Sediment delivery and erosion processes in drained peatlands

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Abstract Sediment delivery and erosion processes have been studied in a number of peatland drainage areas and catchments in order to determine the effects of drainage on sediment and erosion dynamics and mechanics. This information is necessary for management of catchments where sediment poses a serious risk to water protection. Results from recent studies performed in peat mining, peatland forestry and disturbed headwater catchments in Finland are reviewed and potential sediment load management methods are discussed for drainage areas and headwater brooks. The issues especially covered are erosion of organic peat, sediment transport and methods to restore and reduce the impacts of peatland drainage in boreal headwaters.

Key words sediment transport; erosion; peatland drainage; organic and inorganic sediment; stream and catchment restoration; management; stream ecology

INTRODUCTION

Peatland drainage operations result in erosion of peat and underlying mineral soils. In Finland peatlands cover 30% of the total land area and they are often intensively used and managed. Historically, peatlands have been drained for agriculture, forestry and urban settlement, which has resulted in drainage of two-thirds of existing peatlands. Currently, 70 000 ha of open-drained land are maintained/renovated every year for forestry (Statistical Yearbook of Forestry, 2008) and 65 000 ha for active peat mining (Väyrynen *et al*., 2008). These activities result in considerable sediment loads to surface waters. Plans are currently being developed in Finland to increase drainage in order to maintain the forestry drainage network and increase bioenergy supply from drained peatlands. Water protection measures are widely employed for both land uses, but their function is often poor due to variability of runoff volumes and sediment loads (Vuori & Joensuu, 1996; Liljaniemi *et al*., 2003).

The mitigation of sediment losses from peatland forestry drainage waters has become an important issue because of the ditch network maintenance work being carried out on extensive areas annually and new peat mining areas being established. Drainage of peatlands is a major source of sediment and pollution in forestry (e.g. Joensuu, 2002) and peat mining (e.g. Kløve, 1997). Increased erosion of organic peat and inorganic sediments has resulted in eutrophication, sedimentation and loss of biodiversity in downstream watercourses. In natural conditions these headwaters supply little sediment and are valuable habitats. Excess sediment changes stream and lake bed (bottom) characteristics, aquatic biodiversity and spawning grounds (Rask *et al*., 1998; Laine & Heikkinen, 2000; Laine, 2001; Yrjänä 2003). The effects are first seen in headwater streams located close to the sediment source. Because of their environmental isolation, headwater systems support, e.g. genetically isolated species, which are at risk of extinction. The role of headwaters within the catchment and linkages from headwater to downstream systems are poorly understood. Understanding of erosion and sediment transport processes in these environments is key to successful management.

Because drainage areas and headwater brooks are small and numerous, the roles of these systems are typically underestimated. In Finland, there is a clear need to focus sediment research more on peat-dominated catchments, as 30% of the land area is covered by peatlands. As one of the principal problems is excess sediment, especially organic sediment, more research is needed. Understanding the dynamics of organic peat transport and erosion in drainage and headwater areas can improve water quality management in peat drainage areas. The objectives of this paper are to present and review erosion and sediment transport studies carried out in drained peatland watersheds and watercourses during recent years and discuss new methods used to manage these problems.

SEDIMENT TRANSPORT IN DRAINED PEATLANDS AND SMALL BOREAL HEADWATERS

The drained peatland catchment and its fluvial network can be partitioned into two systems, drainage and natural headwater systems, on the basis of process and geomorphological characteristics. Structural differences and the continuous *versus* discontinuous nature of processes distinguish these systems. Sediment transport processes must be understood if pollutant loads from peatland drainage networks are to be decreased. These processes relate to discharge and its spatial and temporal variability; and to local hydraulics where water volume, velocity, transport capacity and their spatial and temporal changes determine the load transported.

Peatlands have been under active research for a long period and central to understanding these systems has been their hydrological function. There is only minor erosion and sediment transport in natural boreal peatland systems (e.g. Mattsson *et al*., 2003) due to dense vegetation cover and its protective nature, low precipitation rate and long periods of frozen soil every year. However, under the influence of new land uses, these systems become strongly influenced by erosion processes (Fig. 1), which are relatively poorly studied in drained peatland areas. Drainage tends to increase the response rate, increasing peak flows in the channels, increasing drainage density and hydrological connectivity, and causing increasing erosion of channel bed and walls, especially if drains extend into mineral soil under a peat layer.

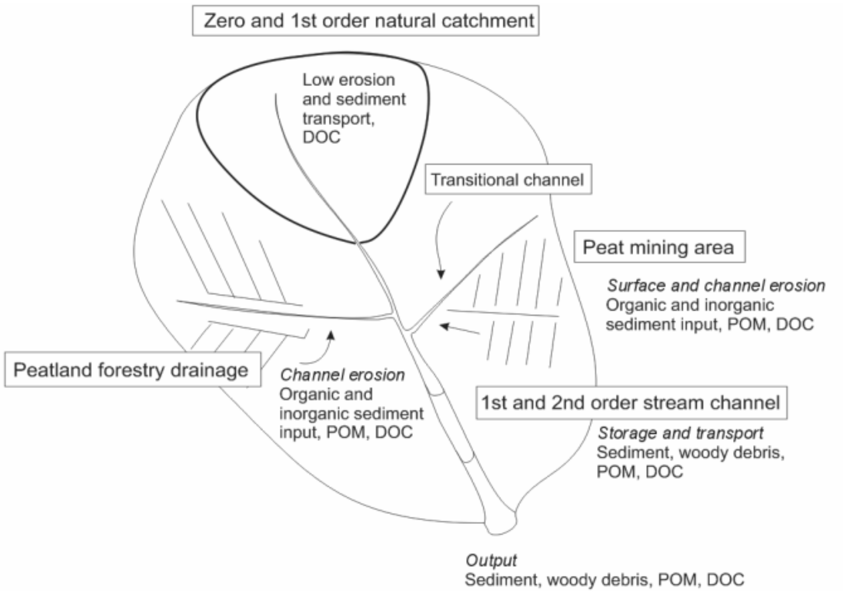

Fig. 1 Erosion and sediment transport processes in peatland-dominated headwater system.

Drainage of peatland forests can increase concentrations of suspended solids, organic matter, nutrients and metals in streams (Kenttämies, 1981; Sallantaus, 1995; Miller *et al*., 1996; Manninen, 1998; Rask *et al*, 1998; Åstrom *et al*., 2001). Drainage also increases organic matter decomposition and results in leaching of nutrients and erosion and weathering of drainage channels (Marttila & Kløve, 2010a). Peak runoff rate during spring and summer has been noted to increase in some catchments during the first years after peatland drainage (e.g. Conway & Millar, 1960; Ahti, 1980; Hyvärinen & Vehviläinen, 1981; Seuna, 1981; Konyha *et al*., 1988; Sirin *et al*., 1991). Increased peak runoff rates produce erosion and sedimentation problems downstream. Previous studies have stressed the importance of the spring snowmelt period (Ahti *et al*., 1995), while recent studies show a dramatic difference in sediment transport processes and underlying mechanics between peak hydrographs (Marttila & Kløve, 2008; Marttila & Kløve, 2010a). Summer peak flows may even play a dominant role in annual sediment yield.

The storm flow response to intense rainfall is rapid in peat dominated regions because of their relatively small storage capacity and short flow paths. Peatland drainage has been noted to increase catchment hydraulic connectivity (Korkalainen *et al*., 2008). Evans & Warburton (2007) reported that runoff from blanket peatlands is typically flashy, with rapid recession, short lag times and fast times to peak in hydrographs. These flashy environments transport major sediment loads during these events and similar phenomena have been observed in drained peatlands.

The reported sediment transport rates from drained areas are high (e.g. Kløve, 1997; Joensuu, 2002) and illustrate the potential for rapid removal of organic peat sediment after drainage operations. Bare fresh peat soil surfaces are relatively resistant to erosion (Aho & Kantola, 1985; Carling *et al*., 1997). However, after drainage operations the bare soil surface in peat mining areas and ditch walls in peatland forestry areas are subject to weathering processes. Wind and water erosion and chemical oxidation affect the peat surface. Rain, snowmelt and runoff are the major causes of erosion in drained areas. In peat mining areas, rain and peat harvesting operations deliver sediment from the bare soil surface to ditches (Kløve, 1997), whereas with erosion in peatland forestry the source of sediment is channel erosion (Marttila & Kløve, 2008). The nature of sediment supply controls the sediment load from these areas. Rainsplash and micro-rill formation are dominant processes for overland flow-induced sediment production (Kløve, 1998), but channel inter-storm storage and flow transport capacity control the sediment load transported downstream (Marttila & Kløve, 2008).

The erosion conditions differ in forested peatland regions. In these areas, the drainage network itself causes major erosion if drains extend into the mineral soil under the peat layers (Heikurainen *et al*., 1978; Konstantinov & Suhorukova, 1980). Therefore, drainage operations on thin peat layers, mire or heath can create a greater risk of erosion. The main sediment sources are weathered channel walls, bank collapse and channel bed erosion by runoff (Marttila & Kløve, 2010a). The nature of transported material can vary in space and time as a result of varying sediment sources, weathering processes, inter-storm channel storage or seasonal conditions (Marttila & Kløve, 2009a). In particular, inter-storm storage has been reported to considerably affect the sediment load. Similar findings have been made in blanket peatlands (Burt & Gardiner, 1984; Francis, 1990; Labadz *et al*, 1991) but weathering in these UK blanket peatland conditions is probably higher than in forestry ditches in Finland due to the Atlantic fringe climate.

Sediment delivery from peat drainage areas to downstream waters is often interrupted because sediment is temporarily stored in or along the ditch and stream bed, banks and flood plains. As in-channel processes dominate the rate of sediment transport, the bed sediment properties play an important role for sediment entrainment. The organic peat sediment has been noted to undergo cohesive characteristics after consolidation and changes in time occurring in the sediment (Marttila & Kløve, 2008). In the cohesive bed, the strength of the bed increases with depth (Krone, 1999; Lau *et al*. 2001), the strengthening process depends on time (e.g. as consolidation) and the bed shear strength increases with time (Zreik *et al*., 1998). Erosion often occurs in large portions of sediments as distinct layers (Lick, 2009). Sediment stabilisation by, for example, bacteria-produced organic matter can also increase cohesion (Black *et al*., 2002; Stone *et al*., 2008), resulting in increased critical shear stress of the sediment. Only few sediment erosion experiments with organic peat sediments have been conducted (Marttila & Kløve, 2008).

Degraded small forest brooks by forest drainage

Erosion in forestry drainage channels usually decreases over time (Joensuu, 2002), but in some reaches it may continue or eroded sediment may affect downstream locations for a long time. Small headwater streams are critical areas for sediment deposition due to their low transport capacity and stream power. They are also important since headwaters make up most of the total channel length and catchment area (70–80%) (e.g. Meyer & Wallace, 2001).

Sediment transit time from drainage areas to natural headwaters and on to the main channel depends on the presence of unconstrained reaches, connection to drainage network, channel gradient, timing of land use operations, and amount of runoff (e.g. Marttila *et al*., 2010a). Changes in channel geomorphology, e.g. gradient and material types, can also modify sediment transport. However, sediment transport to downstream reaches is not a simple phenomenon, as the sediment can be trapped or stored in various locations. Significant amounts of sediment may be deposited on flood plains, trapped in streams or transformed to dissolved organic carbon (DOC) during breakdown of transported organic matter. Periodic or seasonal flooding provides a major mechanism to promote material transfer (Marttila *et al*., 2010a). Recent studies have noted that these fluvial systems can transport organic sediment but problems occur with inorganic sediment larger than 0.45 mm (d_{50}) (Marttila *et al*., 2010a). Sediment deposits and accumulations induce local aggradation, with the fining process of sediment in the downstream direction. Very little is known about these processes, although they may play a significant role in catchment total sediment load. For organic sediments, the degree of humification and other peat characteristics including water content and water repellence are also important (Kløve, 1998). Drying or wetting processes of transported peat sediment may play a significant role in different conditions during the annual cycle. In addition, the effect of erosion and transport of organic sediment on the carbon cycle is still unknown. Particulate carbon (POC) and its transformation to DOC or other elements may play a significant role in the greenhouse gas (GHG) balance in highly eroding catchments. Under natural conditions peatland channels transport almost no sediment (Nanson *et al*., 2009), which imposes special demands for management of disturbed peatland channels.

MANAGEMENT OF EROSION AND SEDIMENT TRANSPORT AT DRAINED CATHMENTS

The management of erosion and transport problems requires effective water protection in drained areas. Conventional methods (e.g. sedimentation ponds, overflow wetlands, etc.) are effective but their function suffers during peak runoff events. Recently, new methods based on peak runoff control (PRC) have been developed for peatland drainage water protection (Kløve, 2000; Marttila & Kløve, 2009, 2010b; Marttila *et al*. 2010b). As flashiness and peak runoff control sediment entrainment and transport from drained peatland areas, water quality management should include peak runoff management.

Installation of structures controlling peak runoff (PRC method) is considered a useful and cost-effective method. These structures store storm runoff waters temporarily in the ditch system and provide a retention time for eroded sediment to settle to the ditch bed and drainage network. The PRC method has been successfully used at peat harvesting sites (Kløve, 2000; Marttila & Kløve, 2009), for peat forest drainage in temperate environments (Amatya *et al*., 2003) and in boreal peatland forestry conditions (Marttila & Kløve, 2010b; Marttila *et al*., 2010b). Recently, erosion prediction methods have also been developed (Leinonen, 2009).

Sediment transport from drainage areas can also be managed in small natural forest brooks, which may have been silted with inorganic or organic sediment. Sediment transport in these altered headwaters can be controlled by restoring natural fluvial processes. Management of water pathways and discharges, especially peak flows, has been observed to effectively influence sediment transport mechanisms. Addition of essential large woody debris to the channel (Tammela *et al*., 2009) and removal of the excess sediment material to the natural flood plains (Marttila *et al*., 2010a) have been found to be effective and simple sediment management methods in headwater areas.

CONCLUSIONS

New information on sediment erosion and transport processes in drained peatland areas can help to improve water quality control in these areas. Direct erosion and transporting forces result from intensive storm flows, which erode material from the soil surface in peat mining areas or from the drainage channel base and side walls in peatland forestry areas. In-channel processes are important for both peatland uses, since the drainage network often constitutes temporary inter-storm storage for eroding and transporting material. Therefore, controlling these processes is a key to effective water quality management, which can be achieved using the PRC method in drainage areas or by utilisation of natural fluvial processes in natural channels downstream.

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