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A GIS-based analysis of catchment properties within a drumlin field

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When considering water protection, the spatial distribution of catchment properties is relevant, since the areas adjoining the water body contribute more to water quality than the remote areas near the water divide. This study presents an approach to describe catchments spatially; two-dimensional descriptions allow calculations of horizontally distributed properties of catchments as a function of distance to the water body by using the concept of the typical water flow path. The study area, situated in a drumlin field in central Finland, included 14 third-order catchments that were further divided into 782 head-water catchments using a 25 m × 25 m digital elevation model. For each head-water catchment, a typical water flow path with slope, elevation, length, relative width, and soil type was calculated. The flow path geometry was diverging towards the water body and there was a 25 m section with a gentle slope adjacent to the water body followed by a steeper slope. Mineral soils dominated throughout the typical water flow path. On the basis of the results, we proposed characteristics for an average head-water catchment with the following properties: area 109.1 ha and length of the water flow path 954 m with maximum elevation 11.5 m. The peatlands were concentrated within a distance of 50 m to the water body; the rest consisted of mineral soil. The results can be utilized, for example, in calculating the impacts of forest management practices on the quality of runoff water. The results offer a baseline for evaluating how typical previously studied catchments are in relation to larger catchment populations. They also enable a regional estimate of the distribution of the relative proportion of areas situated along the water flow path.

Introduction

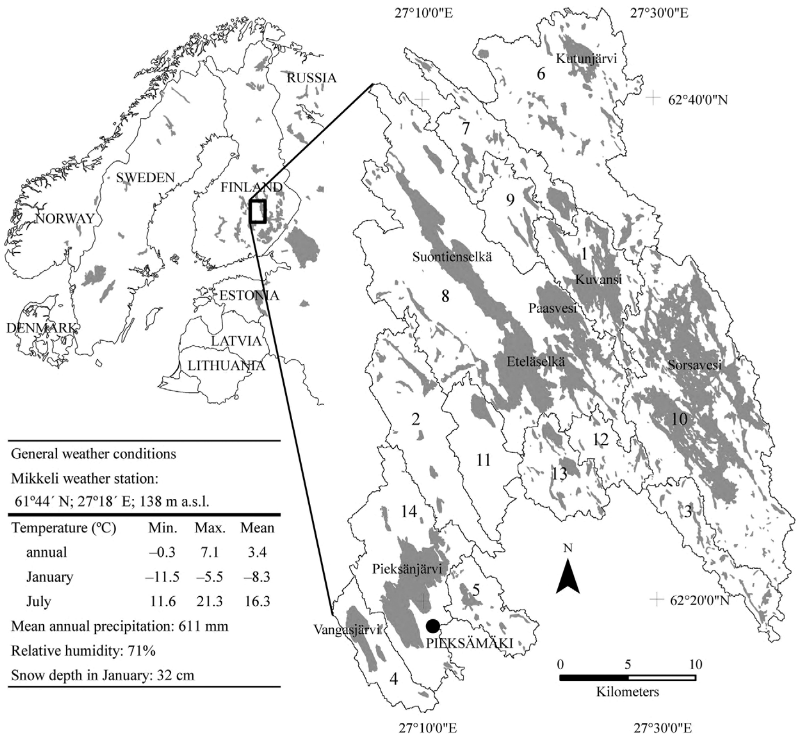
The EU's Water Framework Directive obliges maintaining a "high status" of waters, preventing any deterioration in existing waters, and achieving at least a "good status" of all waters by the year 2015. This requires extensive water resources management and the controlling of point and non-point source loading of nutrients, especially of nitrogen (N) and phosphorous (P). In water resources management, catchments form basic functional areas (Tikkanen 1989, Crave and Gascuel-Odoux 1997). Catchment hydrology, influenced by interactions of meteorological phenomena, vegetation, topography, and soil, controls the quantity and quality of runoff (Mackay and Band 1997, Brown *et al.* 1999, Beven 2000, Ko and Cheng 2004, Kokkonen *et al.* 2006). Topography in particular has been found to control catchment-scale water transport rather than the catchment area itself (McGuire *et al.* 2005). Thus, catchment properties affect also nutrient export, especially from non-point sources such as agriculture and forestry. On a national level, agriculture is the main source of N and P in Finland, but at a local level, forestry may be more significant with regard to head-water catchments (Leivonen 2006).

Catchment properties, such as topography, soil material, and catchment area, are influenced by landforms and geomorphology (Beven 2000). Drumlins, which are one of the most common types of landforms in Finland (Fogelberg and Seppälä 1986), are formed of glacial material consisting mainly of thick basal till (Tikkanen 1989). Drumlins usually contain a bedrock core, which typically lies on the proximal side of the drumlin ridge, and a long tail on the distal side consisting of basal till. The sediment layer blanketing the bedrock core is usually thin, and sometimes, the bedrock is exposed (Glückert 1973, Tikkanen 1989, Hättestrand *et al.* 2004). Steep slopes are mainly situated on the proximal side of drumlins. According to topographical and geomorphological maps (e.g. Fogelberg and Seppälä 1986, Tikkanen 1989), peatlands situated between the elongated drumlin hillocks also characterize the terrain in a drumlin field. The till cover is also susceptible to peat formation (Virtanen *et al.* 2003). The most frequent type of peatland in central Finland is the pine bog (over 50% of peatlands), and the average depth of peat layer is approximately 1.5 m (Virtanen *et al.* 2003). Peat may retain some nutrients, but it is also a source of organically bound nutrients (Kaunisto and Paavilainen 1988).

Soil, bedrock and topographical factors control the distribution of the water flow into surface and sub-surface reservoirs (Beven 2000, Sørensen *et al.* 2006). Subsurface water reacts with the soil matrix, with microbiota, and with vegetation and thus usually contains fewer nutrients than the surface water does (McDowell *et al.* 2001). Steep slopes with fine soils may decrease soil infiltration (Viessman *et al.* 1989, Black 1991, Ko and Cheng 2004) and thus generate surface runoff, which may also increase erosion (Reddy *et al.* 2004). Fine soils typically have also a lower hydraulic conductivity than coarse soils, which results in a slower subsurface flow that facilitates soil saturation. Thus, the presence of fine soils may increase the share of surface runoff from the catchment. If a catchment's topography is convergent towards the water body, subsurface water may exfiltrate onto the soil if the latter does not contain enough free pore space (e.g. Brown *et al.* 1999). If the topography is divergent, however, the flowing water is distributed over a much larger area, decreasing the surface runoff. Crave and Gascuel-Odoux (1997) and McGuire *et al.* (2005) found that the topography controls the spatial distribution of surface water content and of water flow path geometry.

The flow path of water is also an essential factor that controls the quality of runoff water, for during the transport, different biogeochemical processes may control the amount and form of nutrients in the water (Devito *et al.* 1999, Jacks and Norrström 2004). For example, preserving uncut buffer zones between a clear-cut area and the receiving water body is based on the idea that nutrient retention by microbes, vegetation, and soil occurs along the water flow path within the buffer zone area. Buffer zones have been shown to decrease the nutrient export to watercourses (e.g. Ahtiainen and Huttunen 1999). The water flow paths from the water divide to the receiving water body provide information regarding the internal arrangement of catchment properties (McGuire *et al.* 2005, Bogaart and Troch 2006).

In Finland, the latest catchment classification was published in 1993 by the Water and Environment Administration (Ekholm 1993). This classification divided 74 first-order catchments into three hierarchical levels, resulting in a total of 6000 third-order catchments. The effects of forest management practices on runoff quality have been extensively studied in forested head-water catchments (e.g. Finér *et al.* 1997, Ahtiainen and Huttunen 1999, Mattsson *et al.* 2003), which are considerably smaller than the third-order catchments in the classification referred to above. To facilitate the generalization of the results from head-water catchments and



General weather conditions
Mikkeli weather station:
61°44´ N; 27°18´ E; 138 m a.s.l.

Temperature (°C)	Min.	Max.	Mean
annual	–0.3	7.1	3.4
January	–11.5	–5.5	–8.3
July	11.6	21.3	16.3

Mean annual precipitation: 611 mm
Relative humidity: 71%
Snow depth in January: 32 cm

Fig. 1. Location of the study area within northern Europe and a detailed map including information about the weather conditions between 1971 and 2000.

allow their application to larger areas, we need to know how well they represent the "average" head-water catchment of larger areas. Furthermore, as the water flow path within a catchment has an impact on runoff quality, information on the characteristics of the catchment along the water flow path needs to be provided. Computational tools that operate at head-water catchment scale and are based on the idea of typical water flow paths have been developed to predict runoff and N dynamics (Karvonen *et al*. 1999, Laurén *et al*. 2005, Koivusalo *et al*. 2006, Kokkonen *et al*. 2006). If the characteristics of a typical water flow path are known, these tools can be used to upscale a head-water catchment so as to apply the results to larger areas.

The aim of this paper are: (1) to characterize head-water catchments by describing typical water flow paths from the water divide to the receiving water body in terms of slope, elevation, and length, (2) to describe the share of the catchment area along a typical water flow path based on relative width analysis, (3) to identify soil types along the typical water flow path, and (4) to propose characteristics for an average catchment as based on the items listed above.

Material and methods

The study area

The study area is situated in central Finland. The studied area consisted of 14 third-order catchments and covered an area of 967.2 km^2 (Fig. 1). The study area includes a large drumlin field 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). The soil in the study area is mainly glacigenic thick basal till, but also sorted glaciofluvial sediments, such as sand and gravel formations, occur. The bedrock consists of a complex mixture of granites, gneisses, granodiorites, and quartz diorites (Simonen 1987). The study area belongs to the southern boreal climatic zone, in which coniferous forests are dominant (Solantie 1990). The mean annual temperature in the region is 3.4 °C and precipitation is 611 mm a year. In an average year, the study area is covered by snow for five to six months; in January, the mean snow depth is 32 cm (Fig. 1). Weather data (1971–2000) were collected at the

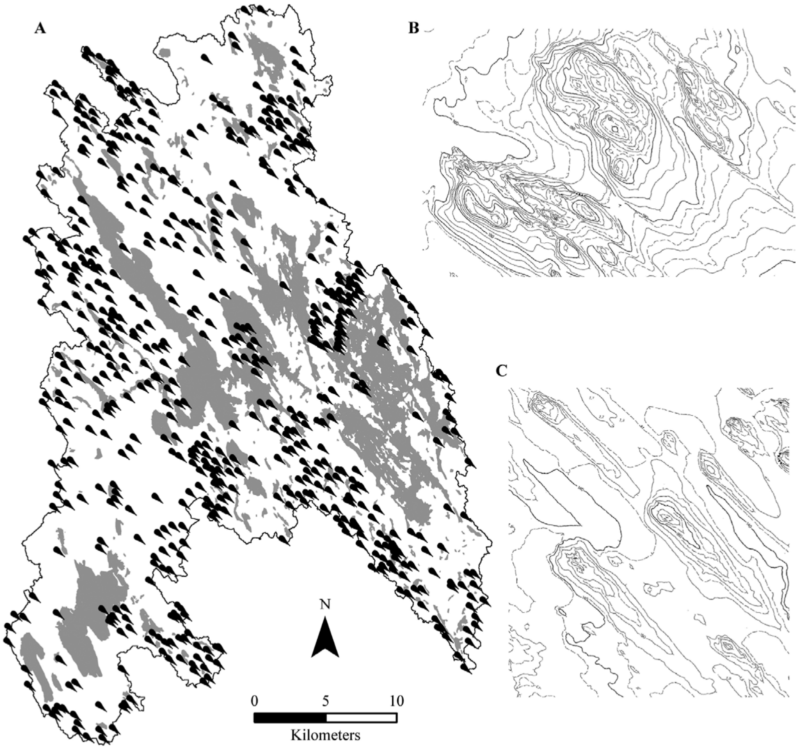


Fig. 2. (**A**) Drumlin locations in the study area, (**B**) contours of complex drumlin shields, and (**C**) typical elongated drumlins. (Contours© National Land Survey of Finland, license number PSAVO/138/2006).

Mikkeli weather station, which is situated about 40 km south of this area (Drebs *et al*. 2002).

The topography of the study area is highly variable; its elevation ranges from 98.0 m to 208.8 m (a.s.l.). The lowest elevations are situated in the Sorsavesi area, which is at the southeastern part of the study area. The highest elevations are to the east of Kuvansi Lake (Fig. 1). Throughout the entire study area, local high tops can be found in places where crag-and-tail drumlins dominate. The maximum slope gradient is 35.0°, and the mean gradient is 1.9°. The steepest slopes are at the proximal side of the drumlins, but in general, the large-scale topography of the study area is relatively flat, as everywhere in southern Finland (Tikkanen 2002).

Drumlin mapping

The drumlins in the study area were mapped by using 1:20 000 raster-based contour maps (cf. Korkalainen and Laurén 2006). Their form was analyzed with GIS-technology. We used a digital elevation model (DEM) with a 25-m pixel size to calculate hillshades, slopes, and aspects in order to identify the drumlins on the map. The geomorphological map of Finland (Fogelberg and Seppälä 1986) was also exploited. Finally, the interpretations of the drumlin landforms were digitized onto the map (Fig. 2A). The sizes and shapes of the drumlins in the study area varied substantially (Figs. 2B and 2C). Fig. 2B represents overlapping drumlin shields. The drumlins in Fig. 2C, however, were fairly typically elongated ones that lie side by side. Most of the drumlins in the study area were situated in groups (Fig. 2A).

In total, we detected 600 drumlins within our study area. The height of the drumlins varied between 1.0 m and 70.0 m, their length between 117 m and 3455 m, and their width between 59 m and 1137 m (Table 1). The form of the drumlins, i.e. their elongation ratio, can be described with a length/width (*L*/*W*) value (Jauhiainen 1975, Hättestrand *et al*. 2004); the bigger the *L*/*W*, the more tapered is the drumlin. In this study, the *L*/*W* varied between 2.0 and 15.9, and the mean *L*/*W* value was 4.2. This means that the drumlins are on average 4.2 times longer than they are wide. This *L*/*W* value is typical in Finland and Sweden (Glückert 1973, Hättestrand *et al*. 2004), but slightly higher than that in northern central Europe (Jauhiainen 1975). In the study area, the mean orientation of the drumlins was 119°, i.e. from northwest to southeast. It is thus reasonable to conceive them as having been formed under the moving ice (Glückert 1973, Aario and Forström 1979, Hättestrand *et al*. 2004).

Catchment analyses

The catchment calculations of both, third-order (Fig. 1) and head-water catchments, were based on analyses using the DEM and a basic map 1:20 000 as a raster dataset showing the locations of lakes and ponds within the study area. For the purpose of this study, water body locations were compiled by merging the stream networks identified from the DEM with the original basic map lake and pond data. We integrated ditched peatlands into the overall peat area and disregarded the effect of ditches on the water flow. The 14 third-order catchments comprising 782 head-water catchments were identified by using hydrological modeling tools (Jenson and Domingue 1988). The areas of the third-order catchments varied from 20.4 km^2 to 170.0 km^2; the average area was 69.1 km^2. The number of head-water catchments within the third-order catchments ranged from 27 to 145.

The head-water catchments of this study were categorized into four types:

Type A: Catchments of streams with no tributaries that drain into lakes or large ponds.

Type B: Catchments of lakes and large ponds that drain into a stream.

Type C: Consecutive adjacent uphill catchments in the stream channels that were delineated to comprise an area of less than 300 ha.

Type D: Remaining areas that drain directly into lakes or ponds instead of streams. These areas are "unnatural" head-water catchments that are excluded from the division of the third-order catchments into head-water catchments. These areas are formed between areas of one or more Type A head-water catchments and can be calculated: Type D = total area of the third-order catchment – area of Types A, B, and C head-water catchments.

Identification of typical water flow paths

The catchments were characterized by using the concept of the typical water flow path from the water divide to the receiving water body. The properties of the typical water flow path included length, slope, relative width, and soil type. The approach used here simplifies the three-dimensional catchment domain into two dimensions (Kokkonen *et al*. 2006). Determining the surface geometry of a typical water flow path, i.e. length and slope, is based on analyzing the DEM of a catchment. By means of the DEM, the direction of the flow was calculated for each pixel according to the direction of the steepest descent (D8 method, e.g. Jenson and Domingue 1988, Oksanen and Sarjakoski 2005b, Sørensen *et al*. 2006). Information on the flow direction allowed the computation of flow accumulation (or an upslope area) grid that shows how large an area drains through each pixel (Sørensen *et al*. 2006). Based on the location of the water bodies on the map and the information on flow accumulation, a stream network that was consistent with the DEM was delineated. Having the flow direction and the water body masks at hand, the flow paths from each grid cell within a catchment were followed until the flow paths intersected a water body.

The difference of elevation between each pixel and its receiving water body pixel was recorded. These differences were then categorized according to the distance from the water

Table 1. Summary of the morphometric characteristics of the drumlins (n = 600).

	Min.	Mean	Max.
H (m)	1.0	17.8	70.0
L (m)	117	977	3455
W (m)	59	232	1137
L/W	2.0	4.2	15.9

H = height, L = length, W = width, L/W = length/width ratio.

body along the water flow path. For class variables, such as soil types in our case, average values cannot be computed. Thus, soil type values were assigned to the characteristic profile according to their prevalence in a given distance interval from a water body. The soil data used in this study included a raster-based dataset 1:20 000 provided by the Geological Survey of Finland. Soil types along the water flow path were categorized into mineral soils, peatlands, and thin peat layers (0.4–0.9 m depth) on mineral soil. While the definition of the typical water flow path implies that catchment properties can take different values as a function of distance to a water body, all areas residing at the same distance to a water body need to be described with a single value. This easily leads to compromises in a realistic description of the spatial distribution of class variables, such as mineral soil versus peatlands (Kokkonen *et al*. 2006).

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 is identified by counting pixels as a function of water flow path distance to the water body.

Statistical analyses

The typical water flow path was divided into a number of sections, each of which represented areas in intervals of 25 m. The average value of the elevation difference in a given distance interval (within one section) determined the profile elevation above the receiving water body in that section. The relative width of the profile and the relative share of soil types were also calculated in intervals of 25 m. In this study, variations within head-water catchments and between third-order catchments were calculated with variance component analysis using the MINQUE-model (minimum norm quadratic unbiased estimation) (Lele and Taper 2002). The analyses were conducted with SPSS Statistical Analysis Software.

Results

About half of the 782 head-water catchments (50.2%) drained into streams of different sizes comprising a proportion of 27.7% of the total area (Type C). Type A comprised 39.8% of the catchments including 33.6% of the total area and Type B 10.0% of the catchments including 31.3% of the total area. However, 7.4% of the total catchment area (967.2 km^2) was classified as remaining areas (Type D) that drained directly into a lake or a pond, instead of a stream. In total, 21.1% of the study area was overlain by water bodies. Mineral soil covered 66.0% and peatlands 12.5% of the total area, while 0.4% was related to other land use types (Table 2).

The surface geometry (Fig. 3), relative width (Fig. 4), and soil type distribution (Figs. 5–7) along the average water flow path in the head-water catchments were calculated. On average, there was a 25 m section with a gentle slope that adjoined the receiving water body. The slope of the water flow path was steepest at the distance interval of 25–100 m from the water body, and thereafter, the steepness of the slope slightly decreased. When the distance to the water body was more than 100 m, variation in the water flow path geometry between the third-order catchments was rather constant. However, variance

Table 2. Land use distribution of the study area (total area 967.2 km^2).

	Water bodies	Mineral soils		Peatlands	Peat layers on mineral soil*	Other land-use types	Total
		Coarse particles	Fine particles				
Area (km^2)	204.2	623.0	15.0	97.0	24.6	3.4	967.2
Percentage	21.1	64.4	1.6	10.0	2.5	0.4	100.0

* Mineral soil with a shallow (0.4–0.9 m) overlying peat layer.

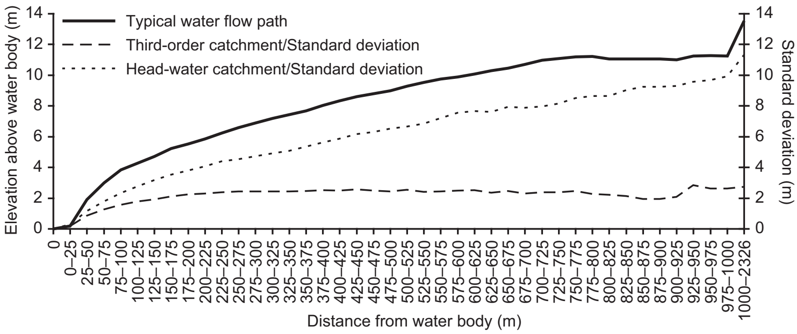


Fig. 3. The typical water flow path and standard deviations of 14 third-order and 782 head-water catchments as average values within 25-m sections along the water flow path.

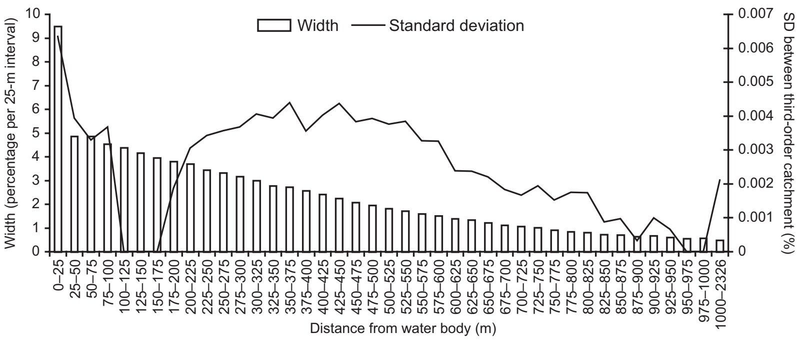


Fig. 4. Relative width of the profile as a function of distance along the water flow path as average values within 25-m sections. Standard deviations between the third-order catchments are shown.

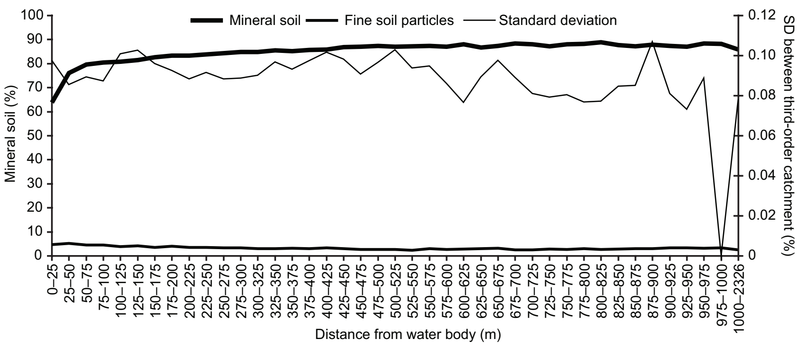


Fig. 5. Proportion of mineral soil as a function of distance along the water flow path as average values within 25-m sections. Thin line shows proportion of fine soil particles. Standard deviations of the mineral soil between the third-order catchments are shown.

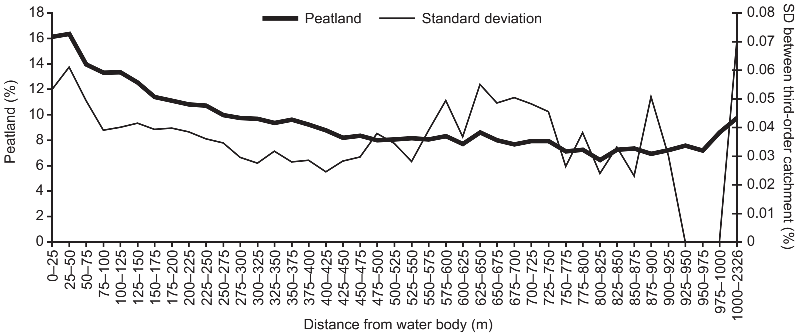


Fig. 6. Proportion of peatlands as a function of distance along the water flow path as average values within 25-m sections. Standard deviations between the third-order catchments are shown.

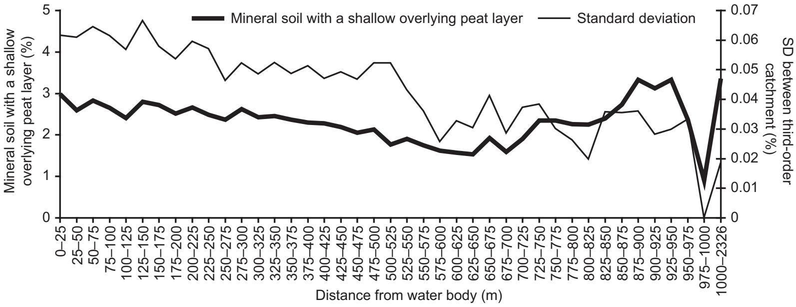


Fig. 7. Proportion of mineral soil with a shallow overlying peat layer as a function of distance along the water flow path as average values within 25-m sections. Standard deviations between the third-order catchments are shown.

within the head-water catchments increased gradually with increasing distance (Fig. 3).

A substantial area of the catchments was concentrated near the receiving water body; based on relative width analysis, an average of 9.5% of the head-water catchment area was no farther than 25 m from the water body. The share of the catchment area decreased along the water flow path with increasing distance to the water body, showing divergent hillslope characteristics (Fig. 4). The variance of the relative width between the third-order catchments fluctuated with increased distance to the waterbody.

Mineral soils dominated throughout the typical water flow path (Fig. 5) at each distance, while the peatlands represented a smaller proportion (Fig. 6). Even though the peatlands were rather evenly distributed along the water flow path, most of them were situated close to the receiving water body, where, correspondingly, the share of mineral soil was smallest. When the distributions of coarse (grain ∅ > 0.06 mm; Ht or coarser) and fine (grain ∅ < 0.06 mm; HHt or finer) mineral soils were compared, coarse mineral soil was found to appear more frequently throughout the water flow path and fine mineral soil was somewhat more frequent near the water bodies than farther away from them. The proportion of mineral soils covered by a thin layer of peat was relatively small and rather evenly distributed over the entire length of the water flow path. The variance of the soil types was, to some extent, fluctuating along the water flow path.

According to the analyses described above, we proposed characteristics for an average head-water catchment in a drumlin field by using the concept of the typical water flow path. The area of the catchment covered 109.1 ha (average area of the 782 head-water catchments) composed of a water flow path with a length of 954 m (average length of the water flow path in headwater catchments) and a maximum elevation of 11.5 m above the water body (average of the maximum elevations of the head-water catchments). The water flow path was diverging towards the water body, and the peatlands were concentrated within a distance of 50 m to the water body. The rest of the water flow path consisted of mineral soil (Fig. 8). Even though soil type values were assigned according to their prevalence at a given distance interval, the proportions of the soil types were calculated, in the case of average catchments, as cumulative proportions along the water flow path using threshold values from the soil proportions within the study area (Table 2).

Discussion

The water flow path approach used in this study represents the catchments in two dimensions, which allows calculations of horizontally distributed properties of catchments as a function of distance to the water body (Kokkonen *et al.* 2006). This is relevant when considering the quality of runoff water, since the areas adjoining the water body probably contribute more to water quality than the remote areas near the water divide. While the model simplification into two dimensions leads to a loss of information with regard to the three-dimensional reality, it also preserves valuable information on the spatial distribution of factors controlling runoff quality. This is an advancement with regard to the present convention of describing catchment properties, such as elevation or soil types, as simple averages without any specific spatial dimension. Because the presented elements affect the behavior of

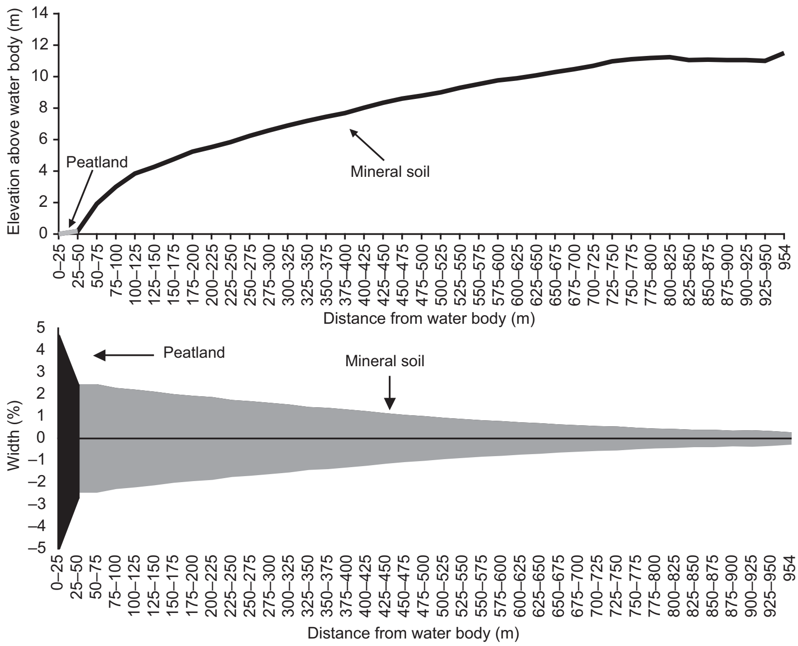


Fig. 8. Characteristics of an average head-water catchment. Top panel: longitudinal section of the typical water flow path and soil type distribution. Bottom panel: a proportion of the catchment area along the typical water flow path.

surface water hydrology and sediment transport (Bogaart and Troch 2006), this kind of information is needed to clarify the quality of runoff water in future research.

In this study, DEM played a significant role in the delineation of catchment topography that is dependent on the resolution of DEM (cf. e.g. Oksanen and Sarjakoski 2005a). We used a DEM with a resolution of 25 m that may have been too coarse in describing the small-scale topography relevant to the water flow, because it may contain imprecisions that result from inhomogeneous source data (Valtakunnallisen korkeusmallin uudistamistarpeet -ja vaihtoehdot 2006). However, it was the best available DEM for such a large area as studied here. Previous studies have been conducted to explain DEM-based errors on surface derivatives. Oksanen and Sarjakoski (2005a) found that an increase in DEM vertical error also increased the error in surface derivatives. They also noticed that spatial autocorrelation appears to have varying effects on error propagation, depending on which application is used. In addition, Oksanen and Sarjakoski (2005b) showed that automatic catchment delineation is very sensitive to DEM uncertainty, due to the random errors of a DEM. In the near future, a DEM with a resolution of 10 m will become available and might also specify the results of this study (Valtakunnallisen korkeusmallin uudistamistarpeet -ja vaihtoehdot 2006).

Width analysis of the typical water flow path revealed that 9.5% of the catchment area was situated closer than 25 m from the receiving water body, as measured along the flow path of water. These areas are potentially used as buffer zones, where forestry operations, such as clear-cuttings and site preparations are restricted to reduce nutrient export and to protect biodiversity (Lowrance *et al*. 1984, Dworak *et al*. 2004).

In our study, the average elevation of the area near a stream was ca. 20 cm above stream level. Because of their low elevation, the riparian areas are probably annually washed with spring floods, which makes them vulnerable to nutrient export. Moreover, the generation of surface runoff in this area was intensified by soil wetness as manifested in the presence of peatlands (a proportion of ca. 19%) (Figs. 6 and 7). Previously, Crave and Gascuel-Odoux (1997) observed that elevation difference within a catchment correlates negatively with soil moisture. They also found that soil moisture status is more variable in lower than in higher elevations. In our study, steep slopes that adjoined the area above the water flow path (Fig. 3) as well as the occurrence of fine mineral soils (a proportion of ca. 5%) (Fig. 5) generate surface runoff. On the other hand, a diverging hillslope decreases the generation of surface runoff. An increase in share and volume of surface runoff usually leads to an increase in nutrient export from the catchment (House and Warwick 1998, McDowell *et al*. 2001).

The categorization of soil types showed that, contrary to our expectations, peatlands existed along the entire length of the typical water flow path (at least a proportion of 7%) rather than that they would mainly concentrate close to the water body. Using the wetness index, Rodhe and Seibert (1999) and Günther *et al*. (2004) also noticed that peatlands were found not only close to the stream, but also in other topographic positions as well as near the catchment divide. The topographic wetness index is used to quantify the topographic control on hydrologic processes. This method combines the local upslope contributing area with slope and depends on the way the accumulated area of upstream cells is routed to downstream cells (Günther *et al*. 2004, Sørensen *et al*. 2006). The soil map which we applied may not have recognized small peatlands, paludified areas, or riparian zones that usually surround water bodies in Finland. Thus, the proportion of peat or thin peat layers near the water bodies may be underestimated in our study, even though drumlin fields typically have a rather low share of peatlands. The proportion of peatlands within the study area was 12.5% in relation to the total land area, whereas, on average, it is 28% in Finland (Virtanen *et al*. 2003).

Although water flow path approach studies are scarce in literature, some of the discovered characteristics can be considered typical of drumlin landforms. A large within-catchment variation of the water flow path elevation may originate in the asymmetric form of a drumlin peak, the steepest slopes of which are at the proximal side of the drumlin ridge, while the distal side is characterized by gentle slopes. Diverging hillslopes are frequently formed into catchments characterized by the drumlin field, i.e. its topography is dominated by drumlin peaks and flat peat areas between them. The hillslope gradient is primarily controlled by the geomorphological settings of the catchments (Bogaart and Troch 2006).

Long-term studies to monitor the export of nutrients from forested areas have been conducted in catchments draining into streams (e.g. Finér *et al*. 1997, Ahtiainen and Huttunen 1999, Mattsson *et al*. 2003). In our study, the fraction of this type of catchments (Types B and C) was 59% of the total land area, while 7.4% of the total area drained directly into a lake or a pond, instead of a stream (Type D). Type D areas covered the remnants excluded from the division of the third-order catchments into head-water catchments. These areas are heterogeneous, short and wide, and close to a water body. The areas adjacent to lakes can be an important source of nutrient export, as the delay in runoff entering the lake is short.

Our compilation of characteristics of an average catchment was based on the results of the proportions of peatlands and mineral soil along a typical water flow path. Although our description of an average catchment was hypothetical, it was informative in describing the spatial distribution of factors affecting runoff quality, such as landform, slope, and soil type. In a typical water flow path approach, not all information concerning class variables, such as soil types in the case of this study, is retained (Kokkonen *et al*. 2006). If several soil types exist, only one can be selected to represent the soil type at a given point within the water flow path. In this study, the peatlands were located next to the water body, where the relative fraction of the peatlands was largest, even though mineral soil was also abundant in this region. The share of peatlands in the average head-water catchment was fitted to equal the measured share in the whole region (Table 2). Only natural geological and geomorphological factors were included in this study, and anthropogenic changes, such as ditches in peatlands, were excluded. Ditching probably shortens the water flow path, concentrates the peat areas near the water body, and decreases variation in water flow path topography.

The average catchment can be utilized, for example, in calculating the impacts of forest management practices on runoff water quality by using hydrological and water quality models based on the two-dimensional catchment representation described by Karvonen *et al*. (1999), Laurén *et al*. (2005), Koivusalo *et al*. (2006), and

Kokkonen *et al*. (2006). Furthermore, the results offer a baseline for a geomorphological evaluation of how typical the monitored research catchments (e.g. Finér *et al*. 1997, Ahtiainen and Huttunen 1999, Mattsson *et al*. 2003) are within larger catchment populations (Beven 2000). Moreover, they make it 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 calculating the costs of restricting forestry operations in this area for the purposes of water protection. Because the average catchment approach is a pioneering study in the field of large-scale water flow path studies, several directions for future research can be recommended, including other geomorphological landforms with vegetation dataset and the effects of anthropogenic changes on water flow path geometry. In addition, applications using the topographic wetness index are recommended to be included in water flow path studies.

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