Impacts of peatland drainage on the properties of typical water flow paths determined from a digital elevation model

Timo Korkalainen, Ari Laurén, Harri Koivusalo and Teemu Kokkonen

ABSTRACT

Peatland drainage enhances tree growth, changes catchment hydrology and increases export of nutrients and suspended solids to water bodies. In this study, impacts of peatland drainage on the properties of water flow paths in terrestrial parts of catchments were assessed in terms of slope, elevation, length and soil type. Three study catchments (area 31.8–153.5 km^2) were delineated using a 25 m × 25 m digital elevation model (DEM). Typical water flow paths were calculated for each catchment to characterize the mean elevation above the receiving water body as a function of distance along water flow paths. The resulting two-dimensional (2D) profile also allowed calculations of horizontally distributed properties of catchments as a function of distance to the water body. Peatland drainage decreased the length and elevation of the typical water flow path, and increased the area near water bodies. Increasing drainage from 10.7% to 55.4% of the total catchment area increased the area residing close to a water body (no farther than 25 m) from 17.1% to 60.7%. This area estimate is useful for assessing the costs of water protection, arising from restricting forestry operations in the vicinity of water bodies.

Key words | catchment, DEM, GIS, peatland drainage, water flow path

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INTRODUCTION

Drainage has been a major anthropogenic change in peatland hydrology in Finland; 53% of 8.9 million ha of peatlands has been drained for forestry (Virtanen *et al.* 2003). Drainage ditches in peatlands have a remarkable impact on water resources at the national scale. The total length of ditches is ~1,300,000 km (Finnish Statistical Yearbook of Forestry 2006), while the length of rivers is ~53,000 km and the length of lake shoreline is ~215,000 km (Kuusisto 2004).

The average peat depth in Finnish peatlands is approximately 1.4 m. *Sphagnum* peats account for 54%, *Carex* peats for 45% and *Bryales* peats for 1% of peatlands (Virtanen *et al.* 2003). Because soil conditions in peatlands do not sustain forest growth (Prévost *et al.* 1999), drainage is a prerequisite for a successful forest production in peatlands (Huikari 1952; Heikurainen 1959). Drainage of peatlands has increased the annual forest growth in Finland by ~24 million m^3 (Tomppo 2005). Along with enhancing tree growth, peatland drainage has environmental impacts such as changes in the hydrological behaviour of catchments, increasing concentrations of suspended sediments (Prévost *et al.* 1999; Nieminen *et al.* 2005) and increasing transport of nutrients (Cirmo & McDonnell 1997; Ahtiainen & Huttunen 1999).

Robinson (1990) and Åström *et al.* (2005) found that the impact of drainage on runoff depends on soil type, ditch network characteristics, location of land use changes in relation to the catchment outlet and hydrometeorological conditions. According to Nieminen & Ahti (2000), drainage increases spring runoff and flooding after heavy rains during summer. Prévost *et al.* (1999) and Robinson *et al.* (2003) also noticed that drainage sustains summer low flows and increases the nutrient content of peat soil water. Robinson

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et al. (2003) reported significant increase in peak flows after drainage in the early stages of the forest cycle, and that the effects of drainage may last for ten years or even longer. Archer (2003) also showed that changes caused by drainage could be detected as flow pulses in a small catchment (1.5 km^2), whereas in a larger catchment (335 km^2) the changes were less observable. Again, Robinson *et al.* (2003) found reductions of 10–20% in peak flows after forest canopy had become established. The experimental sites of Robinson (1990), Archer (2003) and Robinson *et al.* (2003) were situated on the Atlantic fringe where both precipitation and winter temperatures are rather high and snow is relatively infrequent leading to active rainfall runoff response throughout the year. The climatic and hydrological conditions on the Atlantic fringe differ remarkably from those in Finland, and these differences result in different patterns of sediment and nutrient transport.

Peatland drainage lowers the level of water table (Cirmo & McDonnell 1997), improves aeration in soil (Watters & Stanley 2007), increases pH and maximum temperatures in soil (Prévost *et al.* 1999) and increases the number of soil animals that indicate conditions for a more efficient organic matter decomposition and nutrient cycling (Silvan *et al.* 2000). Prévost *et al.* (1999) found rising concentrations of minerals N, Ca, Mg, Na and S in soil water after drainage. Drainage results in peat subsidence and increases leaching of mineral nutrients to the receiving water body (Cirmo & McDonnell 1997; Prévost *et al.* 1999; Åström *et al.* 2005). Åström *et al.* (2005), however, found that drainage may decrease leaching of dissolved organic N and C.

The transport of nutrients from the terrestrial part of the catchment to the receiving water body is controlled by the flow path of water, because different biogeochemical processes control nutrients in different flow domains, such as soil surface, root zone, deep peat layers and macropores. Drainage changes the internal arrangement of catchment properties by increasing the share of area close to water bodies, which include all ditches, streams and lakes. Drainage brings each point in a catchment closer to a water body and decreases the average length of the water flow path in a terrestrial system. Construction of a ditch network also alters the natural continuum of water flow paths. The shorter water flow path results in a shorter residence time of water and decreases the buffering capacity of a catchment, which increases nutrient leaching from upland areas to the water body (Cirmo & McDonnell 1997). When the nutrient load has entered ditches, means for controlling the load are scarce since the water and nutrient flow is considerably faster in ditches than in the terrestrial system.

The ditches and their close surroundings in the peatlands form an important interface between land and water. Ditched areas can be seen as environmental transition zones where rapid changes in the water table and flow occur during rainfall events (Cirmo & McDonnell 1997). Transition interfaces form riparian zones close to narrow ditches hosting a heterogeneous plant composition. Plant composition changes both in space and time and the riparian habitat may even be lost as a result of changes in the water table level (Baird *et al.* 2005). Riparian areas play a critical role in determining the transport of N from upland areas to the water body (Cirmo & McDonnell 1997).

Even although impacts of peatland drainage have been studied from the perspectives of forest growth (Sarkkola *et al.* 2004), hydrology (Archer 2003; Jutras & Plamondon 2005) and water protection (Nieminen & Ahti 2000), studies concerning the impacts of drainage on the properties of water flow paths within catchments have so far not been documented. Drainage changes catchment hydrology by disturbing the natural pathway of water from the water divide to the receiving water body. The motivation of this work is to study how peatland drainage changes water flow path properties in terms of slope, elevation, length and share of mineral soil and peatland using the concept of a two-dimensional (2D) typical water flow path. It is hypothesized that, even at low drainage intensities, the drainage has a major impact on water flow paths.

THE STUDY SITES

Mujejärvi catchment

Mujejärvi catchment is a third-order catchment that is situated in eastern Finland (Figure 1) and belongs to the major drainage basin of Pielinen (Ekholm 1993). The area of the catchment is 111.0 km^2, elevation ranges from 197.0 m to 295.0 m a.s.l. and the mean elevation is 225.6 m.

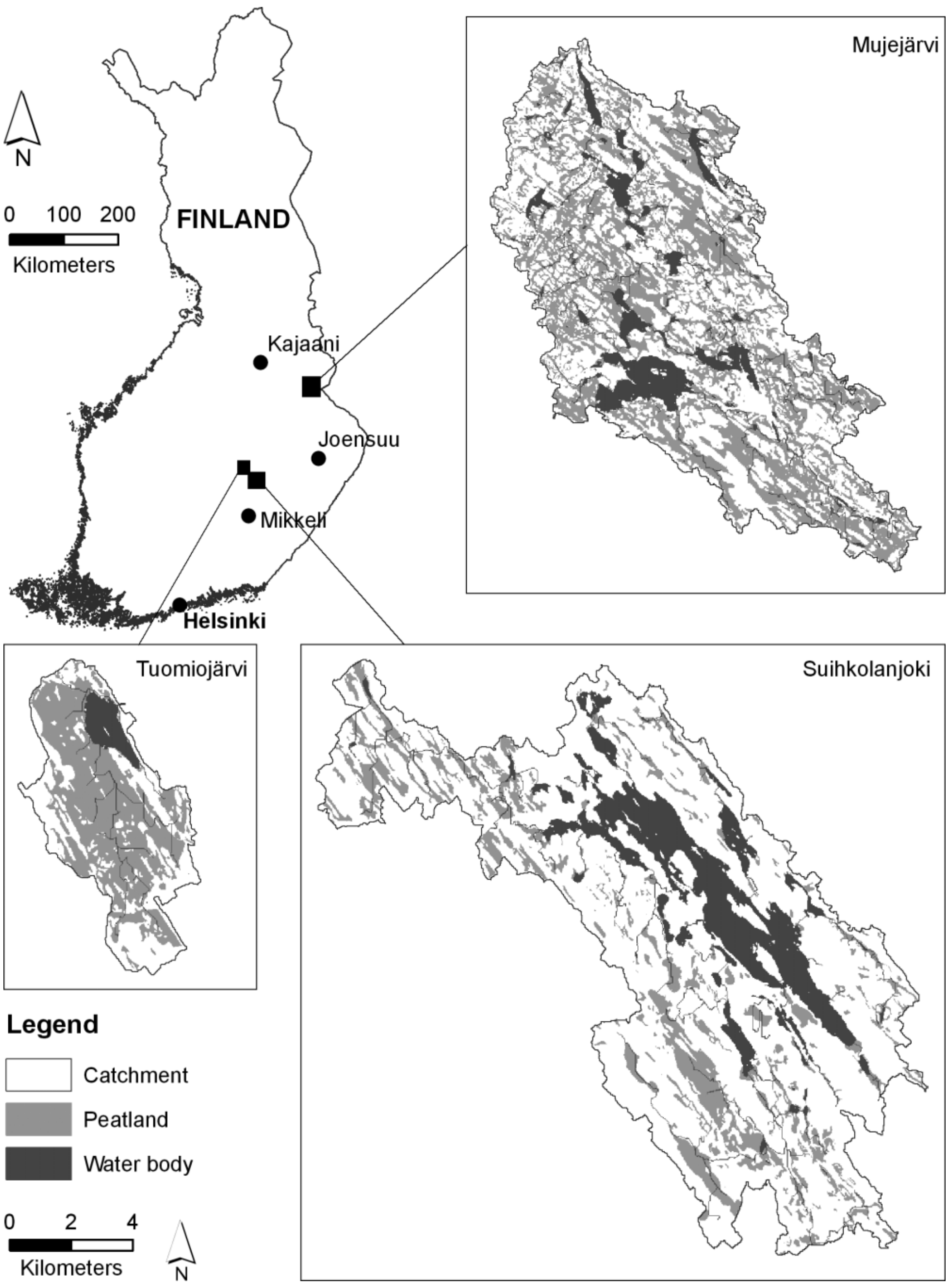

Figure 1 | Locations of the studied catchments in eastern Finland.

The maximum slope gradient is 24.7° and the mean gradient is 2.3°. Mineral soils cover 48.5% and peatlands 42.0% of the total area. The majority of the peatlands were drained for forestry during the period from the 1950s to 1970s (Table 1). A forest inventory was not compiled for this study, but according to the Finnish Statistical Yearbook of Forestry (2006) the mean growing stock is ~105 m^3/ha in this area and the forest growth is ~4.7 m^3/ha/year. Most common tree species are Scots pine and Norway spruce.

Bedrock consists mainly of granites and amphibolites (Virkkala 1949). The most common soil type is till that covers a drumlin field located within the catchment. Mean orientation of the drumlins is 140° (southeast). Sand and gravel formations are found in the middle and south-eastern

Table 1 | Land use distribution of the studied catchments

					Peatland		
Catchment		**Total area**	**Water bodies**	**Mineral soil**	**Undrained**	**Drained**	**Other land use**
Mujejärvi	km^2	111.0	9.7	53.8	6.3	40.3	0.9
	%	100	8.7	48.5	5.7	36.3	0.8
Suihkolanjoki	km^2	153.5	21.0	107.6	7.7	16.4	0.8
	%	100	13.7	70.1	5.0	10.7	0.5
Tuomiojärvi	km^2	31.8	2.0	11.9	0.3	17.6	0.0
	%	100	6.3	37.4	0.9	55.4	0.0

parts of the study area as esker formations. The main land use type in the study area is forestry, but there are also large forest areas in the natural state and ponds. The Mujejärvi catchment belongs to the middle-boreal climatic zone and Maanselkä climatic region (Solantie 1990).

Mean annual temperature is +1.5°C, the coldest month is January (mean temperature −11.4°C), and the warmest month is July (+15.7°C). Mean annual precipitation is 606 mm and mean relative humidity is 68%. The study area is covered with snow for six months every year; in April, the mean snow depth is 44 cm. Weather data (1971–2000) is collected at the Kuhmo weather station about 30 km north of the Mujejärvi catchment (Drebs *et al.* 2002).

Suihkolanjoki catchment

Suihkolanjoki catchment (153.5 km^2) is situated in central Finland (Figure 1). Elevation ranges from 90.0 m to 170.0 m a.s.l. and the mean elevation is 115.9 m. The maximum slope gradient is 27.3° and the mean gradient is 2.0°. Mineral soils cover 70.1% and peatlands 15.7% of the total area (Table 1). Peatlands in this area were drained from the 1950s to 1970s (Table 1). A forest inventory was not compiled for this study, but according to the Finnish Statistical Yearbook of Forestry (2006) the mean growing stock is ~138 m^3/ha in this area and the forest growth is ~5.9 m^3/ha/year. Most common tree species are Scots pine and Norway spruce.

Bedrock consists of a complex mixture of granites, gneisses, granodiorites and quartz diorites (Simonen 1987). The soil in the study area is mainly glacigenic thick basal till. The study area includes a drumlin field (Korkalainen *et al.* 2007) that belongs to the Pieksämäki drumlin complex and is one of the largest drumlin fields in Fennoscandia. Overall, the Pieksämäki drumlin complex consists of about 11,000 drumlins (Glückert 1973). Mean orientation of the drumlins in the study area is 122° (southeast). The study area belongs to the southern boreal climatic zone (Solantie 1990). The mean annual temperature in the region is +3.4°C, the coldest months are January and February (mean temperature −8.3°C) and the warmest month is July (+16.3°C). Mean annual precipitation is 611 mm and mean relative humidity is 71%. The study area is covered with snow from five to six months every year; in April the mean snow depth is 19 cm. Weather data (1971–2000) is collected at the Mikkeli weather station about 60 km south of Suihkolanjoki catchment (Drebs *et al.* 2002).

Tuomiojärvi catchment

Tuomiojärvi catchment (31.8 km^2) is situated north of Suihkolanjoki catchment (Figure 1). Elevation ranges from 100.3 m to 160.0 m a.s.l. and the mean elevation is 115.2 m. The maximum slope gradient is 15.9° and the mean gradient is 0.8°. Mineral soils cover 37.4% and peatlands 56.3% of the total area. Almost all peatlands are drained for forestry (Table 1). Drainage times, forest growth and bedrock and soil properties as well as climatic conditions are similar to Suihkolanjoki catchment.

CATCHMENT DELINEATION

The catchments (Figure 1) were delineated using a 25 m × 25 m filled digital elevation model (DEM). Using a filled grid, local depressions in topography were avoided. Based on the DEM, flow direction was calculated for each cell according to the direction of the steepest descent (D8 method) (Jenson & Domingue 1988; Oksanen & Sarjakoski 2005; Sørensen *et al.* 2006). Information about the flow direction allowed the computation of flow accumulation (or an upslope area) grid that shows how large an area drains through each cell (Sørensen *et al.* 2006). Based on the flow accumulation information, a stream network was delineated by using a flow accumulation threshold value that reproduced the location and extent of the natural brooks and streams in the basic map (1:20,000 scale). Water body locations were compiled by merging the stream network identified from the DEM with the information available from the 1:20,000 scale map (Korkalainen *et al.* 2007). Finally, catchments upslope from the stream gauge locations were delineated.

Properties of typical water flow paths

The catchments were characterized by using a concept of a typical water flow path that forms a longitudinal section (hillslope) from a water divide to the receiving water body. This two-dimensional description allows calculations of horizontally distributed properties of catchments as a function of distance to the water body. The properties of the typical water flow path included length, surface slope, relative width and soil type (mineral soil and peatland). In this study, all three catchments were described with a single typical water flow path (Koivusalo *et al.* 2006).

The typical water flow path was calculated by using a raster-based DEM, catchment boundary and water body masks. The distance along the water flow path from all DEM raster cells to the receiving water body was computed by following the water flow path (i.e. steepest path) until the path intersected a water body cell. The distance and the elevation difference between each start cell and its receiving water body cell were recorded. The elevation data was categorized into 25 m distance intervals, and for each interval the mean elevation was computed. For class variables such as soil types, average values at distance intervals cannot be computed. Thus, the prevalence of the soil types were recorded at a given distance interval from a water body. The soil data used in this study was a raster-based dataset at a scale of 1:20,000. The length of the typical water flow path was cut-off at the distance where 95% of the catchment area was covered. Only a few individual water flow paths

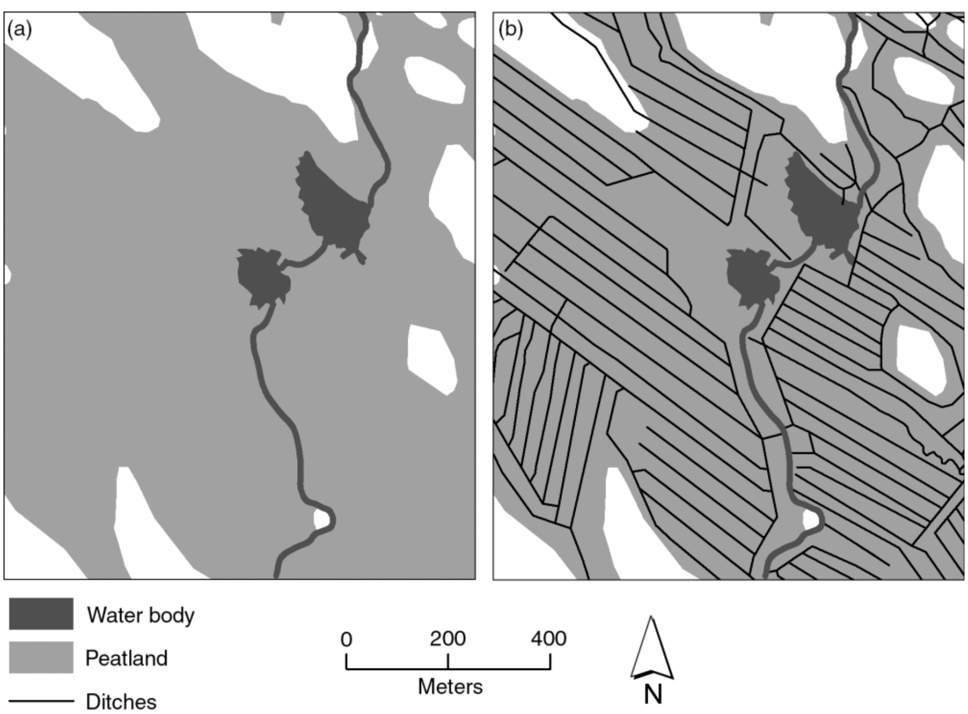

Figure 2 | (a) Unditched (= estimated) and (b) ditched (= present) peatland conditions at Mujejärvi catchment.

contribute to the remaining 5% of the catchment area, and therefore the number of cells decreases in the sections near the upslope end of the water flow path. Computing average elevation from a small number of cells results in unrealistic elevation fluctuations at the tail of the water flow path.

A two-dimensional catchment description can account for convergent or divergent topography within catchments by means of a width function (Shreve 1969). The width function describes how large a proportion of a catchment area resides in a given distance interval. It was identified by counting the number of cells residing at each distance interval along the typical water flow path. The distribution of mineral soil and peatland areas along the typical water flow path were assigned based on the spatial distribution of these two soil types at a given distance from the water body. It was determined by counting cells that fall within mineral soil and peatland masks.

Properties of the typical water flow paths were analysed first by neglecting the ditches in peatlands. This resulted in an undrained schema. Second, water flow paths were determined with the ditches, whose locations were available from the 1:20,000 maps. This resulted in a drained schema (Figure 2).

RESULTS AND DISCUSSION

In the undrained schema, the maximum elevation of the typical water flow path was 20.2 m at a distance of 1125 m at Mujejärvi catchment (Figure 3(a)), 15.6 m at a distance of 1,400 m at Suihkolanjoki (Figure 3(b)) and 17.1 m at a distance of 2,150 m at Tuomiojärvi (Figure 3(c)). In the undrained schema, 50% of the catchment area was closer than 350 m from the water body at Mujejärvi, 425 m at Suihkolanjoki and 700 m at Tuomiojärvi. Draining decreased the maximum elevation of the typical water flow path at Mujejärvi and Tuomiojärvi, whereas at Suihkolanjoki the change was minor (Figure 3(a–c)). Drainage obviously decreased the distance to a water body; in the drained schema, 50% of the catchment area was closer than 50 m from the water body at Mujejärvi, 200 m at Suihkolanjoki and 25 m at Tuomiojärvi.

In the undrained schema, the share of the catchment area decreased evenly with an increasing distance from

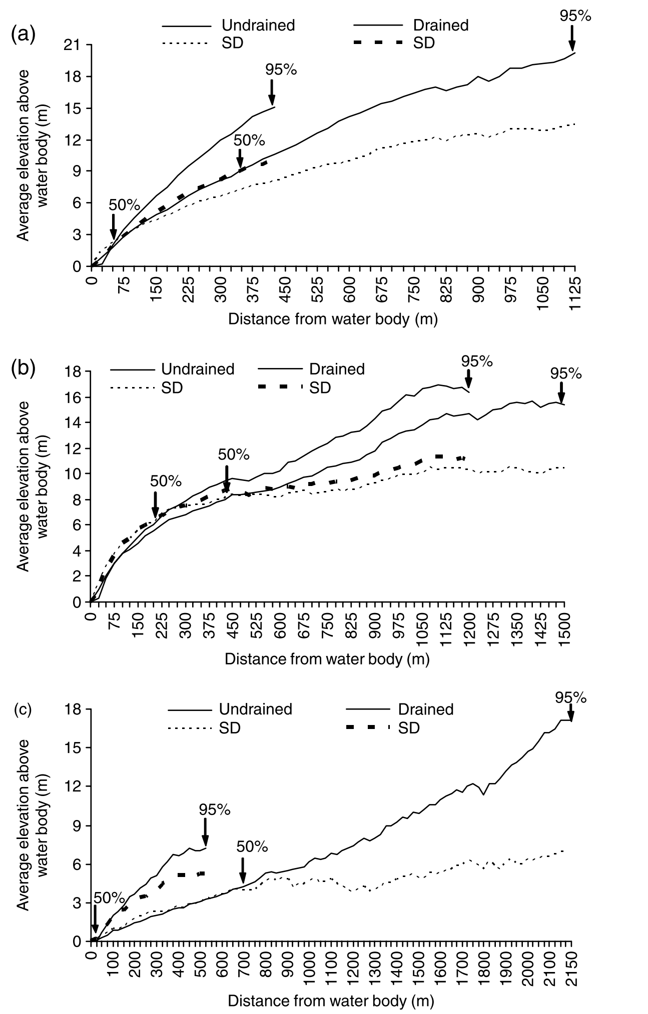

Figure 3 | The typical water flow paths of (a) Mujejärvi, (b) Suihkolanjoki and (c) Tuomiojärvi catchments in undrained and drained schemas. Average elevations are shown in 25 m distance intervals along the typical water flow path. Numbers show proportions (50% and 95%) of the catchment area located closer to a water body than the distance at the arrow tip (SD: standard deviation of the typical water flow paths).

the water body (Figures 4(a–c)). On average, 4.1% of the catchment area at Mujejärvi, 3.8% at Suihkolanjoki and 1.4% at Tuomiojärvi was no farther than 25 m from a water body. With drainage, the area close to a water body increased drastically: at Mujejärvi, Suihkolanjoki and Tuomiojärvi, 40.0%, 17.1% and 60.7%, respectively of the catchment area was closer than 25 m from a water body.

In the undrained schema, peatlands were distributed along the water flow path (Figures 5(a)–7(a)). After drainage, almost all peatlands were concentrated next to the receiving water body (Figures 5(b)–7(b)). At Mujejärvi

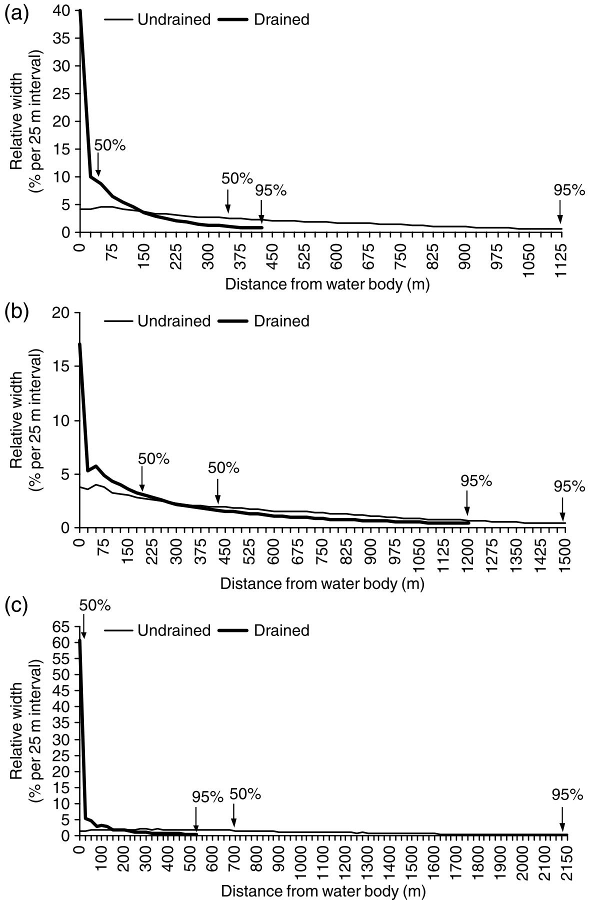

Figure 4 | Relative widths of the profiles at (a) Mujejärvi, (b) Suihkolanjoki and (c) Tuomiojärvi catchments in undrained and drained schemas. Width distribution refers to percentage of total catchment area and is shown as a function of distance along the typical water flow path in 25 m distance intervals. Numbers show proportions (50% and 95%) of the catchment area located closer to a water body than the distance at the arrow tip.

87.1%, at Suihkolanjoki 75.4%, and at Tuomiojärvi 98.9% of peatlands was no farther than 25 m from the water body.

Koivusalo *et al.* (2006) found a substantial variation of flow path elevations within head-water catchments (0.56 km^2 and 0.24 km^2) in eastern Finland indicating that the water flow path can be very different in various parts of the catchment. However, increasing the size of the catchment to third-order catchments (69.1 km^2) does not drastically increase the variation in the flow path elevation (Korkalainen *et al.* 2007). Therefore, the scale of this analysis did not restrict the applicability of the water flow path method with respect to previous studies (Laurén *et al.* 2005; Koivusalo *et al.* 2006; Kokkonen *et al.* 2006; Laurén *et al.* 2007).

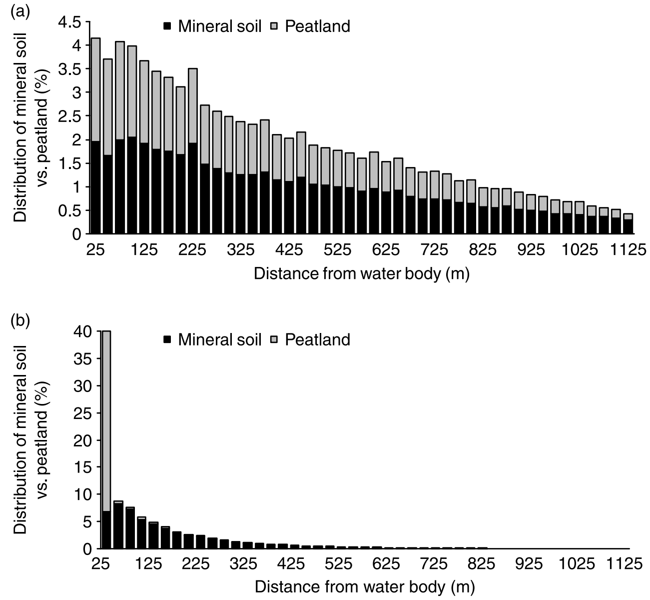

Figure 5 | Width distribution and fractions of mineral soil versus peatland at Mujejärvi catchment for (a) undrained and (b) drained schemas. Fractions are shown as a function of distance along the typical water flow path in 25 m distance intervals.

Although drainage was found to clearly change the profile geometry and increase the area close to water bodies, some uncertainties exist in the calculations. This study is based on comparison between the existing drained schema

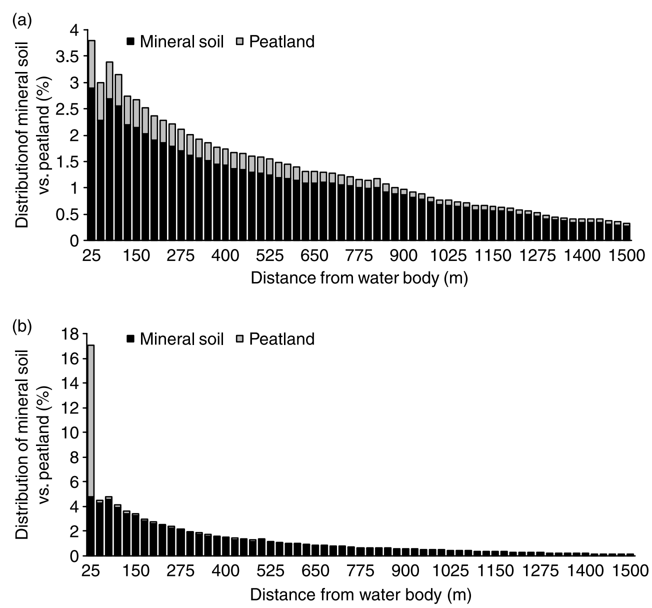

Figure 6 | Width distribution and fractions of mineral soil versus peatland at Suihkolanjoki catchment for (a) undrained and (b) drained schemas. Fractions are shown as a function of distance along the typical water flow path in 25 m distance intervals.

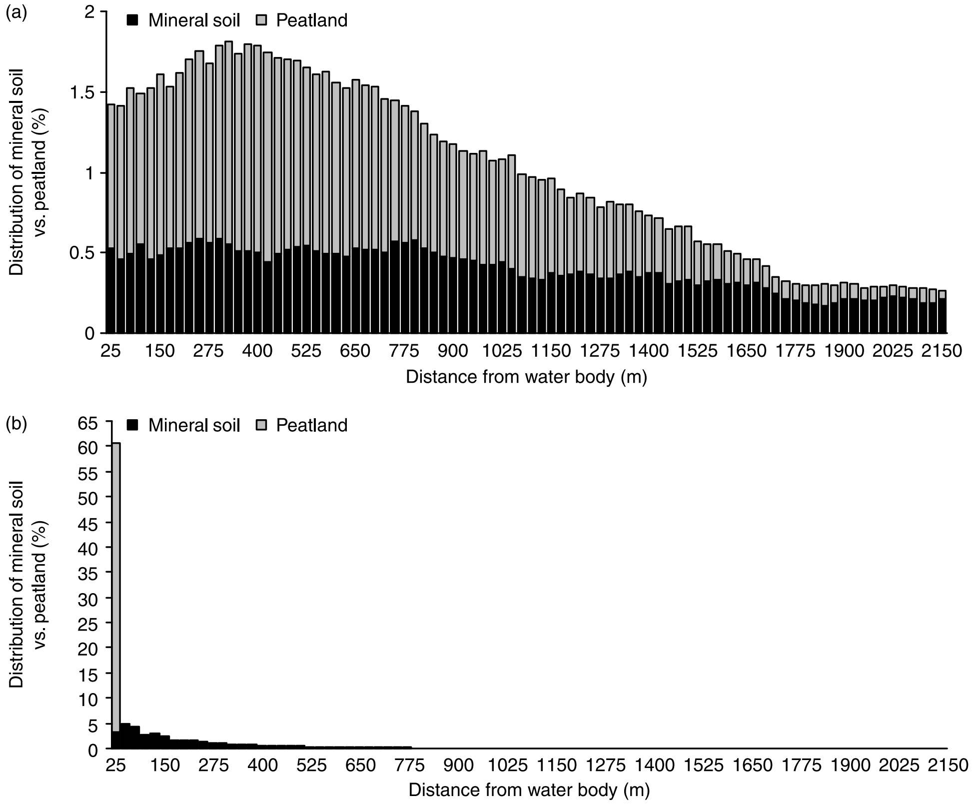

Figure 7 | Width distribution and fractions of mineral soil versus peatland at Tuomiojärvi catchment for (a) undrained and (b) drained schemas. Fractions are shown as a function of distance along the typical water flow path in 25 m distance intervals.

and the reconstructed undrained schema in peatlands. None of the mineral soil was drained. It is challenging to produce accurate locations of the brooks in the undrained schema, because drainage has removed the natural channels in peatlands. The real change caused by the drainage may therefore differ from the calculated one.

The brooks were delineated from a DEM using a threshold value for flow accumulation. This analysis resulted in an approximate location of natural brooks and streams, which were compared with the existing natural channel network available from the 1:20,000 maps. The DEM was the most important data in this study, because it determines topography of the studied catchments. The resolution of the DEM (25 m) may have been too coarse for a detailed description of water flow paths, especially in flat areas near the water bodies. The DEM accuracy is dependent upon the spatial resolution of the height data. It is therefore possible that some elevations and slope gradients of the studied catchments or the topography of typical water flow paths may be inaccurate. In addition, the DEM is likely to contain imprecision that results from inhomogeneous source data (*Valtakunnallisen korkeusmallin uudistamistarpeet -ja vaihtoehdot* 2006). However, drainage changed typical water flow path properties so remarkably that uncertainties in the analysis are not likely to change the implications of this study.

At Suihkolanjoki catchment, proportion of mineral soil was the greatest (70.1%) compared to other catchments (48.5% and 37.4%). Therefore, the drainage did not change the typical water flow path to same extent as at Tuomiojärvi and Mujejärvi catchments. However, changes in the properties of typical water flow paths caused by drainage were also remarkable at Suihkolanjoki catchment where only 10.7% of the catchment area was drained (Table 1). Drainage has been found to increase nutrient loads to water bodies (Ahtiainen & Huttunen 1999). This may be partly attributed to the drastically increased catchment area close to water bodies demonstrated in this study. A shorter water flow path within a catchment results in a shorter residence time of water and decreases the buffering capacity of a catchment (Cirmo & McDonnell 1997). Total load to watercourses increases, because after the nutrient load has entered ditches, means for controlling the load are scarce. It is possible, however, to lead the water from ditches to a peatland buffer area, which can reduce the nutrient loading (Silvan *et al.* 2004). On the other hand, the ditches around peatlands should probably require buffer zones in the mineral soil part of the catchment.

Although the ditches may remain in place, their impact on runoff, sediment and nutrient transport is likely to decrease as the forest matures and the drains are eventually shaded and drains begin to in-fill (Robinson *et al.* 2003). Hökkä *et al.* (2000) also found that the long-term effect of drainage can be seen as decreased runoff that results from improved tree growth and increased evapotranspiration.

CONCLUSIONS

The concept of a typical water flow path provides a new perspective for assessing the implications of drainage at catchment scale by using geospatial analysis tools. Construction of drainage ditches in peatlands was found to have a strong control on the properties of the typical water flow paths in the studied catchments. Drainage substantially shortened the water flow paths and increased the fraction of area near water bodies. Although simplification of the 3D catchment into a 2D typical water flow path leads to a loss of information, the simplification preserves valuable information about the spatial distribution of factors controlling runoff water quality.

Two key controlling factors are soil properties around water bodies, and the fraction of catchment area directly connected to water bodies. The results of this study can be utilized in calculating the impacts of forest management practices on runoff water quality by using hydrological and water quality models based on the 2D catchment representation (Karvonen *et al.* 1999; Laurén *et al.* 2005; Koivusalo *et al.* 2006; Kokkonen *et al.* 2006). It is also possible to estimate the fraction of a catchment area situated at a certain distance along the water flow path from a water body. This area estimate could be used when estimating water protection costs arising from restricting forestry operations in the vicinity of water bodies.

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