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SEDIMENT MOVEMENT IN COLD-REGION FLUVIAL ENVIRONMENTS

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Monitoring flow-sediment interaction from rivers to estuaries

Jouni Salmela

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ABSTRACT

Comprehensive studies reflecting sediment flux in seasonal cold-region fluvial environments via local sediment processes are rare in the literature. To understand sediment flux, flow-sediment interaction needs to be studied in multiple parts of the river network. In addition, seasonal variation, characterized by snow and ice cover, needs to be considered in cold regions.

In this study, I aim to provide new insights into sediment movement in cold-region river networks by studying flow-sediment interaction in river and estuary environments. The study is conducted by combining conventional field measurements, flow measurements, close-range remote sensing and hydrodynamic modelling to gain detailed information about sediment processes under seasonally varying conditions. The comparison of bathymetric mapping methods and monitoring of seasonal and annual morphological changes in shallow river channels is based on close-range remote sensing approaches. Flow conditions are either measured with ADCP or modelled with hydrodynamic modelling to estimate flow-sediment interaction in river and estuary environments. Water sampling and sediment trapping are used to measure suspended sediment concentration and sedimentation rates, respectively. The combination of multiple approaches is expected to provide more detailed information than a single method. This study is conducted in the meandering, sand-bedded, subarctic Pulmankijoki River and hemiboreal non-tidal brackish water estuary of the Baltic Sea.

The study's results suggest that sediment movement in cold-region fluvial environments is episodic and controlled by low- and high-energy conditions. Sediment movement is strongest during high-energy events, such as discharge peaks, strong wind conditions and rapid sea level changes, and during low-energy conditions, sediment movement is calm and mostly depositional. Sediment movement is characterized by a combination of local and regional conditions. Although processes are primarily driven by a variation in discharge and sea level, local conditions, such as channel shape, estuary ice cover and salinity stratification also control sediment movement.

This study shows the benefits of a multimethod approach in sediment movement studies, especially in flow-sediment interaction. Changes in geomorphic units or

estuary sedimentation can be explained with measured or modelled flow conditions. In addition, the combination of multiple remote sensing applications, including LiDAR, photogrammetric mapping and sonar, are needed for highly detailed river environment mapping, enabling detailed change detection and further sediment load estimations.

Sediment movement in cold-region river systems will most likely change due to expected temperature increases and discharge regime shifts caused by climate change. As spring-thaw-induced high-energy conditions in duration and magnitude will be substituted by shorter autumn and winter discharge peaks, sediment movement in river and estuary environments is expected to decrease during the spring thaw. This process may reflect the development and maintenance of geomorphic units in river channels and sediment-rich plume development in estuaries. In addition, coastal sedimentation will most likely increase due to sea ice cover loss, decreasing snow cover and increasing rainfall.

The findings of this thesis can be applied to cold-region fluvial environments, in which strong spring-thaw-induced discharge peaks characterize discharge regime. Further, the thesis improves the understanding of sediment movement and monitoring in cold-region fluvial environments and provides background information for habitat modelling, river restoration, sediment load estimation and nutrient load modelling.

KEYWORDS: sediment movement, sediment flux, sediment measurement, remote sensing, flow measurement, hydrodynamic modelling, sediment trapping, river system, estuary, cold region

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TIIVISTELMÄ

Tämä väitöskirja käsittelee sedimenttivuota kylmän ilmaston virtavesissä. Sedimenttivuohon vaikuttavat uomaverkoston paikalliset tekijät, kuten jokiuoman morfologia sekä rannikoiden jääpeite. Paikallisten tekijöiden vaikutusta sedimenttivuohon on tutkittu kuitenkin verrattain vähän vuodenaikojen mukaan vaihtelevissa virtavesissä. Tutkimalla virtausdynamiikan ja sedimentin vuorovaikutusta uomaverkoston eri osissa, saadaan tietoa sedimenttivuohon vaikuttavista tekijöistä.

Tämän väitöskirjan tavoitteena on selvittää sedimentin kulkeutumisen vuodenaikaisvaihtelua ja siihen vaikuttavia tekijöitä. Tutkimuksen pääpaino on virtausdynamiikan ja sedimentin välisessä vuorovaikutuksessa. Tutkimus toteutetaan yhdistelemällä perinteisiä kenttämittauksia, lähikaukokartoitusta sekä virtausmittauksia ja –mallinnuksia.

Tutkimuksessa hyödynnetään monipuolisesti erilaisia mittaus- ja mallinnusmenetelmiä. Oletuksena on, että tutkimusmenetelmien monipuolinen yhdistäminen tuottaa tarkempaa tietoa suhteessa yksittäisiin menetelmiin. Ensimmäisessä osatutkimuksessa vertaillaan erilaisten syvyysmallinnustekniikoiden soveltuvuutta matalan kirkasvetisen joen kartoittamiseen. Toinen osatutkimus keskittyy jokiuoman muutostulkintaan ja muutoksen mittaamiseen lähikaukokartoitustekniikoilla. Jokiuoman muutosta tarkastellaan suhteessa mitattuihin virtausnopeuksiin. Kolmas osatutkimus keskittyy sedimenttipitoisen jokipluumin esiintymiseen erilaisissa rannikko-olosuhteissa. Viimeisessä osatutkimuksessa vertaillaan kahden syys-kevätkauden (kylmä ja leuto) välisiä sedimentaatioeroja rannikolla hyödyntäen sedimenttikeräimiä ja virtausmallinnusta. Väitöstutkimus toteutettiin subarktisen ja boreaalisen ilmaston virtavesiympäristöissä: Lapissa sijaitsevalla Pulmankijoella ja Saaristomerellä sijaitsevalla Halikonlahdella.

Tulokset osoittavat sedimentin kulkeutumisen olevan jaksottaista. Kulkeutuminen on suurimmillaan voimakkaiden virtausolosuhteiden aikana, joita aiheuttavat esimerkiksi korkeat jokivirtaamat sekä voimakkaat tuuliolosuhteet ja nopeat vedenpinnan korkeusvaihtelut rannikolla. Heikkojen virtausolosuhteiden aikana sedimentin kulkeutuminen on maltillista ja sedimentti pääosin kasaantuu. Kulkeutumiseen vaikuttavat sekä paikalliset että alueelliset tekijät. Alueelliset tekijät, kuten jokivirtaaman vaihtelu, merenpinnan korkeusvaihtelut ja tuuliolosuhteet ohjaavat sedimentin kulkeutumista voimakkaimmin, mutta myös paikalliset tekijät, kuten

uoman muodot, rannikon jääpeite sekä meriveden kerrostuneisuus vaikuttavat kulkeutumiseen.

Yhdistelemällä useita tutkimusmenetelmiä pystytään selvittää virtauksen ja sedimentin kulkeutumiseen vaikuttavia syy-seuraussuhteita. Esimerkiksi mitattujen ja mallinnettujen virtausolosuhteiden avulla on mahdollista selittää jokiuoman geomorfologisten yksiköiden muutoksia ja rannikon sedimentaatiota. Myös jokiuoman korkeusmallien luomiseen tarvitaan usean lähikaukokartoitustekniikan yhdistämistä. Korkeusmallien välisten erojen avulla voidaan arvioida sedimenttikulkeumaa jokiuomassa.

Väitöskirjatutkimuksen perusteella ilmastonmuutoksesta aiheutuva ilmakehän lämpeneminen ja virtaamaolosuhteiden muutos vaikuttavat todennäköisesti sedimentin kulkeutumiseen kylmän alueen virtavesissä. Kevättulvien keston ja voimakkuuksien heikkenemisen sekä syys-talvivirtaamien nousun seurauksena sedimentin kulkeutuminen heikkenee kevättulvien aikana ja lisääntyy muina aikoina. Heikentyvien kevättulvien aikana myös virtausnopeudet todennäköisesti alanevat. Virtausnopeuksien heikkeneminen vaikuttanee myös jokiuoma muotoon sekä sedimenttipitoisen jokipluumin käyttäytymiseen rannikoilla. Tuloksien mukaan rannikkoalueiden sedimentaatio oletettavasti kasvaa ilmastonmuutoksesta aiheutuvan jäätalvien lyhenemisen, vesisateiden yleistymisen ja lumipeitteen vähenemisen seurauksena.

Väitöskirjan tuloksia voidaan yleistää kylmien alueiden virtavesiympäristöihin, joille on tunnusomaista vuosittainen kevättulva. Tulokset tarjoavat myös taustatietoa vesielinympäristöjen mallintamista varten, jokien kunnostustoimenpiteisiin, sedimenttikulkeuman arviointiin ja ravinnekuormituksien mallintamiseen.

ASIASANAT: Sedimentin kulkeutuminen, sedimenttivuo, sedimenttimittaukset, kaukokartoitus, virtausmittaus, hydrodynaaminen mallinnus, sedimenttikeräin, joki, estuaari, kylmä ilmasto

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List of Original Publications

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

I Kasvi, E., Salmela, J., Lotsari, E., Kumpula, T. & Lane, S.N. Comparison of remote sensing based approaches for mapping bathymetry of shallow, clear water rivers. *Geomorphology*, 2019; 333: 180–197.

II Salmela J., Kasvi E., Vaaja M.T., Kaartinen H., Kukko A., Jaakkola A., Alho P. Morphological changes and riffle-pool dynamics related to flow in a meandering river channel based on a 5-year monitoring period using close-range remote sensing. *Geomorphology*, 2020; 352: 106982.

III Salmela, J., Kasvi, E. & Alho, P. River plume and sediment transport seasonality in a non-tidal semi-enclosed brackish water estuary of the Baltic Sea. *Estuarine, Coastal and Shelf Science*, 2020; 205: 106986.

IV Salmela, J., Saarni, S., Blåfield, L., Katainen, M., Kasvi, E. & Alho, P. Comparison of cold season sedimentation dynamics in the non-tidal estuary of the Northern Baltic Sea. *Marine Geology*, 2022; 443,106701.

1 Introduction

Sediment movement from rivers to estuaries is driven by fluvial processes. This movement is called sediment flux. Fluvial processes cause either sediment entrainment, transport or deposition. In general, sediment is transported from erosion zones, e.g., headwaters, to deposition zones, e.g., estuaries. However, sediment movement is not straightforward between the erosion and deposition zones. It is controlled by flow-sediment interaction, which varies along the river network due to, for example, differences in bed sediment grain size, vegetation, channel shape and ice cover (Kasvi et al., 2013b; Lotsari et al., 2019; Milne, 1982; Wang et al., 2015).

Flow is primarily induced by slope, e.g., elevation difference between up- and downstream, in river channels and wind, waves and tides in estuaries. Sediment movement is typically a combination of several mechanisms. For example, the rate of erosion at a channel bed is influenced by high flow velocities, channel geometry and bed sediment grain size (Frothingham and Rhoads, 2003; Kasvi et al., 2013b; Konsoer et al., 2016). In estuaries, sediment movement is primarily controlled by tidal waves and river discharge, and water properties (Restrepo et al., 2018; Uncles et al., 2006).

Sediment has several effects on water bodies, such as enabling fish habitats (Cyrus and Blaber, 1992; Gilbert et al., 1992) and maintaining delta areas (Coleman, 1988). Sediment processes, i.e., deposition and scour in river channels, also affect fish spawning (Montgomery et al., 2011). Excess sediment in water columns increases light attenuation, thereby affecting primary production (Pedersen et al., 2012). In addition, sediment movement is associated with pollutants (Fernandez et al., 2017; Yuan and Yang, 2001) and particulate nutrients, such as nitrogen and phosphorus (Beusen et al., 2005). Higher suspended sediment concentration (SSC) is associated with habitat degradation because of increased sediment deposition on the bottom of water bodies, i.e. river and sea bed (Österling et al., 2010).

As climate change will alter the discharge regime of cold-region rivers (Lotsari et al., 2010; Veijalainen et al., 2010), it will most likely reflect the pattern of sediment movement. It has been found that climate in high latitudes have become warmer and that moisture has increased over the past 50 years (1961–2010) with decreasing snow cover (Aalto et al., 2016). Warming has been found to be strongest during winter months (DJF) and at high latitudes, compared to the global trend (Mikkonen et al., 2015). In addition, climate warming and precipitation increase are projected to continue (Jylhä et al., 2004). Also, loss in sea ice and discharge-regime shifts are expected to have a significant impact on cold-region water environments and their ecological niches (Ingram et al., 1996). Specifically, ice cover has been found to enhance sediment-rich plume development in coastal estuaries (Granskog et al., 2005; Kari et al., 2018) and inhibit coastal erosion (Ryabchuk et al., 2011) and littoral resuspension (Kleeberg et al., 2013). To understand sediment movement, climate change's effects on river networks and life below the water's surface, it is essential to understand the flow-sediment interaction in various parts of the river system.

Approaches to sediment movement studies vary largely in terms of scale and temporal resolution. In the broadest scale, the calculation of sediment yield, describing the amount of sediment eroded from catchment, has been based on, for example, a relationship between discharge and SSC (Holeman, 1968). Due to the development of measurement techniques and computational modelling, it is now possible to focus on more detailed processes, including lateral bank erosion as well as scour and deposition in river channels, which may affect the total sediment yield. With intensive three-dimensional flow measurement or hydrodynamic modelling combined with traditional in situ sediment sampling or modern mobile laser scanning based grain size measurement (Wang et al., 2013), flow-sediment interaction or channel scour and fill can be monitored in great detail in fluvial environments (Calle et al., 2015; Kasvi et al., 2017). Studies on sediment movement in local contexts, e.g., within a meander bend or river unit, provide detailed information about sediment processes along river networks.

Flow-sediment interaction has been widely studied in natural channels and flume experiments (Andrews, 1979; Blanckaert, 2011; Blom et al., 2003; Hjulström, 1935; Hossain et al., 2001; Kasvi et al., 2013b, 2017; Sear, 1996; Traynum and Styles, 2007). Studies have been focused, for example, on erosion-deposition patterns, the development of geomorphic units and wave-induced resuspension (Hodge et al., 2013; Kasvi et al., 2017; Lund-Hansen et al., 1999). The early approaches to flow-sediment interaction were based on individual point or cross-sectional measurements, utilizing rods, sediment traps or propeller-type flow velocity meters (Andrews, 1979; Keller, 1971), for example. These methods have been replaced by acoustic Doppler current profiler (ADCP) and multibeam echo sounding (MBES) for flow velocity and river bed mapping, respectively (Caamaño et al., 2012; Kasvi et al., 2017; Leyland et al., 2017), owing to the development of GPS accuracy. In addition, the use of hydrodynamic modelling to study flow-sediment interaction has increased (Hu et al., 2009).

Recent development of mapping techniques has improved dry and wetted channel topographical surveys along river corridors (Alho et al., 2009; Dietrich, 2017; Flener et al., 2013; Kasvi et al., 2017; Williams et al., 2014), enabling detailed change detection (Flener et al., 2013; Kasvi et al., 2017; Leyland et al., 2017; Lotsari et al., 2014). Change detection is based on repeated surveys within the same river's reach, enabling sediment transport estimations, known as the morphological approach (Vericat et al., 2017). Therefore, the estimation of sediment transport does not solely depend on traditional sediment sampling.

To understand sediment movement across river networks, flow-sediment interaction needs to be studied in both rivers and estuaries. By studying reach-scale processes across river networks, it is possible to find linkages and similarities between the flow-sediment interactions of various sections of the river system. Such studies reflecting sediment flux via local sediment processes and comparing them within a river network are rare. In addition, little is known about how sediment movement is controlled in cold-region fluvial environments under seasonal variations with snow and ice cover.

In this thesis, I examine flow-sediment interaction using 1) a morphological approach with close-range remote sensing (CRRS), 2) in situ flow and sediment measurements and water sampling and 3) hydrodynamic modelling, conducted in cold-region natural environments. With this set of approaches, detailed information of local flow-sediment interaction is achieved and results can be used to explain sediment flux. In this thesis, the term 'cold region' refers to the subarctic-hemiboreal climate located between the 60^{th} and 70^{th} latitudes north, characterized by seasonal snow and ice cover. Intra-annual variation between relatively warm dry summers and cold snow and ice-covered winters forms varying conditions for sediment processes. Quite little is known about cold-season sedimentation dynamics due to harsh winter conditions.

This study is conducted in a subarctic river and a hemiboreal nontidal brackish water estuary (Fig. 1). The main aim of the thesis is to provide new scientific insights into sediment dynamics, focusing on flow-sediment interaction in cold regions, where intra-annual episodic behaviour of sediment dynamics might be of special importance. This study will focus on the effect of local- and regional-scale conditions on sediment movement. In this thesis, the term 'local scale' refers to conditions acting on sediment movement in a limited area, such as geomorphic units in a river channel or sea ice cover. The term 'regional scale' refers to conditions acting on sediment movement in a large spatial area, such as changes in river discharge and sea level. By combining the results from four scientific papers, published in international journals, the main outcomes are summed.

The aims of the thesis are:

1) To determine whether sediment dynamics display episodic behaviour in cold-region river systems (papers II–IV)
2) To derive new insights into the effects of local- and regional-scale conditions on sediment movement (papers II–IV)
3) To demonstrate the combination of close-range remote sensing, hydrodynamic modelling and flow and sediment measurements for better understanding of sediment movement (papers I–IV)
4) To assess the implications of climate change on sediment movement in cold-region river systems (papers II–IV).

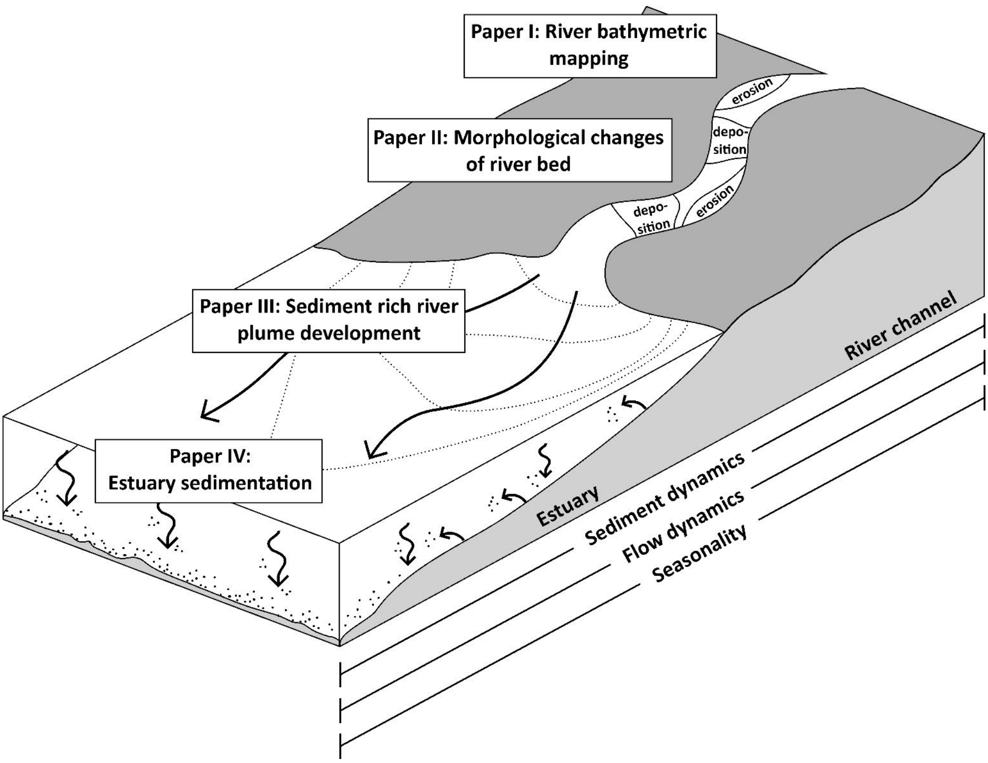

Figure 1. Research design of the thesis. The thesis covers river system, including river and estuary environments. Sediment and flow dynamics together with seasonality forms crosscutting themes across the four papers (I–IV).

In paper I, three high-resolution remote sensing approaches is compared for bathymetric purposes. Echo sounding, bathymetric Structure-from-Motion (SfM) and optical modelling is tested to create bathymetric models for shallow, clear-water river at low and moderate flow stages during 2017. The aim is to find the most accurate and reliable technique for river bathymetry monitoring and to improve river-channel change detection.

In paper II, a combined approach of highly detailed CRRS measurements together with flow measurements is adopted to study the relationship between morphological changes, riffle-pool dynamics, near-bed flow velocities and flow stages in meander bends over consecutive years. The study is conducted by exploiting mobile laser scanning (MLS), UAV-photogrammetry, sonar and ADCP during a five-year monitoring campaign (2013–2017). Seven seamless high-resolution riverine digital elevation models (DEMs) is created for morphological-change detection over the study's duration based on nine DEMs of differences (DODs). The paper describes a highly detailed approach to channel-change detection along the river and flow-sediment interaction under varying flow conditions.

Paper III focuses on the development of sediment-rich river plumes in non-tidal brackish water estuary. The paper describes the development of river plumes under varying discharge conditions, including ice cover and open water. The combination of flow and water quality measurements together with river discharge and wind data provides detailed information of plume development and conditions. The data cover two open water periods, including low and high river discharges and one ice-cover period with high river discharge from 2018 to 2019.

In paper IV, estuary sedimentation in two cold seasons is compared by combining sediment trapping and hydrodynamic modelling. The paper provides new insight into sedimentation differences between cold seasons with very different conditions: a season with permanent snow and ice cover and a warmer snow- and ice-free season with higher rainfall and frequency of the passage of low air pressure systems. Sedimentation differences are reflected in modelled flow conditions, precipitation, ice cover and discharge regime during two cold seasons from 2018 to 2020.

2 Background

2.1 Overview of sediment movement

Rivers form a corridor for sediment movement between catchment areas (source) and coastal areas (sink). Sediments are delivered to rivers mainly by soil denudation (Nearing et al., 2005) and bank erosion (Lotsari et al., 2020). Typically, suspended sediment load in rivers increases with increasing discharge (Leopold and Maddock, 1953). Anthropogenic actions, such as land use, dredging and dam construction may significantly either increase or decrease sediment loads of rivers (Walling, 1999).

Based on sedimentation activity and processes, river networks can be classified into three zones: erosion, transport and accumulation zones. Erosion zones are typically located headwaters due to high channel slope and flow velocities. Transport zones are described as regions through which sediment is mainly passing because of high flow velocity, and they are located between erosion and deposition zones. Despite its name, during low flow, sediment may accumulate temporarily in transport zones, forming occasional sediment storages. These storages are most likely eroded during the next high-flow events. In the end, sediment reaches the deposition zones, including lowlands and estuaries. In deposition zones, gravitational forces exceed forces created by flow, causing sediment settling, river meandering or flood plain development, for example. On the other hand, tidal forces and wave action may enhance sediment resuspension in deposition zones and relocate settled sediment (Nuorteva and Kankaanpää, 2016; Wu et al., 2012). In tidal-dominated areas, sediment may form an estuary turbidity maxima zone (ETMZ), in which sediment particles are kept in suspension by a combination of tidal forces and river flow (Mitchell et al., 2017; Restrepo et al., 2018). However, despite the classifications, no clear borders separate the zones in river systems. The borders are wavering and related to flow conditions. For example, during high-discharge events with high flow velocities, the whole river network may become an erosion zone. Sediments, carried by rivers, may become resuspended and transported by wind, wave, tide and current-induced water motion in to coastal areas. These processes, known as coastal processes, generate and shape coastal landforms, such as beaches and deltas.

2.2 Sediment characteristics

Sediment characteristics and flow conditions define the behaviour and transport of sediment particles. Sediment particles vary in size, shape and composition and consist of minerogenic and organic substances. In this thesis, the term ‘sediment’ refers to minerogenic and organic sediment.

Rivers are typically classified based on the most common sediment particle size in the riverbed, e.g., clay-, sand-, gravel- or cobble-bed river. Mean particle size value (D_{50}) is commonly used to describe a river’s characteristics. D_{50} is the particle size value that divides the sediment sample into two equally weighted portions, i.e., 50-50 % by weight. D_{50} is a particle diameter at which 50% of the material is finer and coarser.

Sediment particles can be classified into two categories based on their physio-chemical properties: non-cohesive and cohesive particles (e.g., Vanoni, 2006: 27). Non-cohesive particles act as an independent unit because they do not form physio-chemical bonds between each other and therefore do not flocculate. However, particle packing in river bed acts on entrainment shear stress, being higher for densely than for loosely packed particles (Hodge et al., 2013). Non-cohesive particles’ size and shape determine the transport rate under various flow conditions, and they are mainly transported as bed load or in suspension. Cohesive sediment consists of fine particles, usually an aggradation of flocs. The size of cohesive particles normally ranges from 0.98 to 63 micrometres (Hjulström, 1935). Cohesive particles form physio-chemical bonds, which may become strong, affecting particle behaviour. For example, the settling velocity is higher for flocs than for individual cohesive particles (Portela et al., 2013). Flocculation is enhanced by the presence of salt; therefore, flocculation is typically strongest in estuary conditions along river networks (Mhashhash et al., 2018; Portela et al., 2013). Because of cohesive particles’ high absorption capacity, contaminants, heavy metals and nutrients forms bonds between cohesive particles; therefore, their transport is strongly linked to sediment transport (Beusen et al., 2005; Fernandez et al., 2017).

Even though the particle size of cohesive sediments is smaller than that of non-cohesive sediments, a higher shear stress is needed for cohesive sediment entrainment due to interparticle bonds (Hjulström, 1935). Therefore, the erosion potential caused by flowing water is not only related to particle size or weight. Particle characteristics not only control sediment transport but also affect river channel geometry and morphological changes (De Almeida and Rodríguez, 2011; Hirsch and Abrahams, 1981; Kasvi et al., 2013b). For example, differences in grain size have been found between geomorphic units (De Almeida and Rodríguez, 2011; Milne, 1982).

2.3 Flow-sediment interaction

In fluvial environments, sediment is transported as dissolved, suspended and bed load (e.g., Charlton, 2008: 53). These categories comprise the total sediment load. Dissolved sediments, with the smallest particle size, are carried in solution and typically classified as particles of less than 0.45 micrometres when monitoring sediment load. Suspended load refers to particles that are transported and maintained in suspension. Bed load refers to sediment transport, in which sediment particles are either rolling or sliding, saltating on the top of the bed in close contact with the bed. Sediment particles in the bed load are mainly too heavy to be lifted into suspension; therefore, smaller particles are mainly in suspension. Particles transported in suspension or bedload are controlled by flow condition, as different initial flow conditions are needed to lift various sizes of particles.

Sediment movement is caused by friction between moving water and sediment particles. Moving water acts on sediment particles by two forces: drag and lift force (Fig. 2). Drag force acts on sediment particles in the direction of the flow caused by the water movement. Lift force acts vertically on sediment particles and is caused by pressure gradient, which is caused by the difference in flow velocity between the top and bottom of a grain (Fryirs, 2013: 85).

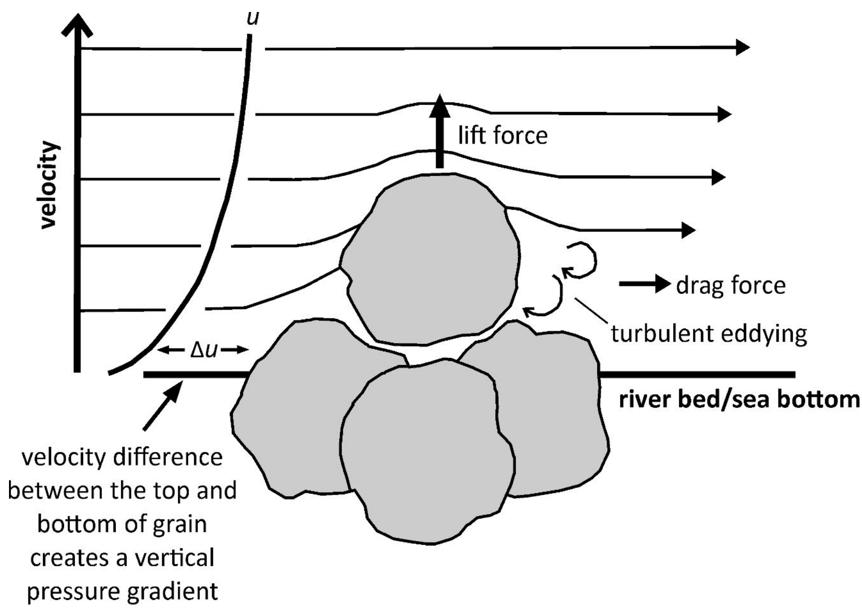

Figure 2. Forces acting on sediment particle entrainment. Drag and lift forces, associated with flow turbulence, entrain grains from the bottom. The vertical pressure gradient, caused by the difference in velocity (*u*) between the top and bottom of a grain, induces lift force. In addition, entrainment depends on particle size and the extent to which the particle protrudes into the flow or is embedded against other grains. Modified from Knighton (1998) and Fryirs and Brierley (2013).

Based on empirical measurements, a clear relationship between the flow velocity and the entrained particle's size has been established, known as the Hjulström diagram (Hjulström, 1935). The Hjulström diagram describes the critical flow velocity for entrainment and settling for various grain sizes. Another way to express moving water's ability to entrain and lift sediment particles into motion is bed shear stress (e.g., Vanoni, 2006: 61). Bed shear stress describes the magnitude of moving water acting on the river or seabed, i.e., a force per unit area of the bed (N m^{-2}) (Charlton, 2008: 69). Bed shear stress is primarily generated by slope-induced flow in rivers and wind- and tidal-induced waves and currents in coastal environments, respectively.

When forces caused by flowing water (F_w) exceed particle's resistance forces (F_r), particle is set in motion:

$$F_w > F_r \tag{1}$$

This threshold is known as critical shear stress. Critical shear stress for each particle is a combination of particle's size, shape and density. In addition, the arrangement of particles on the bed, the mixture of particle sizes and the interparticle bonds between cohesive particles increase critical shear stress. Particle's resistance force (F_r) consists of force due to gravity and particle's weight (F_g), resisting force for resuspension caused by the friction (F_f) and (F_c) cohesion between the particle and the bed (modified from Ji (2017)):

$$F_r = F_g + F_f + F_c \tag{2}$$

Therefore, equation (1) can be rewritten as follows to describe the conditions for particle entrainment:

$$F_w > F_g + F_f + F_c \tag{3}$$

Contrarily, when gravitational force exceeds the forces created by flow, typically during the falling limb of a flood, sediment particles start to sink.

2.4 Sediment processes in river environments

Channel flow conditions induce both vertical and lateral channel erosion (Andrews, 1979; Hickin, 1974). Flow-induced channel scour and deposition lead to the development of geomorphic units, e.g., riffle-pool sequences (Hodge et al., 2013) or point bars (Legleiter et al., 2011). Irregular flow field in channels causes variation in the erosion-deposition pattern along the course of a river. Strong erosion is typically found at the areas with the highest flow velocity (Bridge and Jarvis, 1976; Ferguson et al., 1992; Frothingham and Rhoads, 2003; Kasvi et al., 2017; Keller, 1971), and deposition follows low-flow velocities (Ferguson et al., 1992; Keller, 1971). For example, strong erosion during a flood's rising stage has been found at the concave side of meander bend due to high flow velocities and stream power (Kasvi et al., 2017). In addition to flow conditions, bed grain size also controls sediment processes (De Almeida and Rodríguez, 2011; Hirsch and Abrahams, 1981; Milne, 1982). Changes in channel morphology are also influenced by changes during the preceding year (Gautier et al., 2010; Kasvi et al., 2013a).

As flow conditions change in relation to discharge and water level, sediment transport and the scour-deposition pattern change as well. Typically, channel scour occurs during the rising stage of flood up to peak discharge and deposition during the falling stage (Leopold and Maddock, 1953). Andrews (1979) stated that sections that scour and fill at high flows tend to fill and scour at low flows, respectively. In addition, pools (bathymetric lows) may be filled with fine sediments at low flows, but during the next effective discharge, sediments will be entrained, and the river bed will be scoured, resulting in pools developing at those locations (Andrews, 1979; Keller, 1971). Even within a single flow event, e.g., a flood, erosion and deposition have been found throughout a single meander bend (Kasvi et al., 2017). In-channel variations have been recorded in sediment transport under various discharges magnitudes (Sear, 1996). Sear (1996) found that the sediment transport rate varies among pools and riffles (bathymetric highs) at different discharge stages.

2.5 Sediment processes in estuary environments

Estuaries are partially enclosed transition zones between coastal and river environments that are characterized by the mixture of fresh- and saltwater. Sediment processes are controlled by a combination of river and coastal processes. During high-discharge events, higher flow velocities cause sediments to be transported further seawards, known as river plume, than during low flow (Granskog et al., 2005; Restrepo et al., 2018). In tidal-dominated estuaries, tidal forces may either enhance or inhibit plume development and thereby sediment transport (Stumpf et al., 1993). Typically, the ETMZ, where sediment particles are kept in suspension by a combination of tidal pumping and river flow, can be found in tidal-influenced estuaries (Mitchell et al., 2017; Restrepo et al., 2018). Suspended sediments may be deposited during tide shift, when flow conditions are stable. Tidal pumping also enhances littoral resuspension (Grabemann et al., 1997; Wu et al., 2012), which, together with material carried by the river, maintains high SSC in the ETMZ.

In non- or microtidal estuaries, meteorological-driven sea level changes may lead to resuspension (Pritchard and Hogg, 2003). Compared to river environments, in coastal areas, wind-induced mixing may have a significant role in enhancing sediment mixing and shoreline-bottom resuspension (Lund-Hansen et al., 1999; MacCready et al., 2009; Xia et al., 2007). Wind may also control the shape and behaviour of river plumes (Kourafalou, 2001; Molleri et al., 2010; Stumpf et al.,

1993) In ice-covered estuaries, wind-induced mixing is reduced, resulting in better conditions for plume development (Granskog et al., 2005; Ingram and Larouche, 1987; Kari et al., 2018). In addition to saline-enhanced flocculation (Mhashhash et al., 2018), saline-induced stratification between saline sea water and fresh river water reduces sediment mixing between the fresh surface water and saline bottom water (Ren and Wu, 2014; Stumpf et al., 1993). Sedimentation in estuary environments varies seasonally, driven by changes in river runoff and sediment-trapping processes (Woodruff et al., 2001).

Estuary sediments can be classified as having a riverborne or marine origin. Riverborne sediment is characterized by a higher carbon/nitrogen ratio than that of sediment with marine origin due to the presence of carbon content and terrestrial material (Perdue and Koprivnjak, 2007).

2.6 Monitoring sediment processes

A wide range of approaches can be applied to monitor sediment movement and load along a river network, including conventional field measurements and geomorphological- and flow-based approaches.

Bottle, trap and pump samplers are widely used for estimating suspended and dissolved sediment concentrations, mostly because of their robustness and easy handling (e.g. Benedict, 1947; Lecce et al., 2006). Samples are typically sieved in a laboratory for further analyses. Sediment concentrations can also be estimated indirectly with turbidity sensors (Bayram et al., 2012; Minella et al., 2008), which are commonly used to replace costly and laborious direct SSC measurements. In indirect methods, the SSC is determined based on the correlation between the turbidity and SSC. Traditional bed load samplers, such as Helley-Smith, and sediment traps have been used for decades to monitor bed load transport (Andrews, 1979; Hubbell, 1964; Lane et al., 1996; Leopold and Emmett, 1976; Lisle, 1986; Ryan et al., 2005). Recently, ADCPs have been used to estimate bed load transport and SSC in river and estuary conditions (Hackney et al., 2020; Merckelbach, 2006; Nicholas et al., 2016; Venditti et al., 2016; Williams et al., 2015). ADCP use is based on the backscatter signal intensity, which is correlated with SSC. The above-mentioned techniques are typically used to estimate the sediment transport rate under varying discharge conditions. In low-energy environments, such as receiving bodies of water, including lakes and estuaries, the sediment accumulation rate (SAR) typically is monitored with either cylinder-shaped bottom-moored sediment traps or bottom-sediment coring (Horppila and Niemistö, 2008; Kankaanpää et al., 1997).

Sediment movement can also be estimated with the morphological approach described by Vericat et al. (2017). The morphological approach is based on repeated topographic surveys in the same river reach, e.g., before and after a spring flood, thereby allowing sediment movement to be estimated from channel change. Traditionally, the morphological approach has been based on coarsely spaced cross-section measurements (Ferguson and Ashworth, 1992; Warburton et al., 1993). The recent development and use of CRRS techniques in riverine environments has improved detection accuracy and spatial coverage, enabling detailed topographical surveys, change detection and erosion-deposition-pattern monitoring (Calle et al., 2015; Javernick et al., 2014; Kasvi et al., 2017; Leyland et al., 2017; Lotsari et al., 2014). For example, by utilising laser scanning, sediment deposition can be quantified over the entire river reach instead of at single cross-sections (Calle et al., 2015). In addition, CRRS techniques are favourable for detecting change because they do not disturb the channel bed.

The morphological approach can be conducted with several CRRS techniques, depending on the nature of the study area. In perennial river networks, a bathymetric mapping approach is needed to estimate the channel change and sediment movement. Optical bathymetric mapping was first introduced to coastal applications, before being utilized in river environments (e.g., Flener et al., 2013; Lyzenga, 1981; Westaway et al., 2001). The optical bathymetric technique is passive and based on light attenuation in a water column, using what is known as the Beer-Lambert law. The depth is calculated based on the image pixel's brightness value, which reflects the light attenuation. The depth also can be calculated based on a single spectral band (red, green or blue) or band ratio (Legleiter et al., 2004), depending on the channel's properties. Optical bathymetric modelling in river environments recently has been used for topographic surveys (Legleiter, 2012; Williams et al., 2014; Winterbottom and Gilvear, 1997); however, approaches for long-term channel-change detection and sediment load estimations are rare.

Besides optical modelling, bathymetric mapping and channel-change detection in riverine environments also can be conducted with sonar applications (Kasvi et al., 2017; Parsons et al., 2005). Although optical models can only be used in clear waters, sonar is also applicable in turbid waters. Recently, the development of smaller and lighter sonar equipment and accurate GPS positioning have made possible to operate such equipment from a moving vessel even in shallow waters and provide detailed spatiotemporal bathymetric coverage (Kasvi et al., 2017).

In a river network, sediment may deposit and entrain during peak flows outside of inundated areas e.g., flood plains, point bars or tidal flats (Asselman and Middelkoop, 1995; Kasvi et al., 2013b; Van Maren and Winterwerp, 2013). Laser scanning techniques provide the most detailed accuracy and spatiotemporal coverage for non-inundated areas in perennial river networks (Alho et al., 2011; Kasvi et al., 2013b) and ephemeral river networks (Calle et al., 2015), thereby enabling morphological approaches to estimating sediment movement. The latest developments in low-cost SfM approaches have shown promising results, alongside expensive laser scanning techniques, for topographical surveys (Fonstad et al., 2013). SfM technique have been also tested and implemented for detecting submerged channel sections (Dietrich, 2017; Woodget et al., 2015).

Sediment movement can be also estimated with measured and modelled flow conditions. Flow velocities and calculated shear stresses and stream powers can be used to explain channel change and erosion-deposition patterns (Claude et al., 2014; Kasvi et al., 2017, 2013b). ADCPs are now widely used to measure flow in fluvial environments (Caamaño et al., 2012; Flener et al., 2015; Kasvi et al., 2017; Kostaschuk et al., 2005; Mitchell et al., 2017; Muste et al., 2004; Restrepo et al., 2018; Traynum and Styles, 2007), partly due to their ability to measure three-dimensional flow fields across the whole water column. An ADCP can be attached to a movable platform, e.g., a remote-controlled mini-boat or kayak, to gain high spatiotemporal coverage of flow conditions and the channel bed structure along a river network (Guerrero and Lamberti, 2011; Kasvi et al., 2017).

Along with the three-dimensional flow measurements, hydrodynamic modelling also provides detailed information about flow conditions. Modelling of flow conditions can be used to evaluate erosion and deposition zones along river reaches (Kasvi et al., 2015; Sawyer et al., 2010), thereby enabling the calculation of reach-scale sediment loads. In addition, estuary sediment transport (Hu et al., 2009) and suspended sediment concentrations (Chen et al., 2015) can be modelled. Hydrodynamic modelling enables good spatiotemporal resolutions that are unachievable with in situ measurements. In particular, hydrodynamic modelling is essential for estimating the flow conditions and erosion and deposition potential in ice-cover conditions under which direct measurements typically provide poor spatial resolution (Lotsari et al., 2019).

3 General Characteristics of the Study Areas

This study was performed in Finland between 60° and 70° north (Figs. 3 & 4). The studies for papers I and II were performed in the subarctic Pulmankijoki River, and the studies for papers III and IV were conducted in the hemiboreal Halikonlahti Bay. These two study areas were selected based on their latitudinal location and river characteristics, including their soil type. In addition, climate change is expected to have severe consequences for cold regions in terms of snow cover and precipitation, which is expected to change the discharge regime and therefore sediment movement (Lotsari et al., 2010).

Both areas are characterized by seasonal variation in their climatological conditions, including relatively dry summers and ice-covered winters (Fig. 5). In both study areas, the surface waters are frozen, and permanent snow cover exists for at least part of the year. Typically, winter in Pulmankijoki River lasts between November and May, versus typically between mid-December and mid-March in Halikonlahti Bay. The discharge regimes are characterized by high-flow events during the snowmelt period between March and May (Fig. 5). The discharge of the Pulmankijoki River typically varies between 2 $m^3 s^{-1}$ and 10 $m^3 s^{-1}$ during open-water periods but may exceed 70 $m^3 s^{-1}$ during the snowmelt period in spring. The mean discharge of Uskelanjoki River is 5 $m^3 s^{-1}$, with the highest discharge peaks at > 100 $m^3 s^{-1}$, based on data obtained from the national gauging station (Kaukolankoski, #2500400) from 1970 to 2020.

The Pulmankijoki River consists of mobile sandy-bed sediment (D_{50} = 0.2–3 mm (Kasvi, 2015)), which was deposited during the retreat of the continental ice (Mansikkaniemi and Mäki, 1990). Riffles, pools and bars characterize the river. Its homogenous, non-vegetated river bottom and clear, shallow water offer an ideal environment for CRRS applications. Its sandy mobile sediment offers an ideal environment for rapid morphological changes, thereby enabling sediment entrainment and deposition monitoring within a short time.

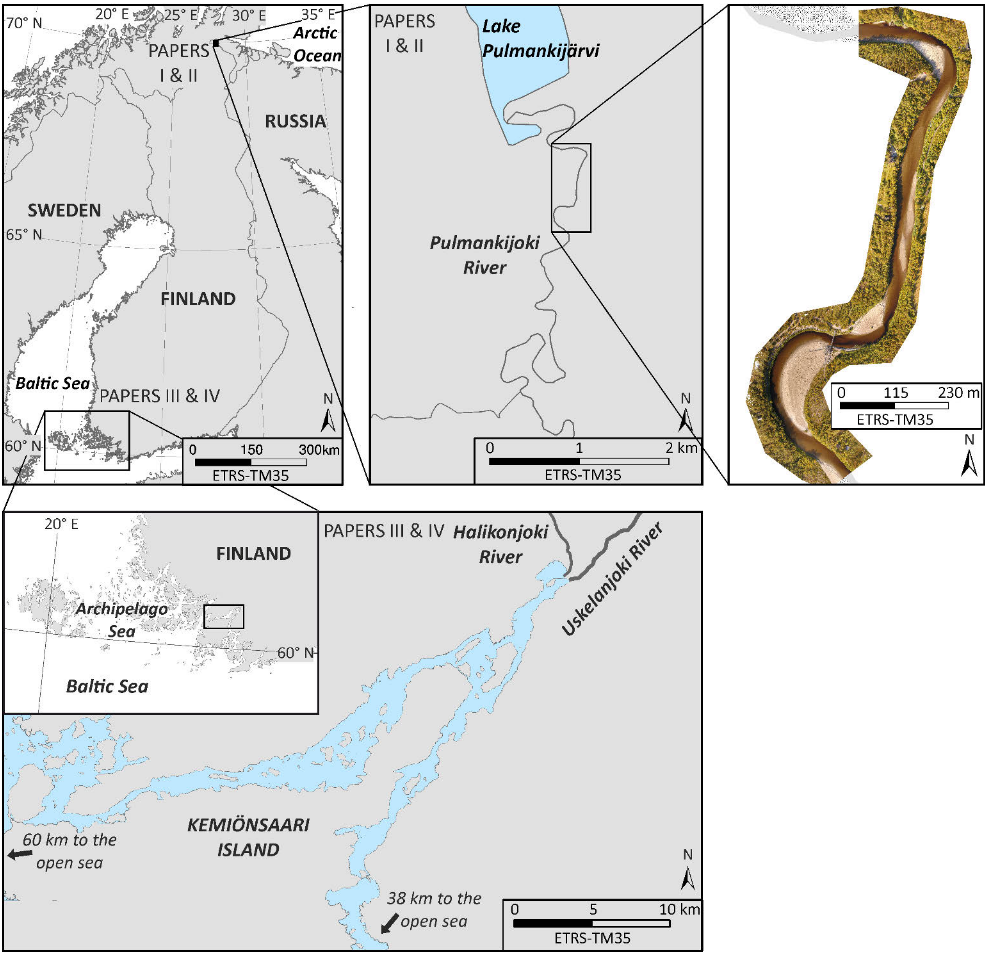

Figure 3. Study area and case study sites. The studies for papers I & II are performed in subarctic Pulmankijoki River and for papers III & IV in hemiboreal Halikonlahti Bay.

Figure 4. Two study areas. Aerial image of sandy meandering Pulmankijoki River on the left and ADCP measurement conducted in non-tidal Halikonlahti Bay on the right.

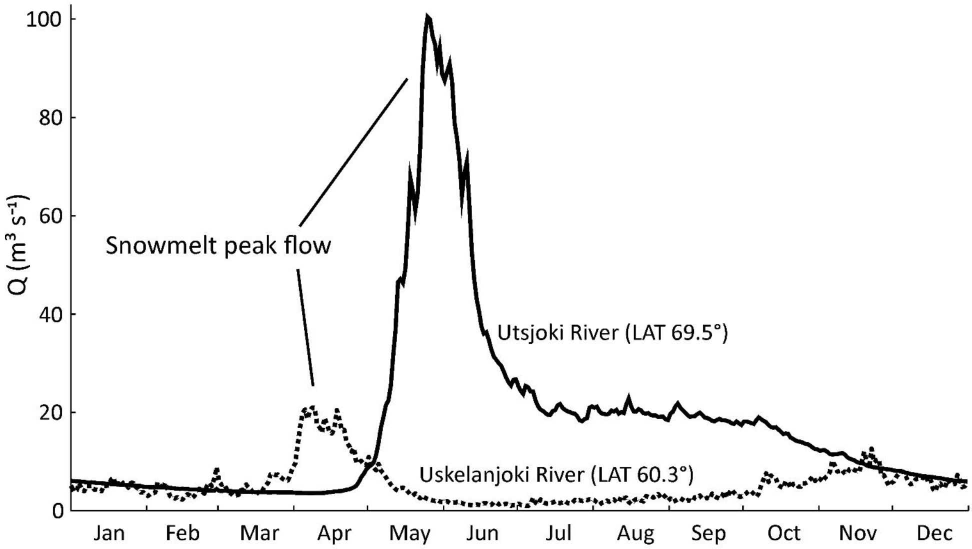

Figure 5. Annual averaged discharge regimes for subarctic Utsjoki River and hemiboreal Uskelanjoki River, 1970–2020. Hydrographs of Utsjoki River and Uskelanjoki River are typical for subarctic and hemiboreal regions, respectively. The Pulmankijoki River (papers I & II) is located in subarctic region, and the studies for papers III & IV were conducted in a Uskelanjoki River estuary.

Halikonlahti Bay, located in the Archipelago Sea, in the Baltic Sea, is a non-tidal brackish water body. Halikonlahti Bay forms an enclosed estuary for the Uskelanjoki and Halikonjoki Rivers, with two openings to the Archipelago Sea separated by Kemiönsaari Island. The Uskelanjoki and Halikonjoki Rivers flow into the bay, together forming the main freshwater inflow into the estuary.

The Pulmankijoki River's drainage area is about 480 km^2 and consists mainly of mires and peatlands, which are typical at high latitudes, without human presence in the drainage basin. Meanwhile, the combined drainage area of the Uskelanjoki and Halikonjoki Rivers (which flow into Halikonlahti Bay) is about 873 km^2 and heavily cultivated, consisting of 36% non-irrigated arable land, based on the CORINE Land Cover classification. The Pulmankijoki River is a meandering sandbed river, and the Uskelanjoki and Halikonjoki Rivers are dominated by clay. The differences in soil material, especially in cohesiveness and grain size, give the rivers individual character and act on their sediment movement and water properties, including turbidity. While rapid morphological changes are expected to occur in sandbed river environments, clay-dominated environments provide the conditions for plume development.

4 Materials and Methods

In this thesis, multiple methods were exploited to monitor and estimate sediment dynamics in riverine and estuary environments (Fig. 6 and Table 1). This research combined high-resolution remote sensing techniques, water quality and sedimentological measurements and hydrodynamic modelling.

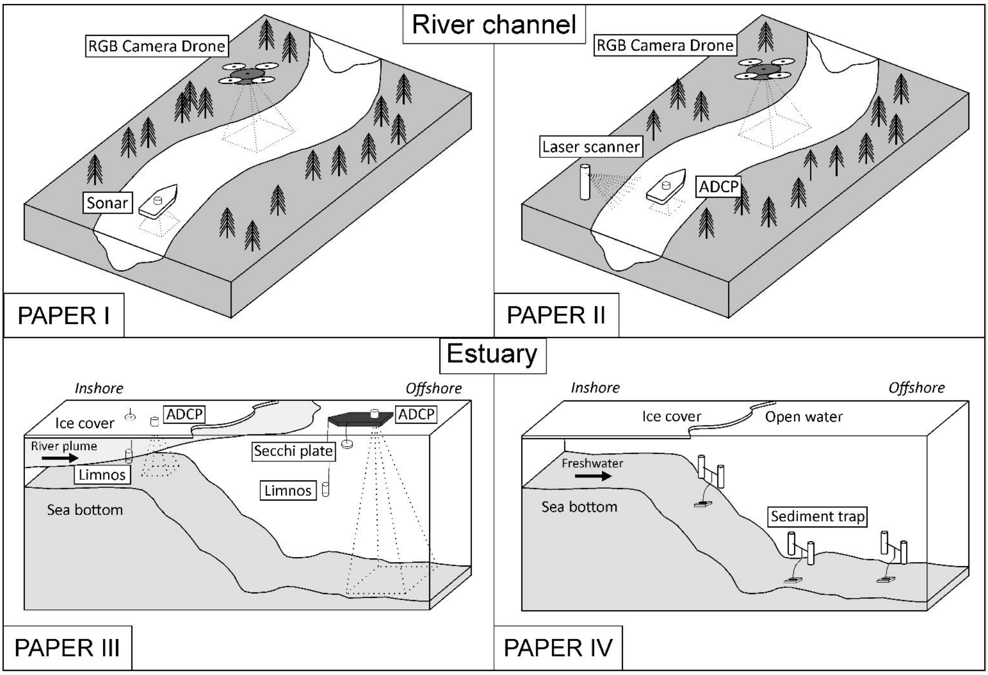

Figure 6. Schematic picture of field methods used in each paper. Methods are described more detail in the text and table 1. Papers I and II focus on river and papers III and IV on estuary environment.

Table 1. Data and methods utilized in this thesis.

	PAPER I	PAPER II	PAPER III	PAPER IV
Flow conditions				
ADCP		X	X	X
Hydrodynamic modelling				X
Discharge				
ADCP	X	X		
National gauging station (external data source)			X	X
Water level				
Water level sensors	X	X		
National gauging station (external data source)				X
Channel geometry				
Bathymetric Structure from Motion	X			
Bathymetric Optical modelling	X	X		
Bathymetric Echo sounding	X	X		
Mobile Laser Scanning		X		
Structure from Motion		X		
RTK-GNSS	X	X		
Estuary bathymetry (external data source)				X
Water quality				
Depth-integrated water sampler	X			
Limnos water sampler			X	
Secchi plate			X	
Sedimentation				
Sediment trap				X
Weather condition (precipitation, snow cover and wind)				
National weather station (external data source)			X	X

4.1 Flow characteristics

4.1.1 Flow conditions

Three-dimensional flow measurements were carried out using an ADCP (Sontek S5 & M9) in both river (papers I and II) and estuary (paper III) environments. In the river environment, measurements were carried out using either a remote-controlled mini boat or a kayak by moving upstream along zigzag-style cross-sections between the left and right banks. In the estuary, a six-minute stationary measurement mode was used at specific site locations to monitor the prevailing flow conditions. The

ADCP was mounted on a raft attached to the stern of an anchored boat, and held by hand during open water and ice cover conditions, respectively.

Discharge data were either measured in situ (papers I and II) or derived from the national gauging station (Kaukolankoski, #2500400), located in the Uskelanjoki River (paper III and IV). Discharge was measured by moving the ADCP along a channel cross-section multiple times to calculate the average discharge. Measurements were conducted next to the sensor at water level to calculate hydrographs based on the relationship between the discharge measurements and water level.

4.1.2 Hydrodynamic modelling

Hydrodynamic modelling was performed to estimate flow and sediment dynamics in paper IV. A three-dimensional hydrodynamic model (Delft 3D) of Halikonlahti Bay was created to estimate hourly flow conditions. The model used a curvilinear grid with cell size variations of 31–80 m in the horizontal direction. The grid contained six layers in the vertical direction of varying cell sizes, based on the water depth at each cell location. The model was based on the bay geometry at 5 m resolution. Two simulations (cold seasons 2019 and 2020) were performed with hourly boundary conditions.

A combination of discharge from two main rivers entering the bay was used for upstream boundary conditions. Sea level data was used as a downstream boundary condition for the model. Calibration was performed using data measured with side-looking sonar (ADCP), collected and administered by the Finnish Transport Infrastructure Agency in the Strömma strait located in the Halikonlahti Bay area. The model was calibrated by adjusting Manning's roughness coefficient. The geometry of the bay area was produced by the Department of Geography and Geology, University of Turku.

4.1.3 Water level

Water level data and discharge measurements were used to create hydrographs in river environment (paper II). The in situ water level measurements were based on bottom-anchored water-pressure sensors and air-pressure sensor for barometric compensation. In paper IV, water levels were used as a downstream boundary conditions in hydrodynamic models. The water level data were derived from two national mareographs: Turku Ruissalo Saaronniemi (#134225) and Hanko Pikku Kolalahti (#134253).

4.2 River channel geometry

Topographic data were collected for papers I and II. In riverine environments, the topographic data is divided into two categories, inundated and non-inundated, based on the wetted area. In this thesis, inundated areas were detected with bathymetric SfM, optical modelling and echo sounding. Non-inundated areas were measured with laser scanning or SfM. Accurate topographic surveys are needed to detect changes and further morphological changes as well as to estimate sediment load. In paper I, bathymetric methods were compared to find the most accurate approach for bathymetric mapping. Bathymetric SfM and optical modelling were based on aerial images collected 50–90 m above the ground using drones. Aerial images were mosaicked and georeferenced based on ground control points (GCPs) measured with a real-time kinematic global navigation satellite system (RTK-GNSS).

Optical bathymetries were modelled based on the pixel brightness value of only the red band. In echo sounding, inundated channel section was measured by an ADCP attached to either a kayak or a remote-controlled mini boat. For the bathymetric surveys, the ADCP utilized either one (vertical) or five (one vertical and four tilted) beams. Much higher point density is achieved within the same time with the latter method.

The topographic surveys for non-inundated areas, such as point bars, were based on either light detection and ranging (LiDAR) or SfM technology. The LiDAR surveys were performed via backpack (BaMLS), boat (BoMLS) or unmanned aerial vehicle (UAV-LS). Spherical reference targets (SRTs) were used to evaluate LiDAR surveys' system calibration accuracy. SfM was based on aerial images collected with RGB camera.

RTK-GNSS measurements were collected for papers I and II given the need for high accuracy. The RTK-GNSS measurements were mainly used to calibrate and validate the topographic models.

4.3 Water quality and sedimentological data

Water quality measurements were conducted for papers I and III. A depth-integrated water sampler was used to estimate the turbidity (FTU) and colour (mg/l Pt) of the river water during bathymetric surveys. The depth-integrated water sampler was moved between the surface and bottom to estimate the water parameters throughout the whole water column, which has a clear link to the behaviour of the optical models but not with the echo-sound-based models.

In the estuary surveys for paper III, water quality was measured with a LIMNOS water sampler, which was descended to the measurement depth. Unlike with a depth-integrated sampler, a LIMNOS sampler samples at the desired depth only, and multiple measurements are needed to collect data across the water column. Turbidity, SSC, temperature and salinity values were measured for paper III. Secchi depths were measured in an estuary environment to detect the plume development and distribution in Halikonlahti Bay.

Sedimentological data were collected and analysed in an estuary (paper IV). Data were collected to compare spatial and cold-season sedimentation differences in Halikonlahti Bay. Four bottom-mounted sediment traps were used to analyse the SAR and sediment composition. Traps were installed before the cold season (September–October) and emptied before the warm season in May during 2018–2020. The SAR, organic and minerogenic composition, C/N ratio and particle size distribution were determined for both cold seasons.

4.4 Weather data

Weather data were derived from national weather stations to estimate wind's effect on plume development (paper III) and the effects of wind, precipitation and snow cover on sedimentation differences between the two cold seasons with very different conditions (paper IV).

5 Results and Discussion

5.1 Cold-region river systems are characterized by episodic sediment movement (papers II–IV)

The results of papers II–IV show that sediment movement in cold-region river systems is episodic. In rivers, sediment movement is strongly linked to discharge variation, which is typically characterized by strong flow peaks caused by spring thaw or occasional rainfall. Based on our findings in paper II, near-bed flow velocities become highest during peak discharges, resulting in erosion and deposition along the river reach. For example, meander bends erode on their concave sides and aggrade at inflexion points because of differences in near-bed flow velocities, resulting in riffle-pool sequences. Therefore, discharge peaks have strong impacts on vertical channel change and on the development of morphological units in cold-region rivers. Our findings are consistent with those of several other studies highlighting the effects of peak discharges on channel erosion, aggradation and the development of morphological units (Kasvi et al., 2017; Keller, 1971; Vetter, 2011).

The results of paper II show that although channel change is most intensive during peak discharge events (in our case, during spring thaw), channel formation also occurs during low-flow stages (paper II). This finding is consistent with previous observations (e.g., Lane et al., 1996; Riley and Rhoads, 2012) stating that changes in river channels can occur outside the flood period during low-flow stages. In addition, the findings of paper II show that channel formation is rather similar along river reach and not just a feature of a particular bend.

During low-flow stages, sedimentation becomes dominant, and the bed elevation differences caused during peak discharge periods disappear, leading to deformation of riffle-pool sequences. For example, paper II's findings show that during the low-discharge period, concave sides aggrade and inflexion points erode, causing pool filling and riffle erosion. Thus, the river may act as temporary sediment storage. The results of paper II accord with those of an earlier study, stating that at low flow, high-flow scouring sections tend to fill whereas filling sections tend to scour (Andrews, 1979).

Based on the findings of papers III and IV, the episodic sediment movement in estuary environments is related to river discharge peaks, storm-induced wind and sea level changes. The development of sediment-rich plume was found to be related to high-discharge events caused by spring thaw or heavy precipitation (paper III). During plume development, sediment movement is strongest, and sediment particles may travel long distances between erosion and deposition zones. During low-flow events, plumes do not exist; therefore, sediment movement is exhausted.

In paper IV, higher sedimentation rates were found in open-water than in ice-cover conditions. These results accord with earlier studies showing higher resuspension in open-water than in ice-cover conditions (Kleeberg et al., 2013; Niemistö and Horppila, 2007). Therefore, sediment resuspension is expected to be strong in open water, especially under high-flow-velocity conditions caused by wind and wave action (Nuorteva and Kankaanpää, 2016; Rasmus et al., 2015). These findings suggest that sediment movement in coastal areas is characterized by variation between ice-cover and open-water periods. Additionally, high-energy conditions, such as storm events, drive episodic sediment movement in coastal environments.

5.2 Sediment movement is driven by local- and regional-scale conditions (papers II–IV)

Sediment movement along the river network is driven by a combination of local- and regional-scale conditions (papers II–IV). Although variations in discharge and flow conditions are the main driving force for sediment movement, local conditions affect sediment movement as well. In paper II, we found that preceding morphological changes influence subsequent changes, and discharge and flow velocities are not the sole determiners of river channel change. For example, deposition can be extremely strong in areas that have significantly eroded previously (paper II). Second, deposition is controlled by flow variation and scour at the upstream part of the river channel: development of pools and riffles, i.e., riffle-pool sequences, are linked (paper II), which previous studies have also shown (Andrews, 1979; Keller and Melhorn, 1978; Thompson, 1986). Scour at pools typically leads to deposition at the adjacent riffle downstream.

Meanwhile, in cold-region estuary environments, sediment-rich plume development is controlled by river discharge, ice cover, wind and salinity stratification simultaneously (papers III and IV). Earlier studies of sediment movement in estuaries have also shown that sediment movement is driven by several factors, including ice ridges, ice cover, wind and the interplay between tidal forces and river runoff (Granskog et al., 2005; Macdonald and Carmack, 1991; Orseau et al., 2017; Stumpf et al., 1993). Paper III shows that even extremely small salinity stratification combined with windless or ice-cover conditions may have strong effects on plume development and sediment movement. These results support previous findings on plume development in environments with low salinity stratification (Granskog et al., 2005; Kari et al., 2018). In paper III, we found a high negative correlation between salinity and SSC in estuary water samples, indicating limited mixing conditions between fresh, sediment-rich surface water and clear, saline bottom water. Additionally, wind and ice cover influence sediment processes in estuaries by enhancing and inhibiting water mixing and littoral resuspension, respectively (papers III and IV). Moreover, sea floor morphology with small cross-sectional areas may influence sediment resuspension because of increased flow velocities compared to surrounding areas (papers III and IV).

5.3 A combination of remote sensing, hydrodynamic modelling, flow and sediment measurements provides detailed approaches for sediment movement studies (papers I–IV)

This thesis shows that a combination of sediment process and flow condition measurements provides comprehensive information about flow-sediment interaction in fluvial environments (papers I–IV). In paper II, channel change and riffle-pool development, measured using CRRS, were explained by measured discharge and near-bed flow velocities, establishing a link between channel change, riffle-pool development and near-bed flow velocities. The results show that when approximately 20% of bankfull discharge is achieved, near-bed flow velocities become higher on concave sides than at inflexion points. This explains the location of strong erosion and aggradation on concave sides and at inflexion points during high discharge, respectively. ADCP-derived near-bed flow velocities provide an explanation for channel change and erosion-deposition patterns.

In papers III and IV, the measured sediment movement and sedimentation, respectively, were explained by measured and modelled flow conditions in the estuary environment. Development of sediment-rich river plumes can be partly explained by estuary flow conditions in open-water and ice-cover conditions (paper III). Flow measurements and SSC measurements support the findings of sediment-rich plume development.

Flow conditions, derived from hydrodynamic modelling, can be used to explain the sedimentation differences in estuary environments (paper IV). Paper IV’s aim was to improve the understanding of sedimentation processes in coastal areas by linking flow conditions with in situ samples collected with sediment traps. Hydrodynamic modelling shows differences in estuary flow conditions between two cold seasons and therefore can be used to improve the understanding of sedimentation processes in coastal areas by linking flow conditions with sediment data.

Papers I and II showed that river channel topography and geomorphic units' development can be detected with great accuracy in shallow, clear river environments using a combination of CRRS approaches. Despite the development of high-resolution CRRS techniques and DEMs, change detection based on several repeated DEM surveys to monitor annual, seasonal and event-scale changes is relatively rare in the literature. The focus has been on mapping and quantifying channel morphology (Flener et al., 2013; Javernick et al., 2014; Williams et al., 2014) instead of detailed change detection. Furthermore, because of their large spatial data coverage, CRRS methods could be used for sediment load estimation within a channel reach by repeated surveys. This is known as the morphological approach, which Vericat et al. (2017) described.

Combined remote sensing techniques for channel-change detection are necessary for rivers, where geomorphic units are inundated mainly during peak discharges (paper II). Additionally, due to low water turbidity and flow conditions, fieldwork typically is deployed during low-flow conditions, when conditions for bathymetric mapping are favourable. Topo-bathymetric LiDAR, operating in the green and infrared region of the electromagnetic spectrum, has shown promising results for simultaneous topographic and bathymetric mapping in river environments (Islam et al., 2022; Kinzel et al., 2021). Due to the high cost, topo-bathymetric LiDAR is not yet widely used in scientific applications but most likely will be used to map river channels in upcoming years. However, it would not provide flow-velocity data; therefore, ADCP measurements are still needed to study flow-sediment interaction.

Our study methods allowed for reliable interpretations of sediment movement in fluvial environments. However, it had some limitations, resulting in recommendations for future research. Owing to the high correlation between turbidity and SSC (0.82–1.00), sediment-rich plume development could be studied only with turbidity measurements, thus omitting laborious SSC calculations. Additionally, ADCPs' signal backscatter intensity should be tested for estimating SSC in the water column, which would provide information regarding flow conditions and SSC values simultaneously (Kostaschuk et al., 2005). CTD-instruments (conductivity, temperature and depth) would support the turbidity measurements for plume monitoring by casting a salinity gradient through the water column. Usage of CTD instruments would transect the entire water column rather than taking only point-based measurements, as in our study. Hydrodynamic modelling proved to be an efficient tool for estimating flow conditions in the estuary environment (paper IV). However, bottom-mounted ADCPs along the estuary, for example next to sediment traps, would provide more accurate and detailed flow data.

However, the use of multiple ADCPs is expensive and typically unrealistic in scientific applications.

5.4 Climate change will change the sediment movement pattern of cold-region river systems (papers II–IV)

Papers II–IV showed that sediment processes are episodic in cold-climate regions, mainly because of climate conditions. In cold-region rivers, sediment movement is strongest during spring thaw, when annual peak discharge typically occurs (paper II). Lotsari et al. (2010) and Veijalainen et al. (2010) have estimated that the discharge regime of cold-region rivers will change in the future, resulting in diminishing spring floods and increasing autumn and winter floods. Change is mainly caused by increases in temperature and precipitation combined with decreasing snow cover. Moreover, in areas currently dominated by snowmelt floods, a future decrease in flood discharges is expected (Veijalainen et al., 2010). The findings in papers II–IV suggest that due to the expected shift in discharge regime and decreasing spring flood magnitude, sediment movement will decrease during spring floods whereas the roles of several discharge peaks with smaller magnitudes occurring during winter and autumn may become more significant. This finding is consistent with those of Lotsari et al. (2010), concluding that sediment movement in cold-region rivers will be shifted towards autumn due to climate change. The discharge regime of the warmer and wetter cold season in paper IV most likely represented an analogue for future cold-season scenarios—that is, several short-term rainfall events produce short discharge peaks instead of a single long-duration discharge peak caused by snowmelt (first cold season). The duration of active flows above critical discharge is suggested to be more important for channel change than discharge magnitude (Vetter, 2011); therefore, several short-term autumn and winter rainfall-induced discharge peaks may have an impact on river-channel change distinct from that of long-term spring floods. However, short-term discharge peaks most likely increase sediment transport and episodic sediment movement.

Because near-bed flow velocity and stream power are related to discharge (paper II) (Kasvi et al., 2017), the changes in discharge magnitude and duration will change erosion and deposition patterns. With reduced stream power, due to shorter spring floods, channels may not scour as deeply as they used to, and geomorphic units, e.g., riffles and pools, may not develop as they used to. Reduced stream power may lead to excess sedimentation in rivers, causing channels' decreased hydraulic efficiency and therefore increased flood sensibility. Moreover, lower near-bed flow velocities may entrain fine-grained sediment, but grains of larger sizes may no longer be transported. These changes in channel geomorphology and bed grain size may influence fish spawning sites and reproduction for grain-size-specific and site-specific fish species (Louhi et al., 2008).

In shallow coastal environments, the lack of ice cover due to temperature increases will become more frequent (Jevrejeva et al., 2004; Vihma and Haapala, 2009). Based on paper IV's findings, the lack of ice cover enhances wind-induced resuspension in coastal areas; therefore, sediment movement is increased. Similar findings have been recorded in cold-region lake environments (Kleeberg et al., 2013; Niemistö and Horppila, 2007). This increase in sediment movement will increase both SSC and turbidity, leading to increased light attenuation in the water column (Pedersen et al., 2012). Moreover, as ice cover reduces wind-induced mixing of surface waters (paper III; Granskog et al., 2005; Ingram and Larouche, 1987), the lack of ice cover may inhibit plume development in estuary conditions. In the future, the discharge regime shift combined with the lack of ice cover most likely will change nutrient-rich spring plume development, which may influence fish populations in shallow coastal regions.

Based on our findings in paper IV, sedimentation in cold-region coastal areas will increase in the future. A clear difference in SAR between two distinctive cold seasons was observed, reflecting catchment erosion and littoral resuspension. Although regular cold-season conditions, including frost, snow accumulation and sea ice cover, lead to punctuated catchment erosion during spring thaws, warmer cold seasons with open sea conditions combined with high frequencies of low air pressure systems and rainfall events cause enhanced catchment erosion not only from land but also via resuspension of littoral sediments.

6 Conclusions

This study focused on sediment movement, flow-sediment interaction and sediment processes in cold-region fluvial environments. The study focused on mapping river channel geometry and detecting changes in a shallow subarctic sand-bed river and sediment-rich plume development and cold-season sedimentation in hemiboreal estuary. By employing a multimethod approach including sediment sampling, CRRS, flow measurements and hydrodynamic modelling, the following conclusions can be drawn:

1) Sediment movement in cold-region fluvial environments is episodic and controlled mainly by a two-part discharge regime: intensive sediment movement and morphological changes in river channels occur during spring thaw, when effective flow conditions are highest in duration and magnitude. Simultaneously, sediment-rich plumes most likely develop in estuary environments. Moreover, in estuary environments, sediment movement's episodic behaviour is characterized by wind-induced resuspension and sea level changes caused by the passage of low-air-pressure systems. Outside of high-energy conditions, sediment movement is calm and mainly depositional in river and estuary environments. Sediment particles may be stored and resuspended multiple times within the river network before reaching the deposition zone. However, during long-lasting high-discharge events, sediment particles may be transported throughout the river network because of high-energy conditions.
2) Sediment movement is characterized by a combination of local and regional processes. Although processes are primarily driven by variation in discharge and sea level, local processes and characteristics, including riffle-pool interaction, channel shape, estuary ice cover, wind and salinity, also affect sediment movement. Additionally, in river channels, preceding morphological changes influence subsequent changes together with flow conditions. Buoyant sediment-rich plume development is driven by high-discharge events combined with salinity stratification and lack of wind-induced mixing.

3) In this study, multiple measuring approaches for monitoring sediment dynamics were successfully combined. Study methods supplemented one another, and a combination of conventional field measurements, CRRS and hydrodynamic modelling enabled detailed analysis of flow-sediment interaction and sediment processes, which is especially needed in complex natural environments. For example, combining flow and sedimentological data, e.g., river-channel change or sedimentation rates, deepens our understanding of flow-sediment interaction, which typically has been studied focusing solely on either sedimentological data or flow conditions. So far, a combination of multiple CRRS measurements for change detection and sediment-load estimation in river environments is needed to achieve the most accurate data.
4) In the future, ongoing climate change with increasing temperatures may change sediment movement patterns in cold-region fluvial environments. Sediment movement is mainly related to high-energy conditions, and it most likely decreases during spring thaw because the decreased duration and magnitude of spring-flood-induced high-energy flow conditions are predicted in earlier studies. This development likely reflects the formation of geomorphic units as well. Furthermore, decreasing sea ice cover may increase littoral resuspension and inhibit sediment-rich plume development in coastal regions. Wet cold seasons most likely increase coastal sedimentation due to intensified rainfall and decreasing snow cover.

In the future, sediment movement studies along the river network could be conducted within a single river network, covering river channel and estuary environments, to find linkages between upstream and downstream parts of the same river network. The development of CRRS, including topo-bathymetric green LiDAR, provides an effective approach for channel geometry measurements and further sediment load estimations. Flow and channel change could be studied within single flow events for improved understanding of flow-sediment interaction during various flow events. Additionally, the effect of ice cover on sediment transport in estuary conditions should gain more attention, especially if winter floods are becoming more frequent because of climate change. A combination of several approaches for sediment movement studies is recommended.

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