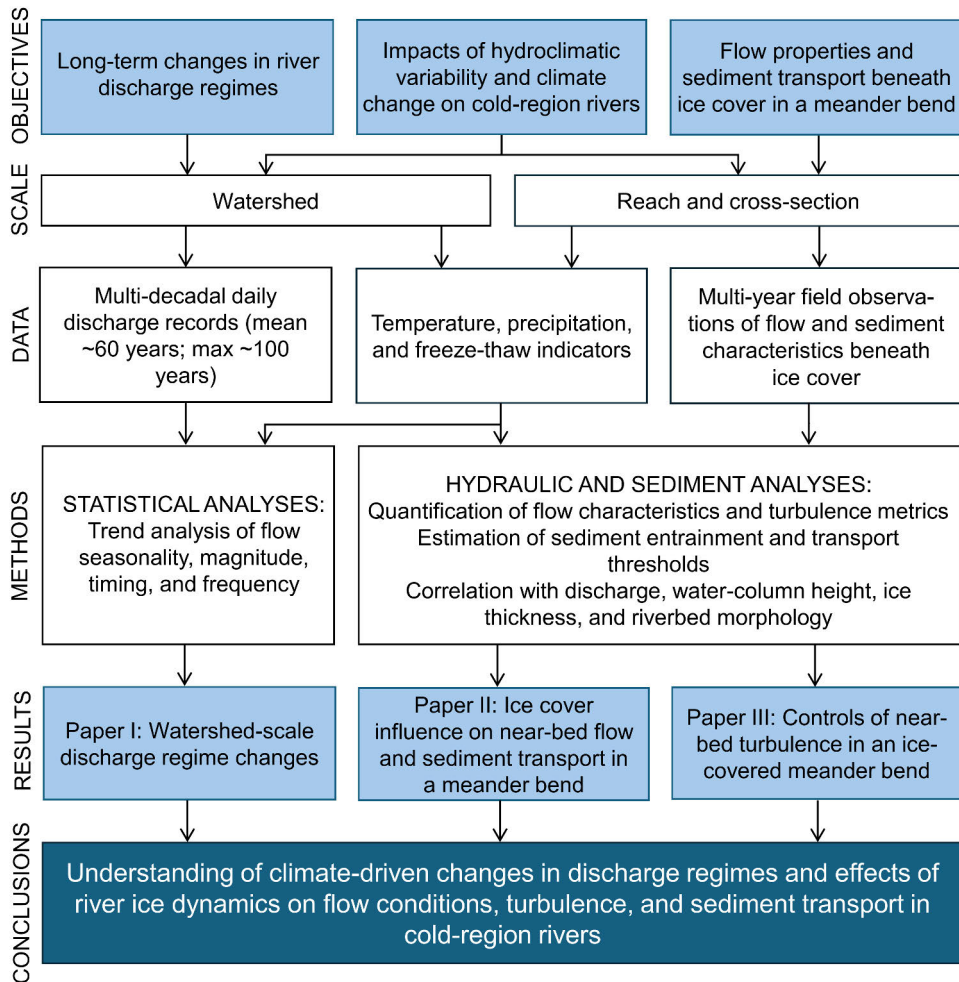


Figure 1. Overview of the objectives, spatial scale, data, methods, results, and conclusions of this thesis. The framework combines watershed-scale analyses of long-term discharge and climate data with reach-scale field observations and hydraulic-sediment analyses to quantify climate-driven changes in discharge regimes and flow and sediment dynamics in seasonally ice-covered cold-region rivers.

2 Background

2.1 Seasonal and regional variability in discharge and hydrological controls

The flow of water through a river cross-section over a given period of time is referred to as discharge. The magnitude of discharge is determined by surface and subsurface runoff processes within the watershed, which depend on the catchment's size, topography, land cover, and hydrological characteristics. In addition, climatic, hydrological, and cryospheric processes, including precipitation patterns, snow accumulation, and snow melt as well as permafrost conditions, govern the timing and magnitude of runoff and further river discharge.

Globally, rivers that freeze seasonally drain more than one third of the Earth's landmass (X. Yang et al., 2020). Climate warming is already altering these systems by reducing the proportion of winter precipitation that falls as snow and by bringing forward the onset of spring snowmelt (Barnett et al., 2005). As a result, in cold regions, peak river runoff is generally shifting towards earlier spring and, increasingly, into winter rather than occurring predominantly in late spring and summer (Burn & Whitfield, 2017; Vormoor et al., 2016). Furthermore, the mean duration of seasonal river ice is projected to decline by approximately 6.1 ± 0.08 days for every $1\text{ }^{\circ}\text{C}$ increase in mean surface air temperature (X. Yang et al., 2020). These high-latitude rivers are therefore undergoing pronounced hydroclimatic change, with discharge and sediment-transport regimes shifting away from snowmelt-dominated (nival) control towards increasingly rain-driven (pluvial) control (T. Zhang et al., 2023). This transition may also alter the seasonal timing of peak flows, as rainfall-driven events can occur outside the traditional spring freshet period and extend into autumn or winter.

River discharge varies throughout the hydrological year and, in cold regions, is strongly influenced by climatic and catchment characteristics, including precipitation, temperature, vegetation dynamics, snow accumulation, and snowmelt (Dettinger & Diaz, 2000; Turcotte & Morse, 2013). Seasonal variability in discharge is commonly characterised using metrics describing discharge magnitude, timing, frequency, and seasonality. These metrics include annual and seasonal mean discharge, the timing and magnitude of high-flow events, and the frequency of

extreme flow conditions. In cold regions, discharge is typically highest during spring as a result of snowmelt whereas lower discharges generally occur during the summer growing season and in winter, when the ground is frozen (Holmes, 2021; Korhonen & Kuusisto, 2010; Rawlins & Karmalkar, 2024). During winter, rivers in cold regions are ice-covered, and discharge dynamics are further modified during ice formation and breakup periods (Beltaos & Prowse, 2009; Turcotte et al., 2011).

In cold regions, such as Finland, the hydrological regime is largely governed by snow-controlled seasonality (Korhonen & Kuusisto, 2010; Schneider et al., 2013). Consequently, even small increases in air temperature can substantially alter runoff timing and discharge regimes, as reduced snow storage and an increased proportion of rainfall shift runoff towards earlier seasons (Barnett et al., 2005; Olsson et al., 2015). In northern Finland, where mean daily winter temperatures typically remain below 0 °C, spring snowmelt produces the annual discharge peak whereas winter runoff remains low due to frozen ground and snow storage (Korhonen & Kuusisto, 2010). In contrast, southern Finland experiences milder winters, where winter precipitation may alternate between rain and snow, leading to episodic runoff events, and the lowest discharges are more commonly observed during summer when evapotranspiration exceeds precipitation (Korhonen & Kuusisto, 2010; Veijalainen et al., 2019). Seasonal and regional differences in discharge regimes are therefore critical for assessing cold-region rivers' sensitivity to climate-change-driven increases in air temperature and changes in precipitation. Shifts in discharge regimes change the structure of the hydrological year (Figure 2) but also influence river-ice processes. Understanding these changes therefore provides context for interpreting variations in flow and sediment transport processes of ice-covered rivers.

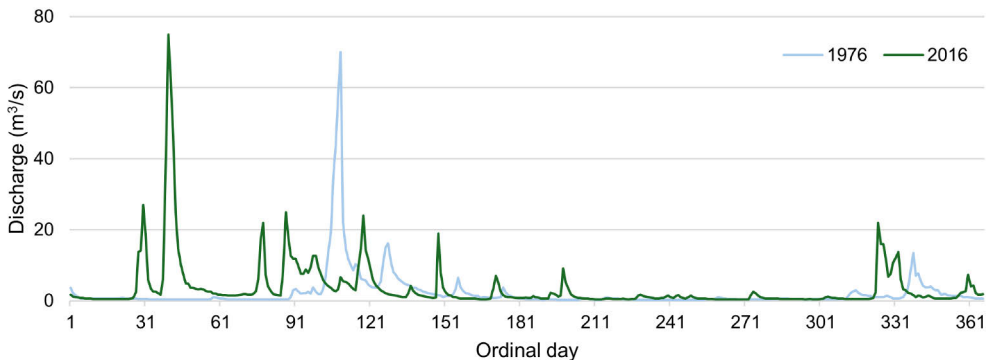


Figure 2. Comparison of annual discharge regimes of the Uskelanjoki River (Kaukolankoski gauging station), southern Finland. The hydrological year 1976 represents relatively typical conditions, with peak discharge driven by spring snowmelt. In contrast, in 2016 the peak discharge occurred during winter due to thaw, followed by smaller discharge events in spring.

2.2 Ice formation, breakup, and ice characteristics

In cold regions, river discharge, water level, and sediment-transport capacity are additionally influenced by river-ice processes, such as seasonal freeze up and breakup, the formation of frazil and anchor ice, and ice jam dynamics (Ettema & Daly, 2004; Turcotte & Morse, 2013). The formation and dynamics of river ice are affected by climatic controls, including air temperature, precipitation, solar radiation, humidity, cloud cover, and wind (Burrell et al., 2023). These climatic controls govern the seasonal evolution of river ice, from formation to breakup.

Ice cover forms when water cools to its freezing point and ice nucleation begins (Figure 3) (Beltaos & Prowse, 2009; Hicks & Beltaos, 2008). Typically, skim ice and border ice are the first types to form in calm and stable reaches whereas other forms, such as frazil ice floes, floes, and pans, develop predominantly in turbulent flows (Burrell et al., 2023; Turcotte & Morse, 2013). As the ice cover develops, newly formed or drifting ice floes move downstream and interact with the existing cover (Burrell et al., 2023). When they reach the ice front, the floes may accumulate by juxtaposition or beneath the cover through hydraulic thickening, depending on the prevailing hydraulic conditions. If frazil particles attach to gravel or boulders on the bed, they form anchor ice. This anchor ice may subsequently release once the water warms above the supercooled state, or if the adhesive forces at the interface are reduced due to solar radiation or mechanical forces exerted by the flow. Upon release, the anchor ice will rise toward the surface. In cases where the buoyant force of anchor ice attached to substrate material exceeds the weight of the material, it may transport sediment downstream by rafting, attach to the underside of the ice cover, and contribute to the formation of hanging dams (Turcotte & Morse, 2013). Before a stable ice cover forms, several episodes of ice formation and melting may occur if water temperatures are exposed to fluctuations (Buffin-Bélanger et al., 2013).

Once ice cover has formed, multiple ice types tend to accumulate and consolidate with the existing cover, resulting in a more continuous and stable ice surface (Beltaos & Prowse, 2009; Turcotte & Morse, 2013). Thickening of the ice cover from the ice underside results from the vertical freezing of the water column downward from the underside of the ice as well as potential frazil accumulation (Beltaos & Prowse, 2009; Turcotte et al., 2011). On the upper surface, ice cover thickening is influenced by snow cover and by the mixing and freezing of water within the snow layer, which may result from rain-on-snow events or from the flooding of river water over the ice cover (aufeis) (Beltaos & Prowse, 2009; Burrell et al., 2023).

When air temperatures rise permanently above 0 °C, ice breakup processes begin. Ice breakup typically progresses through several phases: pre-breakup, onset, drive, and wash (Beltaos, 2003; Hicks & Beltaos, 2008). Ice cover breakup can be triggered in two ways: thermally or mechanically (Beltaos, 2003). Thermal breakup occurs when the ice cover has already deteriorated substantially; its thickness and

strength have been reduced by melting and solar radiation, causing the ice to disintegrate in place with little or no jamming (Beltaos, 2003). The river’s water level rises slowly, often remaining below the level required to lift ice blocks, and flood impacts are modest. Mechanical breakup, by contrast, is driven by rapidly increasing river discharge acting against thick and mechanically strong ice cover (Beltaos & Prowse, 2009). Rising water levels, caused by snowmelt, rainfall on ice, or the accumulation of already broken ice, increase flow forces that fracture the stable ice, detach it from the banks, and transport it downstream (Beltaos & Prowse, 2009; Burrell et al., 2023). The moving ice blocks may encounter stationary ice and form jams, potentially resulting in severe ice jam flooding. Therefore, advanced ice decay and minimal jam formation characterise thermal events whereas mechanical events are governed by the ice’s ability to resist hydrodynamic forces and typically produce more extreme flooding and enhanced sediment entrainment and transport (Beltaos, 2003; Ettema & Daly, 2004; Turcotte et al., 2011).

Ice formation conditions and prevailing hydroclimatic variables control ice thickness and roughness. Under stable ice-cover conditions, the amount of snow accumulating on the ice surface strongly influences ice thickness (Burrell et al., 2023). Rapid accumulation of snow following ice-cover formation insulates the ice, reducing heat loss and potentially resulting in thinner ice, whereas limited or absent snow cover allows for greater heat exchange and promotes faster ice thickening. Depending on thermal and snow conditions, river ice may consist of black ice formed by the downward freezing of water or of snow ice formed by the refreezing of water-saturated snow on top of the ice cover; mechanically, black ice is generally stronger than snow ice (Beltaos & Prowse, 2009; Burrell et al., 2023). Ice underside roughness, which influences near-surface flow turbulence, arises from wave-like ice forms and the accumulation of anchor ice on the underside of the ice cover (Ettema & Daly, 2004; Sukhodolov et al., 1999). This roughness can evolve throughout the winter, if frazil ice is deposited or eroded, and as the ice cover deforms, thickens, or breaks up and ice jam events take place (Ghareh Aghaji Zare et al., 2016).

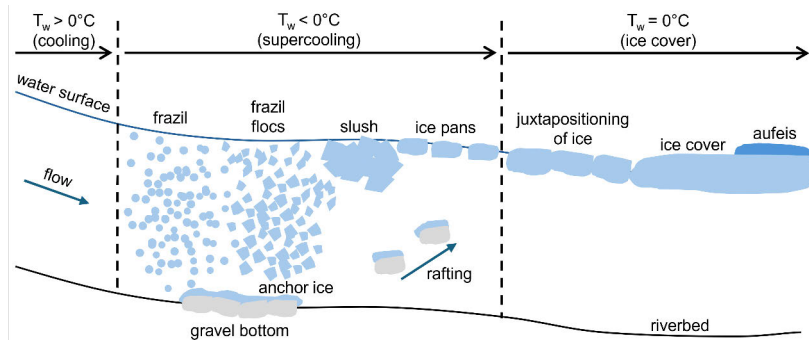


Figure 3. River ice cover formation process, when ice cover is formed through frazil ice accumulating. Adapted from Lindenschmidt (2020).

2.3 Hydraulic effects of river ice on flow properties

The presence of an ice cover introduces an additional roughness layer that increases flow resistance, modifies the velocity profile, increases the wetted perimeter, and alters the overall hydraulic structure of the channel (Muste et al., 2000; Turcotte et al., 2011). This additional roughness layer and therefore increased resistance result in an increase in water level for the same discharge volume compared to open-channel conditions. Flow in an ice-covered channel can therefore be divided into two components: one governed by the channel bed and the other by the ice cover (Larsen, 1969). These combined effects shift the maximum velocity towards the centre of the water column, resulting in an asymmetric velocity profile (Figure 4) (Demers et al., 2011; Jafari & Sui, 2021; Lotsari et al., 2017; Robert & Tran, 2012). The location of the maximum streamwise velocity is determined by the relative roughness of the ice cover versus the channel bed, with the maximum velocity shifting away from the rougher surface (Teal et al., 1994).

Flow beneath ice cover is generally considered fully developed and turbulent (Muste et al., 2000). Because an ice cover shifts maximum velocities closer to the riverbed, it induces steeper velocity gradients, resulting in higher bed shear stresses (K. Smith et al., 2023b). Consequently, the vertical distribution of turbulence within the water column is influenced by conditions at the bed and the underside of the ice cover. Maximum turbulence levels are typically observed near the riverbed and immediately below the ice cover (Robert & Tran, 2012; Sukhodolov et al., 1999). However, turbulence throughout the entire water column beneath an ice cover is often less intense than under open-channel conditions, resulting in reduced sediment entrainment and decreased sediment transport (Muste et al., 2000; Turcotte et al., 2011). Despite this overall reduction, localized increases in turbulence can occur in shallow sections, near banks, or over riffles, where flow velocities are higher than in adjacent areas (K. Smith et al., 2023b). Such intensification is typically associated with reduced water column depth, which constrains the flow and thereby elevates local velocities. Under these constrained conditions, the ice cover defines and limits the vertical extent of the water column, rather than directly restricting the macro-turbulent coherent structures themselves (Lotsari et al., 2020). Nevertheless, their interaction with bedforms and the ice underside can increase the frequency of bursting events, intermittently enhancing sediment suspension and mixing.

In meander bends, the presence of an ice cover further modifies flow patterns, particularly the structure of secondary currents. Under ice-covered conditions, centrifugal acceleration is reduced, resulting in the dampening of the secondary flow spiral. This dampening causes the spiral to split into two weaker, vertically stacked, counter-rotating cells (Lotsari et al., 2017). Such alterations to the secondary flow structure can influence flow characteristics and sediment transport within the bend.

As the presence of an ice cover influences the flow's hydraulic properties, the characteristics of flow turbulence are also modified. Typically, an ice cover reduces the overall magnitude of turbulent kinetic energy (TKE) (Sediqi et al., 2024) although it may locally increase turbulence intensity and shear stresses (Jafari & Sui, 2021; Robert & Tran, 2012). In meander bends, the ice cover further modifies the structure of secondary currents. Studies have demonstrated that flow beneath an ice cover in a meandering channel is separated into two weaker, counter-rotating secondary flow cells (Lotsari, Tarsa, et al., 2019; F. Wang et al., 2021).

Consequently, ice cover affects flow dynamics and sediment transport beneath the ice, particularly in midwinter, when hydraulic and thermal conditions are relatively stable. In contrast, the freeze up and breakup periods are highly dynamic, often short-lived, and therefore considerably more difficult to observe and measure in situ. Despite their brief duration, these transitional phases can induce pronounced changes in flow hydraulics and sediment mobilisation and therefore merit dedicated investigation in future studies. Flow velocities and turbulence characteristics beneath ice cover are commonly quantified using acoustic instruments such as ADCPs and ADVs, which enable high-frequency, point-scale measurements. Instrument selection and configuration vary depending on the study's environmental conditions and the specific objectives (e.g., Giovino et al., 2025; Jafari & Sui, 2021; Koyuncu & Le, 2022; Lotsari et al., 2017, 2019, 2020; Namaee & Sui, 2019; Peters et al., 2017; Polvi et al., 2020; Smith et al., 2023a, 2023b).

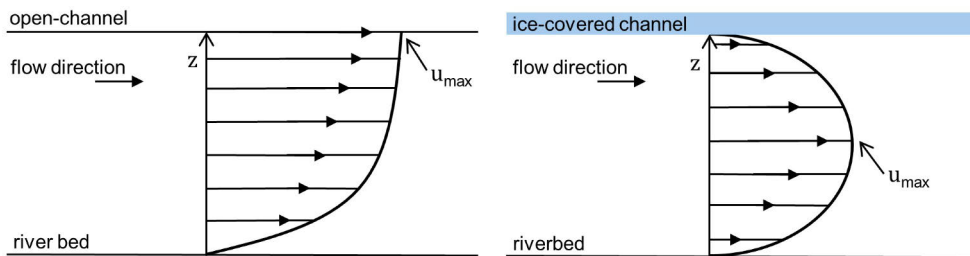


Figure 4. Flow velocity distribution profile in open-channel and ice-covered conditions. u_{\max} is the maximum flow velocity, and z is the distance from riverbed. Adapted from Teal et al. (1994).

2.4 Climate change and altering discharge and ice regimes

Over recent decades, climate change has increasingly reshaped hydrological processes, leading to alterations in river flow regimes (Blöschl et al., 2017; Hall & Blöschl, 2018; Korhonen & Kuusisto, 2010; Schneider et al., 2013) as well as river ice processes, including changes in ice formation (Beltaos & Prowse, 2009; Burrell

et al., 2023; Fukš, 2023) and breakup timing (Magnuson et al., 2000; Norrgård & Helama, 2019; Thellman et al., 2021).

In northern and cold regions, where annual floods are typically driven by spring snowmelt and rainfall, climate change is expected to exert a stronger influence on runoff and flooding than in other regions (Barnett et al., 2005). Ongoing and projected changes in precipitation and temperature patterns are already affecting hydrological dynamics. Studies have documented decreasing spring flood magnitudes (Arheimer & Lindström, 2015; Stadnyk et al., 2021; Veijalainen et al., 2010), earlier timing of spring floods (Arheimer & Lindström, 2015; Bjerke et al., 2025; Blöschl et al., 2017; Fang et al., 2022; Tan et al., 2011) and an increasing frequency of floods occurring outside the traditional snowmelt season (Burn & Whitfield, 2017; Vormoor et al., 2015).

In Finland and northern Europe, warmer winters have led to a greater proportion of precipitation falling as rain rather than snow, together with more frequent midwinter thaw events (Apsīte et al., 2013; Hyvärinen, 2003; Korhonen & Kuusisto, 2010). As a result, spring flow peaks are occurring earlier whereas mean summer discharges are declining as snowmelt takes place earlier and summers become warmer and longer, increasing evapotranspiration (Veijalainen et al., 2019). Climate projections indicate that these seasonal hydrological changes will intensify in the future: winter discharges are expected to increase, snowmelt to occur earlier but with reduced magnitude due to declining snow accumulation, and summer discharges to decrease as a consequence of higher annual evapotranspiration (Arheimer & Lindström, 2015; Bjerke et al., 2025; Olsson et al., 2015; Ruosteenoja & Jylhä, 2021; Veijalainen et al., 2010). In addition, floods driven by extreme precipitation events are projected to become more frequent, particularly during autumn and winter. Similar changes have already been observed in the Baltic region where increases in winter runoff and annual discharge, along with decreases in spring runoff, have been reported (Apsīte et al., 2013; Ilnicki et al., 2014; Klavins et al., 2009), and in Scandinavia, where a pronounced shift towards rainfall replacing snowmelt as the dominant flood-generating mechanism has been identified (Vormoor et al., 2015).

The timing of river ice-cover breakup is primarily controlled by atmospheric and hydrological conditions (Prowse et al., 2007) and most commonly occurs in spring, when rising temperatures induce snowmelt (Beltaos & Prowse, 2009; Cooley & Pavelsky, 2016). However, midwinter thaws have increasingly been observed to trigger breakup events (Burrell et al., 2023; Prowse et al., 2007). These midwinter breakups are mechanical; however, high-discharge, dynamically driven mechanical breakup events in spring are becoming increasingly rare whereas thermal breakups are becoming more common (Cooley & Pavelsky, 2016; Turcotte & Morse, 2013). In addition, ice-cover thickness is often reduced under warmer conditions, making river ice more susceptible to weakening through melting processes (Burrell et al.,

2023; Fukš, 2023). As climate change progresses, thermally driven breakup events are projected to become increasingly common; nevertheless, further research is needed to better understand this phenomenon (Beltaos & Prowse, 2009; Cooley & Pavelsky, 2016; Thellman et al., 2021).

Warmer winters also lead to shorter ice-covered periods and increased hydrological variability within catchments in cold regions (Giovino et al., 2025; J. Wang et al., 2021). However, studies examining the duration of river ice cover and its temporal changes remain limited, primarily due to the scarcity of long-term datasets, their discontinuous nature, or their focus on individual river systems (Newton & Mullan, 2021; Prowse et al., 2007). Across the Northern Hemisphere, river ice observations and time series are particularly sparse, as many long-term monitoring networks have been discontinued. This data gap is especially concerning because under ongoing climate change, rates of hydrological and cryospheric change are accelerating whereas the long-term observational records required to robustly detect and quantify these changes are increasingly unavailable (Prowse et al., 2007). Although remote sensing and satellite data offers a potential alternative for monitoring river ice phenology (Cooley & Pavelsky, 2016; Fukš, 2023), its applicability is constrained by uncertainties related to cloud cover, data availability, and spatial resolution, particularly in smaller rivers (Beaton et al., 2019; Cooley & Pavelsky, 2016; X. Yang et al., 2020). Consequently, remote-sensing-based river ice assessments are particularly challenging in regions such as Finland, where many rivers are narrow and observational constraints are significant. Alternative approaches, including UAVs and higher-resolution satellite imagery, are therefore required to enhance knowledge of smaller (Alfredsen et al., 2018; Thellman et al., 2021).

In contrast, more extensive and continuous data are available for lakes, and analyses of these records show that lakes across the Northern Hemisphere are freezing later and experiencing earlier ice (Benson et al., 2012; Magnuson et al., 2000; Newton & Mullan, 2021; Sharma et al., 2021). In North America, decreases in the length of the river ice-cover season have been observed, together with earlier spring flow peaks (De Rham et al., 2008; Hodgkins et al., 2005; Lacroix et al., 2005), with similar trends reported in the Russian Arctic (L. Smith, 2000; Vuglinsky, 2002).

Consequently, relatively few comprehensive analyses of river ice cover have been conducted in northern Europe. Nevertheless, the available studies consistently indicate a shortening of the river ice-cover period, with ice formation occurring later in autumn and breakup taking place earlier in spring (Fukš, 2023; Klavins et al., 2009; Latkovska et al., 2016; Norrgård & Helama, 2019). In southern Finland, there have already been years during the 2000s in which rivers have not frozen at all or have remained ice covered only for very short periods (Norrgård & Helama, 2022).

2.5 Sediment transport beneath ice cover

Sediment is transported as dissolved, suspended, or as bed load, which together constitute the total sediment load (Charlton, 2007; Dey, 2014). Dissolved sediment, consisting of particles smaller than 0.45 micrometres, is carried in solution. Suspended sediment comprises particles smaller than 0.062 millimetres, whereas larger particles are transported as bed load. However, larger particles can be transported as suspended load if the shear velocity exceeds the particle's fall velocity (De Leeuw et al., 2020; Dey, 2014). The movement of sediment is governed by hydraulic forces exerted by flowing water. Flowing water acts on sediment through two primary forces, drag and lift. When these forces exceed a sediment particle's resistance, the particle is set in motion. This threshold is referred to as the critical shear stress. Flowing water's ability to entrain and mobilise sediment can also be expressed as bed shear stress, which describes the force the flow exerts on the riverbed per unit area (N/m^2). A sediment particle's critical shear stress is controlled by factors including particle size, shape, and density, as well as particle arrangement on the bed, grain size distribution, and interparticle bonds. Once entrained, bed-load sediment moves along the riverbed by rolling, sliding, or saltation. When gravitational forces exceed the forces exerted by the flow, typically during decreasing flow velocities, sediment particles settle and deposit to the riverbed. This relationship between particle size and flow velocity is illustrated by the Hjulström diagram, which defines the critical flow velocities required for sediment entrainment, transport, and deposition (Hjulström, 1935).

In high-latitude regions, studies of sediment transport have mainly focused on large Arctic rivers whereas smaller watersheds have received less attention (Lewis & Lamoureux, 2010). However, these smaller watersheds may be particularly sensitive to climate change and are therefore crucial for understanding how high-latitude regions will respond to future environmental change. It has been predicted that global temperature increases lead to a substantial rise in sediment yields in Arctic watersheds (Gordeev, 2006; Lewis & Lamoureux, 2010; Syvitski, 2002).

Historically in cold regions, snowmelt-driven discharge peaks have governed the magnitude and timing of peak sediment transport (Cockburn & Lamoureux, 2008) whereas the stable ice-covered period has traditionally been assumed to be largely inactive in terms of sediment transport, as reduced bulk velocity and shear stress limit sediment transport capacity (Ettema, 2002; Turcotte et al., 2011). However, studies have demonstrated that this assumption is incorrect, showing that sediment transport does occur during the ice-covered season even at low discharges, and that these processes have been largely overlooked in the literature (Ettema & Daly, 2004; Turcotte et al., 2011). One contributing factor is the methodological complexity associated with collecting sediment transport data under ice-covered conditions (Shen, 2025); nevertheless, the number of field-based sediment transport studies

conducted under such conditions has increased in recent years (Beltaos & Burrell, 2016; Kämäri et al., 2015; Koyuncu & Le, 2022; Polvi et al., 2020).

Sediments can nonetheless be transported at discharges much lower than the critical thresholds for incipient motion defined for open-water conditions, primarily due to ice-related processes rather than increased discharge magnitude. These processes include sediment rafting by frazil and anchor ice, release of anchor ice from the bed, pressurised under-ice flow, ice jam hydraulics, and enhanced sediment supply associated with freeze–thaw processes (Turcotte et al., 2011). During the freeze up phase, repeated freeze–thaw cycles weaken riverbanks and increase sediment supply by reducing the critical shear stress of bank material, altering hydraulic gradients, and exposing new sediment sources (Ettema & Daly, 2004; Turcotte et al., 2011). As bankfast ice develops, it initially protects banks and the channel bed from erosion; however, when detached or loaded, it can entrain bank material and facilitate downstream sediment rafting. Freeze–thaw cycles may continue during the ice-covered period in milder climates, further enhancing sediment supply, particularly during warm events that increase runoff and discharge (Burrell et al., 2023). Finally, during the melt phase, ice-cover breakup increases sediment transport capacity and sediment supply while sediment rafting may resume (Ettema & Daly, 2004; Shen, 2025; Turcotte et al., 2011). Ice jamming during breakup can also locally enhance sediment transport capacity.

Under stable ice-covered conditions, near-freezing water temperatures increase kinematic viscosity, which enhances bed drag, reduces particle fall velocity, and modifies hydraulic resistance and suspended-sediment transport efficiency (Ettema, 2006; Ettema & Daly, 2004). If the ice cover is freely floating on the channel, it reduces the magnitude of bed shear stress compared with similar open-water conditions (Beltaos & Prowse, 2009; Turcotte et al., 2011). Reduced bed shear subsequently decreases the flow's sediment-transport capacity. However, if the ice cover is fixed to the banks or is sufficiently thick, it can locally increase near-bed shear stress (Jafari & Sui, 2021; Sediqi et al., 2024; K. Smith et al., 2023b). This effect is particularly likely in situations where the flow is constricted and forced by the ice. Although stable ice cover typically reduces the total transport of bedload and suspended sediment compared to open-water conditions, local and transient phenomena, such as ice jams, flow acceleration, and the formation and release of anchor ice, can still generate high sediment transport rates during ice-covered periods (Muste et al., 2000; Shen, 2025; Turcotte et al., 2011).

Although sediment transport rates during ice-covered seasons are generally lower than those observed during the open-water season, short-lived ice-related events can contribute substantially to winter sediment transport (Polvi et al., 2020; Turcotte et al., 2011). Nevertheless, substantial uncertainties remain in estimating winter sediment fluxes, largely due to the challenges associated with measuring

bedload and suspended sediment transport beneath ice cover under harsh conditions and the limited availability of data across ice (Ettema & Daly, 2004; Shen, 2025). At the same time, projected increases in winter temperatures, higher freeze–thaw frequencies, and shorter ice-covered periods are expected to alter the timing and mechanisms of sediment transport in cold-region rivers (Beltaos & Prowse, 2009; Blåfield, Marttila, et al., 2024; Fukś & Wiejaczka, 2025; Newton & Mullan, 2021; Prowse et al., 2011). Despite advances in sediment transport research, winter sediment fluxes remain poorly quantified, underscoring the need for additional field-based observations under ice-covered conditions (Lotsari, Lind, et al., 2019; Shen, 2025; Turcotte et al., 2011).

3 Study Areas

This study was conducted in Finland. The studies for Papers II and III were conducted in the subarctic Pulmanki River, and Paper I focused on the 19 unregulated major rivers of Finland. In this context, an unregulated river refers to a river where no active flow regulation measures are implemented.

Climate change is projected to have pronounced impacts on cold regions through rising air temperatures and changes in precipitation magnitude and phase, particularly via alterations in snow cover (Barnett et al., 2005; Burrell et al., 2023; Trenberth, 2011). Warming in cold regions increases the proportion of precipitation falling as rain rather than snow whereas earlier snowmelt reduces seasonal snowpack. These processes enhance late-winter and early-spring flood risk, decrease summer water storage, and increase the likelihood of drought conditions. Concurrently, poleward shifts in storm tracks and an increase in the frequency and intensity of extreme precipitation events further amplify hydrological variability (Trenberth, 2011). Together, these changes modify river discharge regimes, the timing and thickness of river ice cover, and associated sediment transport processes (Lin et al., 2025; H. Wang et al., 2024; X. Yang et al., 2020).

Finnish rivers have traditionally been characterised by a nival flow regime, with peak discharges occurring during spring snowmelt (Melin, 1970). However, recent observations indicate a climate-driven shift in this pattern. The transition zone between snow-dominated and rain-dominated watersheds has been observed to migrate northward (Blåfield, Marttila, et al., 2024; Meriö et al., 2019). In addition, projected climate-change-driven increases in hydro-climatic extremes (more intense and/or more frequent floods) are expected to increase discharge variability, which will accelerate river mobility (Leenman et al., 2025).

The duration of river ice cover also varies markedly across Finland as a function of geographic location and climate. These regional differences reflect Finland's wide latitudinal extent between approximately 60°N and 70°N. In northern Finland, ice cover may persist for up to eight months due to long and cold winters, exerting a strong control on river hydrology. In contrast, milder winters in southern Finland result in a substantially shorter ice-covered period, often limited to a few months or occurring intermittently. Clear differences between rain-dominated and snow-

dominated watersheds further contribute to spatial variability in hydrological regimes across the country.

3.1 Finnish catchments

Finland is situated within the subarctic-hemiboreal climate zone. According to the Köppen-Geiger climate classification, the majority of the country is characterised by cold, short summers (Dfc) whereas the coastal regions experience comparatively warmer summers (Dfb) (Peel et al., 2007) (Figure 5). The Gulf Stream warms Finland's climate by bringing warm ocean water from the Atlantic toward Northern Europe, which moderates temperatures and makes the climate milder than in other regions at the same latitude (Autio & Heikkinen, 2002). Finland experiences four distinct seasons, with cold, snowy winters and short, rainy summers (Jylhä et al., 2010). Precipitation is moderate throughout the year. Over the past century, the average annual precipitation has been approximately 600 millimetres (Irannezhad et al., 2014) whereas annual snowfall has shown a decreasing trend toward the end of the century (Irannezhad et al., 2017). The annual precipitation in Finland typically ranges from approximately 450 to 700 mm, with coastal areas receiving more rainfall and the northern regions experiencing drier conditions. The mean annual runoff in Finland increased from 301 mm during the period 1931–1990 (Kuusisto, 1992) to 320 mm during 2000–2019 (Tilastokeskus, 2020).

Recent studies have shown that climate warming has led to substantial reductions in the duration of persistent snow cover and the length of the thermal winter, particularly in southern and central Finland (Bjerke et al., 2025; Kaboli et al., 2026; Luomaranta et al., 2019). However, Finnish discharge regime change assessments are based on earlier climatological reference periods and updated evaluations that reflect the impacts of the most recent climate conditions on river discharge remain limited (Hyvärinen, 1988, 1998, 2003; Hyvärinen & Leppäjärvi, 1989; Korhonen & Kuusisto, 2010; Kuusisto, 1992). Consequently, the magnitude and seasonal characteristics of recent changes in precipitation and temperature and their implications for snow cover and thermal winter have not yet been comprehensively quantified. This study addresses this knowledge gap by comparing the two most recent climatological periods (1961–1990 and 1991–2020).

Climate change is expected to affect Finland's hydrology, as climate zones shift northwards and the overall climate becomes more temperate and wetter (Jylhä et al., 2010; Vehviläinen & Lohvansuu, 1991). However, there remains uncertainty regarding future regional climate evolution, as a potential weakening or collapse of the Atlantic meridional overturning circulation during this century could reduce the influence of the Gulf Stream and lead to regional cooling (Ditlevsen & Ditlevsen, 2023; Liu et al., 2017).

The discharge regimes of Finnish rivers are primarily governed by precipitation patterns and the seasonal climatic cycle (Hyvärinen, 1986; Olsson et al., 2015). Finland is divided into three hydrological regions based on their distinct hydrological properties: (A) lake-rich southern/central catchments, (B) coastal catchments, and (C) northern snowmelt-dominated catchments. The division is based on the hydrological and environmental characteristics of the regions, and this division is used in this thesis. The first group (region A) comprises rivers and watersheds located in the Finnish lake district in southern and central Finland. In region A, watersheds typically contain a substantial proportion of lakes, which provide considerable water storage capacity and thereby moderate seasonal fluctuations in discharge. This group includes both Köppen-Geiger climate classes situated in Finland (Dfb and Dfc).

The second group (region B) consists of coastal catchments primarily formed by rivers discharging into the Baltic Sea, particularly the Gulf of Bothnia and the Gulf of Finland. In contrast to region A, region B is characterised by smaller watershed areas with fewer lakes, resulting in short but high-magnitude discharge peaks and periods of low flow. Major flow events typically occur during the spring snowmelt; however, individual heavy rainfall events can also cause flooding throughout the year. Due to the limited water storage capacity, runoff is less regulated, leading to rapid variations in discharge. This group is mainly located in a humid continental climate with warm summers and cold winters (Dfb).

The third group (region C) includes rivers located in Northern Ostrobothnia and Lapland. In region C, watershed areas are generally extensive, and the most pronounced discharge peaks typically occur in spring as a result of snowmelt. Watersheds in this group are characterised by a subarctic climate (Dfc). Hydrological observations used in this study are obtained from Finland's nationwide hydrological observation station network, which is coordinated by the SYKE and provides comprehensive coverage of the country (see Chapter 4.2.1).

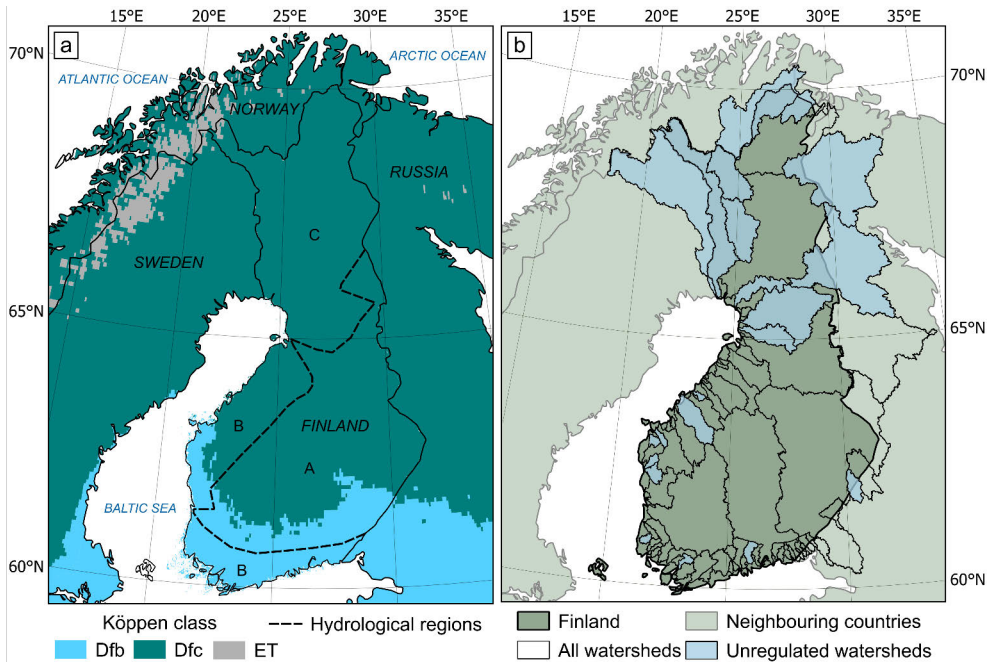


Figure 5. Location of Finland, Köppen climate classification, and hydrological regions of Finland (a) as well as the spatial distribution of unregulated and regulated watersheds of Finland (b). Letters A, B, and C correspond to hydrological regions of Finnish river systems, adapted from Korhonen & Kuusisto, 2010: (A) lake-rich southern and central catchments, (B) coastal catchments, and (C) northern snowmelt-dominated catchments. Köppen climate classes are ET = Arctic tundra climate; Dfb = cold, humid climate with warm summers; and Dfc = cold, humid climate with cold summers, adapted from (Rubel et al., 2017).

3.2 Pulmanki River

The Pulmanki River (Finnish: *Pulmankijoki*) is located in the northernmost part of Finland and is therefore part of hydrological region C. The climate of the Pulmanki River watershed is classified as cold, with no dry season and a cold summer (Dfc), according to the Köppen–Geiger climate classification system (Peel et al., 2007). The Pulmanki River is a sand bed, a meandering river, and a tributary of the Tana River, which forms part of the border between Finland and Norway and ultimately flows into the Arctic Ocean.

The Pulmanki River is divided into two sections, the upper and lower reaches, separated by Lake Pulmankijärvi. Research conducted in this thesis focuses on the upper reach of the Pulmanki River, known as the Ylä-Pulmankijoki (hereafter referred to as the Pulmanki River). The Pulmanki River's watershed area is 484 km² (Alho & Mäkinen, 2010), and the river flows through the Pulmanki Valley, where the river has eroded a channel 30 metres deep. In this ancient fjord, glaciofluvial

material was deposited during the retreat of the continental ice sheet (Mansikkaniemi & Mäki, 1990).

In winter, air temperatures can decline to $-40\text{ }^{\circ}\text{C}$ in the study site, and ice cover is persistent during this period. Freeze up typically begins in October, and a stable ice cover persists until April or May. During the study period (2016–2024), the onset of the thermal winter (the period when the daily mean temperature remains below $0\text{ }^{\circ}\text{C}$) occurred in October or early November and lasted until April or early May. The formation of ice cover creates an additional upper boundary layer that substantially modifies hydraulic conditions for up to eight months each year in the study site.

The Pulmanki River's discharge regime exhibits strong seasonality, with the main flood event occurring during spring snowmelt. Discharges typically range from 50 to $80\text{ m}^3/\text{s}$ in spring, decrease to around $4\text{ m}^3/\text{s}$ in summer, and fall below $2\text{ m}^3/\text{s}$ in autumn and winter (Blåfield, Calle, et al., 2024; Kasvi et al., 2015; Lotsari, Lind, et al., 2019). Annual precipitation is around 450 mm , and about half of it falls as rain during the summer period.

The study area of Papers II and III is one simple, symmetric meander bend of the Pulmanki River, characterised by a radius of curvature of 110 m and an apex width of approximately 20 m (Lotsari et al., 2014) (Figure 6). The riverbed in this bend primarily comprises mobile sand and is unvegetated, clear, and shallow. It is bedload-dominated and predominantly sandy, with a median bed material size (D_{50}) of 0.56 mm (Lotsari et al., 2022).

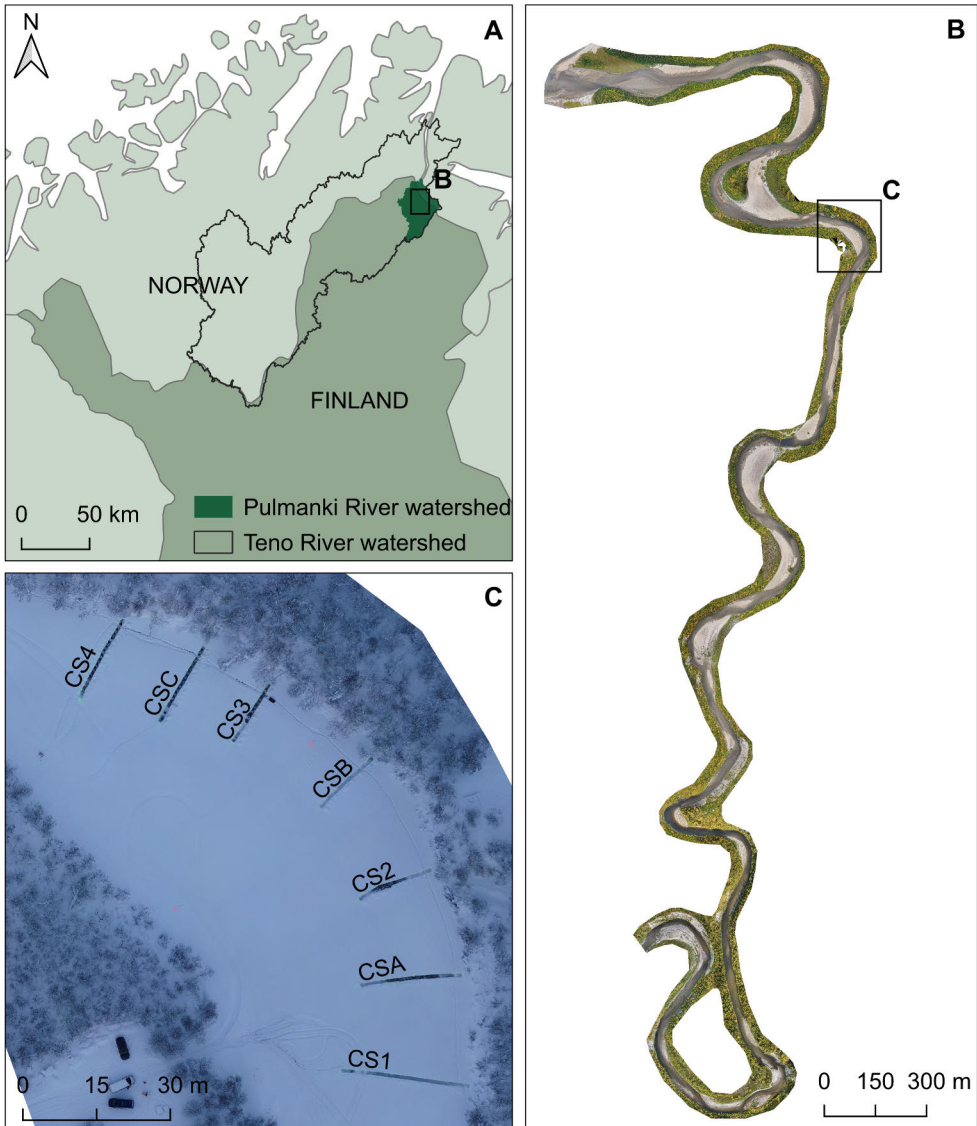


Figure 6. Location of the Pulmanki watershed (A), the entire Pulmanki River study reach in autumn 2025 (B, orthomosaic: Karoliina Korkiakoski), and the studied meander bend and its cross-section (CS1-CS4) locations in winter 2021 (C). Flow direction is from south to north.

4 Material and Methods

In this thesis, multiple methods were applied to analyse changes in discharge regimes as well as flow and sediment transport characteristics beneath river ice cover (Table 1). The methods were grouped according to the main categories presented in Table 1 and included discharge and velocity measurements, sediment and flow dynamics assessments, hydrological and meteorological monitoring, channel geometry and ice-cover observations, and statistical analyses. All datasets were spatially referenced, enabling the integration of hydrological, geomorphological, and ice-related observations within a spatially explicit analytical framework.

Discharge and velocity were quantified using ADCP and ADV measurements (Papers II–III) and data from gauging stations (Paper I). Sediment transport and flow dynamics were investigated through bed-load and bed-sediment sampling and derived hydraulic parameters (Paper II) as well as calculated turbulence parameters (Paper III). Hydrological and meteorological conditions were characterised using data from national monitoring networks (Papers I and III), and channel geometry and ice characteristics were documented using VRS-GNSS measurements, measuring rods, and photographic observations (Papers II–III). Statistical analyses were applied to identify trends and relationships in the data (Papers I–III).

Table 1. Data and methods used in the three papers of the thesis.

	Paper I	Paper II	Paper III
Discharge and velocity			
ADCP measurements		X (winters 2016–2021)	X (winters 2016–2024)
ADV measurements		X (winters 2016–2021)	X (winters 2020–2024)
Discharge records (national gauging stations)	X		
Weather data			
Air temperature and precipitation (national weather stations)	X		X
Freeze-thaw indicators			X
Sediment and flow dynamics parameters			
Bedload (Helley-Smith sampler)		X	
Bed sediment sampling (Van Veen sampler) and particle D_{10} , D_{50} and D_{90}		X	
Critical mobility parameter		X	
Critical shear velocity		X	
Transport stage parameter		X	
Turbulence parameters (TKE, Reynolds shear stress, turbulence intensity)			X
Statistical analyses			
Mann-Kendall trend test	X		
Sen's slope	X		
Spearman's correlation coefficient			X
Pearson correlation coefficient		X	
Channel geometry and ice characteristics			
VRS-GNSS, measuring rod and photos		X	X

4.1 Weather data

Weather and climate data from national and regional sources were used to characterise the thermal and hydrological conditions influencing river-ice formation, winter severity, and seasonal discharge variability. Air temperature and precipitation records from the Finnish Meteorological Institute (FMI) stations were analysed to derive thermal winter indicators and to assess long-term climatic trends relevant to flow and ice dynamics (Papers I and III).

Daily temperature data from the Nuorgam weather station (70.082028°N, 27.896500°E) were used to determine freeze–thaw indicators. These included the thermal-winter onset (defined as the date when mean daily temperature permanently falls below 0 °C), the first occurrence of a mean daily temperature below 0 °C, the number of thaw days (mean temperature > 0 °C), and frost sums (cumulative cold degree days). Together, these metrics formed the basis for classifying winter severity and for interpreting interannual variability in river-ice formation, discharge, and under-ice flow (Paper III).

Climatological normal periods (1961–1990, 1991–2020) of temperature and precipitation were used to contextualise long-term discharge trends and changes in flow seasonality (Paper I). Temperature and precipitation values for climatological normal periods were calculated from FMI’s 10×10 km² ClimGrid dataset (Ilmatieteen laitos, 2016). This dataset is a gridded climate product for Finland. The dataset is produced using a statistical interpolation method that accounts for topography and water bodies, yielding spatially continuous fields based on weather station observations.

Together, the meteorological datasets used provided the climatic framework for analysing how temperature and precipitation variability influence discharge regimes, ice-cover dynamics, and winter-flow processes in subarctic rivers. Datasets are publicly available through FMI’s data services.

4.2 Discharges and flow characteristics

Flow velocities and discharges were obtained from national gauging stations of SYKE (Paper I) and in situ measurements using an ADCP (Sontek M9) and an ADV (Sontek FlowTracker with 2D or 3D probe) to measure flow characteristics beneath ice cover (Papers II and III).

4.2.1 Hydrological observation stations

Hydrological observation stations in Finland form a nationwide monitoring network that provides data on the state and dynamics of water systems (SYKE, 2024). These data are used to assess water resources and current hydrological conditions and

support water management, regulation, flood risk management, environmental protection, research, and public information. The SYKE coordinates the network. In Paper I, discharge data were obtained from SYKE's publicly available hydrological database, Hertta. The dataset of Paper I includes daily mean discharge records from 36 gauging stations across 19 unregulated watersheds in Finland (Figure 7). The timespan of the used data was 1911 to 2021, with a mean time series length of approximately 60 years. Unregulated rivers were chosen to study in Paper I to minimise human influences, such as dams, hydropower operations, and other flow-management practices, thereby ensuring that observed discharge changes could be attributed primarily to climate-driven hydrological shifts.

The gauging stations are distributed throughout the country and encompass catchments ranging from small to large river systems, with corresponding differences in lake coverage, land use, and annual runoff. Discharge values are derived either from daily water-level observations using the rating-curve method, in which measured water levels are converted to discharge via a station-specific rating curve, or from automated discharge measurements. To ensure data reliability and robust time series analyses, only months and years with more than 90 % of daily discharge observations were included in the analyses presented in Paper I. Ice cover, frazil ice, and ice damming can disturb winter discharge records; however, ice reduction in southern rivers is modest, resulting in relatively reliable winter discharge estimates. In contrast, for northern rivers, verified measurements and lake-outlet data were used to minimise ice-induced bias.

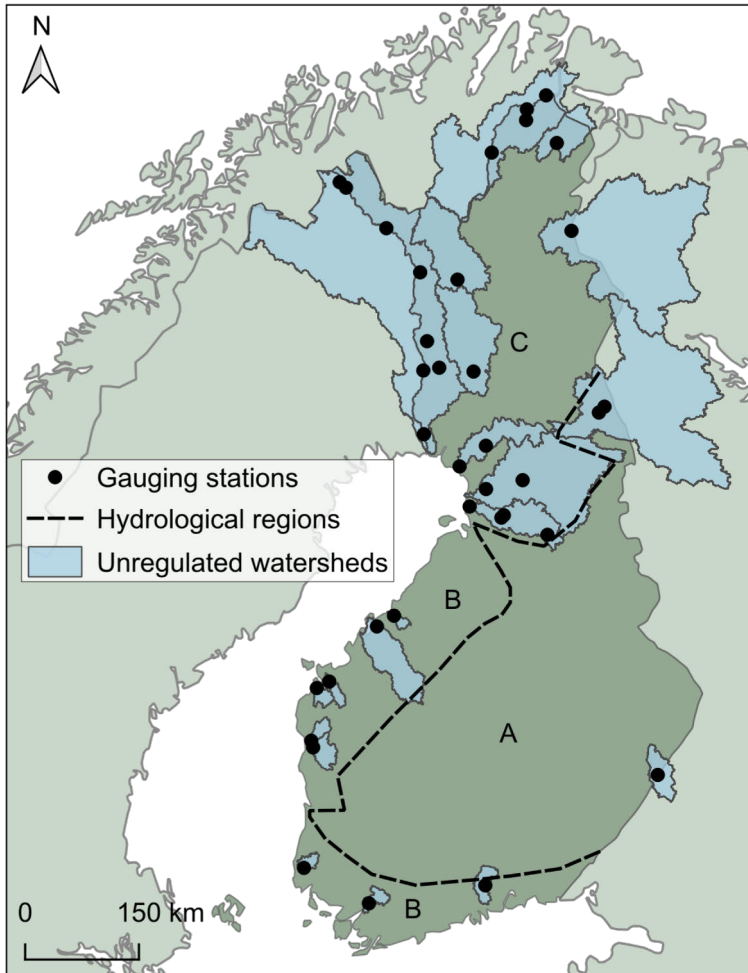


Figure 7. Spatial distribution of unregulated watersheds and gauging stations included in Paper I and the hydrological regions of Finland.

4.2.2 Discharges and flow characteristics under ice-covered conditions

Acoustic Doppler instruments were used to measure two- and three-dimensional flow conditions beneath ice cover in subarctic rivers as part of a long-term data collection on winter hydraulics and sediment processes in Papers II and III. Measurements were conducted during midwinter field campaigns through holes drilled in the ice cover along cross-sections oriented perpendicular to the main flow direction (Figure 8). Cross-section locations were verified with a VRS-GNSS (Trimble R10 or R12i) device to ensure consistent positioning between years. At each measurement point, ice thickness and total water depth were measured to

support the interpretation of the vertical velocity structure and near-bed flow conditions. Annually, the number of drilled and measured holes varied between 90 and 110. The variation in the amount was due to annual differences in water level stage during the freeze up and geomorphological changes of the channel and point bar. The location of each drill hole was measured using VRS-GNSS.



Figure 8. Two ADCP measurement setups are used to collect data beneath the ice. In the first, the ADCP (SonTek M9) device is handheld by the researcher (A), and in the second, it is attached to a tripod (B).

These field data were collected from a seasonally ice-covered meander bend of the Pulmanki River and were used to investigate under-ice flow structure, near-bed hydraulics, and sediment transport processes (Papers II and III). Partly overlapping datasets, complemented with measurements of ice thickness, water depth, and bedform morphology, were also used to examine multiyear variations in under-ice turbulence and hydrodynamic response (Paper III).

The ADCP (SonTek M9) was operated in a stationary, cross-sectional mode to obtain velocity profiles and compute cross-sectional discharge using the mid-section method (Figure 8). The ADV (SonTek FlowTracker/FlowTracker2) was used to obtain high-resolution near-bed velocity measurements in shallow areas where

ADCP profiling was limited and to complement ADCP data (Figure 9). Together, these instruments provided complementary datasets describing the spatial distribution of velocity within the water column and detailed near-bed flow behaviour beneath ice cover.

Where water depth permitted, the ADCP was operated in stationary mode from the ice surface to obtain time-averaged vertical velocity profiles and cross-sectional discharge. In shallower locations, or where near-bed data were required, ADV was deployed as a point sensor approximately 3–4 cm above the bed to collect high-frequency velocity records. Combined, these measurements provided cross-sectional and near-bed flow information under seasonal ice cover (Papers II and III). For the ADCP measurement, each stationary measurement lasted 60 seconds whereas the ADV measurements lasted between 50 and 120 seconds, depending on the measurement year and ADV device used.

ADV velocity measurements were recorded in a local coordinate system where the x-axis is oriented perpendicular to the tagline, the y-axis is aligned along the tagline, and the z-axis (for 3D measurements) points vertically upwards. These correspond to the velocity components v_1 , v_2 , and v_3 , respectively.

ADCP velocities were measured in ENU coordinates (east, north, up), which correspond to the same velocity component as for ADV. For both datasets, the streamwise (u) and cross-stream (v) velocity components were obtained by rotating the horizontal velocity components counterclockwise by an angle, α , which represents the counterclockwise angle between v_1 and the total planar velocity:

$$u = v_1 \cos(\alpha) - v_2 \sin(\alpha), \quad \text{Equation 1}$$

$$v = v_1 \sin(\alpha) + v_2 \cos(\alpha). \quad \text{Equation 2}$$

The vertical velocity component was defined directly as

$$w = v_3 \quad \text{Equation 3}$$

The average speed was calculated as (Wilcox & Wohl, 2006)

$$\sqrt{\overline{u}^2 + \overline{v}^2 + \overline{w}^2} \quad \text{Equation 4}$$

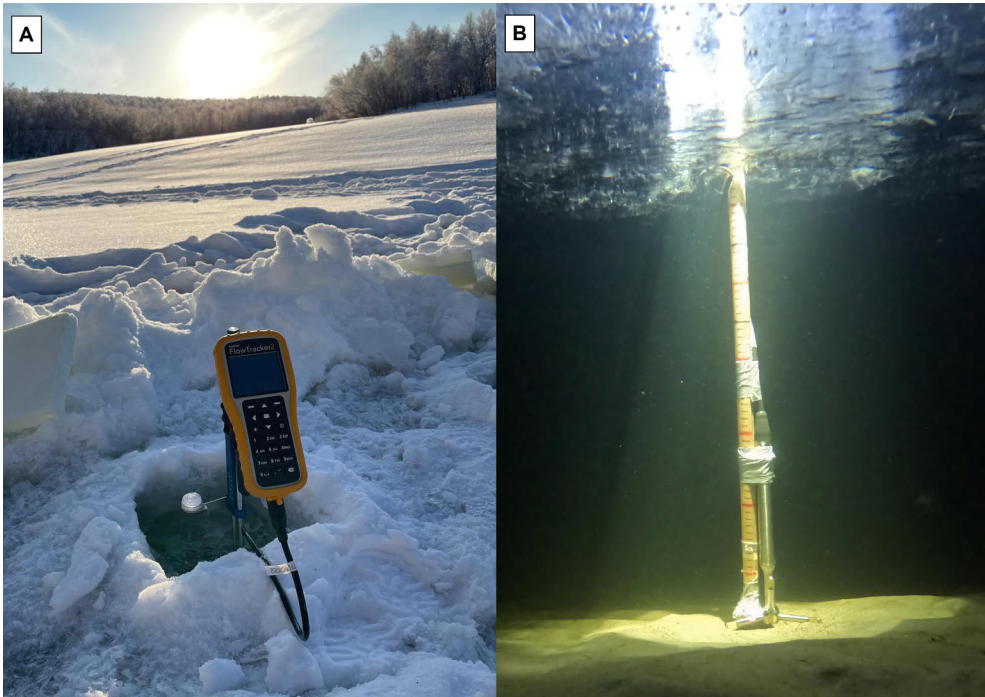


Figure 9. Near-bed velocity measurements were collected using an ADV (SonTek FlowTracker/FlowTracker2). Field setup showing the handheld deployed above the ice surface (A) and the sensor positioned below the ice cover (B). During measurements, the sensor was located approximately 4 cm above the bed (Photos: Petteri Alho & Mandi Hannula).

4.2.3 Applicability and limitations of acoustic flow measurements in natural environments

When combined, ADCPs and ADVs can be used to capture water-column-scale flow patterns and near-bed flow structures. ADCPs provide velocity profiles across the entire water column and are relatively quick and efficient to deploy, and ADVs can be used to complement these measurements by resolving flow at local scales (Das & Debnath, 2025). Accurate estimates of flow and discharge depend on data quality. ADCPs and ADVs are subject to inherent uncertainties which arise from physical, geometrical, environmental, and device user-related factors (Das & Debnath, 2025; Nystrom et al., 2007). In clear-water conditions, such as those in the Pulmanki River during winter, a low signal-to-noise ratio (SNR) can bias flow measurements because there are too few suspended particles to reflect the acoustic signal to the instrument. These SNR-related issues were addressed through a data-filtering procedure that removed biased measurements.

Sidelobe and bottom interference limit the reliability of ADCP measurements in the lowest part of the water column, where signal reflections may bias velocity estimates (Nystrom et al., 2007). Similarly, blanking distance (5 cm) and screening distance (20 cm) beneath the ADCP device prevent measuring in shallower locations than 25 cm of water beneath the sensor (SonTek, 2022). This poses challenges when conducting measurements in small streams, which are often shallow even during the open-water season. Whereas the ADCP integrates velocity over a relatively large sampling volume, the ADV measures at a much smaller, point-like volume (Jamieson et al., 2010; Sukhodolov, 2012). As a result, even small errors in sensor placement, such as misalignment with the flow direction, can introduce significant biases and affect the calculated estimates derived from the measured velocities.

Although measuring flow beneath an ice cover with acoustic methods in natural environments is challenging, flume experiments are also subject to inherent limitations (Demers et al., 2011, 2013). Whereas flume conditions are well controlled, physical factors such as flow depth, discharge, water temperature, and ice-cover characteristics are constrained (Dey, 2014; Robert & Tran, 2012; Simons & Richardson, 1966; Sukhodolov et al., 1998). Moreover, flows in flumes are typically more uniform than in natural rivers, meaning that three-dimensional and spatially non-uniform flow dynamics under ice-covered conditions cannot be fully reproduced (Robert & Tran, 2012; Sukhodolov et al., 1998). Further development of acoustic methods suited for ice-covered conditions is therefore required to enable field measurements that are efficient to conduct and collect data spatially representative of the natural environment.

4.3 River ice cover and bedform characteristics

Ice thickness and total water depth were measured directly through drilled holes at seven fixed cross-sections during midwinter field campaigns conducted between 2016 and 2024 at the Pulmanki River study site (Papers II-III). At each cross-section, drill holes were spaced at approximately one-meter intervals. These point measurements were used to calculate the water column height beneath the ice (i.e., total depth minus ice thickness). This value was then used to determine the depth at which ADCP measurements were taken, as the instrument's minimum profiling range (20 cm) and blanking distance (5 cm) prevent measurements in shallower locations (SonTek, 2022). During some field campaigns, the ice conditions were photographed and recorded using game and action cameras to verify the timing of stable ice formation as well as the properties and conditions beneath the ice cover.

Bedform observations were collected during the 2024 field campaign in conjunction with ice and flow measurements. Riverbed conditions were surveyed at every drill hole used for under-ice velocity measurements to ensure spatial

correspondence between hydraulic and bedform data. At each location, an action camera (GoPro Hero12) mounted on the measurement rod together with a ruler for scale was lowered through the ice to the riverbed and rotated 360° to record the bed surface and its immediate surroundings. The video footage was analysed in the laboratory to interpret grain size and small-scale bedform characteristics. Each site was classified according to the dominant bedform type (e.g., plane bed or dunes), and the results were synthesised to describe cross-section-scale riverbed topography. Bedform types were subsequently compared qualitatively with ADCP- and ADV-derived hydraulic metrics from 2024, examining the correspondence between bedform occurrence and variations in turbulence parameters (Paper III).

Visual ice classification (smooth or rough) and bedform observations collected in 2024 supported the qualitative interpretation of ice and riverbed conditions. Together, these field measurements provided the physical basis for analysing the relationships among ice thickness, water column geometry, and near-bed flow in the meander bend.

4.4 Velocity components and turbulence parameters

To quantify near-bed turbulence under ice-covered conditions, velocity parameters were first derived from the ADCP and ADV measurements, after which the turbulence characteristics were computed. In Paper III, turbulence parameters, TKE, Reynolds shear stresses, and turbulence intensity (TI) were calculated for both measurement systems when applicable.

4.4.1 Analysis of turbulence parameters from ADV data

To estimate turbulence production under the ice cover, TKE can be calculated as (Groom & Friedrich, 2019; Jamieson et al., 2010)

$$TKE = \frac{1}{2} \left(\overline{(u')^2} + \overline{(v')^2} + \overline{(w')^2} \right), \quad \text{Equation 5}$$

where overbars denote time averages and u' , v' and w' are the fluctuating components of the streamwise (u), cross-stream (v) and vertical (w) velocity components. The instantaneous velocity fluctuations were obtained by subtracting the time-averaged mean velocity at each point:

$$u'(x, t) = u(x, t) - \overline{u(x)}, \quad \text{Equation 6}$$

$$v'(x, t) = v(x, t) - \overline{v(x)}, \text{ and} \quad \text{Equation 7}$$

$$w'(x, t) = w(x, t) - \overline{w(x)}. \quad \text{Equation 8}$$

Reynolds shear stresses quantify the turbulent momentum exchange between velocity components and were computed as (Jamieson et al., 2010):

$$\tau_{uv} = -\rho \overline{u'v'}, \quad \text{Equation 9}$$

$$\tau_{uw} = -\rho \overline{u'w'}, \text{ and} \quad \text{Equation 10}$$

$$\tau_{vw} = -\rho \overline{v'w'}, \quad \text{Equation 11}$$

where ρ is the density of water, and overbars denote time averages.

Turbulence intensities describe the relative magnitude of velocity fluctuations normalised by their mean velocities. They were calculated as (Groom & Friedrich, 2019):

$$TI_u = \frac{\sqrt{\overline{(u')^2}}}{\bar{u}}, \quad \text{Equation 12}$$

$$TI_v = \frac{\sqrt{\overline{(v')^2}}}{\bar{v}}, \text{ and} \quad \text{Equation 13}$$

$$TI_w = \frac{\sqrt{\overline{(w')^2}}}{\bar{w}}, \quad \text{Equation 14}$$

These parameters provide a dimensionless measure of turbulence strength in each principal direction.

4.4.2 Analysis of turbulence parameters from ADCP data

The ADCP measures flow velocity using four acoustic beams, allowing only quantities expressible in terms of beam velocities (b_i) to be reliably derived (De Serio & Mossa, 2015; Gilcoto et al., 2009; Stacey et al., 1999). Following De Serio & Mossa (2015), the velocity components (u, v, w) can be expressed as

$$u = \frac{b_1 - b_2}{2 \sin\theta}, \quad \text{Equation 15}$$

$$v = \frac{b_3 - b_4}{2 \sin\theta}, \text{ and} \quad \text{Equation 16}$$

$$w = \frac{b_1 + b_2 + b_3 + b_4}{4 \cos\theta}, \quad \text{Equation 17}$$

where ϑ is the opening angle of the device configuration, in our case 25° (SonTek, 2013). These relationships yield the mean flow velocity components for the ADCP dataset.

Beam velocity variances (b'_{1-4}) were used to calculate the shear stresses, as De Serio & Mossa (2015):

$$\overline{(b'_1)^2} = \overline{u'^2} \sin^2 \vartheta + \overline{u'w'} \sin \vartheta \cos \vartheta + \overline{w'^2} \cos^2 \vartheta, \quad \text{Equation 18}$$

$$\overline{(b'_2)^2} = \overline{u'^2} \sin^2 \vartheta - \overline{u'w'} \sin \vartheta \cos \vartheta + \overline{w'^2} \cos^2 \vartheta, \quad \text{Equation 19}$$

$$\overline{(b'_3)^2} = \overline{v'^2} \sin^2 \vartheta + \overline{v'w'} \sin \vartheta \cos \vartheta + \overline{w'^2} \cos^2 \vartheta, \quad \text{Equation 20}$$

$$\overline{(b'_4)^2} = \overline{v'^2} \sin^2 \vartheta - \overline{v'w'} \sin \vartheta \cos \vartheta + \overline{w'^2} \cos^2 \vartheta, \quad \text{Equation 21}$$

from these, the Reynolds shear stresses are determined as

$$\tau_{uw} = -\rho \overline{u'w'} = -\rho \frac{\overline{(b'_1)^2} - \overline{(b'_2)^2}}{4 \sin \vartheta \cos \vartheta}, \quad \text{Equation 22}$$

$$\tau_{vw} = -\rho \overline{v'w'} = -\rho \frac{\overline{(b'_3)^2} - \overline{(b'_4)^2}}{4 \sin \vartheta \cos \vartheta}. \quad \text{Equation 23}$$

As u' , v' , and w' cannot be expressed solely in terms of beam velocities and the beam angle, the full TKE and turbulence intensities cannot be computed from ADCP data. However, a lower-bound estimate of TKE can be derived (De Serio & Mossa, 2015):

$$\begin{aligned} TKE_{min} &= \frac{3}{8} \left(\overline{(b'_1)^2} + \overline{(b'_2)^2} + \overline{(b'_3)^2} + \overline{(b'_4)^2} \right) \\ &= \frac{3}{4} \left(\left(\overline{(u')^2} + \overline{(v')^2} \right) \sin^2 \vartheta + \overline{(w')^2} \cos^2 \vartheta \right). \end{aligned} \quad \text{Equation 24}$$

4.5 Bedload and riverbed sediment analysis

Sediment data were collected and analysed from the Pulmanki River (Paper II) to quantify bedload transport volume as well as riverbed sediment characteristics. Bedload data collection took place during winter field campaigns and was supplemented with riverbed samples from the open-water season. Bedload samples were obtained using a Helley-Smith pressure difference sampler (Helley & Smith, 1971) during the winters of 2020 and 2021, and riverbed sediment samples were collected using a Van Veen grab sampler during the 2020 autumn open-water season (Figure 10).

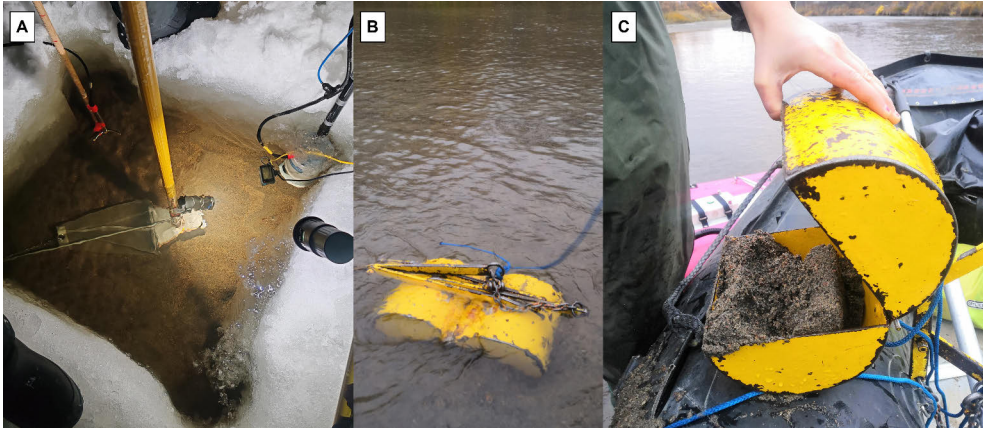


Figure 10. Helley-Smith sampling from ice-covered conditions (A) and Van Veen sampling (B, C) during the open-water season (Photos: Linnea Blåfield).

Helley-Smith samples were taken at the high-flow points of cross-sections (middle or outer bank). Each sample was collected over a 6-minute period, and the sampler intake opening was 77 mm. The bedload was calculated using the equation

$$G/(b * T), \quad \text{Equation 25}$$

where G is the dry weight (kg), b is the intake opening (m), and T is the measurement time (min) (Morales et al., 2019).

The Van Veen grab sampler was used to map the grain-size distribution of the riverbed. Samples were taken from the left bank, mid-channel, and right bank at each cross-section. These samples were used to represent bed conditions across the study reach. All samples, including bedload samples, were oven-dried at 105 °C, weighed, and dry-sieved in the laboratory to determine particle-size distributions and bedload transport volumes. Bedload samples that were too small to be sieved were excluded from the analysis. Grain-size distribution was analysed using half-phi interval sieves, and D_{10} , D_{50} , and D_{90} values were determined.

To determine critical shear velocity, a parameterisation of the (Shields, 1936) curve was applied following the approach of (Van Rijn, 1984), where the non-dimensional grain size (D_*) is used. After determining the observed shear velocity (u_*) and the critical shear velocity (u_{*c}), the transport stage parameter was defined.

Particle size parameter (D_*) was calculated as

$$D_* = D_{50} \left[\frac{(s-1)g}{\nu^2} \right]^{\frac{1}{3}}, \quad \text{Equation 26}$$

where s is the specific density and calculated as ρ_s/ρ . ρ is the mass density of water (g/m³), ρ_s is the sediment density, g is the gravitational acceleration, and ν is the kinematic viscosity.

The critical mobility parameter (θ_{cr}) was defined according to Van Rijn (1984). For the mean grain size (0.5557 mm), the following equation was used:

$$\theta_{cr} = 0.14(D_*)^{-0.64} \quad \text{Equation 27}$$

And for Van Veen samples with higher mean grain sizes and therefore higher particle size parameter, the critical mobility parameter was defined as

$$\theta_{cr} = 0.04(D_*)^{-0.10} \quad \text{Equation 28}$$

These resulting values were then used to calculate the critical shear velocity (u_{*c}) for all measurement locations and study years. The critical shear velocity was derived using the Shields equation (Van Rijn, 1984):

$$u_{*c} = \sqrt{\theta_{cr}((s-1)gD_{50})} \quad \text{Equation 29}$$

The observed shear velocity (u_*) was determined from near-bed velocity measurements using the logarithmic velocity profile (Wilcock, 1996):

$$u_* = \frac{u\kappa}{\ln(\frac{z}{z_0})} \quad \text{Equation 30}$$

where u is the measured near-bed velocity (m/s), $\kappa = 0.4$ (von Kármán constant), z is the measurement height above the bed (m), and z_0 is the bed roughness length (m). Following Namaee and Sui's (2019) reasoning, the bed roughness length (z_0) was defined as the mean grain size (D_{50}), representing the roughness height of the sediment bed. This approach was chosen due to the similarity between the Pulmanki River and the experimental conditions of (Namaee & Sui, 2019), including flow depths (~1.3 m) and sediment sizes (0.47–0.58 mm).

The transport stage parameter (T) was calculated, based on Van Rijn (1984), as

$$T = \frac{u_*^2 - u_{*c}^2}{u_{*c}^2} \quad \text{Equation 31}$$

where u_* is the observed near-bed shear velocity and u_{*c} the critical shear velocity.

4.6 Statistical analyses

Statistical analyses used in this thesis employed a combination of parametric and non-parametric methods to examine relationships and long-term trends. Spearman's rank correlation (Kendall, 1975; Spearman, 1904) was used to assess associations between non-normally distributed turbulence metrics and hydrological or ice-related variables (Paper III), and Pearson's correlation coefficient (Pearson & Galton, 1895) was applied where variables were approximately normally distributed, particularly in analyses of near-bed flow and sediment-transport parameters (Paper II).

For long-term discharge records, monotonic trends were detected using the non-parametric Mann-Kendall test (Kendall, 1975; Mann, 1945), and statistically

significant trend magnitudes were quantified with the Theil-Sen slope estimator (Paper I) (Sen, 1968; Theil, 1950). To account for autocorrelation effects, the Zhang pre-whitening method was applied before significance testing (X. Zhang et al., 2000). Statistical significance was evaluated at $p < 0.05$ in all analyses (Papers I-III).

5 Results and Discussion

5.1 Climate change is driving shifts in discharge regimes in cold-region rivers (Paper I)

The first aim of this dissertation was to quantify long-term changes in river discharge regimes and to link variations in volume, magnitude, and timing to climatic drivers using multi-decadal discharge records. These results are based on Paper I.

In Paper I, data from 36 gauging stations, comprising more than 765,000 daily discharge observations, were analysed together with temperature and precipitation data from two climatological normal periods (1961–1990 and 1991–2020). The temporal coverage of the discharge records spanned from 1911 to 2021, with the mean length of the time series being approximately 60 years. Gauging stations were distributed across Finland (Figure 7) and classified into three groups according to watershed location and characteristics. The results showed that spring floods advanced at 21 of the 36 stations, with shifts ranging from 6 to 68 days, whereas autumn flow peaks were delayed, particularly in northern catchments. These changes are associated with shorter winter durations, earlier snowmelt, and a shift from snow- to rain-dominated precipitation patterns.

At the same time, clear seasonal changes in discharge volumes were identified. Nine stations showed declining high discharge (HQ) magnitudes, and eleven stations exhibited increasing low discharge (NQ) magnitudes. Declines were primarily evident in spring high-flow volumes whereas increases occurred in winter and autumn low-flow volumes. Despite these seasonal shifts, annual total discharge remained largely unchanged, indicating a redistribution of flow volume within the hydrological year. During the later climatological period (1991–2020), a larger number of statistically significant discharge trends were detected than during 1961–1990, including reduced spring flow volumes, earlier spring flood peaks, and higher flow volumes during the winter and autumn low-flow seasons. Also, the mean discharge (MQ) increased at nine stations during the later period.

Regionally, the most pronounced changes were observed in Region B (southern and coastal Finland), where the strongest advances in spring flow timing and the largest decreases in spring flow volumes were detected. In Region C (northern Finland), autumn flow peaks occurred later and winter low flows

increased, consistent with enhanced late-autumn and winter runoff under warmer and wetter conditions. In this region, NQ and MQ generally increased whereas HQ decreased. Spring flow timing advanced in the southern part of Region C whereas no clear timing trend was detected in its northern part. In Region A (Lake Finland), the dominant changes included earlier spring flood timing and reduced early-summer flows; however, the interpretation of these results is limited by the small number of unregulated catchments available for analysis in this region, as the amount of them was two. According to Meriö et al. (2019), the southern part of Region C lies near the threshold between rain-dominated and snow-dominated watersheds, which likely explains the observed advances in spring flow timing in that region. Region B is entirely rain-dominated, as is Region A, with the exception of its northernmost parts.

Overall, the net effect is a redistribution of water from pronounced spring floods towards more moderate flows later in the year. A comparison between the two most recent climatological periods further indicated an approximately 9% increase in precipitation across Finland, primarily during winter, along with a 1.3 °C increase in annual mean temperature (Jokinen et al., 2021). Similar hydrological responses to increasing temperature and precipitation have been documented in northeastern Europe, where earlier spring snowmelt flood timing has been observed and attributed to rising temperatures (Blöschl et al., 2017), alongside an increasing contribution of winter and rain-dominated floods (Hall et al., 2014). By the end of the 21st century, the Arctic is expected to undergo a transition from snow-dominated to rain-dominated precipitation regimes (McCrystall et al., 2021). Consistent with this projection, distinct snow- and rain-dominated watershed regimes have been identified in Finnish catchments (Meriö et al., 2019), with the snow–rain threshold migrating northward (Blåfield, Marttila, et al., 2024). As snow-related processes become less influential under continued warming, flood seasonality in northeastern Europe is expected to shift from snowmelt-dominated regimes towards other flood-generating mechanisms, particularly heavy rainfall (Hall & Blöschl, 2018).

Recent studies show that climate warming has not only intensified but fundamentally altered seasonal dynamics through earlier spring onset and a longer thermal spring, particularly in northern and coastal Finland (Kaboli et al., 2026). These changes are closely linked to large-scale atmospheric circulation, especially positive phases of the Arctic oscillation, the North Atlantic oscillation, and the Scandinavian pattern (Irannezhad et al., 2015, 2017; Kaboli et al., 2026), and were anticipated by earlier modelling studies, with further intensification projected toward the end of the 21st century (Ruosteenoja et al., 2016).

Taken together, these results demonstrate that climate change is substantially altering river flow patterns and seasonal discharge regimes in Finland. Spring floods are occurring earlier, and high-flow events are becoming more frequent in late autumn and early winter. These hydrological shifts contribute to

shorter ice-cover durations, a trend observed globally (Magnuson et al., 2000; Newton & Mullan, 2021; X. Yang et al., 2020), regionally (Blaskey et al., 2023; Chen & She, 2020; Fuk s & Wiejaczka, 2025; Klavins et al., 2009; Latkovska et al., 2016), and locally (Helama et al., 2013; Kuusisto & Elo, 2000; Sharma et al., 2016). Reported declines in ice-cover duration vary spatially, ranging from less than one day to up to 11.5 days per decade (Fuk s, 2023).

In addition, thaw events in late autumn and winter increasingly trigger flooding as rainfall and snowmelt occur simultaneously and, in some cases, may induce premature ice-cover breakup when rising discharge fractures an already formed ice cover (Beltaos & Prowse, 2009; Burrell et al., 2023). Combined with the advancing timing of spring floods, these processes are altering traditional flood seasonality, leading to flood occurrence during periods when society and infrastructure are not fully prepared. Despite a general decline in spring flood magnitudes, overall flood risk remains significant, as extreme weather events may still generate high-magnitude floods. Moreover, the ecological and geomorphological consequences of early ice-breakup events remain poorly understood, and the observed seasonal redistribution of flows marks the need to explicitly consider flow timing in water-resource management and climate change adaptation planning.

5.2 Flow characteristics and sediment transport in the near-bed region of the ice-covered meander bend (Papers II-III)

The second aim was to characterize near-bed flow and sediment transport under ice by quantifying turbulence parameters, assessing how near-bed flow controls sediment entrainment and bedload transport under varying hydrological conditions, and supporting these findings with field bedload measurements. Discharge and river morphology have been identified as key factors influencing sediment transport in cold-region rivers (K m ri et al., 2015; Shen, 2025; Syvitski, 2002; Turcotte et al., 2011).

This aim was addressed through the analyses presented in Papers II and III. Paper II focuses on hydrological and velocity controls on bedload transport beneath ice cover, and Paper III examines near-bed turbulence characteristics under ice-covered conditions (Figure 1). The results of Paper II indicate that sediment transport occurs over a sand bed beneath ice cover in a meander bend, even at low discharges during midwinter. While this behaviour is consistent with the high mobility typically associated with sand-bed rivers, the finding provides important field-based evidence of active sediment transport under ice-covered conditions. Given that the studied reach is a sand-bed river, these findings are most directly applicable to similar

environments, and further research is required to determine whether they can be extended to other settings, such as gravel-bed rivers, where sediment transport typically requires higher flow velocities (Hjulström, 1935). The calculated results are supported by field bedload measurements, which confirm active sediment transport in near-bed locations.

During high-discharge winter conditions, such as those induced by increased winter runoff associated with elevated groundwater levels, bedload transport occurs throughout the entire studied meander bend. In contrast, during low discharge conditions, sediment transport is restricted to the inlet and apex zones, where flow velocities are sufficient to exceed the critical threshold for sediment motion. These results also highlight pronounced spatial heterogeneity across the meander bend, with relatively shallow upstream and inner-bend areas exhibiting higher near-bed velocities, turbulence, and shear stresses, whereas deeper downstream and outer bend pool sections are characterised by lower turbulence levels. Sediment transport in near-bed locations follows a similar spatial pattern. These findings are consistent with previous research (Lotsari, Tarsa, et al., 2019) and clearly demonstrate that sediment transport beneath ice cover should be considered when examining winter flow conditions, modelling those conditions, and assessing the impacts of climate change. Sediment transport in cold region rivers is episodic, and the highest transport rates are concentrated during high-flow peaks, when near-bed velocities are greatest (Blåfield et al., 2025; Salmela et al., 2020; Syvitski, 2002). Similarly, during the ice-covered season, sediment transport occurs episodically through processes such as ice rafting, ice breakup, ice jams, and freeze–thaw cycles (Beltaos & Burrell, 2016; Ettema & Daly, 2004; Polvi et al., 2020; Turcotte et al., 2011). Consistent with the episodic nature of sediment transport beneath ice, the results indicate that flow turbulence and near-bed shear stresses are sufficient to mobilise bed material and maintain it in transport in natural environments, as observed in laboratory settings (Jafari & Sui, 2021; Muste et al., 2000; Namaee & Sui, 2019; Robert & Tran, 2012).

This observation raises the question of how ice-covered conditions influence turbulence characteristics, particularly in the near-bed region, where flow governs shear stresses and sediment transport. Studies have shown that river ice alters flow distribution and magnitude, resulting in greater spatial variability in depositional and erosional zones than under open-channel conditions and indicating substantial modifications to the turbulence field beneath ice cover (Koyuncu & Le, 2022; Lotsari et al., 2020). Despite this, interactions among river ice, flow, and sediment transport remain relatively poorly understood (Shen, 2025). Paper III therefore focuses on quantifying how hydrological conditions beneath ice cover influence near-bed turbulence and sediment transport potential.

The results indicate that the height of the water column beneath the ice cover exerts a primary control on turbulence, with TKE and turbulence intensities

decreasing as the water column beneath ice cover becomes deeper. This reduction is particularly evident near the bed, where TKE and turbulence intensities decline with increasing flow depth beneath the ice. In addition, ice thickness was found to influence turbulence characteristics: thicker ice generally reduces overall TKE whereas under low-flow conditions it can enhance streamwise and vertical turbulence intensities due to increased shear associated with rough ice surfaces. When sediment transport was considered, similar results were observed: thicker ice reduces velocities and sediment transport capacity. Bed morphology further modulates these effects, as reaches characterised by dune-covered beds exhibited higher TKE and near-bed shear stresses than plane-bed reaches, indicating that the combined roughness of bedforms and shallow water column above intensifies near-bed turbulence. The role of discharge further modulates these effects, as ice cover strongly dampens turbulence during low to moderate flows whereas under high-discharge conditions, the influence of ice diminishes and near-bed turbulence levels approach those observed under open-channel conditions. In sections affected by bottom-fast ice, the effective flow area is reduced, which concentrates discharge into the deepest parts of the channel and enhances near-bed velocities, whereas at the apex a negative relationship between ice thickness and near-bed velocity is observed. Across all hydrological conditions, a clear correspondence is observed between near-bed hydraulic forcing and sediment transport potential, such that areas with elevated near-bed velocities, higher turbulence levels, and increased shear stresses also exhibit greater bedload transport. It should be noted that these relationships are based on correlation analyses, which assume independence among observations. However, in this study, measurements collected within individual winter periods are likely not fully independent, as they are influenced by similar conditions, which may affect the statistical significance of the observed annual correlations. In addition, the variability between winter periods, such as changes in bed morphology and ice conditions, introduces heterogeneity to the dataset and may reduce the overall dependency among observations.

Taken together, these findings demonstrate that the height of the water column beneath ice cover has a significant impact on near-bed turbulence characteristics. Shallower water columns beneath ice cover are associated with elevated near-bed turbulence levels whereas greater flow depths, resulting from increased water column heights, are linked to lower values of turbulent kinetic energy and turbulence intensity near the bed. Similar findings were reported for macro-turbulent flow structures and velocities at the same study site (Lotsari et al., 2020; Lotsari, Tarsa, et al., 2019) as well as in flume experiments (Muste et al., 2000) and natural environments (Koyuncu & Le, 2022). Given that projected future changes in ice regimes indicate a tendency towards thinner ice covers, corresponding changes in water levels and flow depths beneath ice cover are also expected (Beltaos

& Prowse, 2009; Lotsari, Lind, et al., 2019; Park et al., 2016). Such reductions in ice thickness are therefore likely to increase the height of the water column beneath the ice, with consequent effects on flow velocities and near-bed turbulence. Consequently, future ice-covered flow conditions may exhibit reduced near-bed turbulence, potentially resulting in decreased sediment transport capacity during winter periods.

5.3 From shifting discharge regimes to altered under-ice hydraulics and sediment dynamics: implications of river ice in cold-region rivers (Papers I-III)

This chapter comprises the main hydrological, hydraulic, and sediment-transport findings of this thesis in the context of ongoing climatic change. The final aim of this thesis was to integrate these results to improve the prediction of winter sediment dynamics and morphodynamic responses under climate change.

Long-term hydrological analyses presented in Paper I demonstrate that climate change is altering the seasonal distribution of discharge in Finnish rivers, with effects to the timing, magnitude, volume and frequencies of high and low flow events. These findings are consistent with projections of declining snowmelt-induced floods (Veijalainen et al., 2010) and observed shifts towards earlier spring floods and increased winter and late-autumn runoff (Gohari et al., 2022). Although ice freeze up and breakup patterns were not analysed in this thesis, the observed hydrological changes imply shorter ice-covered seasons and modified ice conditions, consistent with other research (Norrgård & Helama, 2022). Ice cover nevertheless remains an important regulator of flow properties and sediment transport during winter, and climate-driven alterations to discharge regimes are therefore likely to modify wintertime flow dynamics and sediment transport.

Results from Papers II and III show that sediment transport occurs beneath ice cover in a meander bend of a subarctic river even during the lowest midwinter discharges and that transport rates increase with increasing wintertime discharge. The confining effect of ice cover provides a mechanistic explanation for this behaviour (Ettema & Daly, 2004). By reducing the effective cross-sectional flow area relative to open-channel conditions, ice cover forces a given discharge through a smaller flow area, resulting in elevated flow velocities and the exceedance of critical thresholds for sediment transport. In the absence of ice cover, higher discharges and consequently higher velocities may be required to achieve sediment transport rates comparable to those observed under ice-covered conditions. These findings demonstrate that wintertime processes can play a significant role in sediment dynamics in cold-region rivers.

This study further demonstrated that the height of the water column beneath ice cover strongly influences near-bed turbulence characteristics. Variations in ice thickness and discharge modify water column height, which in turn regulates near-bed turbulence levels and sediment transport potential. Shorter ice seasons, more frequent freeze–thaw cycles, and shifting discharge regimes are therefore expected to reshape wintertime turbulence and sediment dynamics (Fukš, 2023; X. Yang et al., 2020). These results indicate that winter morphodynamic models should explicitly incorporate ice-related processes to accurately represent sediment transport under cold-region conditions.

Hydrological change is also expected to influence the temporal structure of high-flow events. Instead of a single pronounced spring flood peak, future discharge regimes may be characterised by multiple short-term winter discharge peaks associated with thaw events and rainfall, as highlighted by (Salmela et al., 2022). Furthermore, the duration for which discharge exceeds the sediment movement threshold has been suggested to be more influential than discharge magnitude alone (Vetter, 2011). This implies that even if peak spring flood magnitudes continue to decline, overall sediment transport may increase due to a higher frequency of lower-magnitude events. This perspective can also be considered through the concept of effective discharge, which emphasises the discharge range that contributes most to long-term sediment transport (Wolman & Miller, 1960). Although individual wintertime high-flow events may transport smaller sediment volumes than spring floods, their higher frequency may result in a greater cumulative contribution. Consequently, these wintertime events may exert a significant geomorphological influence relative to less frequent but higher-magnitude spring events. In addition, the increasing occurrence of double-peaking flood events, in which a single flood exhibits two discharge peaks (Blåfield, Marttila, et al., 2024), is likely to further enhance sediment transport, as such events generate higher sediment loads than single-peaking floods.

Observed changes in Finnish river discharge regimes, including earlier and smaller spring flood peaks and increased winter low-flow volumes (Paper I), indicate a wider trend toward altered hydraulic forcing and shortened ice-cover duration. Similar trends have been documented in previous studies, observed as earlier ice-cover breakups and winters without river ice (Norrgård & Helama, 2022). These changes reduce the period of ice-covered flow and consequently modify the influence of river ice on winter hydraulic conditions, flow structure, turbulence, and sediment transport. Although the magnitude and timing of these changes vary regionally, river ice remains a key regulator of velocity distributions, near-bed shear stresses, and bedload transport in cold-region rivers.

The absence of river ice cover can reduce the formation of ice jams during spring and thereby limit the potentially destructive floods they may cause. However,

the loss of ice cover also entails adverse impacts on society and the environment (Burrell et al., 2023; Turcotte et al., 2020). Ice breakup and ice jam release generate high flows that mobilise ice and are therefore highly erosive (Beltaos & Burrell, 2021). These events produce peaks in sediment transport, particularly in suspended sediment concentration. For instance, (Giovino et al., 2025) observed that reduced ice-covered conditions promote the infilling of gravel beds with fine material, which can negatively affect habitat suitability. In combination with reduced spring flood volumes and weaker ice breakups, the removal of fine-grained material is diminished, further compromising habitat suitability (Beltaos & Burrell, 2021; Thellman et al., 2021). Taken together, these findings emphasise the importance of accounting for river-ice processes when assessing future sediment dynamics and morphodynamic responses to climate change in cold regions. Comparisons with previous studies and other cold-region rivers suggest that the mechanisms identified in this thesis are not site-specific but are likely applicable across a wide range of ice-affected fluvial systems.

6 Conclusions

The focus of this thesis was to examine how cold-region rivers are changing under warming climate. The thesis combines multi-decadal shifts in discharge regimes on a watershed scale to reach-scale sediment transport processes and hydraulics beneath seasonal river ice cover. By combining discharge trend analyses with nearly decade long time series of winter-time field measurements from a subarctic meander bend, this thesis provides a combined view of how hydroclimatic conditions affect the ice-covered season and how these conditions are changing in response to climate warming. By combining these two long-term, time series-based approaches together with hydroclimatic data, the following conclusions were drawn.

1. Seasonal discharge patterns are shifting, with winter flow conditions undergoing a significant change.

Climate change is altering the timing and seasonal distribution of the river discharge regime across Finland. The dominant signal is a shift away from spring snowmelt dominance towards higher winter and autumn flows, together with earlier spring flood timing. At the same time, annual total discharge volumes remain largely stable, indicating that climate warming primarily drives a reorganisation of runoff within the hydrological year rather than a change in overall water availability. These changes have effects on river ice conditions, including shorter ice-covered periods and the frequency and magnitude of midwinter high-flow events.

2. River ice influences near-bed hydraulics, and sediment transport occurs even during low winter discharges.

Reach-scale observations from a single meander bend of the Pulmanki River indicate that the ice-covered period is morphodynamically active, even under low-discharge conditions. Bedload transport and sediment entrainment potential were observed beneath the ice cover at low discharges, with higher transport rates occurring during periods of increased winter discharge. The threshold for sediment motion was exceeded in every study year, demonstrating that sediment transport persists throughout the winter season and should therefore be explicitly considered in assessments of wintertime river processes.

Turbulence analyses also showed that the height of the water column beneath the ice cover is a primary regulator of near-bed turbulence. Shallower under-ice flow conditions were associated with elevated turbulence levels and shear stresses whereas greater water column heights beneath the ice led to dampened turbulence. Ice thickness also influenced hydraulic conditions by modifying flow resistance and enhancing flow confinement. In addition, local turbulence was affected by riverbed morphology, with higher turbulence levels observed over dune-covered beds compared to plane-bed sections.

Overall, the results indicate that sediment transport and turbulence dynamics beneath ice cover are governed by the combined effects of under-ice flow structure, controlled by water column height, ice thickness, and ice-underside roughness, together with prevailing discharge conditions.

3. Climate-driven changes in discharge and river regimes will alter flow conditions, ice regimes, and sediment dynamics in the future.

Climate-change-driven warming increases winter runoff, advances the timing of spring flood peaks, and alters flood event frequency. In combination, these changes modify river ice regimes, with consequent effects on flow conditions beneath the ice cover. These altered hydraulic conditions, in turn, influence wintertime sediment transport dynamics. Although spring flood magnitudes are declining, the increased frequency of winter high-flow events, enhanced freeze–thaw variability, and the progressive loss of river ice affect the duration and timing of periods when sediment mobility thresholds are exceeded. As a result, sediment transport is likely to become less concentrated during the spring freshet and increasingly distributed across multiple wintertime events, meaning that the role of ice cover in sediment processes must also be taken into account.

In the future, studies of flow conditions beneath ice cover could be extended to a wider range of hydrological conditions, such as early winter, midwinter, and late winter, as well as broader channel reaches and additional study locations. Furthermore, advances in remote sensing techniques could improve the understanding of river ice phenology and timing, thereby enabling the extension of such studies to smaller streams, which are currently underrepresented compared to larger rivers. In addition, the development of automated and photogrammetric methods for sediment transport measurements could enhance the quantification and understanding of sediment transport processes beneath ice cover. Rather than relying solely on acoustic pointwise measurements from individual drill holes, side-looking, cross-sectional measurement approaches could further improve the characterization of under-ice flow conditions by capturing the full channel cross-section. Nevertheless, despite ongoing methodological advances, the study of river ice cover

continues to require fieldwork and equipment capable of operating under freezing conditions.

Overall, the results of this thesis demonstrate that climate change is reshaping cold-region rivers not only by altering discharge regimes but also by modifying flow and sediment processes beneath seasonal ice cover. Winter is shown to be an active and integral regulator of cold-region river morphodynamics. As climate warming continues and discharge and ice regimes become increasingly variable, understanding wintertime processes will be essential for anticipating future channel responses, ecosystem impacts, and risks to water resources in cold-region river systems.

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