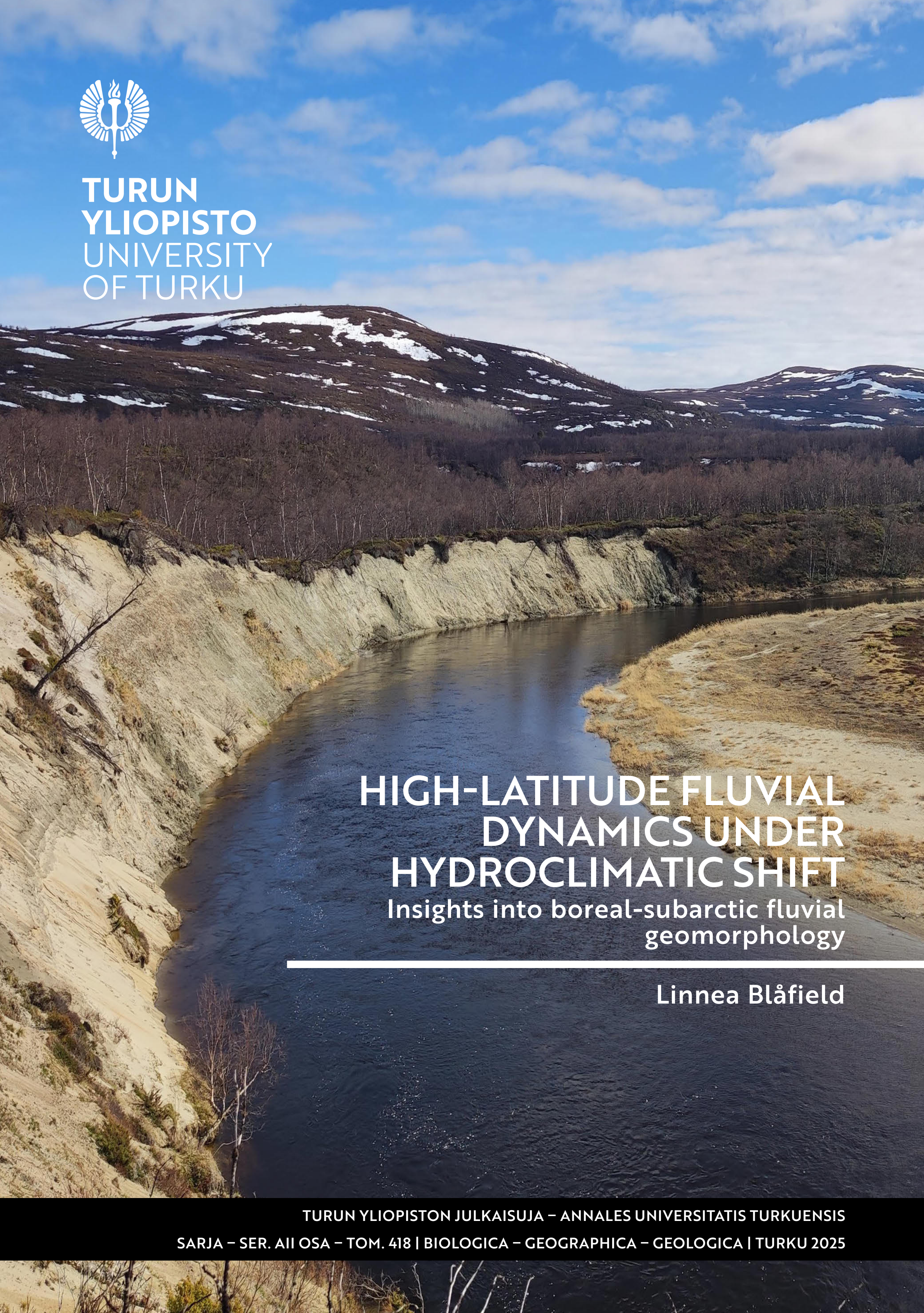

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Linnea Blåfield

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ABSTRACT

This thesis examines high-latitude fluvial dynamics in the context of changing hydroclimatic conditions, focusing on climate-driven alterations to geomorphological processes in meandering rivers. The study targets rivers in the boreal-subarctic zone, a transitional region between temperate and Arctic climates, where rivers are particularly sensitive to climate-related changes. Climate change is expected to significantly affect fluvial dynamics, altering hydrological regimes and landscape stability. Understanding these interactions is crucial for predicting future sediment fluxes, landscape evolution, and ecological impacts. The research combines hydroclimatic and morphological time-series from boreal-subarctic rivers, field data, remote sensing, and morphodynamic modelling to assess the effects of hydroclimatic shifts. The study focuses on two Finnish rivers with contrasting conditions: the boreal Oulankajoki and the subarctic Pulmankijoki. The thesis includes three case studies: i) time-series analysis of hydroclimatic and morphological data to assess climate-driven changes in meander migration and sediment transports seasonality, ii) morphodynamic modelling of one hydrological year to evaluate temporal shift in sediment connectivity, and iii) modelling of morphological responses to variability in flood events. Key findings indicate that spring floods, once the primary drivers of sediment transport, are losing prominence due to earlier snowmelt, milder winters, and increased rainfall in other seasons. This shift has resulted in more event-driven sediment connectivity, with heightened variability in transport processes and morphological responses. Multi-peaking floods, prolonged thaw periods, and intensified rainfall are emerging as critical drivers of sediment dynamics. The study underscores the importance of sediment connectivity and the need for high-resolution monitoring and modelling in a changing environment. The findings demonstrate that while large-scale patterns of change are consistent, their impacts can vary significantly between catchments, providing crucial insights for predicting sediment loads, evaluating landscape resilience, and informing sustainable river management.

KEYWORDS: Sediment connectivity, Sediment transport, Hydroclimatic regime, Morphodynamic modelling, Boreal-subarctic, Close-range remote sensing, Climate change, Regime shift

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TIIVISTELMÄ

Tämä väitöskirja tutkii muuttuvien hydrologisten ja ilmastollisten olosuhteiden vaikutusta sedimentologisiin prosesseihin boreaalissubarktisissa virtavesissä. Lämpenevä ilmasto muuttaa hydrologisia prosesseja, kuten sadantaa ja kevättulvia, mikä vaikuttaa virtavesien kuljettaman sedimentin määrään ja ajankohtaan, veden laatuun sekä maisemaan. Koska boreaalissubarktinen alue on erityisen herkkä näille muutoksille juuri tällä hetkellä, tutkimuksessa tarkastellaan sedimentin kulkeutumiseen vaikuttavia tekijöitä kahdessa eri jokiympäristössä, Oulankajoessa ja Pulmankijoessa. Kolme osatutkimusta yhdistävät pitkiä aikasarjoja, kenttämittauksia, kaukokartoitusta ja morfodynaamista mallinnusta. Ensimmäisessä osatutkimuksessa analysoidaan 50 vuoden hydrologisia ja geomorfologisia aikasarjoja jokimutkien liikkeen ja sedimenttikuljetuksen muutosten ymmärtämiseksi. Toisessa tutkitaan sedimenttivuon kytkeytyvyyttä yhden hydrologisen vuoden aikana, ja kolmannessa mallinnetaan tulvahuippujen muodon ja piikikkyyden vaikutuksia uoman morfologiaan. Tulokset osoittavat kevättulvien merkityksen vähenevän lumen, heikentyneiden talviolosuhteiden sekä lisääntyneen kesä- ja syys-sadannan vuoksi. Nämä muutokset pidentävät sedimentinkuljetuskausia ja lisäävät yksittäisiä, lyhyitä kytkeytyvyysepisodeja. Tämä johtaa sedimenttikuljetuksen tasaisempaan jakautumiseen hydrologisen vuoden sisällä ja morfologisten muutosten heterogeenisyyden kasvuun. Lyhyellä aikavälillä paikalliset tekijät, kuten yksittäiset jokimuodostumat ja sedimentin laatu vaikuttavat morfologisiin muutoksiin, mutta pitkällä aikavälillä hydrologiset ja ilmastolliset tekijät ovat hallitsevia. Tutkimus korostaa sedimenttikytkeytyvyyden ja -kuljetusprosessien ymmärtämisen, jatkuvan seurannan tärkeyttä sekä valuma-aluekohtaisen tarkastelun merkitystä tulevaisuuden jokiympäristöjen hallinnassa.

ASIASANAT: Sedimenttivuon kytkeytyvyys, Sedimentin kulkeutuminen, hydrologiset ja ilmastolliset olosuhteet, morfodynaaminen mallinnus, boreaalissubarktinen alue, lähikaukokartoitusmenetelmät, ilmastonmuutos, Siirtymävaihe

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Abbreviations

ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
ALS	Airborne Laser Scanning
CFD	Computational Fluid Dynamics
C_v	Sediment connectivity value (ratio of erosion to deposition)
D_{50}	Median sediment grain diameter
DEM	Digital Elevation Model
Dfc	Cold Subarctic Climate, Köppen Classification
DoD	Digital Elevation Model of Difference
EDM	Electronic Distance Measurement
GIS	Geographical Information System
FMI	Finnish Meteorological Institute
GCP	Ground Control Point
GNSS	Global Navigation Satellite System
GUI	Graphical User Interface
HVC	High Velocity Core
IDL	International Date Line
IMU	Inertial Measurement Unit
LiDAR	Light Detection and Ranging
MHQ	Mean High Discharge (m^3/s)
MNQ	Mean Normal Discharge (m^3/s)
°N	Degrees North
P	Precipitation (mm)
p75	75th Percentile
Q	Discharge (m^3/s)
Rm/W	Meander Radius to channel width
SfM	Structure-from-Motion
S/P	Snow to Precipitation Ratio
SSC	Suspended Sediment Concentration
SYKE	Finnish Environmental Institute

T	Temperature (°C)
TLS	Terrestrial Laser Scanning
ToF	Time of Flight
TTS	Total Transported Sediments
UAV	Unmanned Aerial Vehicle
ULi	Under Water LiDAR
VRS-GNSS	Virtual Reference Station-Global Navigation Satellite System

List of Original Publications

This thesis is based on the following original publications referred with Roman numerals:

I Blåfield, L., Mattila, H., Kasvi, E., & Alho, P. (2024). Temporal shift of hydroclimatic regime and its influence on migration of a high-latitude meandering river. *Journal of Hydrology*, *633*, 130935.

II Blåfield, L., Calle, M., Kasvi, E., & Alho, P. (2024). Modelling seasonal variation of sediment connectivity and its interplay with river forms. *Geomorphology*, *463*, 109346.

III Blåfield, L., Gonzales-Inca, C., Alho, P., Kasvi, E. (2025). Morphological response to climate-induced flood event variability in a subarctic river. *Earth Surface Dynamics.* (pre-print)

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1 Introduction

Rivers are significant geomorphological agents and the primary conveyors of sediment (Fryirs and Brierley, 2013; Wohl et al., 2017). They are continuously reshaping the landscape through processes of fluvial dynamics, which refer to the interaction and movement of water and sediment in rivers. The interactions between flow conditions and sediment characteristics drive processes such as sediment entrainment, transport, and deposition from source to sink. However, these processes are not straightforward but involve a combination of several factors, including flow velocity, sediment particle size, and the geomorphic characteristics of the channel (Frothingham and Rhoads, 2003). Variations in these factors create spatial and temporal changes in how sediment moves through the system, leading to diverse landscape features. This complex flow-sediment interaction highlights both; short-term changes, such as sediment connectivity, the degree to which sediment can move freely through different sections of the river, and long-term adjustments, such as the gradual migration of meanders.

The seasonality and magnitude of fluvial dynamics within the river channel are largely controlled by the specific characteristics of hydroclimatic regimes (Cockburn & Lamoureux, 2008; Kämäri et al., 2015; Costa et al., 2018). In high-latitude regions (> 60°N), which include boreal, subarctic, and Arctic climate zones, snowmelt-driven spring floods have traditionally been the dominant contributors to water flow and sediment fluxes, serving as key drivers of morphological adjustment (Syvitski, 2002; Gordeev, 2006; Kasvi et al., 2015). However, this region is warming at a rate two to four times faster than the global average, leading to altered hydroclimatic conditions with direct impacts on flow-sediment interaction (Ahmed et al., 2020; Syvitski et al., 2021; Beel et al., 2021; Rantanen et al., 2022; Zhang et al., 2022). These changes in hydroclimatic conditions affect not only short-term sediment fluxes but also contribute to long-term geomorphic and landscape evolution.

High-latitude rivers are projected to become hotspots of sediment fluxes by the end of the century due to melting permafrost and shifting hydrological regimes (Syvitski, 2002; Gordeev, 2006; Ahmed et al., 2020). These changes are expected to have significant implications for ecosystem functioning, water quality, carbon cycling, and landscape evolution (Syvitski, 2002; Gordeev, 2006; Macdonald et al., 2015). Consequently, the boreal-subarctic climate region, i.e., the transition zone between temperate and Arctic climate regions, deserves particular attention. This transitional zone is characterised by significant seasonal temperature variation, low precipitation, and landscapes dominated by boreal forests or tundra. Unlike Arctic regions, where permafrost and glaciers control sediment availability, the boreal-subarctic region allows researchers to assess the immediate impacts of hydroclimatic shifts on fluvial dynamics, morphological processes, and sediment fluxes since most sediment is already available in the landscape. As the high-latitude region continues to undergo profound hydroclimatic transformation, understanding the interactions between hydroclimatic conditions, flow-sediment interaction, and morphological processes in their past, present, and future forms is crucial for predicting river behaviour, managing sediment budgets, and maintaining ecosystem stability (Favaro and Lamoureux, 2015; Feng et al., 2022). By studying these ongoing and already occurred changes in the boreal-subarctic region, we are able to prepare for changes that will occur later in the Arctic. The ecological and landscape-scale implications of these changes are significant. Altered sediment fluxes can affect water quality, aquatic habitats, and nutrient cycling, with cascading effects on both terrestrial and aquatic ecosystems (Stall, 1972; Douglas et al., 2018; Hauer et al., 2018). For example, increased sediment flux during non-traditional seasons may smother spawning grounds for fish or destabilise riparian vegetation and banks, leading to habitat loss and reduced biodiversity (Langendoen et al., 2009; Kemp et al., 2011; Fryirs, 2013; Liu et al., 2017). On a broader scale, shifts in sediment budgets and connectivity from source to sink may influence the long-term stability and resilience of entire landscapes, particularly in regions that are extremely vulnerable to climate-driven changes (Fryirs, 2013; Beel et al., 2021).

Despite the growing recognition of climate-driven changes in fluvial dynamics, sediment fluxes, and morphological processes, substantial knowledge gaps remain, especially regarding the temporally varying functional aspects of sediment fluxes and morphological adjustment, i.e., functional sediment connectivity (Cossart et al., 2018; Hooke & Souza, 2021; Najafi et al., 2021). As functional sediment connectivity is highly responsive to hydroclimatic conditions, it will be an essential factor in predicting how river systems adapt to hydroclimatic shifts. While the flow-sediment interaction and structural connectivity have been widely studied, functional connectivity, particularly in high-latitude areas, has received limited attention in the literature (Najafi et al., 2021). Early studies of flow-sediment interaction emphasised structural processes, the development of geomorphological features, and erosion-deposition processes (Hjulström, 1935; Leopold & Wolman, 1957; Blanckaert, 2011; Heckmann et al., 2018). These studies often relied on sporadic field measurements with low spatiotemporal resolution, typically limited to individual point or cross-sectional measurements (Andrews, 1979). However, recent advances in high-resolution field measurement technologies, close-range remote sensing, and various mapping tools have enabled detailed spatiotemporal analyses of flow-sediment interaction, sediment fluxes, and morphological change detection across various scales, thus enhancing sediment connectivity analysis (Flener et al., 2013; Kasvi et al., 2015; Leyland et al., 2017; Vericat et al., 2017; Najafi et al., 2021). As a result, sediment flux estimations no longer depend solely on traditional field sampling.

Despite these advancements, less than 10% of the world's rivers sediment load is currently monitored, resulting in significant gaps in our understanding of sediment dynamics and seasonality under changing hydroclimatic conditions (Syvitski et al., 2021). This is a key challenge in sediment connectivity research, as limited real-time monitoring of sediment fluxes fails to capture temporal variation and functional dynamics. As a result, less than 15% of studies worldwide have addressed functional connectivity (Najafi et al., 2021). One solution to missing monitoring data has been the use of computational fluid dynamics (CFD), which can be used for morphodynamic modelling of rivers and estimating sediment transport rates, erosion, deposition, and morphological adjustment (Kasvi et al., 2015; Williams et al., 2016a; Milan et al., 2018). It has been widely applied in various studies, from detailed flow-sediment interaction modelling of meander bends to large-scale sediment flux analysis and change detection (e.g., Lotsari et al., 2010; Nicholas et al., 2013; Kasvi et al., 2015; Williams et al., 2016a). However, high spatiotemporal resolution computational modelling is time-consuming and resource-intensive. As a result, most models focus on specific events, typically covering periods of a few days to a few weeks (Coulthard et al., 2007; Williams et al., 2016a). Additionally, these models require a substantial amount of data for construction and calibration. The lack of continuous, high-resolution field data complicates model calibration and validation, leading to potential inconsistencies between modelled and actual sediment dynamics and thus increasing uncertainty.

In this thesis, fluvial dynamics and morphological processes under changing hydroclimatic conditions are examined (Fig. 1) using: i) Hydrological, meteorological and geomorphological time series data based on in situ close-range remote sensing measurements, national gauging stations, field sampling, and historical aerial images. ii) Computational morphodynamic modelling with high spatiotemporal resolution field data. iii) The Index of Connectivity and a sediment budgeting approach. With this multi-method approach, detailed information about the impacts of hydroclimatic shifts on fluvial and sediment dynamics in boreal-subarctic rivers can be obtained.

In context of this thesis, the term "high-latitude" refers specifically to the boreal-subarctic climate zone, characterised by long, cold winters with snow and ice cover, short, cool, and dry summers, and significant seasonal temperature variations. The study was conducted in Finland, between 66° and 70°N, focusing on two meandering rivers; one situated within a tundra ecosystem and the other in a boreal ecosystem. According to Veijalainen et al. (2010), both rivers are expected to undergo contrasting hydrological changes due to climate change by the end of the century. In the subarctic Pulmankijoki River, the annual hydrological cycle and discharge magnitudes are not anticipated to change significantly, whereas in the boreal Oulankajoki River, the magnitude of spring flood discharge is projected to decrease significantly. These contrasting conditions and the ongoing hydroclimatic shift offer a unique opportunity to study changes in the seasonality of flow-sediment interactions, sediment transport dynamics, and functional sediment connectivity. The findings of this thesis provide valuable insights into fluvial and sediment dynamics under changing hydroclimatic conditions, offering a basis for predicting the impact of climate change on future sediment fluxes and landscape stability in high-latitude regions, and for planning sustainable river management practices.

The aims of the thesis are:

i. To assess temporal variation of functional sediment connectivity and morphological response, and their interplay with hydromorphological characteristics (II - III).

ii. To analyse the impact of changing hydroclimatic conditions on seasonality and magnitude of flow-sediment interaction in high-latitude rivers (papers I & III).

iii. To evaluate the key drivers for short- and long-term variability of morphological adjustment under varying hydroclimatic conditions in high-latitudes (I - III).

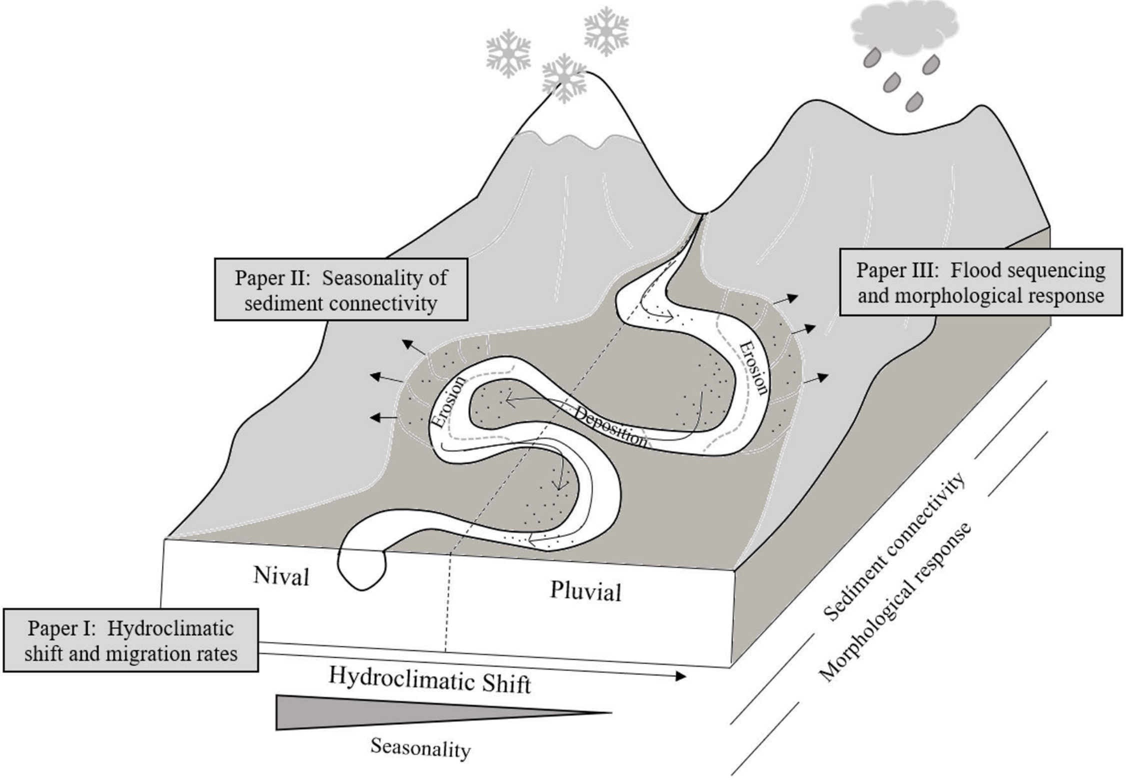

Figure 1. Research design of the thesis. The thesis covers climate change impact on flow-sediment interaction, sediment connectivity, and to their controls in high-latitude meandering rivers. The seasonality, morphological response and hydroclimatic condition form crosscutting themes of the three papers (I-III).

Paper I examines the impact of hydroclimatic shifts on the geomorphic evolution of a boreal meandering river in northern Finland over five decades. It identifies significant warming trends, reduced spring flood magnitudes, and an increase in high-discharge events occurring outside the traditional spring flood period. The study links these changes to meander migration rates, demonstrating how climate-induced shifts in hydrology influence river erosion and landscape evolution. The findings highlight the critical role of thaw seasons in regulating future sediment fluxes and underscore the importance of high-resolution, long-term monitoring of sediment transport. The research also suggests that the timing of peak sediment transport is shifting, rather than showing significant changes in overall sediment volumes.

Paper II combines comprehensive field observations with morphodynamic modelling of one hydrological year to examine the spatiotemporal variation of functional sediment connectivity and links the functional process with the Index of Connectivity. By assessing functional connectivity across different discharge magnitudes and meander bends, it identifies thresholds and physical characteristics that influence functional sediment transport processes on a bend-to-bend scale. The research highlights the episodic nature of sediment connectivity and its dependence on river morphology, providing valuable insights into the interplay between geomorphological characteristics and sediment transport processes. The findings contribute to quantifying functional sediment connectivity and its temporal variation through a novel multi-method approach.

Paper III investigates how climate-induced variability in flood events affects the morphological responses of a subarctic meandering river. It uses a 32-year dataset of climate parameters and discharge hydrographs to classify flood events based on their volume and sequence. The flood event types are correlated with seasonal and annual climatic conditions. The study employs morphodynamic modelling to understand the effects of flood characteristics on sediment transport dynamics and channel morphology. Key findings include the observation of increasing multi-peaking floods and their impact on river system stability by increasing the heterogeneity of sediment transport processes and sediment hysteresis, leading to greater complexity in morphological response patterns.

2 Background

2.1 Fluvial Dynamics and Sediment Transport

Fluvial dynamics refer to the physical processes and forces through which rivers shape and interact with the landscape (Fryirs and Brierley, 2013; Robert, 2014). They involve a complex interplay of hydrological processes, sediment transport, and channel morphodynamics, all influenced by climate and hydroclimatic regimes. The key dynamic processes driving channel evolution and landform development include discharge, flow regime, and flow velocity, which in turn regulate sediment entrainment, transport, and deposition within the channel (Dey, 2014; Wohl, 2014). River channels themselves exhibit a variety of morphologies, ranging from meandering and braided systems to anastomosing networks (Fryirs and Brierley, 2013; Wohl, 2014). In addition to channel morphology, rivers can be classified based on the predominant sediment particle size found in their riverbeds, such as sand- or gravel-bed rivers. These morphological characteristics are influenced by factors such as underlying geology, flow dynamics, and sediment supply. Furthermore, fluvial dynamics contribute to the formation of distinct landforms, including point bars, terraces, oxbow lakes, and alluvial fans, which evolve over time due to sediment transport and other fluvial processes.

In this thesis, the term "sediment" refers specifically to sand and gravel particles of minerogenic origin. Sediment transport in fluvial systems is shaped by the interplay of sediment characteristics and flow conditions and can be divided into three interconnected stages: entrainment, mobilisation, and transport (e.g., Hickin and Nanson, 1974; Fryirs and Brierley, 2013). Together, these processes lead to erosion and deposition. Entrainment is the initial detachment of sediment particles from the riverbed and banks due to fluid forces when the shear stress exerted by flowing water (F_w) exceeds the critical threshold (F_r) (Equation 1) needed to overcome gravitational (F_g), frictional (F_f), and cohesive forces (F_c) between the particle and the riverbed.

$$F_r = F_g + F_f + F_c \qquad \text{Equation 1}$$

Thus, particle entrainment can be described as follows (equation 2) (modified after Ji (2017) and Salmela (2022)):

$$F_w > F_g + F_f + F_c \qquad \text{Equation 2}$$

Sediment mobilisation occurs due to friction between flowing water and sediment particles, with two primary forces acting on the particles: drag force, which acts in the direction of flow, and lift force, caused by differences in flow velocity above and below a particle, creating a pressure gradient (Fryirs, 2013). Thus, particles are mobilised and transported, i.e., eroded, when the force of flowing water (F_x) exceeds the particle's resistance force, i.e., the critical threshold:

$$F_w > F_r \qquad \text{Equation 3}$$

Sediment transport occurs as dissolved load, suspended load, or bedload, which together constitute the total transported sediment load (TTS) (Folk, 1954; Knighton, 1998). Dissolved sediments, generally smaller than 0.45 micrometres, remain in solution. Suspended sediments, usually assumed to be < 0.062 mm, are carried within the water column, whereas bedload, usually assumed to be > 0.062 mm, consists of particles that move by rolling, sliding, or saltating along the riverbed. Because bedload particles are generally too heavy to be lifted into suspension, they play a crucial role in shaping bed morphology through particle exchange. This makes coarse sediments morphologically-important. However, evidence of gravel and larger particles being transported as suspended load in large flood events have been reported (Hooke, 2019). Particles of specific size can go in and out of suspension during a discharge event. In addition to flow conditions, the mode and distance of sediment transport are influenced by sediment particle characteristics, such as size, shape, composition, and minerogenic consistency. When flow velocity decreases and gravitational force (F_x) exceeds the forces created by flowing water, sediment particles settle on the riverbed, leading to depositional forms (sinks). This interaction between particle size and flow velocity is well documented in the Hjulström diagram (Hjulström, 1935), which defines the critical flow velocities required for sediment entrainment, transport, and deposition.

Sediment particle size is usually expressed using the Wentworth scale (Wentworth, 1922), which classifies particles ranging from boulders to cobbles, gravel, sand, silt, and clay. The primary material of a bulk sediment sample is described by a characteristic grain diameter (D), such as the median D_{50} value, which represents the particle diameter at which 50% of the sample material is finer and 50% is coarser (Fryirs and Brierley, 2013). Sediment particles can also be classified based on their chemical properties into non-cohesive and cohesive particles (Vanoni, 2006). Non-cohesive particles, such as sand and gravel, do not form physio-chemical bonds and therefore behave as independent grain units. The transport rate of non-cohesive particles is influenced by their size and shape under varying flow conditions (Roberts et al., 2004; Ferreira et al., 2015). These particles are generally transported as bedload, although they may occasionally be carried in suspension under specific flow conditions.

Conversely, cohesive particles are fine-grained, typically smaller than 63 micrometres, and form physio-chemical bonds that bind them together (Son, 2009; Hodge et al., 2013). These bonds can be strong enough to form sediment flocs, clusters of sediment that significantly influence particle behaviour by increasing resistance to erosion. As a result, cohesive sediment particles require higher shear stress for erosion compared to non-cohesive particles. Thus, erosion potential and volume are not solely related to particle weight or size. Once mobilised, cohesive sediments are generally transported as suspended load. They tend to settle in low-velocity flows, but when flocculated, they may settle even at higher flow velocities. Thus, fluvial dynamics, sediment transport, and sediment characteristics directly influence and control channel geometry, geomorphological units, and morphological change. Fine cohesive particles like silt and clay create narrow, stable channels (Schumm, 1960). In contrast, coarser, non-cohesive sandy sediments form wider, more dynamic channels that frequently meander and develop point bars, riffle-pool sequences, and terraces. The cohesiveness of fine particles enhances bank stability and erosion resistance, while non-cohesive sediments are more easily eroded and transported, leading to faster channel migration (Langendoen et al., 2009; Fryirs, 2013). Geomorphological units, such as bars and floodplains, reflect sediment characteristics: non-cohesive materials form shifting bars, while cohesive sediments settle in slower flows, creating more stable floodplains (Carey, 1969; Ogden et al., 2007). These dynamics drive feedback loops between sediment deposition and flow dynamics, continuously reshaping river morphology, influencing erosion and deposition patterns, and channel migration rates.

2.2 Flow-sediment Interaction in Meandering Rivers: Bank Erosion and Migration

Bank erosion and channel migration are fundamental processes driving the geomorphological evolution of rivers. These changes are caused by the continuous flow-sediment interaction, which shapes channel morphology over time. In meandering rivers, specific flow characteristics play a crucial role in these transformations. These rivers are composed of sinuous bends of varying amplitudes and wavelengths, connected by relatively straight inflection reaches (Leopold and Wolman, 1960; Hooke, 1984). Sandy point bars form on the convex side, while deeper pools and high banks develop on the concave side (Leopold & Wolman, 1960). The curved channel creates a three-dimensional flow field, resulting in a distinct type of flow-sediment interaction: helicoidal flows redistribute sediment, constantly eroding the outer bank while depositing it on the inner point bar (Dietrich & Smith, 1984). The combination of flow, hydraulic forces, and the sedimentological properties of the bank is often referred to as the "bank pull process," which causes the bank to progressively shift outward. These processes, driven by the high-velocity core (HVC) and secondary flows, enhance bank erosion and meander migration, along with the outward surface flow, and can lead to neck cut-offs, oxbow lakes, and high terraces (Bridge & Jarvis, 1976; Hooke, 1980; Rodriguez and Garcìa, 2000).

The flow structure in a meander bend depends on discharge volume and flow velocity, and sediment transport mirrors the flow structure: coarse material is transported along the outer bank in high flow velocity, whereas finer material is transported along the inner bank (Hooke, 2003a; Kasvi et al., 2013). When discharge increases during a flood, the influence of point bar morphology on flow decreases, and the flow may cut across the point bar surface. This causes the HVC to shift further downstream and the secondary flow to weaken (Dietrich and Smith, 1983; Thompson, 1986). As a result of the HVC shift, the hotspot of bank erosion moves downstream. The increased flow velocity reduces the spatial variability of bedload transport, which in turn affects sediment sorting and the morphology of the point bar (Bridge and Jarvis, 1976; Dietrich and Smith, 1984; Ferguson et al., 2003; Pyrce and Ashmore, 2005). Helicoidal flow leads to sediment accumulation on the convex side of the channel, causing the point bars to expand towards the outer bank, a process known as "bar push". As bends mature and the point bars grow outward, pushing against the outer bank, the high curvature causes the HVC to shift from downstream to upstream, thereby shifting the hotspot of bank erosion upstream as well. This process results in increased bend asymmetry (Hickin and Nanson, 1974; Hooke, 1995; Pyrce and Ashmore, 2005).

The stability of riverbanks plays a critical role in erosion and migration processes, with cohesive banks resisting erosional forces more effectively than non-cohesive banks. In general, bank erosion involves two main processes: the detachment of sediment particles and the entrainment of the detached particles. Sediment particles are typically detached through pre-wetting, desiccation, and freeze-thaw activities (Fryirs and Brierley, 2013). Bank material becomes more erodible when wet, allowing sediment to be entrained, for example, during high discharges when the banks are submerged. Desiccation causes dry material from the upper bank to slide down to the toe of the bank, making it more easily erodible by flow. Freeze-thaw cycles can cause thermal erosion, reducing the cohesion of sediment particles. Systemic and local factors, such as hydroclimatic regimes, basin geology, sediment supply, vegetation, and the feedback from neighbouring bends, further influence fluvio-morphological processes in meandering rivers (Hooke, 2007; Gautier et al., 2010). The hydroclimatic regime governs the magnitude and seasonality of flow events, bank erosion, and sediment transport processes. Therefore, hydroclimatic shifts can lead to changes in sediment supply, transport rates, erosion, and deposition processes, with further consequences for flow patterns and channel morphology. Geological factors, such as narrow valley confinement, may cause meanders to migrate downstream as the bedrock limits typical lateral migration. The roots of trees and other vegetation increase cohesion and bank stability while creating hydraulic resistance, which reduces near-bank flow velocities. Feedback mechanisms between adjacent bends also influence sediment transport, connectivity, and channel evolution by either amplifying or dampening geomorphological responses (Gautier et al., 2010).

Recent studies have shown that migration rates of large, sinuous rivers in the Arctic permafrost region have decreased by 20% over the past half-century due to climate change (Ielpi et al., 2023). Similar findings have been reported in semi-arid regions in Australia (Larkin et al., 2020), in cold semi-arid regions of the USA (Schook et al., 2017), and in the subcontinental region of Europe (Elznicová et al., 2022), with timescales ranging from the Holocene to the past few centuries. All these studies highlight the role of decreased fluvial energy. Yet, in boreal-subarctic regions, fluvial activity and high-energy extreme discharge events have increased outside the traditional spring flood season (Korhonen & Kuusisto, 2010; Lintunen et al., 2024). In addition, extreme rainfall events have become more common in the region (Nikulin et al., 2011), which can lead to increased fluvial activity, bank erosion, and sediment transport rates, as found in a study by Kärkkäinen & Lotsari (2022) on a boreal high-latitude meandering river.

2.3 Sediment Connectivity

Sediment connectivity describes the potential for sediment transfer and the processes leading to sediment transport from source to sink across the catchment (Hooke 2003b, Bracken et al., 2015; Wohl, 2017). It is a comprehensive framework for analysing the pathways of sediment particles through the river network. Essentially, it determines whether a sediment particle detached in one part of the network (source) can reach another point within the system (sink) without encountering obstacles. Therefore, the catchment network can be either connected or disconnected. The concept of sediment connectivity is often divided into two terms: structural connectivity and functional connectivity. Structural connectivity is typically quantified based on physical linkages and characteristics within the static landscape (Wainwright et al., 2011; Wohl, 2017; Najafi et al., 2021). It provides a theoretical framework for how sediment could move based on physical barriers and features, such as topography or the gradient of the landscape. In contrast, functional connectivity describes the actual processes and conditions of sediment transport at different spatiotemporal scales (Borselli et al., 2008; Cavalli et al., 2013; Bracken et al., 2015). It is a dynamic measure of sediment transfer, considering variability, seasonality, and specific events, providing insights into when and how sediment transport occurs under different conditions. Some studies have further divided these two main concepts into lateral, vertical, and longitudinal connectivity (Fryirs, 2013; Nicoll and Brierley, 2017; Heckmann et al., 2018), depending on the perspective. In this work, the focus was on longitudinal functional connectivity.

The term “connectivity” originates from ecology, where it has been used to explain how spatial arrangements affect species movement across landscapes (García-Ruiz et al., 1996; Wohl, 2017). Over time, this concept was adapted to hydrology and geomorphology when early research recognised that the transfer of water and sediment depends on the spatial configuration of the landscape and the presence or absence of physical barriers. Sediment connectivity as a research topic has gained considerable attention in recent years within hydrology and geomorphology (Bracken et al., 2015; Najafi et al., 2021). The focus has been on integrating GIS-based modelling frameworks and high-resolution data, leading to comprehensive analyses of sediment pathways and their implications for river morphology. This has shifted sediment monitoring from localised erosion measurements to large-scale sediment flux analyses, covering entire river networks and catchment areas. Modern applications of sediment connectivity span a range of fields, from catchment management to environmental modelling (Fryirs et al., 2007; Rice, 2017; Heckmann et al., 2018; Keestra et al., 2019; Najafi et al., 2021). One of the most prominent applications is sediment yield analysis through erosion and deposition processes. This has led to the development of various sediment connectivity indices, allowing for the mapping and prediction of potential sediment transport areas (Borselli et al., 2008; Cavalli et al., 2013; Cossart & Fressard, 2017; Keesstra et al., 2018; Calle et al., 2020). Additionally, digital elevation models (DEMs) and geographic information system (GIS) approaches have enabled precise mapping of sediment pathways and erosion hotspots, which have benefitted agriculture and forestry (Heckmann et al., 2018; Burguet et al., 2018; Cislaghi and Bischetti, 2019). Another widely used application is in environmental impact assessments, where sediment connectivity helps predict downstream impacts from activities such as mining, construction, deforestation, and other practices affecting water quality and sediment loads (Poeppl et al., 2017; Poeppl et al., 2020).

Despite recent advances in research methods, quantifying functional sediment connectivity remains a challenge (Hooke and Souza, 2021). Only a few studies have addressed the challenges of functional connectivity at the catchment scale (Croke et al., 2013; Bracken et al., 2015; Thompson et al., 2016), and even fewer have done so at the reach scale. The issue lies in the dynamic nature of functional connectivity and the real-time variability of sediment transport in rivers during seasonal or episodic events, such as flooding or intense rainfall (Turnbull et al., 2018; Heckmann et al., 2018; Najafi et al., 2021). Therefore, most current research relies on structural indicators of the catchment and does not capture the temporal variability of connectivity. The temporal aspect could be enhanced by increasing sediment monitoring through continuous, real-time measurements across the catchment, or by modelling with computational fluid dynamics, as demonstrated in this work. Unlike conventional empirical analyses that compare conditions before and after events, such as the widely used digital elevation model of difference (DoD) (Eltner et al., 2018; Heckmann and Vericat, 2018; Calle et al., 2020), modelling offers high temporal resolution, enabling detailed insights into sediment processes occurring during or between events. However, comprehensive field measurements under varying conditions are required for accurate modelling, and therefore, models representing sediment connectivity at high spatiotemporal resolutions remain scarce.

Additionally, interest in the feedback mechanism between structural and functional connectivity has grown, as it influences landscape evolution over time (Wainwright et al., 2011; Najafi et al., 2021). This concept refers to the process where sediment movement causes changes in the environment, which in turn further affect sediment movement. The feedback can either amplify (positive feedback) or dampen (negative feedback) the initial changes. Understanding feedback is critical in geomorphology as it helps explain the causal relationships, causes, and consequences between landscape units, such as river forms and sediment connectivity. In this work, the interplay between river forms and sediment connectivity was analysed in the short term (Güneralp et al., 2022). However, long-term analyses covering decades of geomorphological data are needed to fully understand the feedback mechanism and the hierarchy of functional sediment transport, as these self-reinforcing or self-stabilising processes play a crucial role in determining sediment dynamics, catchment stability, and landscape resilience and recovery over time (Fryirs and Brierley, 2013).

2.4 Hydroclimatic Shift Impact on Sediment Processes at High-latitudes

Climate change has significantly impacted hydroclimatic conditions and sediment transport processes in high-latitude rivers by altering the hydrological cycle and sediment availability (Syvitski, 2002; Favaro and Lamoureux, 2014; Ahmed et al., 2020; Sippel et al., 2020 Zhang et al., 2022). Historically, hydrological processes, such as ice- and snowmelt-driven seasonal discharge peaks, have controlled the magnitude and timing of sediment transport in high-latitude rivers (Cockburn and Lamoureux, 2008). However, with rapid warming occurring at rates more than double the global average (Rantanen et al., 2022), and alterations in precipitation patterns and temperature, high-latitude rivers are now experiencing pronounced hydroclimatic shifts from snow-controlled (nival) regions to jointly controlled (mixed) and, ultimately, to rain-controlled (pluvial) regions (Zhang et al., 2023).

This trend, combined with increasing sediment availability, reduced winter conditions, and prolonged thaw seasons, is reshaping the sediment transport regime by altering traditional hydrology, sediment transport patterns, volumes, and seasonality (Arnell, 1999; Gordeev, 2006; Cockburn and Lamoureux, 2008; St. Jacques and Sauchyn, 2009; Kociuba et al., 2012; Coch et al., 2018; Zhang et al., 2023). High-latitude rivers have typically had low sediment loads, but modelling predicts substantial increases in sediment loads in the Arctic and subarctic climate zones for every degree Celsius of warming, with some estimates as high as 22–30% (Syvitski et al., 2002; Gordeev, 2006).

The regime shift is evident in cold regions across the world (Andrew et al., 2005; Korhonen & Kuusisto, 2010; Ahmed et al. 2020, Qin et al., 2020; Tananaev & Lotsari 2022; Zhang et al., 2022). Areas such as the Canadian and Russian high Arctic, the subarctic, and the high-elevation Tibetan Plateau have experienced changes in their annual sediment loads due to rising temperatures and intensified precipitation (Favaro and Lamoureux, 2014; Gordeev, 2019; Zhang, 2022). In the Arctic climate zone, rising temperatures contribute to glacier and permafrost melt, increasing sediment availability, while intensified rainfall leads to higher river discharges beyond the traditional snowmelt-driven spring flood season. This combination can mobilise significant amounts of sediment, altering riverine and deltaic systems and ultimately leading to sediment transport regime shifts (Zhang et al., 2022). However, the specific impacts of hydroclimatic shifts on high-latitude rivers remain poorly understood, particularly regarding how sediment transport dynamics and connectivity evolve in response to these changes. The complexity arises from the interplay between locally increasing sediment availability, shifting precipitation patterns, and changing hydrological regimes, all of which vary spatially and temporally.

The seasonality of sediment transport processes is likely shifting alongside hydrological factors. However, for a sediment transport regime to shift, a change in the magnitude of sediment transport is also required (Syvitski, 2002; Gordeev, 2006; Zhang et al. 2023). Sediment transport regimes shift through three stages: thermally controlled (nival), thermally and precipitation-controlled (mixed), and precipitation-controlled (pluvial), in which processes such as extreme rainfall and flooding become dominant drivers (Zhang et al., 2022). The increasing sediment flux in Arctic and subarctic rivers can lead to significant alterations in river morphology, landscapes, land-ocean interactions, biodiversity, and the biogeochemical cycling of carbon, nutrients, and pollutants (Syvitski, 2002; Gordeev, 2006; Coch et al., 2018; Ahmed et al., 2020). It is likely to accelerate sedimentation in water reservoirs and estuaries, and to have impacts on hydropower systems. Additionally, it can increase turbidity levels and affect the quality of drinking water sources, thereby impacting water management practices. Ultimately it could lead to increased geodiversity. The trajectory of hydroclimatic changes suggests that the subarctic sediment regime will continue to evolve towards greater variability and instability, with cascading effects on ecological, infrastructural, and socio-economic systems.

As climate change intensifies the hydroclimatic shift, it becomes essential to examine its effects within transitional climate zones, where early signals of these changes are already visible. Thus, this thesis focuses on the high-latitude boreal-subarctic climate zone, where changes in hydrological regimes are already observable to some extent, providing a basis for estimating and predicting future impacts on the Arctic climate zone. The study areas are situated within the Finnish boreal-subarctic environment, and the remainder of this chapter focuses specifically on this region. Unlike in Arctic regions with glaciers and widespread permafrost, the Finnish boreal-subarctic landscape has limited permafrost and no glacial cover, meaning that most sediment is already available for transport (Kersalo & Pirinen, 2009; Pirinen, 2012; Pulliainen, 2020). In Finland, the snow-precipitation threshold zone that determines the controlling factor for hydrology is located approximately at the level of the Arctic Circle (66° North). Below this threshold zone, a shift from snow control to precipitation control in hydrology is evident, whereas above the threshold, no significant shifts have yet occurred (Meriö et al., 2019).

The general trend in Finland indicates that below the threshold zone, the hydroclimatic shift is advancing the timing of spring floods while reducing their magnitude (Korhonen & Kuusisto, 2010; Lotsari et al., 2010; Veijalainen et al., 2010; Gohari et al., 2022; Lintunen et al., 2024). These changes reflect broader shifts in seasonal precipitation patterns and temperature regimes, altering the balance between snowfall, snowmelt, and rainfall-driven runoff. As a result, the traditional dominance of snowmelt-driven floods is weakening, making way for more complex seasonal flood patterns. Although snowfall has increased in some northern parts of Finland, more frequent rain-on-snow events and mid-winter melting have reduced overall snowpack accumulation across the country, leading to lower snowmelt-driven spring flood peaks (Pirinen et al., 2012; Luomaranta et al., 2019). However, regional variation in the impacts of climate change within Finland is significant (Lindgren et al., 2017). At the same time, changes in seasonal precipitation distribution are contributing to shifts in flood timing and intensity. Increased summer and autumn precipitation is driving more frequent floods outside the traditional spring flood period, while reduced winter conditions and shortened ice-covered periods are contributing to higher winter baseflows (Moragoda et al., 2017; Qin et al., 2020; Irannezhad et al., 2021). Increased temperatures, freeze-thaw days, and precipitation falling as rain instead of snow in winter have significantly increased winter flooding in southern Finland. The shortening of ice-covered periods has introduced new dynamics into Finnish river systems (Gohari et al., 2022; Lintunen et al., 2024). Historically, ice jams and ice break-up floods have played a significant role in shaping river channels, particularly in northern Finland, where ice-related processes have contributed to episodic bank erosion and sediment redistribution (Koutaniemi, 1984, 1995). However, with milder winters reducing ice thickness and duration, ice break-ups are occurring more gradually, leading to weaker mechanical erosion and potentially altering sediment transport patterns.

Despite advancements in understanding climate-driven hydroclimatic shifts in Finland, significant knowledge gaps remain, particularly regarding sediment transport dynamics under changing environmental conditions. While studies have documented shifts in flood seasonality, ice-cover duration, and precipitation patterns, their precise impact on erosion, sediment transport, and deposition patterns remains uncertain (Lotsari et al., 2019). One of the key unknowns is how sediment fluxes will evolve in response to increasing precipitation variability. Although autumn and winter floods are becoming more dominant (Veijalainen et al., 2010; Lintunen et al., 2024), their capacity to transport and redistribute sediment compared to reduced spring flood conditions remains unclear. Thus, it is uncertain whether these floods outside the spring flood season will transport sediment in similar magnitudes to spring floods and how this will affect the short- and long-term morphological responses of river systems.

2.5 Monitoring of Morphological Change and Sediment Transport Processes in Rivers

Monitoring sediment, morphological change, and sediment transport in rivers is essential for understanding river dynamics, landscape evolution, ecosystem stability, and for managing water resources under climate change. Currently, sediment monitoring is severely limited, with sediment loads measured in fewer than 10% of the world’s rivers, and long-term data from subarctic river basins is even rarer (Syvitski, 2002; Zhang et al., 2023). Bedload monitoring, in particular, has received much less attention compared to suspended load, partly due to the more demanding measurement methods. A wide range of methods can be applied to monitor morphological change, sediment movement, and flux, either as bedload or suspended load (Muhammad et al., 2019). These approaches include conventional field and laboratory measurements, flow-based methods, geomorphological mapping, and modelling. In the early 20th century, measurements were based on empirical field observations and laboratory experiments (Lane, 1937; Friedkin, 1945; Hooke, 1984). These measurements were conducted with low spatiotemporal resolution, usually as point measurements or cross-sectional surveys across the river (Bridge and Jarvis, 1976; Warburton et al., 1993). Traditionally, bedload transport was monitored using samplers such as the Helley-Smith (1971), sediment traps, or tracers (Hubbell and Sayre, 1964; Leopold and Emmett, 1976; Lane et al., 1996). Bottle and pump samplers, traps, and turbidity sensors have been widely used for monitoring suspended load (Benedict, 1947; Lecce et al., 2006; Bayram et al., 2012; Salmela et al., 2022). However, these methods are labour-intensive, offer low spatial coverage, and are prone to errors due to sampling placement or manual handling (Muhammad et al., 2019).

In the early 20th century, flow-based approaches were implemented alongside one-dimensional flow velocity measurements using mechanical current meters or propeller-type velocity meters (Bathurst et al., 1979). Sediment transport rates were estimated based on flow velocity and discharge calculations. Acoustic measurement technologies emerged in the late 20th century, enabling three-dimensional data collection from the water column. Devices such as Acoustic Doppler Velocimeters (ADV) and Acoustic Doppler Current Profilers (ADCP) became commonly used to measure flow fields and bathymetry, either at specific points or from a moving platform. These devices employ sound waves to assess sediment dynamics and particle movement in water with high resolution. Recently, multibeam sonar (MBES) technology has been used to measure real-time bedload transport volumes and suspended sediment concentration (SSC) in three and four dimensions (Best et al., 2010; Simmons et al., 2010; Simmons, 2017). Both acoustic and multibeam sensors transmit an acoustic signal. The backscatter intensity of the signal is correlated with SSC or bedload, allowing for the calculation of the amount of sediment travelling past the device over a given period. In the 21st century, large-scale particle image velocimetry (LSPIV) techniques have been used to capture bedload transport rates from high-quality video recordings (Eltner et al., 2020; Pajunen et al., 2024). LSPIV analysis tracks sediment particles by observing pixel movements within the video frame. Additionally, acoustic geophones and hydrophones have been used for bedload monitoring. The impact plates of these devices record seismic vibrations generated by moving sediment particles, allowing sediment transport volumes to be estimated (Wyss, 2016; Rickenmann, 2017). These methods enable automated sediment monitoring to some extent, but they require extensive calibration and further development (Muhammad et al., 2019).

Traditionally, morphological changes were quantified using elevation differences obtained through line measurements with geometric levelling (Koutaniemi, 1976, 1995; Bitelli et al., 2000). However, by the mid-20th century, remote-sensing methods had become increasingly prevalent. This shift was driven by greater availability of aerial imagery, technological advancements, and the growing use of photogrammetric surveys for mapping geomorphological formations (Ray, 1960; Brice, 1974). By the turn of the millennium, remote-sensing-based digital elevation models (DEMs) had become commonly used in topographic surveys as airborne photogrammetry techniques were further developed. Recently, unmanned aerial vehicles (UAVs) have been used for repeated topographic surveys on various scales, such as before and after a flood event (Carbonneau and Dietrich, 2017; Vericat et al., 2017; Calle et al., 2020). Optical bathymetric mapping and Structure-from-Motion techniques based on UAV imagery have further enhanced the mapping of geomorphological formations and fluvial processes, both below and above the water surface (Brasington et al., 2003; Flener et al., 2013; Javernick et al., 2015; Calle et al., 2018; Kasvi et al., 2019).

Another widely used close-range remote-sensing method for monitoring morphological change is LiDAR (light detection and ranging), which was developed in the early 21st century (Charlton et al., 2003; Liang et al., 2022). LiDAR systems, such as laser scanners, operate based on either the time of flight (ToF) or the phase shift of a laser pulse at a specific wavelength and frequency. Laser scanning can be conducted using various static or mobile platforms, such as terrestrial laser scanning (TLS) on the ground, airborne laser scanning (ALS), or boat-mounted mobile mapping systems (BoMMS) (Alho et al., 2009; Hohenthal et al., 2011; Flener et al., 2013; Vaaja, 2011). These systems typically use infrared wavelengths ranging from 700 nm to 1500 nm and measure millions of points with millimetre-level accuracy. They differ in accuracy and efficiency: TLS provides the highest point accuracy but is limited in regional coverage (Liang et al., 2022). Mobile and BoMMS platforms allow for better regional coverage but require additional global navigation satellite systems (GNSS) and inertial measurement units (IMU) for positioning. ALS offers significantly broader coverage and improved efficiency but requires further development in sensor resolution and technology.

Traditional laser scanning approaches do not penetrate the water surface, leaving gaps in the point clouds of river environments. However, the latest advancements in green-wavelength laser systems, multi-channel technology, and dual-laser systems have opened new possibilities. These lasers have been successfully used in underwater bathymetric LiDAR surveys (ULi), with water penetration rates up to 2.5 times the Secchi depth (Ahmed & Bakken, 2023; Kastdalen et al., 2024). In general, LiDAR and laser scanning systems have enabled high-resolution mapping of geomorphological formations, change detection, grain size, and bed roughness in river environments. One challenge in conducting LiDAR measurements is vegetation which may cover the land surface or river bed, and thus, cause uncertainty in detecting the actual surface of the geomorphological forms.

Additionally, sediment transport can be estimated using computational hydro- and morphodynamic models, which are based on flow velocity, bed shear stress, and stream power (hydrodynamic), or by evaluating areas of erosion, deposition, and total sediment transport volumes (morphodynamic) (Kasvi et al., 2014; Williams et al., 2016a). These models allow for larger-scale evaluations at higher spatiotemporal resolutions compared to conventional field measurements. However, accurate calibration data from field measurements during various discharge events and seasons is necessary. Despite advances in automated systems, the inherent variability in sediment transport over time and space, coupled with high costs and operational challenges, means that there is no universally superior method for sediment monitoring (Muhammad et al., 2019). Conventional techniques continue to play a vital role, particularly for calibrating and validating newer technologies and models.

2.6 Computational Modelling of Sediment Transport Processes

Computational modelling, as discussed here, refers to computational fluid dynamics (CFD) which is based on the conservation laws of mass and momentum. Hydraulic modelling has become one of the primary tools for studying fluid flows, nutrient transport, and sediment transport dynamics in fluvial systems (Lane et al., 1999; Nicholas, 2000, 2003; Ma and Ingham, 2005; Zawawi et al., 2018; Shaheed et al., 2021). Modelling tools are used to analyse and predict flow behaviour, sediment transport, and other hydrodynamic interactions in various hydrological and hydraulic systems. Nowadays, a wide range of CFD-based modelling tools is available, including both commercial and open-access options. CFD models vary in usability, some have graphical user interfaces (GUIs) for easy setup (e.g.**,** HEC-RAS 2D, MIKE 21/3, FLOW-3D), while others require coding for advanced customization (e.g., OpenFOAM, CFD Python, Ansys Fluent). Delft3D, used in this thesis, offers both GUI and scripting options for flexibility and is one of the most used commercial CFD software.

The calculations of fluid and sediment movements in CFD are based on the Reynolds-averaged Navier-Stokes shallow water equations. These equations can be solved in one, two, or three dimensions and applied to both steady and unsteady flow scenarios. A computational grid, either structured (equally sized rectangles) or curvilinear (irregular quadrilaterals) that adapts to river boundaries, defines the model's computational domain. The principles of morphodynamic modelling involve simulating the interplay between hydrodynamics, sediment transport, and bedform evolution. To set up a morphodynamic model, various datasets are required (Lane et al., 1999; Schuurman et la., 2013; Kasvi et al., 2014; Williams et al., 2016a). Essential components include channel geometry, spatiotemporally varying boundary conditions (e.g., discharge and water level), riverbed roughness, sediment composition, and transport magnitude. Within the model boundaries, sediment transport is calculated as bedload, suspended load, or a combination of both using empirical formulas (e.g., Meyer-Peter & Müller, 1948; Engelund & Hansen, 1967; van Rijn, 1984, 1993). Bottom morphology is dynamically updated at each time step based on the modelled sources (erosion) and sinks (deposition), ensuring that the hydrodynamics are always calculated on the correct bathymetry. However, model parametrisation is determined by the user, which can significantly affect the model results. Therefore, care must be taken when selecting parameters and calibrating the model.

Morphodynamic modelling can be used to simulate current, past, and hypothetical future events with higher spatiotemporal resolution compared to field measurements alone. Since the 1990s, one- and two-dimensional morphodynamic models have been increasingly applied in fluvial geomorphology to study processes such as sediment transport, bank erosion, and meander migration (Bridge, 1992; Hodkinson & Ferguson, 1998; Darby et al., 2002; Lane & Ferguson, 2005; Schuurman et al., 2013). By the early 21st century, three-dimensional models had become more prevalent, offering more detailed insights into sediment and flow dynamics (Lesser et al., 2004; Kasvi et al., 2015). Two-dimensional models require relatively lower computational power compared to three-dimensional models while still capturing variations in flow conditions and sediment transport. Advances in remote-sensing and field measurement technologies have further refined these models with high spatiotemporal data resolution, allowing for more detailed and complex simulations (Kasvi et al., 2015; Xu et al., 2025). For example, morphodynamic modelling has been successfully used to analyse sediment dynamics in the context of habitat sustainability, flood risk management, and sediment supply to estuaries and delta areas (Daneshvar et al., 2017; Salmela et al., 2022).

Recently, the concept of sediment connectivity has gained prominence in morphodynamic modelling, but despite recent advances, modelling functional connectivity remains a challenge. Few studies have utilised morphodynamic modelling to analyse landscape stability and sediment budgeting (Rousseau et a., 2017; Wang et al., 2024), and most of these models are still based on static before-and-after event approaches (Williams, 2016; Cucchiaro et al., 2019), which lack the detailed temporal variation necessary to analyse functional connectivity. This is where morphodynamic models with high spatiotemporal resolution can contribute to understanding the functional aspects of connectivity, as demonstrated in this thesis.

3 Characteristics of the Study Areas

Finland is located in the high-latitude area (> 60°N), where ecological zones of boreal forest and tundra dominate (Fig. 2A). Despite being at similar latitudes to tundra-dominated regions in North America and Siberia, Finland's milder climate and moderate precipitation, largely influenced by the Gulf Stream, along with favourable soil conditions, allow boreal forests to extend further north. There are no glaciers in Finland, and permafrost can be found only sparsely, mostly in the form of palsa mires in the northernmost areas (Kersalo & Pirinen 2009; Pulliainen et al., 2020). This study was conducted between 66° and 70° North in two different river systems (Fig. 2B): the boreal Oulankajoki River (Paper I) and the subarctic Pulmankijoki River (Papers II and III). Both study areas belong to the Köppen climate classification of boreal-subarctic climate, described as “Cold, without a dry season, but with a cold summer” (Dfc). Currently, the Oulankajoki River lies near the snow-precipitation (S/P) ratio threshold zone (Meriö et al., 2019), where hydrology is influenced by both precipitation and snow. The Pulmankijoki River remains within a snow-dominated (*nival*) hydrological regime. These rivers were selected for study because both represent free-flowing, unregulated meandering rivers with long monitoring history but exhibit different hydroclimatic conditions and contrasting climate change forecasts for hydrology (Veijalainen et al., 2010). Both rivers feature sandy, mobile beds, highly eroding banks, and relatively clear and shallow water, which together offer an ideal environment for monitoring sediment processes.

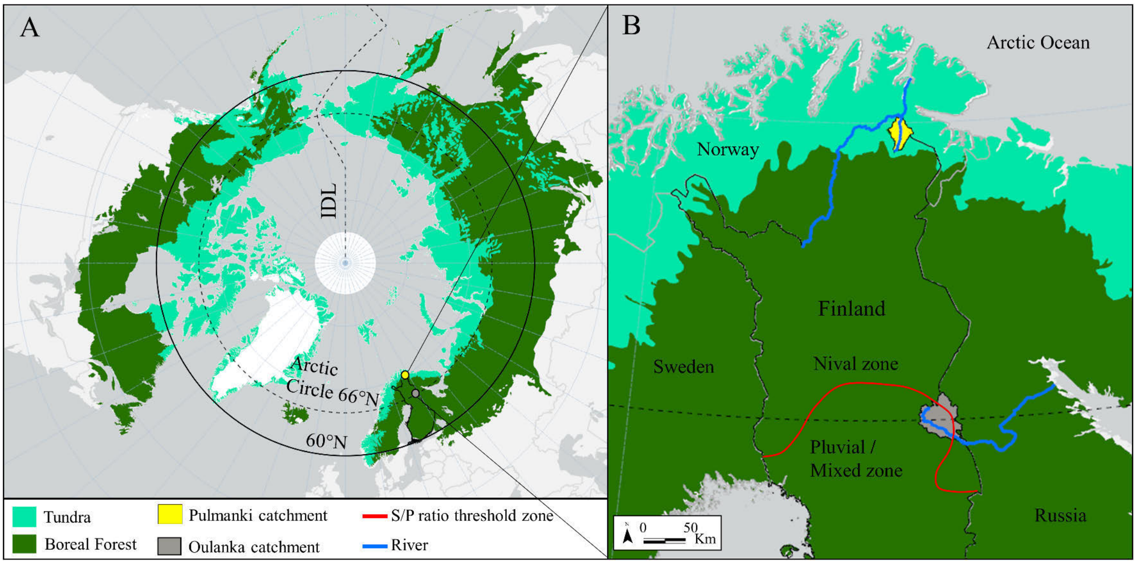

Figure 2. Location of study areas. **A**) Location of Finland in the context of High-latitude region and the prevalent ecological zones. **B**) The study of paper I was performed in a boreal Oulankajoki River, and studies of papers II and III in a subarctic Pulmankijoki River. S/P ratio threshold zone indicating the hydrological regime is based on work of Meriö et al., (2019). IDL = International Date Line.

3.1 Oulankajoki River

The Oulankajoki River, located in north-eastern Finland, flows through the Oulanka National Park, established in 1956 (Fig. 3). Its name, meaning “a flooding river,” aptly describes its nature, as it is shaped by hilly and steep topography, a low percentage of lakes (4.7%), and a high proportion of peatlands (40%) within its 2,100 km^2 catchment. The 135-kilometre-long river discharges first into Lake Paanajärvi and eventually into the White Sea on the Russian side of the border. The river’s upstream section flows through a bedrock canyon, but after passing a geological knick-point marked by the 15-metre-high Kiutaköngäs waterfall, the valley widens to between 600 and 1,000 metres. This valley is filled with glaciofluvial material deposited after the final retreat of the Fennoscandian Ice Sheet, allowing the river to meander. The river has carved its channel 40 metres deep into these sediments. Since the valley is still relatively narrow, it limits the river’s ability to migrate laterally, resulting in meanders that maintain low sinuosity and migrate longitudinally downstream relatively quickly compared to other Fennoscandian rivers (Koutaniemi, 1984). The surrounding landscape is dominated by high river terraces, oxbow lakes, and boreal forest.

The annual mean temperature is currently around +2° Celsius, although the continental climate causes large seasonal temperature fluctuations, ranging from -

48° to +32° Celsius. Summers are relatively dry since nearly half of the annual total precipitation (~550 mm) falls as snow during the winter months, from November to April. The river channel is ice-covered during this period. Spring floods, triggered by ice breakup, ice jams, and snowmelt, occur annually in early May, while additional high-discharge peaks are associated with intense precipitation events during late summer and autumn, typically in August and September. The annual discharge ranges from a low winter baseflow of 3 m^3/s to peaks of 462 m^3/s during the snowmelt season in May (MNQ: 5.2 m^3/s; MHQ: 266 m^3/s). Outside the spring flood and ice-covered seasons, discharge typically varies between 10 and 120 m^3/s.

The study for Paper I focuses on two meander bends and their banks located within a 4-kilometre stretch of the river's lower course. Bend 1 spans 1 kilometre along its thalweg and occupies the entire 600-metre-wide valley, which is confined by bedrock. Bend 2 has a 600-metre thalweg and is situated in a valley section up to 1 kilometre wide, with glaciofluvial confinement on one side and bedrock on the other. The outer bank of Bend 1 is 450 metres long and 3–7 metres high, compared to Bend 2's 300-metre-long, 3–5-metre-high bank. Bend 1 features coarser sediment (D_{50}: 0.18–46 mm) than Bend 2 (D_{50}: 0.2–33 mm) and has a higher ratio between meander-radius to channel width (Rm/W: 4.5 vs. 3.3) and sinuosity (1.8 vs. 1.4). Both banks contain cobbles and pebbles up to 80 mm, with the bank material classified as slightly gravelly and gravelly sand. Bend 1 has a lower slope (0.22 m/km) compared to Bend 2 (0.27 m/km). Both banks experience annual ground frost to a depth of 0.3–1.0 metres from October to May, followed by thawing just before or during the spring flood peak (Koutaniemi, 1979, 1984; 1987 and 2000).

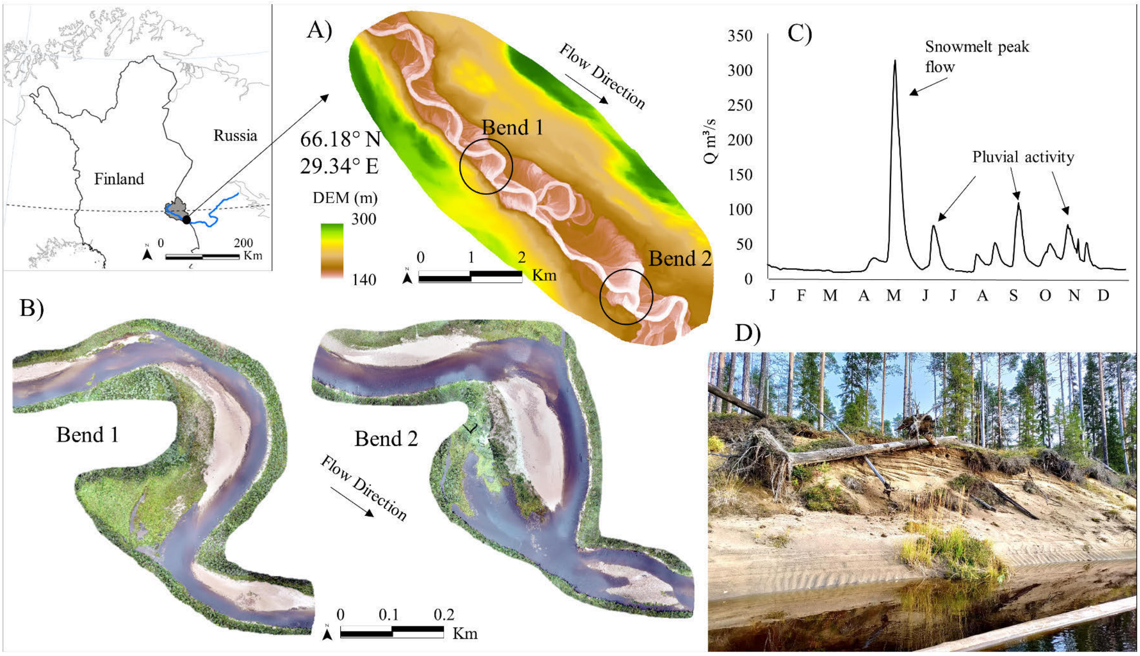

Figure 3. The study area of Oulankajoki River. **A**) DEM of Oulankajoki Valley and location of bends 1 and 2. **B**) SfM based orthomosaics of the bends 1 and 2. **C**) Typical hydrograph for Oulankajoki River with low winter baseflow, high snowmelt peak flow and pluvial activity during summer and autumn. **D**) Sandy river bank with fallen trees.

3.2 Pulmankijoki River

The Pulmankijoki River is located in the northernmost Finland, where it flows freely and discharges first into the Tana River, and then into the Arctic Ocean on the Norwegian side of the nation border (Fig. 4). The 58-kilometre-long river drains a catchment area of 484 km², consisting mainly of moraine formations and peatlands including permafrost-rich palsa mires (Marthinussen, 1960, 1962). The region's vegetation is dominated by low tundra shrubs and alpine birches. The river flows through an ancient fjord, where tens of metres of glaciofluvial material were deposited during the retreat of the last continental ice sheet approximately 10,000 years ago. As a result, sediment availability is guaranteed for the river. The Pulmankijoki River has eroded its channel 30 metres deep into these sediments and continues to evolve through neck cut-offs and the formation of oxbow lakes (Mansikkaniemi, 1967; Mansikkaniemi and Mäki, 1990).

The climate in this region is influenced by the Asian continent and the Atlantic Ocean, and by the warming effect of the Gulf Stream (Autio & Heikkinen, 2002). The annual mean temperature is -1°C, with significant fluctuations ranging from -45°C to +32°C. Thermal winter typically begins in mid-October and lasts until mid-

May, while the other seasons are short but distinct. During thermal winter, the river remains frozen. The annual spring flood occurs in late May due to snowmelt and ice breakup. Discharge varies from 0.5 m^3/s during the ice-covered season to 100 m^3/s during the spring flood. During the open-water season, discharge typically ranges between 2 and 10 m^3/s. Annual precipitation totals around 450 mm, with half falling as rain between June and September.

The study area for Papers II and III is a 6-kilometre section of the river's upper course, which includes 13 meander bends of varying planform types, evolutionary stages, and sinuosities. The mean slope of this reach is 0.2 m/km. The particle size of the riverbed, point bars, and banks ranges from 0.01 to 13 mm, and the channel belongs to textural groups ranging from fine sand to slightly gravelly sand. The riverbed is characterised by riffles, pools, and ripples, with sandy bedload (D_{50} ~0.43 mm) dominating sediment transport during both high and low discharges. The bed material is mostly poorly sorted. The amount of suspended load is minimal for most of the year, even during the spring flood peak (180–280 mg/l). The annual spring flood event causes significant vertical changes on the point bar surfaces (up to ± 0.5 metres) and bank erosion of 0.1–0.5 metres. The streambed is not vegetated.

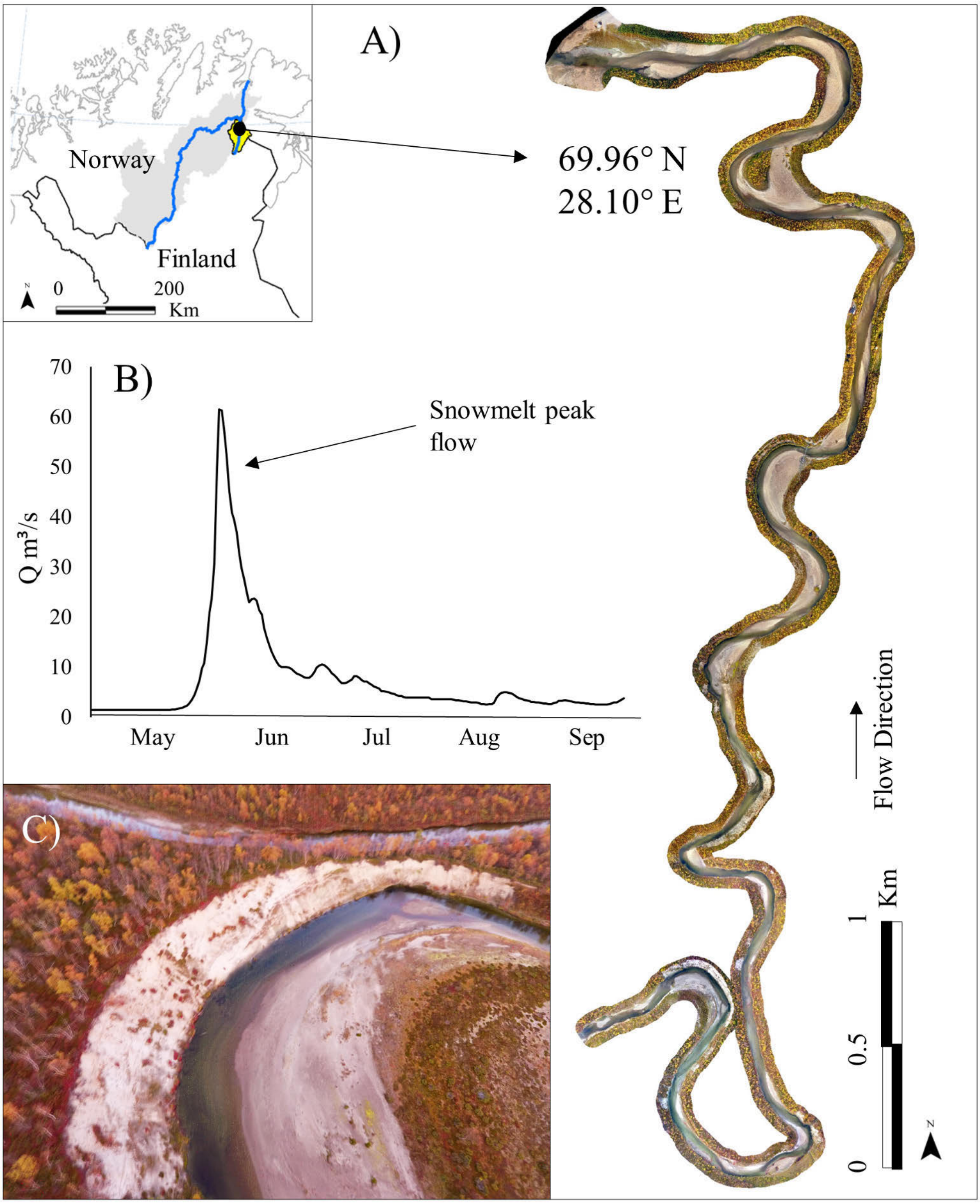

Figure 4. The study area of Pulmankijoki River. **A**) Aerial mosaic of the studied river reach. **B**) Typical hydrograph of open water season. **C**) Aerial image of sandy meander in convex side and high sandy bank on concave side.

4 Materials and Methods

In this thesis, a range of close-range remote sensing methods (ADCP, TLS, EDM, UAV) were employed alongside more conventional field measurements to capture flow characteristics (II & III), bank erosion (I), and channel bathymetry and topography of surrounding areas (I, II, and III). The temporal resolution of the field data was enhanced through orthophotos and historical aerial imagery (I) provided by the National Land Survey of Finland and the Finnish Defence Intelligence Agency. Additionally, national weather and discharge records from the Finnish Environment Institute (I, III) and the Finnish Meteorological Institute (I, III) were utilised. Morphodynamic modelling was applied to analyse spatial-temporal variation of sediment connectivity and morphological change (II, III), and a series of statistical analyses were conducted on hydroclimatic parameters to assess trends and shifts over the 50-year (I) and 30-year (III) periods. Details of the data and methods used in each paper can be found in table 1.

Table 1. Data and methods used in this thesis.

Method/data	Paper I	II	III
Flow & discharge conditions			
ADCP		X	X
National gauging stations	X		X
Water level			
Water level sensors		X	X
VRS-GNSS		X	X
National gauging station	X		
Meteorological data			
National weather stations	X		X
Channel geometry			
Bathymetric Structure-from-Motion		X	X
Topographic Structure-from-Motion	X	X	X
Terrestrial Laser Scanning	X		
EDM Geodimeter	X		
Historical aerial images	X		
Orthoimages/mosaic	X	X	
Sediment and bedload sampling			
Particle D50	X	X	X
Bedload transport magnitude		X	X
Manning’s Roughness		X	X
Statistical analyses			
Pettitt test	X		
Spearman’s rank coefficient	X	X	X
Mann-Kendall trend test	X		
Morphological analyses			
Meander migration	X		
Meander characteristics		X	
Morphodynamic modelling		X	X
Morphological response			X
Sediment budgeting		X	
Sediment Connectivity		X	
Sediment transport		X	X

4.1 Flow Characteristics

4.1.1 Flow Conditions

Discharge data was obtained through in-situ measurements (Papers II & III) and from national gauging stations (Papers I & III). The in-situ data was used in creating the rating curves for hydrograph generation. The generated hydrographs were later used in flood event classification (chapter 4.1.2), and as a boundary condition in the morphodynamic model (chapter 4.6). Three-dimensional in-situ flow and discharge measurements were conducted in the Pulmankijoki River using an ADCP (Sontek M9). These measurements, taken at nine specific sites along the river reach, captured flow velocity, direction, and discharge under various flow conditions (spring flood and autumn low flow). The ADCP was mounted on a floating platform, which was either remote-controlled (Fig. 5A) or attached to the bow of a zodiac (Fig. 5B), depending on flow conditions. Measurements were performed cross-sectionally, moving from the left to the right bank.

Discharge time-series from national gauging stations were used in the statistical analyses in paper I (chapter 4.5) and in flood event classification in paper III (chapter 4.1.2). The gauging stations used are located at the Oulankajoki River (Kiutaköngäs #7300100), maintained by the Finnish Environmental Institute (SYKE), and at the Tana River (Polmak Nye #234.18.0), maintained by the Norwegian Water Resources and Energy Directorate (NVE). These gauging stations record daily minimum, maximum, and average discharge (m^3/s), and the data is publicly available through SYKE and NVE data services.

Figure 5. The ADCP attached to **A**) Remotely controlled platform and **B**) The floating platform with ADCP attached to a bow of a Zodiac.

4.1.2 Hydrograph Generation and Flood Event Classification

In situ water pressure measurements were conducted at 15-minute intervals in the Pulmankijoki River during the open-water seasons from 2008 to 2023. These measurements were taken using nine bottom-anchored water pressure sensors (Solinst, Levelogger 5) (Fig. 6A). An air pressure sensor (Solinst, Barologger) located at the research site was used to perform barometric compensation on the Levelogger readings. Sensors were deployed at the site annually after ice breakup and retrieved before winter. Daily water level and discharge measurements were collected from the sensor locations during field campaigns held each spring and autumn. These measurements were performed using a virtual reference station global navigation satellite system (VRS-GNSS) (Fig. 6B) and an ADCP.

A third-order polynomial function was applied to calculate rating curves linking water pressure, water level, and discharge measurements, enabling the creation of hydrographs. The hydrograph for the year 2018–2019 was used in the morphodynamic model presented in Paper II. In Paper III, the hydrograph time series was extended back to 1992. Pulmankijoki River hydrographs from 2008 to 2023, along with daily discharge data from the Polmak Nye measurement station (1992–2023), were used to reconstruct hydrographs for the Pulmankijoki River for the years 1992–2007. The Polmak Nye station is located in the main channel of the Tana River at the point where the Pulmankijoki River discharges into it.

The hydrographs for 1992–2007 for the Pulmankijoki River were derived from the Polmak Nye station data using a rating curve and a third-order polynomial function relating the Polmak Nye station discharge (Q) and the Pulmankijoki River discharge (Q) for 2008–2023, as derived from the Leveloggers. In this way, a 32-year discharge time series was generated. These hydrographs were classified into distinct flood event types using Python. A flood threshold of 23.46 m³/s (the 75th percentile, p75 discharge) was set to identify significant spring flood events in May and June. High and low flood events were defined as being above or below the mean flood discharge of 40 m³/s. The classification process involved analysing features such as peak timing, prominence, height, and duration. To enhance peak detection, the data was smoothed using the Savitzky-Golay filter (scipy.signal.savgol_filter) with a window size of 11 and a polynomial order of 3. Peaks were then identified and classified into distinct event types using the "find_peaks" function from the same module.

Finally, four flood event types were detected from the hydrographs: A) High single peak (Q > 40 m³/s), B) Low single peak (Q < 40 m³/s), C) Two peaks (Q > p75, Q < p75, Q > p75), D) Wavy peak (two Q > p75 peaks). For morphodynamic modelling purposes, the most representative event of each type was selected. Precipitation-driven discharge peaks from July to September were excluded since none of them exceeded the flood discharge of 23.46 m³/s.

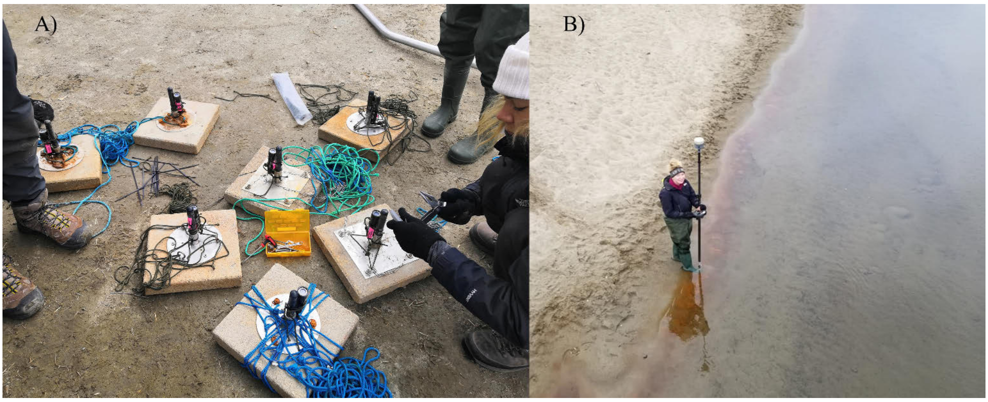

Figure 6. Measuring of water level with **A**) Water pressure sensors attached to bottom anchors ready to be placed in the river. **B**) Measuring a VRS-GNSS point from the sensor location.

4.2 River Geometry

Topographic and bathymetric data from the study areas were collected in-situ for Papers I, II, and III. In this thesis, inundated areas were measured using bathymetric SfM (Structure-from-Motion), while non-inundated areas were measured using topographic SfM, a terrestrial laser scanner, and a geodimeter (Koutaniemi, 1979, 1984, 2000). In addition to in-situ data, a set of historical aerial images and rectified orthoimages was used to map the river bank retreat and migration rates.

4.2.1 UAV-based SfM

Topographical and bathymetric SfM models based on orthomosaics and DEMs were used for mapping the river bank retreat and migration rates in paper I, and for modelling purposes in paper II and III. The orthomosaics and Digital Elevation Models (DEMs) for the Pulmankijoki and Oulankajoki Rivers were created using aerial images captured from 50–90 metres above ground with drones (DJI Phantom 4, DJI Matrice 210 V2 RTK) (Fig. 7A). The images were taken with an RGB camera from a nadir perspective and at a 30° oblique angle to improve SfM accuracy. The aerial images were georeferenced using ground control points (GCPs) measured with VRS-GNSS (Fig. 7B), and orthomosaics and DEMs based on these georeferenced images were generated using Pix4D software following the procedure by Micheletti et al., (2015). In Oulankajoki River, the retreat of the meander bend was calculated based on changes observed in aerial images and elevation models over three consecutive years. The refraction-induced bias caused by light passing through water was corrected using a multi-camera refraction correction method based on the work of Dietrich (2017). For the Pulmankijoki River, a bathymetric SfM model was created for both autumns (before and after the modelled event) based on the orthomosaic and camera properties. The refraction-corrected bathymetric SfM and the topographic DEM of the first autumn was used as input geometry in the morphodynamic model presented in Papers II and III. The DEM and bathymetric SfM of the second autumn was used as model validation in paper II. In addition, the orthomosaic and DEM of the first autumn of Pulmankijoki River were used to map meander characteristics, while the orthomosaic of the Oulankajoki River was used to map riverbank retreat and erosion volume.

Figure 7. Collecting aerial images for the orthomosaic and mapping of bathymetry/topography with **A**) DJI Matrice 210 V2 RTK and DJI Phantom 4. **B**) Measuring GCP points with VRS-GNSS.

4.2.2 Meander Characteristics

In Paper II, meander characteristics from Pulmankijoki River were measured and mapped to evaluate their interplay with functional sediment connectivity. The characteristics were observed from an SfM-based orthomosaic and DEM, supplemented by field sampling. Distinct meander characteristics were Sinuosity, defined as the ratio of the river's length along the thalweg to the valley length, the radius of curvature at the bend apex, and the point bar area were derived from the orthomosaic. Individual bank height was obtained from the DEM, while channel slope and sediment particle size (D_{50}) were determined during field campaigns. The meander planform type was classified following the approaches of Hooke (1984) and Frothingham and Rhoads (2003). These characteristics were used to assess the physical properties of point bars that control sediment connectivity and the feedback mechanism at the bend-to-bend scale.

4.2.3 Meander Migration Data

In Paper I, a terrestrial laser scanner (TLS), geodimeter, SfM-based orthomosaics, orthophotos, and historical aerial images were used to measure riverbank retreat, erosion volume, and meander migration rates. TLS measurements were conducted annually between 2020 and 2022 during the low-water phase in October, when the exposed area was largest (Fig. 8A). The TLS (Riegl, VZ-400i) was mounted on a tripod and repositioned around the point bar area between scans. Reflective targets were placed on the point bar surface and outer banks to georeference the scanned point clouds. The TLS point cloud was further processed by removing vegetation and fallen trees from the vertical banks (Fig. 8B). Annual retreat and erosion volumes were calculated by subtracting successive vertical bank surface models. Geodimeter measurements (AGA EDM Geodimeter Model 76) were carried out during three separate field campaigns between 1975 and 1995 (Koutaniemi, 1979, 1984, 1987; 2000) and by staff of the Oulanka Research Station from 2008 to 2020. Markers were positioned along the outer bank margins, and the distance between a fixed benchmark on the point bar and these markers was measured annually each autumn, enabling trigonometric calculations of bank migration rates and erosion volumes. Historical aerial images from 1976 to 2003 were georeferenced in GIS software using stable markers within the river environment. These rectified images, along with orthophotos from 2004 to 2022, were used to map riverbank margin retreat and calculate migration rates for years lacking TLS or geodimeter data (Fig. 8C).

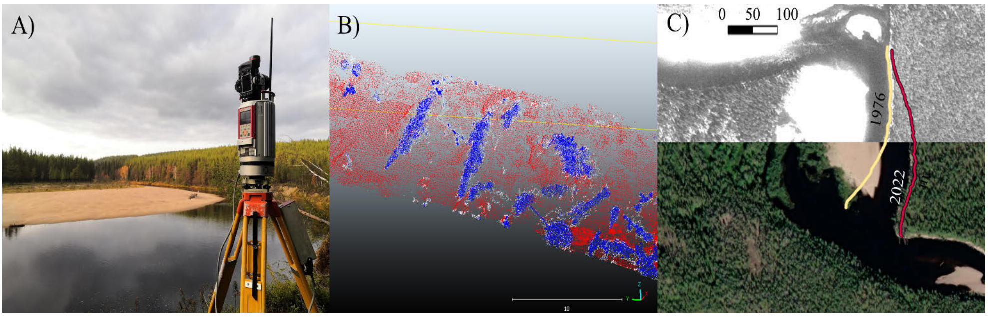

Figure 8. Measuring and mapping of bank erosion and meander migration. **A**) Terrestrial Laser Scanner (TLS). **B**) TLS point cloud of the river bank. **C**) Historical aerial image of year 1976 and orthomosaic of year 2022 overlaid with bank margins mapped.

4.3 Sediment and Bedload Sampling

Sediment samples were collected from riverbanks, the channel bed, and point bar surfaces in each study to determine sediment particle size variation, textural classifications (Papers I, II, and III), and to analyse morphological change (Paper II).

In addition, the samples were used to define sediment fractions and to adjust Manning's roughness coefficient in the morphodynamic model (Papers II and III). A van Veen grab sampler was used for riverbed sampling (Fig. 9A), and a small spade was used for sampling the banks and point bar surfaces (Fig. 9B). The location of each sample was measured with VRS-GNSS. The collected samples (~0.5 kg) were dry sieved at half-phi intervals and analysed using the GRADISTAT program (Blott and Pye, 2010). To quantify bedload transport volume, a series of bedload transport samples was collected from the Pulmankijoki River using a hand-held Helley-Smith sampler (Papers II and III) (Fig. 9C). The sampler had a 152 x 152 mm opening, a 3.22 expansion ratio, and a polyester bag with a 0.02 mm mesh. The sampler was held perpendicular to the flow, and the samples were collected under varying discharge conditions (high, medium, low) because the temporal variation in sediment transport is significant. Alongside each sample, six-minute stationary ADCP measurements were taken to capture the flow conditions at each sampling point (Fig. 9C). The sampling spot was located at the downstream section of the river in a meander bend that has been intensively monitored since 2005. The samples were taken from three different locations (right bank, middle, and left bank) in four different cross-sections within one meander. Three samples were collected per sampling spot to ensure the representativeness of the samples. The bedload transport samples were subsequently used to calibrate and validate the transport rates in the morphodynamic model.

Figure 9. Collecting sediment and bedload samples. **A**) Van Veen grab sampler in the bottom of the river. **B**) Sampling point bar surface with a small spade. **C**) Taking bedload transport sample with a Helley-Smith sampler (left) simultaneously with stationary ADCP measurements (right).

4.4 Meteorological Data

Meteorological data was used to determine the climatic conditions in the study areas over the periods 1975–2022 (Paper I) and 1992–2023 (Paper III). The data was obtained from the Finnish Meteorological Institute's (FMI's) open data service from two gauging stations: Kiutaköngäs (Paper I) and Nuorgam (Paper III). For Paper I, daily values of temperature, precipitation, ground frost, and snow depth were used to derive a total of 16 variables, including various daily, monthly, and annual (hydrological year) variates for the 49-year period (table 2). For paper III, daily temperature, precipitation, and snow depth values were used to derive annual (hydrological year) and spring time (March-April-May) minimum, mean, maximum, and total variates for the 32-year period.

4.5 Statistical Analyses

In Paper I, a 49-year time series of various geomorphological, hydrological, and meteorological parameters (table 2) were tested to identify trends, significant shift points, and correlations between the geomorphological and hydroclimatic variables. In Paper II, correlations between meander characteristics and erosion, deposition, and connectivity values were analysed to identify possible linkages. The Mann-Kendall trend test (Mann, 1945; Kendall, 1975), including adjustments for serial correlation (Hamed and Rao, 1998) and outlier filtering (Sen, 1968), was applied to the time series data from the Oulankajoki and Pulmankijoki rivers at a significance level of 0.05 (Papers I and II). Shift points within the time series (Paper I) were assessed using the non-parametric Pettitt test (Pettitt, 1979), a method based on the Mann-Whitney two-sample rank test that identifies significant changes in the mean of a time series without sensitivity to outliers. Monotonic correlations between variables were tested in Papers I and II using the non-parametric Spearman's rank coefficient (Spearman, 1906) and correlation coefficient analysis (Iman and Helton, 1988) to eliminate covariates.

Table 2. Main variables and the variables derived from the main variables used in the statistical analyses in Paper I. T and P data is obtained from FMI's open data service. Q and WL data is obtained from SYKE's open data service. Morphological data variables are based on the field measurements. M = Monthly, A = Annually.

Main variable	**Temperature (°C)**	**Precipitation (mm)**	**Discharge (m^3/s)**	**Water level (m)**	**Morphology**
Derived Variable	Tmean (M/A)	Total P (M/A)	Mean Q (M/A)	Mean WL (M/A)	Erosion volume Bank 1 (A)
	Tmin (M/A)	P0-5 (M/A)	MinQ (M/A)	MinWL (M/A)	Erosion volume Bank 2 (A)
	Tmax (M/A)	P5-15 (M/A)	Max Q (M/A)	Max WL (M/A)	Migration rate Bank 1 (A)
	DTR (M/A)	P15-25 (M/A)	Q volume (A)	P90 WL (A)	Migration rate Bank 2 (A)
	Frost days (M/A)	P>25 (M/A)	P90 Q (A)	P90 WL days (A)	Net volumetric change Bend 1 (A)
	Frost sum (M/A)	Snow sum (M/A)	Total P90 volume (A)	P90 WL days during spring flood (A)	Net volumetric change Bend 2 (A)
	Freeze-thaw days (M/A)	Snow cover days (M/A)	Spring flood volume (A)	Day of WL > P90 (Spring flood) (A)	
	Ground frost days (M/A)		P90 % of total Q (A)	Day of WL < P90 (spring flood) (A)	
	Thermal spring star day (A)		Spring flood % of total Q (A)		
			P90 peaks outside spring flood (A)		
			Day of Max Q (A)		
			Day of Q > P90 (spring flood)		
			Day of Q < P90 (spring flood) (A)		
			Flood days total (A)		
			Flood days spring (A)		

4.6 Morphodynamic Modelling

Morphodynamic modelling of one hydrological year (Paper II) and various flood events (Paper III) was used to analyse the seasonality and controlling factors for sediment transport, functional sediment connectivity, and the type of sediment hysteresis and morphological response in the subarctic Pulmankijoki River. Depth-averaged, two-dimensional CFD model was used to simulate the flow and morphodynamic conditions in both papers. Delft3D software was selected for modelling because it is widely used and validated by scientific literature, which proofs that it is suitable for modelling and studying complex hydro- and morphodynamic interactions (Nicholas et al., 2014; Kasvi et al., 2015; Williams et al., 2016). An 2x2-metre curvilinear mesh was built in the FLOW2D module of Delft3D. The model's geometry was based on a bathymetric model derived from an SfM aerial mosaic like described in section 4.2.1. A discharge rating curve based on Levelogger, ADCP, and VRS-GNSS measurements was used as the upper boundary condition, and the water level was used as the downstream boundary condition in each simulation. A default scheme for dry cell erosion of banks was used which assigns erosion evenly to the adjacent wet and dry cell. No further adjustment of the bank erosion equation was made since the focus was on longitudinal sediment transport. Steady water level and steady discharge (0.63 $m^3/s/$) were used for the entire ice-covered season based on Lotsari et al. (2020) under ice measurements since Delft-3D cannot implement ice-covered flow.

In Paper II, the hydrograph for 2018–2019 was used to run the one-year simulation, and in Paper III, four spring flood hydrographs of different shapes were simulated based on the measured and calculated hydrographs from 1992 to 2023. Multiple sediment fractions and a varying Manning's roughness parameter, based on field samples, were used to improve the modelled geometry and sediment transport rates. The bedload transport magnitudes were calibrated using Helley-Smith bedload samples collected under various discharge conditions. The flow conditions were calibrated to match the water level and flow velocity measurements collected in the field at three different locations within the modelled reach during spring flood and autumn low flow conditions. The calibration runs were validated against field measurements from corresponding field campaigns with correlation of 0.95 for flow velocity, correlation of 0.98 for water level, and correlation of 0.93 for bed load transport.

In a two-dimensional, depth-averaged model, the horizontal momentum with simplified Reynolds stress in the x-direction (Equation 4) and y-direction (Equation 5) is calculated using secondary flow correction as follows (Delft3D-Flow, 2011):

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial h}{\partial x} + \frac{gu\sqrt{u^2+v^2}}{C^2 h} = -\frac{1}{\rho_0}P_x + F_{sec,x} + V_h\left(\frac{\partial^2 u}{\partial x^2}\right) + \frac{\partial^2 u}{\partial y^2} \qquad \text{Equation 4}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial_h}{\partial x} + \frac{gv\sqrt{u^2+v^2}}{C^2 h} = -\frac{1}{\rho_0}P_y + F_{sec,y} + V_h\left(\frac{\partial^2 v}{\partial x^2}\right) + \frac{\partial^2 v}{\partial y^2} \qquad \text{Equation 5}$$

Where g is the gravitational acceleration (m/s^{-2}), $P_{x,y}$ is the pressure (Pa), d is the water depth (m), ρ_0 is the reference density of water (kg/m^{-3}), V_i is the horizontal eddy viscosity. F_{sec} is the correction term of the secondary flow effect, accounting for horizontal shear stress originating from the secondary flow.

The shear stress at the riverbed in two-dimensional, depth-averaged simulations is induced by a turbulent flow, which is assumed to be given by a quadratic friction law as follows:

$$\tau = \frac{g\rho_0 u|u|}{C^2} \qquad \text{Equation 6}$$

Where T is dimensionless bed shear stress, g is the gravitation, ρ_0 is the reference density of water (kg/m^{-3}) and C is the Chezy's coefficient (m$^{0.5}$/s^{-1}).

Bottom roughness of the model was computed according to Manning's formulation as follows:

$$S_{b,x} = |S_b|\alpha_{bn}\frac{u_{cr}}{\overrightarrow{|u_b|}}\frac{\partial z_b}{\partial_n} \qquad \text{Equation 7}$$

Where the $|S_b|$ is the magnitude of the unadjusted bed load transport, α_{bn} is a user-defined coefficient, u_{cr} is the critical velocity (near-bed), $\overrightarrow{|u_b|}$ is the fluid velocity vector (near-bed), and $\frac{\partial z_b}{\partial_n}$ is the bed slope.

The van Rijn (1993) sediment transport equation was used to model the sediment transport conditions below (bed load), and above (suspended load) the van Rijn's reference height (boundary layer of bedload and suspended load). The reference height is calculated using the following formula:

$$c_a = f_{sus}0.015\rho_s\frac{D_{50}T^{1.5}}{aD_*{}^{0.3}} \qquad \text{Equation 8}$$

Where f_{sus} is the calibration parameter, c_a is the sediment concentration at the reference height (kg/m^{-3}), ρ_s is the density of sediment particles (kg/m^{-3}), D_{50} is the median sediment diameter (m) and T is a dimensionless bed shear stress.

In the van Rijn approach, so-called source and sink terms are used to calculate the morphological change and sediment transfer between the riverbed and the flow.

The quantities of the source and sink terms are calculated within the reference height as follows:

$$Source = \frac{D_v c_a}{\Delta z} \qquad \text{Equation 9}$$

$$Sink = c_{rl}\left(\frac{D_v}{\Delta z} + w_s\right) \qquad \text{Equation 10}$$

Where D_v is the vertical eddy diffusivity (m^2/s^{-1}), c_{rl} is the mass concentration of sediment in the reference layer (kg/m^{-3}), and Δz is the vertical distance of reference layer from the reference height a (m).

The suspended sediment transport above the Van Rijn's reference height is calculated as follows:

$$\begin{aligned} &\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial vc}{\partial y} \\ &= \frac{\partial}{\partial x}\left(D_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial c}{\partial y}\right) + S \qquad \text{Equation 11} \end{aligned}$$

Where c is the sediment concentration (m/s^{-1}), D is the eddy diffusivity (m^2/s^{-1}), and S is the source/sink term (kg/m^{-2}) of erosion and deposition flux.

Bed load magnitude (equation 12) and the direction of transport (equation 13) below the van Rijn's reference height is calculated as follows:

$$|S_b| = f_{bed} 0.5 n \rho_s D_{50} u'_{*} D_{*}{}^{-0.3} T \qquad \text{Equation 12}$$

$$\begin{aligned} S''_{b,x} &= \frac{u_b}{|q_b|}|S''_b| \\ S''_{b,y} &= \frac{v_b}{|q_b|}|S''_b| \qquad \text{Equation 13} \end{aligned}$$

Where f_{bed} is the calibration parameter for bed load, n is the availability of sediment, u' is the effective bed shear velocity, D_* is a dimensionless particle diameter, T is a dimensionless bed shear stress, u_b,V_b are the components for depth-averaged near bed velocity (m/s^{-1}), and q is the depth-averaged near bed velocity.

Since bedload transport is affected by the bed-level gradient, two bed slope directions are distinguished**:** the slope in the initial direction of the transport, i.e., the longitudinal bed slope, and the slope in the perpendicular direction, i.e., the transverse bed slope. The longitudinal bed slope causes changes in the sediment transport rate, which is given by:

$$\overrightarrow{S'_b} = \alpha_s \overrightarrow{S''} \qquad \text{Equation 14}$$

Whereas the primary effect of transverse bed slope is change in transport towards downslope direction. The equation for transverse bed slope based on Bagnold (1966) is calculated as follows:

$$\alpha_s = 1 + \alpha_{bs}\left(\frac{\tan(\emptyset))}{\cos\left(\tan^{-1}\left(\frac{\partial z}{\partial s}\right)\right)\left(\tan(\emptyset)+\frac{\partial z}{\partial s}\right)} - 1\right) \qquad \text{Equation 15}$$

Where α_{bs} is a user-defined tuning parameter, $\emptyset$ is the internal angle of friction of bed material, and $\frac{\partial z}{\partial s}$ is the bed slope in the direction of bed load transport.

4.7 Sediment Connectivity and Budgeting

In Paper II, functional sediment connectivity was analysed along the longitudinal axis of the Pulmankijoki River reach. The connectivity value was calculated based on monthly source/sink outputs from the morphodynamic model. This calculation utilised an approach based on the ratio of total eroded to total deposited sediments, following Calle et al. (2020), to determine the connectivity value (C_v) for each grid cell (Equation 16). This method could be directly applied to the model's source (erosion) and sink (deposition) outputs without further modification.

$$C_v = \frac{Erosion}{Deposition} \qquad \text{Equation 16}$$

The result of this equation quantifies functional connectivity downstream, with a high connectivity value ($C_v > 1$) when a cell acts as a sediment source (i.e., a cell from which sediment is transported downstream) and sediment flux increases. A low connectivity value ($C_v < 1$) is assigned when a cell functions as a sediment sink (i.e., where sediment is deposited) and sediment flux decreases. Equilibrium ($C_v = 1$) is achieved when the volume of sediment eroded from, and deposited within, a cell is roughly balanced, resulting in a stable sediment flux volume entering and leaving the cell. Sediment budgeting at the bend-to-bend scale was calculated based on the sediment flux volume entering and leaving a bend.

$$F_i = F_{i-1} + \frac{Erosion_i}{Deposition_i} \qquad \text{Equation 17}$$

Where F_0 is the initial sediment flux entering the first bend, $Erosion_i$ is the total erosion volume at bend *i, $Deposition_i$* is the total deposition volume at bend *i, F_{i-1}* is the total sediment flux entering bend *i,* and F_i is the total sediment flux exiting bend *i.* The outcome of this equation indicates sediment flux volume entering and exiting each bend based on functional C_v. In this way, the relative change of sediment flux between bends could be estimated.

5 Results and Discussion

In this chapter, the main findings of the three papers included in this thesis are presented, integrated and discussed. These results can be applied to sand-bed river systems in the high-latitude boreal-subarctic climate region.

5.1 Spatiotemporal Variation of Sediment Connectivity and Morphological Response Drive Long-term Morphological Adjustment

To fulfil the first aim of this thesis, this chapter analyses the results from Papers II and III to investigate how spatiotemporal variations in sediment connectivity and morphological response contribute to long-term morphological adjustment through their interaction with hydromorphological characteristics.

Highlights: Functional sediment connectivity is episodic and highly spring flood-dependent rather than solely governed by sediment availability in subarctic rivers. The seasonality of sediment transport, connectivity, and morphological adjustment is primarily hydrology-driven, yet during low discharge, local controls become increasingly significant. Sediment transport within the system does not directly correspond to net erosion or deposition at specific locations, as flood event type and number of peak sequences critically shape the morphological response. Thus, sediment transport is not always proportional to discharge volume but is instead modulated by water flow, sediment grain size, flood sequencing, and morphological adjustment mechanisms.

The seasonality of sediment transport, connectivity, and morphological adjustment was controlled by hydrology over a distinct period of time based on the results of Paper II. However, sensitivity to local controlling factors, particularly particle size and meander planform type, increased significantly during discharge episodes below the threshold discharge magnitude of ~20% of bankfull. The majority of the annual sediment load (70%) was transported during the snowmelt-driven spring flood when the threshold discharge was exceeded. However, parts of the channel remained mobile throughout the year, even during low discharges. The high connectivity episode during spring flood and moderate flow periods in summer and early autumn accounted for a total of 93% of the annual sediment load and was responsible for the majority of the morphological changes in the riverbed. This aligns with previous studies (Syvitski, 2002; Gordeev, 2006; Cockburn and Lamoureux, 2008; Favaro and Lamoureux, 2014; Bracken et al., 2015; Wohl, 2017; Beel et al., 2021), which show that sediment flux in cold-climate rivers is largely governed by a few extreme flow events rather than being a continuous process. Paper II is one of the first studies to utilise morphodynamic modelling for assessing the spatiotemporal variation of functional connectivity and to combine the morphological results with the Index of Connectivity, which is typically not designed to represent functional sediment connectivity processes (Najafi et al., 2021). The finding regarding point bar individual characteristics controlling sediment dynamics is consistent with the findings of Gautier et al. (2010), Hooke and Yorke (2010), and Lotsari et al. (2014b), who state that point bar characteristics impact the morphological processes experienced by the bend. In addition, the functional aspect of source and sink areas for sediment could be detected by analysing the model source and sink terms with the Index of Connectivity in Paper II. The analysis of the morphological change predicted by the model indicated that erosion was more consistent compared to deposition, a phenomenon previously recognised by Kasvi et al. (2015) and Lotsari et al. (2019).

Additionally, the bend-to-bend budgeting and sediment flux volume analysis in Paper II showed that the sediment flux magnitude and the net volumetric change were not connected. This implies that the amount of sediment moving within the system does not directly correspond to the net erosion or deposition at given locations, meaning that certain river sections act as transport corridors rather than as sources or sinks. This could indicate a flush-through effect, previously discussed by Bracken et al. (2015) and Cossart et al. (2018), or that the sediment in transport is being replaced by new material, thereby maintaining high transport capacity and low net erosion/deposition. The lack of correlation between volumetric change and flux magnitude can partly be explained by the finding that local geomorphological factors control functional connectivity. However, since hydrology was the major contributor, variations in flow dynamics likely play a significant role. Although flow dynamics were not analysed in detail in Paper II, previous findings by Kasvi et al., (2015) support this interpretation.

Furthermore, the flood event type and peak sequences play an important role in determining the morphological response of the riverbed, based on the results of Paper III. The flood event type and sequences, i.e. the hydrograph shape, had a significant impact on the sediment transport pattern and morphological response of the riverbed. Multi-peaking floods resulted in more complex sediment hysteresis loop than single-peaking floods, a phenomenon previously observed in flume studies (Mao et al., 2012). The complex hysteresis loop resulted in high heterogeneity in morphological features compared to single-peaking events, which produced distinct riffle-pool formations. Similar year-to-year variability in morphological responses has been observed by Hooke and Yorke (2010), Lotsari et al. (2014a, 2014b), and Salmela et al. (2020), despite the long-term consistency in morphological adjustment. This supports the above findings that short-term (annual) heterogeneities maintain the long-term balance within the river system.

The distribution of sediment particle size was also found to affect the morphological response pattern in Paper III, highlighting the importance of field measurements and correct model parameterisation. The counter clockwise hysteresis detected in Paper III implies that sediment is temporarily stored before transport is fully activated, leading to a delayed response in sediment flux relative to discharge. This supports the interpretation in Paper II that connectivity in subarctic rivers is spring flood-dependent rather than a simple function of sediment availability. The increase of multi-peaked floods occurrence observed in Paper III can have significant implications for future sediment connectivity. When sediment is temporarily stored between the peaks, it can lead to multiple fragmented connectivity episodes within a single event, rather than a continuous transport phase. This phenomenon has been observed in previous studies (Hooke, 2007; Gautier et al., 2010; Kasvi, 2015; Wohl, 2017), where flood duration, flow depth, sediment structure, and prevailing channel morphology significantly influence transport rates. Thus, rather than responding directly to peak discharge, sediment movement is influenced by the sequence and characteristics of each flood peak, leading to complex, episodic connectivity patterns within the event. Furthermore, the results confirm that sediment flux volume is not always proportional to discharge volume, even though it is hydrologically controlled. This reinforces the finding that functional connectivity in river systems is controlled not only by water flow but also by sediment characteristics, flood sequencing, and morphological response mechanisms.

These findings highlight the necessity of understanding how event-specific factors, such as hydrograph shape, sediment characteristics and possible exhaustion, and the sequential flow variability alter sediment flux patterns over time. The results of Papers II and III suggest that short-term spatiotemporal heterogeneities in hydrology and sediment transport play an important role in system behaviour, functional sediment connectivity, and morphodynamic response patterns. While the long-term morphological adjustment of river systems is largely shaped by both climatic and geomorphic characteristics, the findings demonstrate how functional sediment connectivity promotes both immediate responses and long-term adjustments in river morphology. As functional sediment connectivity and sediment redistribution become more episodic and localised, and the volumetric differences between episodes diminish, identifying sediment sources and sinks becomes crucial for predicting river behaviour and managing sediment budgets effectively. This means that sediment is no longer transported in a steady, predictable manner but is instead mobilised, temporarily stored, remobilised, and redeposited multiple times within a hydrological year. Further sediment connectivity studies at global and local scales are needed to achieve a comprehensive understanding of sediment flux processes and related concepts, including mobilisation, remobilisation, storage, cascades, detachment, transport, deposition, and sediment budgeting. This is becoming increasingly important in high-latitude areas, which will become hotspots of sediment transport due to climate change (Syvitski, 2002; Gordeev, 2006).

5.2 Hydroclimatic Change Significantly Alters the Sediment Transport and Morphological Processes in Boreal-subarctic Rivers

To fulfil the second aim of this thesis, this chapter summarises the results from Papers I and III to analyse how hydroclimatic change alters sediment transport and morphological processes in boreal-subarctic rivers, with a particular focus on its effects on the seasonality and magnitude of flow-sediment interactions.

Highlights: Reduced winter time conditions and increased rainfall instead of snow result in earlier onset of spring floods, multi-peaking hydrographs and a decline in spring flood magnitude, and thus are driving shift of the hydrological regime. Intensified precipitation in late summer has led to greater fluvial energy outside the spring flood season, contributing to enhanced sediment mobilisation. The prolonged freeze-thaw cycles and rain-on-snow events play a crucial role in sediment mobilisation and bank erosion by controlling sediment availability. Sediment transport episodes are becoming strongly event based rather than season based due to a reduced contrast in fluvial energy between high and low flow periods and increased sediment availability. Multi-peaking floods lead to increased heterogeneity in sediment hysteresis and morphological response pattern.

Hydroclimatic change is profoundly altering fluvial and sediment transport dynamics boreal-subarctic river systems. In Paper I, the transition period of the hydroclimatic shift was identified from the 50-year time series analysed (Figure 10A). The first variables to shift were temperature-derived variables in the mid-1990s. Discharge-derived variables shifted approximately 10 years later. Evidence of increased precipitation intensity was detected in the Oulankajoki River; however, the annual mean precipitation did not show a significant trend, and some precipitation variables had not yet shifted based on the Pettitt test results. This could indicate that pluvial control will further increase in the future once shift points for all precipitation variables are reached. The rise in fluvial energy driven by increased monthly precipitation outside the spring flood season (Figure 10B) suggests that this phenomenon is becoming a significant contributor to sediment mobilisation. This is supported by the fact that spring flood volume had significantly decreased, and the onset of thermal spring and the spring flood had advanced by almost two weeks over the observed period (Figure 10C). A notable increase in winter baseflow was also detected (Figure 10C). The increased monthly temperatures in winter (October - April) (Figure 10B), and the fact that majority of all the shifts (Figure 10D) took place during winter and spring highlights that special attention should be paid to sediment processes occurring specifically during these periods.

These observations are consistent with previous findings from Finnish rivers and rivers across Northern Eurasia and Canada (Andrew et al., 2005; St. Jacques and Sauchyn, 2009; Korhonen and Kuusisto, 2010; Duan et al., 2017; Gohari et al., 2022; Irannezhad et al., 2022). The shift in temperature and precipitation mean values, preceding a shift in hydrological variables, has also been noted in previous studies across the world (Salarijazi et al., 2012; Melo and Wendland, 2016; Belihu et al., 2018; Conte et al., 2019; Zhang et al., 2020; Getahun et al., 2021). Many of these studies highlight the importance of precipitation shifts in areas where river discharge depends on rainfall (Melo and Wendland, 2016; Belihu et al., 2018; Zhang et al., 2020), whereas the role of temperature shifts is emphasised in regions where temperature alters water availability through snowmelt timing or evapotranspiration. Therefore, the Oulankajoki River has shifted from nival towards pluvial control and can be classified as a mixed-region, where the nival control diminishes and pluvial control increases.

The observed prolonged freeze-thaw periods in late autumn and early spring (Paper I) extend the duration during which sediment remains available for transport, potentially increasing fluvial erosion through mechanical weathering and wetted conditions (Walling, 2009; Fryirs and Brierley, 2013). This effect is further amplified by the observed warming winters, during which precipitation falls as rain instead of snow, contributing to immediate runoff and the loss of river ice cover. The lack of ice cover has been found to further increase sediment transport during winter (Lotsari et al., 2020; Pajunen et al., 2024). Similarly, earlier spring thaws and increased spring precipitation are making rain-on-snow events more frequent which further contribute to altered sediment transport dynamics and timing. These observed changes in fluvial energy can lead to a decrease in the seasonal variability of sediment transport due to reduced volumetric contrast between transport episodes and seasons. In addition to hydrological factors, recent studies have identified freeze-thaw conditions as key drivers of bank erosion and sediment mobilisation in cold regions (Costa et al., 2018; Li et al., 2019; van Rooijen & Lotsari, 2024; Lotsari et al., 2024).

Slightly increasing, but non-significant trends were detected in the bank erosion and meander migration data (Paper I), suggesting that although the timing of peak fluvial activity is shifting, the total mobilised sediment volumes have remained relatively stable. While the hydroclimatic regime has already shifted in the

Oulankajoki River and is expected to do so in the Pulmankijoki River in the future, the sediment transport regime cannot shift without pluvial control exceeding the threshold for additional sediment mobilisation (Lamoureux, 2000; Beel and Lamoureux, 2018; Zhang et al., 2023). In systems where sediment is readily available, such as in the boreal-subarctic region, this threshold can be met relatively quickly, resulting in accelerated changes in sediment dynamics and morphological responses. For example, Kärkkäinen and Lotsari (2022) found that sediment loads outside the spring flood season have reached volumes comparable to typical spring flood sediment flux, further supporting this observation. However, in systems requiring larger-scale landscape disturbances, such as those driven by permafrost thaw, the transition may take longer (Favaro and Lamoureux, 2014, 2015; Zhang et al., 2022, 2023). In these cases, the delayed response reflects the time required for underlying geomorphological and hydrological processes to catch up with shifting climatic drivers.

The results of paper III indicate that even in the subarctic regions where hydroclimatic shift is not yet fully taken place, the evolving flood characteristics are already impacting river morphology and sediment transport patterns. Rising temperatures, rain-on-snow events, and spring precipitation falling as rain instead of snow are contributing to an increased frequency of multi-peaking spring flood events, which can intensify geomorphic activity and increase short-term heterogeneity of bedforms. The observed increase in double-peaking floods and decline in single-peaking floods suggests potential shifts in river system stability, sediment loads, and long-term morphological adjustments. If certain morphological responses begin to accumulate, it could significantly alter sediment transport patterns and eventually long-term morphological adjustment, as the long-term accumulation of heterogeneities may cause instability in the river system like found by Bracken et al., (2015), Wainwright et al., (2015) and Heckmann et al., (2018). This re-organisation of sediment dynamics within the system could occur even without a fundamental shift in the sediment transport regime. Instead of regime shift, gradual adjustments in sediment connectivity, redistribution patterns, and morphological responses could lead to noticeable changes in channel stability and sediment flux over time. Such changes may be driven by alterations in flood sequencing, shifting seasonal flow regimes, or increased frequency of extreme events, rather than a complete transformation in sediment transport dynamics. Consequently, local-scale sediment storage and remobilisation could become more dominant factors in shaping long-term morphological adjustments within the river system.

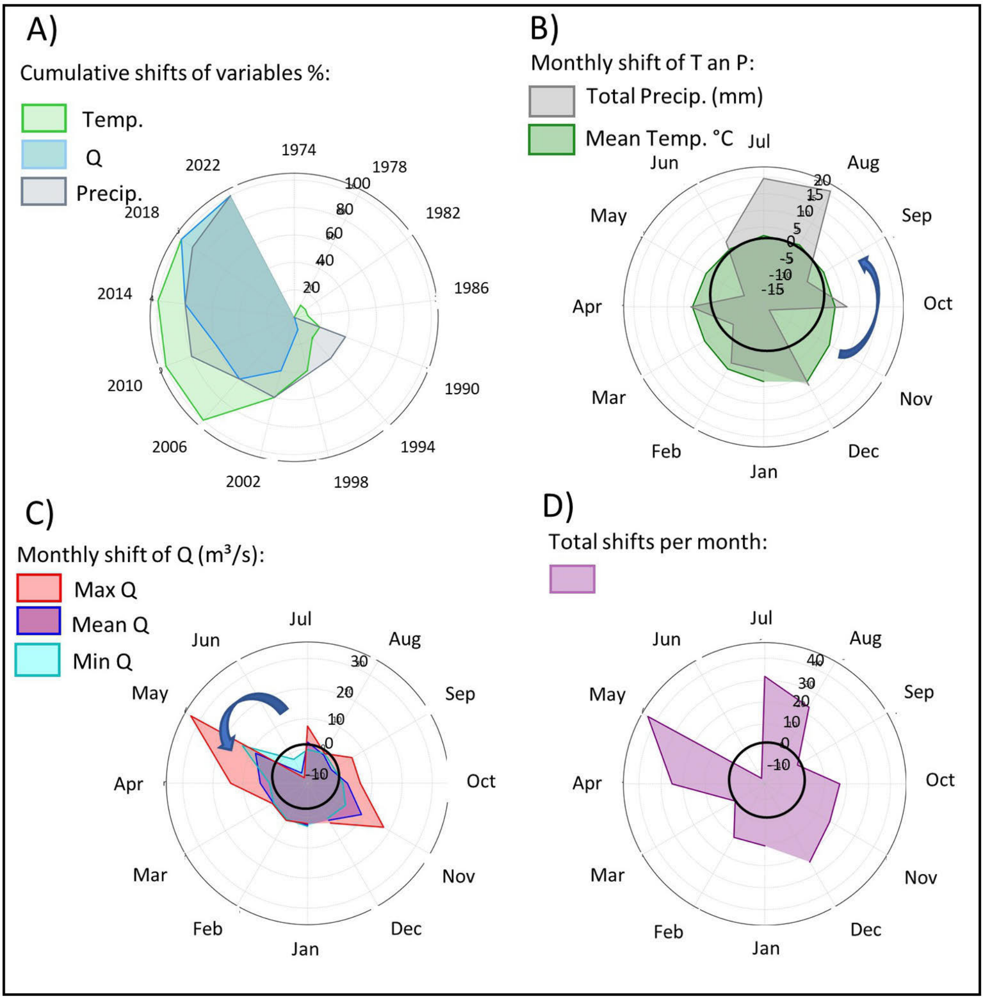

Figure 10. A summary of the key changes observed in monthly and annual hydroclimatic data over the past five decades. **A**) The cumulative shift of main variables based on PettA strong signal of reduced winter conditions, earlier spring floods, increased winter baseflow, and increased late summer (July–August) precipitation was detected. The winter period (October–March) showed the most significant volume of change throughout the observed timeframe.

5.3 Changing Sediment Transport Dynamics Underscore the Importance of Continuous Monitoring and Modelling

In this chapter, I summarise the key findings of this thesis to fulfil the third aim by assessing the key drivers of short- and long-term variability in morphological adjustment under changing hydroclimatic conditions in high-latitude boreal and subarctic rivers. Additionally, I discuss the practical implications of these findings and the future challenges in monitoring and modelling sediment transport dynamics in these environments.

Highlights: The short- and long-term variability in morphological adjustment are shaped by multiple interlinked hydroclimatic processes and can be highly catchment specific. The shifting balance between nival and pluvial activity along with the non-linear flow-sediment interaction play increasingly important role in boreal-subarctic sediment dynamics by posing challenges for maintaining channel stability. Thus, spatiotemporally intensive, long-term sediment monitoring and modelling is needed to catch the ongoing rapid changes, and to develop adaptive river management strategies.

The key processes influencing sediment dynamics under changing hydroclimatic conditions, as recognised in this thesis, include shifts in the balance between nival and pluvial activity, prolonged freeze-thaw cycles, and evolving flood regimes, all caused by climate change. The observed decreasing seasonal variation and increasing heterogeneity in sediment dynamics, highlight the need for process-based modelling and advanced sediment monitoring. The observed non-linearity between hydrology, sediment flux, and morphological net volumetric change underscore the complexity of flow-sediment interaction and functional sediment connectivity in meandering river systems, and the need for long time-series of both sedimentological and hydrological data. These findings collectively demonstrate the value of long-term geomorphological data and sediment records with robust spatiotemporal coverage, which is an aspect that remains a significant global challenge still today (e.g., Walling, 2009; Keestra et al., 2018; Syvitski et al., 2022; Zhang et al., 2022).

As the results of Paper II suggest, longitudinal functional sediment connectivity in the river channel is episodic, and a certain threshold discharge volume must be exceeded for the channel to be connected. The role of active flow above the critical threshold discharge has been found crucial to morphological change, rather than the peak discharge magnitude of a given flood event (Vetter, 2011; Kasvi, 2015; Salmela et al., 2020). If increased fluvial activity outside the spring flood season exceeds the local threshold for sediment mobilisation and connectivity, it is likely that the total sediment transport volume will increase to some extent, as long as spring floods continue to exceed this discharge threshold. This also indicates that sediment transport and connectivity episodes will become event-based rather than seasonal, as they are at the moment. The modelled hysteresis pattern detected in Paper III, and the previously observed (Zhang et al., 2022) time-lag between hydroclimatic and sediment regime shifts, suggest that the relationship between the driving force and sediment transport is often non-linear. Additionally, the increased frequency in sequential flood peaks could further complicate future sediment fluxes and impact functional connectivity, especially if such events occur multiple times during the open-water season and consistently exceed the sediment transport threshold, as found by Tananaev and Lotsari (2022) in Siberia. Unlike the current sediment transport regime in boreal-subarctic region, which is largely driven by a single major flood event, these changes could shift sediment dynamics towards a more continuous and unpredictable pattern. This would have significant implications for river morphology over time, as the control exerted by morphological characteristics, as identified in Paper II and by Gautier et al. (2010), Hooke and Yorke (2010), and Lotsari et al. (2014), would decrease in contrast to the increasing influence of hydrological control.

Each paper in this thesis demonstrates the application of a combination of close-range remote sensing methods, statistical analysis, and conventional field measurements across different spatiotemporal scales. While many of these methods have previously been used in fluvial geomorphological studies (Alho et al., 2019; Flener et al., 2013; Dietrich et al., 2017; Kasvi et al., 2019; Calle et al., 2020), their integration presented in this thesis, particularly in terms of spatiotemporal resolution, is novel in the context of sediment dynamics and functional connectivity analysis. This multi-method approach shows that by combining comprehensive field measurements, high-resolution CFD modelling, time-series of hydroclimatic data, and the Index of Connectivity, the dynamic and temporal aspects of sediment transport, connectivity i.e., its functionality, and morphological response, can be effectively analysed. This integrated framework addresses a key challenge highlighted in previous research (Brasington et al., 2000; Bracken et al., 2014; Heckmann & Vericat, 2018; Keesstra et al., 2018; Najafi et al., 2021), which underscores the necessity of functional modelling that integrates hydrodynamics, sediment properties, and hydroclimatic data at high spatiotemporal resolution for accurately assessing and managing sediment connectivity in fluvial systems. This thesis and many previous studies (Rodriguez et al., 2004; Lotsari et al., 2014; Kasvi, 2015; Williams et al., 2016a, 2016b; Bosboom et al., 2020), have proven CFD models as effective tool in evaluating morphological processes at multiple scales.

However, high spatiotemporal resolution data is needed for boundary conditions, calibration, and validation to ensure the model is representative of real-world conditions (Kasvi, 2015; Williams, 2016a). The accuracy of these models relies heavily on user-defined parameters, particularly sediment grain size, which can significantly influence morphodynamic outcomes, and has been found crucial in morphodynamic models (Pinto et al., 2006; Nicholas et al., 2013a, 2013b; Lotsari et al., 2014; Bosboom et al., 2020). The primary focus of the model used in Papers II and III was on sedimentological parameters, which ultimately performed with satisfactory results. The accuracy of the model, however, descended as the model progressed and the correlation values for flow velocity, water level and bed load transport lowered from 0.91, 0.96 and 0.98 to 0.84, 0.91 and 0.83, respectively. The morphological outcome of the model was validated using ADCP, VRS-GNSS and

DEM, representing the situation in the end of the modelled hydrological year. The model predicted the morphological changes on wet pixels with a correlation of 0.91, and in dry pixels with 0.93. Comparison of random points, both wet and dry, between the SfM-based DEM and modelled geometry indicated correlation of 0.85. Thus, we can say that the model performed generally well. However, it is important to acknowledge the limitations of the model in predicting morphology, as the parametrisation was kept relatively simple to ensure computational efficiency. In addition, Delft-3D cannot simulate ice-covered flow, and the representation of lateral erosion through source and sink terms is rather simplistic. Previous studies (Lotsari et al., 2014; Lotsari et al., 2020; Lotsari et al., 2022) have recorded significant changes in sediment transport patterns during ice-covered period, so this can be considered as an uncertainty in the results in paper II. The simplicity of lateral erosion, however, is not considered an issue in this case as Pulmankijoki river experiences mostly vertical and longitudinal changes (Vaaja et al., 2013; Kasvi, 2015; Lotsari et al., 2019).

The regional and temporal variability in sediment transport processes found in this thesis and other studies in high-latitude regions (Gordeev, 2006; Favaro and Lamoureux, 2014; Lotsari et al., 2014; Croghan et al., 2024) poses another significant challenge for modelling as boreal-subarctic regions exhibit diverse geomorphic and climatic conditions, making it difficult to generalise findings across regions. Croghan et al. (2024) highlighted how seasonal and spatial variability in sediment transport in subarctic headwater catchments depends on soil composition and vegetation. Hooke (2007) and Favaro (2013) noted similarly that sediment connectivity and mobilisation vary between catchments with different degrees of hydrological connectivity and climatic conditions. Therefore, future studies should closely monitor these factors to capture the full spectrum of changing sediment dynamics. Another challenge lies in defining the critical thresholds at which hydroclimatic drivers, such as multi-peaking floods, prolonged freeze-thaw cycles, permafrost thaw, or extreme rain-on-snow events trigger irreversible sediment mobilisation. McDonald and Lamoureux (2009) highlight that while flood discharge thresholds are often used to estimate sediment transport, these thresholds vary greatly depending on local geomorphic characteristics and seasonal conditions. This variability underscores the importance of conducting comparative studies across high-latitude regions to better understand how local conditions affect sediment flux. As hydroclimatic regimes continue to evolve, the predictability of sediment fluxes and morphological responses becomes increasingly challenging.

These changes will have implications on practical usage of river environments, river system management, engineering restorations and decision-making in both urban and rural contexts. Thus, understanding the evolving hydroclimatic conditions and sediment fluxes, is crucial for mitigating risks associated with erosion, sediment deposition, and floodplain stability, which can have significant consequences for infrastructure, water quality, and biodiversity. River engineering projects, such as dam operations, dredging, and bank stabilisation, must therefore account for shifting hydroclimatic patterns to ensure long-term sustainability and resilience. Furthermore, the implications extend to policy and governance, requiring a more integrated frameworks that balances these changes with socio-economic needs. Ultimately, as hydroclimatic variability intensifies, a more holistic and interdisciplinary approaches for river system and sediment flux monitoring and management, like demonstrated in this study, will be essential in maintaining the functionality, geodiversity, biodiversity and ecological state of fluvial environments.

6 Conclusions

This thesis focused on the impact of climate change on fluvial and sediment dynamics in high-latitude rivers. The research was conducted on two high-latitude rivers, utilising 30- to 50-year hydroclimatic and geomorphological time series, as well as computational morphodynamic modelling and the Index of Connectivity. By adopting this comprehensive multi-method approach, consisting of field measurements, modelling, statistical analyses, and quantitative tools, the following conclusions can be drawn:

1. **Seasonal variation in flow-sediment interaction decreases, while heterogeneity of morphodynamics increases in boreal-subarctic rivers.** The contrast between seasonal sediment volumes is diminishing due to the impacts of climate change. Historically, a single major event, the spring flood, accounted for the majority of the annual sediment load. However, reduced winter conditions, advancing springs, and increasing multi-peaking floods and pluvial activity are resulting in lower peak sediment volumes during the spring flood and an increase in sediment transport during other seasons. This leads to altered sediment transport dynamics and morphological responses, and increases the heterogeneity and complexity of sediment transport and morphological processes.

2. **Sediment connectivity episodes will become event-related rather than season-related in boreal-subarctic area.** Sediment connectivity is controlled by flow conditions whenever the threshold discharge magnitude is exceeded. In contrast, below the threshold value, local morphological factors such as sediment grain size and meander planform geometry become more impactful, controlling the extent and efficiency of sediment transfer. Currently, connectivity episodes in nival systems are distinctly season-related. However, due to climate change and increased pluvial activity, the frequency of single, sporadic high-energy connectivity episodes is expected to rise, making them strongly event-driven, like seen on the pluvial/mixed region. As a result, sediment transport will become more heterogeneous, shifting from seasonal fluxes

to frequent episodic events. These high-energy episodes may intensify erosion, deposition, and channel changes, disrupting sediment budgets and long-term stability, and creating new geomorphic hotspots.

3. **Continuous monitoring of sediment fluxes and source-to-sink processes is needed to capture the short- and long-term dynamics of sediment transport and morphological adjustment.** This study highlighted that by combining spatiotemporally intensive field measurements, modelling, and quantitative tools, functional sediment processes can be assessed with high resolution and detail. Such an approach, conducted with continuous real-time monitoring, would provide critical insight into the seasonal and episodic patterns, enabling the identification of river-specific thresholds for sediment redistribution processes and connectivity. It would support the development, calibration, and validation of advanced modelling approaches, such as digital twins. In the context of climate change, as high-latitude rivers become hotspots of sediment transport, continuous data collection would further benefit river management strategies. The sensitive freeze-thaw seasons, in particular, should be subject to intensified monitoring in the future.

These findings highlight the profound impacts of climate change-induced hydroclimatic shifts on fluvial and sediment transport dynamics in high-latitude rivers, revealing a transition from seasonal to event-driven fluvial dynamics and increasing complexity in sediment transport processes. The findings emphasise the need for continuous monitoring and advanced modelling, such as digital twins, to capture evolving patterns and thresholds of sediment transport. Future research should integrate real-time data with predictive multi-method approaches to improve the understanding of short- and long-term morphodynamic feedback. As Arctic rivers become critical hotspots of sediment transport, these efforts will be key to ensuring their resilience in a changing climate.

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