TIMO KORKALAINEN

Geomorphology in Relation to Forest Site Productivity and Catchment Properties – A Geospatial Approach

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Cover picture Esker landform at Mujejärvi catchment. Photo by Timo Korkalainen.

TIMO KORKALAINEN

GEOMORPHOLOGY IN RELATION TO FOREST SITE PRODUCTIVITY AND CATCHMENT PROPERTIES – A GEOSPATIAL APPROACH

ACADEMIC DISSERTATION

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Abstract

Geomorphology has been a traditional research field in Finnish geography since the 1800s. Currently, modern geospatial methods allow new applications in geomorphology. In this study, geomorphology and geospatial analysis tools were used to research forest site productivity and the spatial arrangement of catchment properties in southern, central, eastern, and northern Finland. In total, 15 phytogeomorphological site variables were used to explain forest site productivity on mineral soils. Productivity was expressed in relation to the height and age of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* [L.] Karst.). On drained biogenic areas, productivity was expressed in relation to the height and volume of Scots pine (*Pinus sylvestris* L.) stands that were approximately of the same age. Productivity was explained by the total peat nitrogen (N) concentration. The spatial arrangement of catchment properties was studied from 782 head-water catchments by using the water flow path approach from the water divide to the receiving water body. Water flow paths from all grid cells to the receiving water body cell were computed in the studied catchments. Water flow paths length, surface slope, elevation, relative width, and soil type were determined. The typical water flow path represented average values from water flow path data. In total, 600 drumlins were identified in catchments. In this study, the water flow path approach was enforced to clarify the impacts of artificial peatland drainage on the spatial arrangement of catchment properties. The study area consisted of three third-order catchments. Digital elevation models (DEMs) with 25 m raster size and 1:20 000 raster maps were used to determine phytogeomorphological site variables, morphometry, catchments, and water flow paths within the studied areas by using geospatial analysis tools. Forest site productivity studies were utilized with data provided by the Finnish National Forest Inventory (NFI9) and by the Forest Research Institute of Finland. The results showed that phytogeomorphological site variables increased forest site productivity. The latitude coordinate, the length of the growing season, and the temperature sum were the best single explanatory parameters. An increasing total peat nitrogen concentration increased forest site productivity in drained biogenic areas. Drumlin landforms characterized the shape of the water flow paths. The typical water flow path profile in a drumlin field was diverging towards the water body, and there was a gentle slope close to the water body followed by a steeper slope. Mineral soils dominated throughout the typical water flow path. Peatland drainage drastically decreased the length and elevation of the typical water flow path and increased the area and proportion of peatlands near the water bodies in the studied third-order catchments. The results of this study can be utilized when assessing forest site productivity in northern boreal conditions. The concept of the typical water flow path can be utilized when calculating the impacts of forest management practices on runoff water quality.

Keywords: Catchment, DEM, forest site productivity, geomorphology, GIS, phytogeomorphology, water flow path

Tiivistelmä

Geomorfologiaan (maanpinnanmuotoihin) liittyvä tutkimus on ollut perinteinen maantieteen alaan kuuluva tutkimuskenttä jo 1800-luvulta lähtien. Nykyinen paikkatietomenetelmien nopea kehittyminen on avannut uusia näkökulmia geomorfologiseen tutkimukseen. Tässä väitöskirjassa hyödynnettiin geomorfologiaa ja paikkatietomenetelmiä metsän kasvupaikan tuottavuuden ja valuma-alueiden ominaisuuksien tilajärjestyksen tutkimuksessa Etelä-, Keski-, Itä- ja Pohjois-Suomessa. Tutkimuksessa määritettiin 15 fytogeomorfologista (maanpinnanmuodon ja kasvillisuuden suhdetta kuvaavaa) muuttujaa, joilla selitettiin kivennäismaiden kasvupaikkojen tuottavuutta. Tuottavuutta kuvattiin männyn ja kuusen pituuden ja iän välisenä riippuvuutena. Ojitetuilla turvemailla kasvupaikan tuottavuutta kuvattiin mäntymetsikön pituudella ja tilavuudella likipitäen samanikäisissä metsiköissä. Tuottavuutta selitettiin turpeen kokonaistyppipitoisuudella (N). Valuma-alueiden ominaisuuksien tilajärjestystä tutkittiin 782 latvavaluma-alueella. Tilajärjestyksen kuvaamisen lähtökohta oli korkeusmallista määritetty veden valuntareitti vedenjakajalta vastaanottavaan vesistöön. Valuntareitti laskettiin vuorollaan jokaisesta korkeusmallin solusta lähtien. Tutkimuksessa määritettiin valuntareittien pituus, kaltevuus, korkeus, leveys (valuma-alueen pinta-ala tietyllä valuntareitin etäisyydellä vesistöstä) sekä maalaji. Valuntareittiaineiston keskitunnukset edustivat valuma-alueen tyypillistä valuntareittiä. Tutkituilta valuma-alueilta kartoitettiin yhteensä 600 drumliinia. Valuntareittilähestymistapaa sovellettiin tutkittaessa metsäojituksen vaikutusta valuma-alueiden ominaisuuksien tilajärjestykseen. Aineistona tutkimuksessa oli kolme kolmannen jakovaiheen osavaluma-aluetta. Fytogeomorfologisten muuttujien määrittämisessä, morfometrian (muoto-oppi) analysoinnissa sekä valuma-alueiden ja valuntareittien laskemisessa hyödynnettiin solukooltaan 25 metrin rasterimuotoisia korkeusmalleja, 1:20 000 mittakaavaisia rasterikarttoja sekä uusimpia paikkatietotyövälineitä. Yhdeksännen valtakunnallisen metsävarojen inventoinnin (VMI9) mittauksia sekä Metsäntutkimuslaitoksen koeaineistoja hyödynnettiin kasvupaikan tuottavuuden tutkimuksissa. Tulokset osoittivat, että fytogeomorfologiset muuttujat selittivät metsän kasvupaikan tuottavuutta. Yksittäisistä muuttujista pohjoiskoordinaatti, kasvukauden pituus sekä lämpösumma selittivät parhaiten mineraalimaiden kasvupaikan tuottavuutta. Ojitetuilla turvemailla kokonaistyppipitoisuuden kohotessa myös kasvupaikan tuottavuus lisääntyi. Drumliinikentän tyypillisen valuntareitin leveys lisääntyi kohti vastaanottavaa vesistöä. Lisäksi valuntareitin topografia oli suhteellisen tasainen lähellä vesistöä, jonka jälkeen sen profiili jyrkkeni. Kivennäismaalajit olivat vallitsevia tyypillisellä valuntareitillä. Turvemaiden ojitus lyhensi merkittävästi tyypillisten valuntareittien pituutta ja korkeutta tutkituilla kolmannen jakovaiheen osavaluma-alueilla. Myös valuma-alueen pinta-ala ja turvemaiden osuus lähellä vesistöä kasvoi huomattavasti ojituksen jälkeen. Tutkimuksessa saatuja tuloksia voidaan hyödyntää määritettäessä metsän kasvupaikan tuottavuutta boreaalisissa olosuhteissa. Tyypillisiä valuntareittejä voidaan hyödyntää, kun ennustetaan metsätalouden vaikutuksia pinta- ja pohjavesien laatuun.

Avainsanat: Digitaalinen korkeusmalli, fytogeomorfologia, geomorfologia, kasvupaikan tuottavuus, paikkatietojärjestelmä, valuma-alue, valuntareitti

Esipuhe

Olin kiinnostunut luonnonmaantieteestä jo lukiossa ja halusin jatkaa sen opiskelua myös jatkossa. Kohdallani yliopistoon pääseminen ei kuitenkaan ollut ihan helppo juttu. Kun vihdoin helpottava kirje opiskelemaan hyväksymisestä kolahti postilaatikkoon, niin päätin, että ilman tohtorin tutkintoa en yliopistosta lähde! Tunnistan edelleen sen hetken, josta juuret tällekin tutkimukselle juontavat. Seisoskelin toisen opiskeluvuoden syksyllä Joensuun yliopiston maantieteen laitoksella tutkiskellen ilmoitustaulua, kun nykyisin jo eläkkeellä oleva luonnonmaantieteen professori Erkki Jauhiainen saapui luokseni. Hän kysyi tuttavallisesti, että olisinko kiinnostunut liittymään luonnonmaantieteen seminaariryhmään. Olin hieman hämmentynyt, olinhan vasta reilu vuosi sitten aloittanut opintoni yliopistossa. Olin kuitenkin kiinnostunut asiasta ja sanoin, että mikäs siinä. Pian olimme myös yhtä mieltä, että joku päivä teen väitöskirjan. Varsin pian havaitsimme, että geomorfologiaan (maanpinnanmuotoihin) liittyvä tutkimus voisi olla minun tutkimusalaani. Samoihin aikoihin kiinnostuin valtavasti myös paikkatietojärjestelmistä. Kun huomasin, että geomorfologiaa voidaan kuvata kolmiulotteisesti paikkatietomenetelmien avulla, niin tutkimusaiheesta ei ollut enää epäselvyyttä. Tutkin geomorfologiaa ennen väitöskirjatyötäni professori Jauhiaisen ohjauksessa sekä pro seminaari että pro gradu -töissäni. Tutkimusalueenani oli Mujejärven valuma-alue kotikaupungissani Nurmeksessa. Mujejärven valuma-alue tutkimuskohteena oli minulle helppo valinta – olinhan liikkunut siellä paljon ja pidin alueesta erityisesti sen luonnonmaisemien ansiosta. Samainen valuma-alue oli yhtenä tutkimusalueena myös väitöskirjatyössäni. Ensimmäisenä haluan osoittaa kiitokset Erkki Jauhiaiselle motivoivasta asenteesta ja erityisesti siitä, että loit pohjan koko geomorfologiselle tutkimustyölleni, jota tämä väitöskirja edustaa.

Nykyisin luonnonmaantieteen professorina Joensuun yliopistossa toimii Alfred Colpaert. Alfredista tuli väitöskirjaohjaajani Erkin jäätyä eläkkeelle. Toisena ohjaajana tutkimukseni alusta saakka on toiminut MMT Ari Laurén metsäntutkimuslaitokselta. Arin innovatiiviset ideat ja taito ohjata tieteellisen tekstin tuottamista ovat olleet ensiarvoisen tärkeitä. Arilla oli tärkeä rooli myös rahoituksen hankinnassa tähän tutkimukseen. On ollut hieno kokemus työskennellä pätevien ohjaajien kanssa. Väitöskirjan tekijän sekä ohjaajien yhteistyön saumattomuus ilmeni muun muassa yhteenveto-osiota valmisteltaessa, jossa kiireinen aikataulu ja väittelijän halu saada työ valmiiksi korostivat ohjaajien pätevyyttä toimia yhteisen tavoitteen eteen. Haluan lämpimästi kiittää Aria ja Alfredia, että omistauduitte tutkimukseeni. Valmistelin väitöskirjaani Joensuun yliopiston maantieteen laitoksella elokuuhun 2005 asti. Työtiloista ja ATK-laitteista on pitkälti kiittäminen silloista maantieteen laitoksen johtajaa professori Markku Tykkyläistä. Markku on tutkimukseni loppuun saakka auttanut myös useissa muissa väitöskirjatyöhön liittyvissä käytännön asioissa.

Tärkein tutkimukseni rahoittaja on ollut Suomen kulttuurirahaston Pohjois-Karjalan maakuntarahasto. Tutkimustani ovat rahoittaneet myös Joensuun yliopiston matemaattis-luonnontieteellinen tiedekunta sekä Maa- ja vesitekniikan tuki ry. Tutkimusmateriaalia ja muuta tukea tutkimukselle saatiin sen alkuvaiheessa Metsähallituksen Nurmeksen tiimiltä. Geologian tutkimuskeskukselta hankittiin runsaasti paikkatietoaineistoja ja Metsäntutkimuslaitokselta metsävara- ja kasvupaikkatietoja. Nykyinen monitieteinen tutkimuskenttä vaatii taakseen myös yhteistyötahoja. Olen ollut onnekas sen suhteen, että tutkimuksessani on ollut mukana ammattitaitoisia tutkijoita ja muita asiantuntijoita. Heitä olivat muun muassa FT Keijo Nenonen, FM Raimo Nevalainen ja FL Hannu Rönty Geologian tutkimuskeskuksesta; MMT Risto Ojansuu, MMT Kari T. Korhonen, professori Seppo Kaunisto, MH Mikko Moilanen ja FT Pekka Pietiläinen Metsäntutkimuslaitokselta. Eräänä mieliin painuvana asiana mainittakoon tilanne, kun väistelimme Pekka Pietiläisen kanssa tielle juoksevia poroja tutustuessamme Posio−Taivalkoski−Pudasjärvi alueella sijaitseviin koealoihin, jotka olivat mukana tässä tutkimuksessa. Tutkimukseni kautta tutustuin myös TkT Teemu Kokkoseen ja TkT Harri Koivusaloon (nyk. Metsäntutkimuslaitoksella) Teknillisestä korkeakoulusta. Väitöskirjassani esitetyt valuma-aluemallinnukseen liittyvät paikkatietomenetelmät ovat pitkälti heidän kehittämiään. Englantilaisen filologian jatko-opiskelija FM Katrin Korkalainen Oulun yliopistosta on tarkastanut kieliasun väitöskirjassani. Haluan tässä vaiheessa osoittaa suuret kiitokset tutkimukseni rahoittajille ja tukijoille sekä kaikille teille, joiden kanssa minulla on ollut ilo työskennellä tutkimukseni eri vaiheissa.

Väitöskirjani on valmistunut syksystä 2005 asti yliopiston ulkopuolisen työn ohella. Vapaa-ajan käytön ongelmia ei ollut, kun aamuisin, iltaisin tai viikonloppuisin istuin tietokoneen ääreen ja orientoiduin jälleen väitöskirjatutkijaksi. Silloinen työnantajani Pohjois-Karjalan maakuntaliitto kuitenkin tuki tutkimustani ja sainkin joka kuukausi käyttää yhden työpäivän tutkimukseni tekemiseen. Arvostan suuresti tätä elettä! Vaikka väitöskirjan valmisteleminen muun päätyön ohella vaatii paljon, niin huomasin myös, että olin jopa motivoituneempi tavoitteeni saavuttamisen suhteen, kun ollessani päätoimisena tutkijana. Huomasin myös, että kykenin/kykenen soveltamaan tutkimuksesta saamaani tietotaitoa päätyössäni.

Eivät nämä kuluneet vuodet kuitenkaan ole olleet pelkkää työntekoa. Kaikesta vuosien varrella tapahtuneesta hauskanpidosta saankin osoittaa kiitokset veljilleni ja ystävilleni. Väitöskirjaprosessia ovat mukavasti tauottaneet monet Mujejärvelle suuntautuneet eräreissut, vuosittaiset Rukareissut tai muut mökki- ja kalastusreissut. Tälläkin hetkellä on jo seuraava Mujejärven reissu suunnitteilla. On mukavaa, kun on, mitä odottaa. Lisäksi Freestyle-hiihdon parissa toimiminen ja sitä kautta saadut kaverit sekä Suomessa että ulkomailla ovat olleet tärkeässä roolissa vapaa-aikaani.

Tärkeimmät ja arvokkaimmat kiitokset ansaitsevat kuitenkin oman perheen jäsenet, jotka ovat tukeneet minua sekä väitöskirjaprosessin aikana että muussa elämässäni. Ilman vanhempieni tukea ja kannustusta en varmasti olisi saanut tehtyä työtä aikaiseksi. Kiitän myös veljiäni Tomia perheineen sekä Tuomasta. Erityisesti haluan osoittaa kiitokset Anu-vaimolleni, joka on nähnyt ja kokenut kaikki ylä- ja alamäet, mitä tutkimusprosessi on tuonut mukanaan puhumattakaan siitä, että suuri osa vapaa-ajastani on kulunut tietokoneen ääressä. Jatkossa tilanne on toinen.

HALUAN OMISTAA VÄITÖSKIRJANI HEIKKI-UKIN MUISTOLLE

Joensuussa vappuna 2008

Timo Korkalainen

List of original articles

I) Timo Korkalainen and Ari Laurén (2006). Using phytogeomorphology, cartography and GIS to explain forest site productivity expressed as tree height in southern and central Finland. *Geomorphology* **74**, 271–284.

II) Timo Korkalainen, Pekka Pietiläinen and Alfred Colpaert (2007). The effect of total peat nitrogen on the height and volume of Scots pine (*Pinus sylvestris* L.) stands in three fertilized and drained peatlands in northern Finland. *SUO (Mires and peat)* **58**(3–4), 75–85.

III) Timo Korkalainen, Ari Laurén and Teemu Kokkonen (2007). A GIS-based analysis of catchment properties within a drumlin field. *Boreal Environment Research* **12**, 489–500.

IV) Timo Korkalainen, Ari Laurén, Harri Koivusalo and Teemu Kokkonen (2008). Impacts of peatland drainage on the properties of typical water flow paths determined from a digital elevation model. *Hydrology Research* **39** (in press).

Authors' contribution:

Timo Korkalainen has had the main responsibility for all calculations, analyses, modeling works, and for writing the papers. Ari Laurén planned the researches in papers I, III, and IV, and Pekka Pietiläinen in paper II. Teemu Kokkonen and Harri Koivusalo developed the methods for the GIS analyses in papers III and IV. The articles were written together with the co-authors.

CONTENTS

Original articles

General terminology

Anthropogenic

Effects, processes, objects, or materials that are derived from human activities as opposed to those occurring in natural environments without human influences. Anthropogenic changes are, for example, artificial peatland drainage or artificial diversion of groundwater-table.

Aspect

Refers to the direction towards which a topography slope faces. Here, aspects are calculated according to a DEM.

Catchment

A region of land where water drains downhill into a water body. A catchment is sometimes also called a drainage basin or a watershed and it is one of the most significant factors determining the amount of flooding. In this context, all catchments are geospatially determined from a DEM.

DEM

A digital elevation model (DEM) is a raster-based (a grid of squares) digital representation of ground surface topography.

Drumlin

A drumlin is an elongated whale-shaped hill formed by glacial action. Its long axis is parallel to the movement of the ice, with the blunter end facing towards the glacial movement. Individual drumlins can be as much as a hundred meters high and ten kilometers long, and they can occur in extensive fields or clumps in places in the Lake Region, in eastern Finland, or in northern Lapland. Most drumlins also have a bedrock core.

D8 method

A method to calculate the direction of the water flow for each raster cell according to the direction of the steepest descent of eight neighboring cells.

Esker

An esker is a long, winding ridge of stratified sand and gravel. An esker is created when the deposits of subsurface glacial streams are placed on the ground after glacial melting. Eskers can run across Finland in chains that reach lengths of several hundred kilometers. Eskers are approximately oriented towards the direction of glacial movement.

Finnish National Forest Inventory

Established for monitoring and assessing forest resources and for developing forest inventory methods in Finland.

Forest site productivity

In this context, forest site productivity is the production at a certain site that is expressed as tree or stand height and volume assessments.

Geomorphology

The study of landforms including their origin and evolution and the processes that form them.

GIS

A geographical information system (GIS) is a tool for capturing, storing, analyzing, and managing spatial data and associated attributes which are spatially referenced to the earth. It merges information in a computer databases with spatial coordinates onto a digital map.

Growing season

The period of each year when vegetation grows. It is determined by the climate of a certain site. Location, temperature, daylight hours (photoperiod), and rainfall are all critical environmental factors that affect the growing season.

Highest shoreline

The nature of the Baltic Sea has changed in the course of its four main postglacial stages. The highest shoreline refers to an elevation above the current sea level of the uppermost shore level of the Baltic Sea as it was during the latest deglaciation. It is located at a present altitude of about 220 m a.s.l. in north Finland and 100 m a.s.l. in south-east Finland.

Lake index

The proportion of lakes (%) for a circular area with a radius of 15 km.

Morphometry

The measurement of the form and shape of geomorphological landforms. Measurements are manipulated statistically or mathematically in order to discover inherent properties. Morphometrical studies are commonly utilized, e.g., in the fields of geomorphology and hydrology.

Physical Geography

A field of knowledge that studies natural features and phenomena on earth from a spatial perspective. Physical Geography is a subdiscipline of Geography.

Phytogeomorphology

A synthesis of the relationships between vegetation and landforms in studies related to the surface topography of the earth. In this context, phytogeomorphology refers to the interaction between geomorphological landform and tree growth.

Radiation index

In this context, theoretical incoming radiation (kJm^{-2}growing season^{-1}).

Relative width of the water flow path

The width function describes how large a proportion of a catchment area resides at a given distance interval along the water flow path. It is identified by counting the number of cells residing at each distance interval along the water flow path.

Sea index

The proportion of seas (%) for a circular area with a radius of 20 km.

Slope

The measurement of steepness. Here, slopes are calculated according to a DEM.

Soil

The layer of unconsolidated material found at the earth's surface that has been influenced by the soil forming factors: climate, relief, parent material, time, and organisms. Soil normally consists of weathered mineral particles, dead and living organic matter, air space, and soil solution. In this context, 'peatland' is used as the opposite of 'mineral soil.' 'Soil' is also used to refer to sediment texture.

Temperature sum

In this context, the cumulative total annual temperature sum with the threshold +5°C.

Water divide

The dividing line or separation between adjacent catchments. In hilly areas, the divide lies along topographical peaks and ridges, but in flat areas, especially in peatlands, the divide may be invisible, just a more or less notional line on the ground on either side of which falling raindrops will start a journey to different water bodies.

Water flow path

The shortest elevation−distance of a water flow path from each cell in a catchment to the receiving water body.

1. Introduction

1.1. Background of the study

The framework for this study originates from physical geography, especially from geomorphology. Geomorphology has a long tradition as a geographical research field; primitive geomorphological mapping was practiced in Russia already in the 1870s (Spiridonow 1956). However, it was a German geographer, Siegfried Passarge, who created the first guidelines for presenting geomorphological maps at the beginning of the 1900s (Passarge 1912; 1914). In the early 1900s, W. M. Davis presented the Davisian system of landscape analysis in the USA, which involved recognizing the long-term, cyclical nature of erosion in landforms and landscape analysis. Geomorphological cartography was introduced in Finland by Ragnar Hult at the end of the 1800s and was continued by Iivari Leiviskä and J.G. Granö in the early 1900s. After that, geomorphological mapping of Finland was actively practiced between 1960 and 1980. Many areas, especially from southern and western Finland, were subject to geomorphological research. Fogelberg (1968) concluded that geomorphological maps were important in Finland for various purposes, such as planning, the military, ore prospecting, and for the progress of scientific geomorphology. Allison (1991) emphasized the usefulness of geomorphological maps for civil engineering and landslide mapping. The first proper geomorphological mapping in Finland was done in the area of Tammela, by Aartolahti in 1968. Other researches done by Aartolahti include the Virtaankangas−Säkylänharju esker area (1972a), the esker and dune complex of Rokuanvaara (1973), hummocky moraines in northern Finland (1974), and glacial mound fields in northern Savo (1975). Fogelberg (1970) studied geomorphology in the area of Vääksy and Vierumäki, Glückert (1973) in the areas of Keitele and Pieksämäki, and Heikkinen and Tikkanen (1979) in Finnish Lapland. The first geomorphological map covering the whole of Finland (1:1 000 000 scale) was presented by Fogelberg & Seppälä in 1986. Tikkanen (1981; 1989) and Tikkanen et al. (1985) published detailed geomorphological maps of southern and western Finland. Rönty (1999; 2002) studied geomorphology in the areas of Kuopio, Joensuu, and Kainuu, and Korkalainen (2002) in the Mujejärvi catchment in eastern Finland.

Geomorphological mapping is based on understanding the physical processes affecting the soil. The current appearance of the Finnish landscape was formed during the latest glaciation, resulting from glacial processes, when the soil surface was affected by powerful erosion (Kujansuu 1990; Tikkanen 1994). Finland has been beneath the continental ice sheet several times during its Quaternary history. The ice sheet associated with the Weichselian glaciation reached its maximum extent about 18 000–20 000 BP. In the area of Finland, the ice sheet was more than three kilometers thick. The ice margin began to retreat from the southernmost parts of the Baltic basin around 13 500–13 000 BP. After that, deglaciation proceeded very rapidly, so that by about 12 000 BP, the ice margin was situated close to the south coast of Finland and then continued to proceed all over Finland (Tikkanen & Oksanen 2002).

Deglaciation exposed large areas of accumulated and eroded sediments in Finland (Aartolahti 1990). The ice and its melting waters formed different relief types and geomorphological landforms that can be characterized according to their form and sediment type (Fogelberg 1977). The landform and its sediments partly determine also vegetation types. The knowledge of geomorphological processes (Donner 1978; Tikkanen 2002) and sediment distribution in different geomorphological landforms (Walsh et al. 1998; Shroder & Bishop 2003) has facilitated also the study of interactions between geomorphology and vegetation, i.e., phytogeomorphology (Howard & Mitchell 1985). Tree growth is known to be related to several phytogeomorphological site properties such as topography, elevation, slope, aspect, and sediment texture (Viro 1962; Poso & Kujala 1973; Stage 1976; Tamminen 1991; 2000).

Geomorphology has a major effect on the water flow along the topography (Viessman et al. 1989). Therefore, geomorphology is closely related to catchment hydrology. Geomorphology determines elevation differences within catchments and also catchment boundaries. Catchments are highly variable of their topography, depending on bedrock properties and proportions of sorted and unsorted sediments as well as on peatlands in catchments. Catchments are naturally defined units in a landscape. However, anthropogenic effects, such as peatland drainage, may change natural catchment boundaries. Studying catchments involves an understanding of the water balance through the interaction of climate, vegetation, sediment, and topography. In this way, the complex and long-term processes that determine geomorphology also determine the topological properties of catchments at all scales. Depending on geomorphological properties, catchments are clearly spatially separated through their larger-ordered catchments. Thus, they are multiscale with many small sub-catchments (Mulligan 2004). Catchments are appropriate for most surface hydrological studies and are widely used. Hydrological studies were previously investigated at catchment-scale, e.g., in a water quality perspective. Areas near water bodies are sensitive to nutrient and sediment leaching. In addition, peatland drainage may enhance the nutrient load into water bodies (Cirmo & McDonnel 1997; Ahtiainen & Huttunen 1999; Pietiläinen et al. 2007).

Phytogeomorphological and hydrological studies in catchment-scale typically benefit from new modeling technologies with Geographical Information Systems (GIS). GIS has facilitated the analysis of spatial numerical data (Dragicevic & Marceau 2000). This has enhanced the development of new methods for processing forest and hydrological data. For example, simulation models based on statistical processing of empirical field data can be used to predict forest dynamics (Hynynen & Ojansuu 1996; Hynynen et al. 2002; Huth et al. 2004). In addition, measured or simulated tree variables are handled more and more with GIS for different purposes, such as land use interpretation (Erb 2004) and forest ecosystem mapping (Merganič et al. 2004). GIS is also used for hydrological studies. In fact, the simulation and prediction of hydrological variables have been in use by hydrologists for more than 70 years. However, in the beginning only simple parameterization and input data were available. From the 1980s onwards, the availability of high performance computers that could undertake vast numbers of calculations has allowed the numerical representation of distributed hydrological processes in a catchment. This trend has continued during the 2000s. Using distributed models, i.e., rasters or digital elevation models (DEMs) that break space into discrete units, leads to analyses of one-, two-, or three-dimensional space using a GIS (Kelly 2005). A DEM and its conversions for slope, aspect, and hillshade were found to be useful in studying geomorphology and catchment hydrology. A DEM has also been used in the analysis of catchment properties in terms of water flow paths from the water divide to the receiving water body along geomorphological surfaces (Laurén et al. 2005; Koivusalo et al. 2006; Kokkonen et al. 2006).

This study can be seen as an extension to traditional geomorphological research, in which new geospatial techniques have been utilized in the analysis of forest site productivity and catchment properties. In previous studies, local variables, e.g., temperature sum and length of the growing season have been used to explain tree growth (Koivisto 1970; Roiko-Jokela 1980). Tree growth has also been explained by some parameters affected by morphometry, such as solar radiation on different hillslopes (Poso & Kujala 1973; Stage 1976). Solar radiation is known to be affected by the latitude, slope, and aspect of a site. However, systematically studied phytogeomorphological variables and large-scale geomorphological classification have not been used in research of forest site productivity. Presently, geomorphology provides new tools for studying forest site productivity.

In previous hydrological catchment-scale studies, the number of catchments has usually been limited and has been described without considering the spatial arrangement of catchment properties. In the context of water protection, the spatial arrangement of the catchment properties and the representativeness of the studied catchments among larger catchment populations are of great relevance. So far, studies that describe the catchment properties spatially and in large catchment populations are scarce. In the absence of knowledge about variation in large populations, a generalization of results from small catchment studies is difficult.

This thesis can be seen as multidisciplinary research, connecting the fields of physical geography (mineral soil and peatland geomorphology, catchment analyses, environmental impacts) to forest science (tree growth modeling, forest management practices, environmental impacts of forestry), modern geoinformation sciences (spatial-, DEM-, multilevel-, and catchment analyses), and statistics. It is, however, to be emphasized that the operative research field, from the perspective of which this study is concluded, is physical geography.

1.2. Geomorphological characteristics of the Finnish landscape

The landforms of Finland contain sediments of different grain sizes forming geomorphological landforms in mineral soils. Glacigenic unsorted till is the main sediment type in Finland, covering about 50% of all surface deposits (Taipale & Saarnisto 1991; Koivisto 2004). Glacial till is further separated into ablation and basal till. Glaciofluvial material, i.e., gravel and sand, covers about 7% of all surface deposits (Taipale & Saarnisto 1991). Biogenic landforms cover about 30% of all landforms. The morphometrical properties of these geomorphological landforms depend on their origin and on the conditions existing during their formation.

The relief of Finland is relatively gentle, but its detailed topography is highly variable (Tikkanen 2002). The most distinctive geomorphological landforms are large ice-marginal formation chains, especially those of the Salpausselkä area in the southern, southeastern, and eastern parts of Finland (Aartolahti 1972b; Rainio 1991; Saarnisto 1991; Punkari 1996). Drumlins, consisting of thick basal till, occur all over the country, but there are two especially large drumlin fields in Pieksämäki and Keitele, covering about 25 000 km^2. The Pieksämäki drumlin field is one of the largest drumlin fields in Fennoscandia and probably on earth (Glückert 1973). Hummocky moraines, covering ablation till, occur to a smaller extent. Some of the most characteristic geomorphological landforms in Finland are eskers (Wiśniewski 1973; Seppälä 1984), and they exist all over the country as long, northwest to southeast chains (Punkari 1996). Undulating basal till, formed without any specific form, is a dominant geomorphological type in Finland, and the most common relief type is a glacially affected old erosion surface (Fogelberg & Seppälä 1986).

When the continental ice sheet margin was retreating, its melting waters formed the stages of the Baltic Sea. About 62% of Finland's current surface area has been covered by the waters of the Baltic Sea at some stage. The freshwater Baltic Ice Lake (12 600−10 300 BP) was built up against the ice margin by the Salpausselkä marginal formations. The Ice Lake stage was at a level of 25 meters above that of the ocean, with an outflow through the straits of Öresund. As the ice margin continued to retreat, the Ice Lake discharged through a number of channels that opened up in central Sweden, until it reached the ocean level. At the same time, saline water from the ocean began to flow into the Baltic Sea marking the beginning of the mildly saline Yoldia Sea stage (10 300−9 500 BP). As the rate of land uplift in central Sweden was faster than the rise in ocean level and the connecting channels rose above sea level, the Baltic Sea was once more isolated to form the freshwater Ancylus Lake (9 500−8 000 BP). During its existence, the outflow channel to the ocean shifted to the Straits of Denmark, and the major lake systems of central Finland became isolated from the Baltic Sea. When the ocean level was rising, a greater influx of saline water began to take place through the Straits of Denmark, marking the Litorina Sea stage (7 500−4 000 BP). The eustatic rise in ocean level led to a transgression at the beginning of the Litorina Sea stage. As a result, the water level on the south-east coast of Finland rose by a few meters. Little or no land uplift from the sea was recorded in south-western Finland. After a transgressive period early in the Litorina Sea stage, the shoreline displacement in Finland has proceeded at a steadily declining rate. Since then, the Baltic Sea has been at its present level, as the Limnea Sea (Taipale & Saarnisto 1991, Tikkanen & Oksanen 2002). There are large areas in Finland that have never been touched by the waves of the Baltic waters. These areas occur especially in the eastern and northern parts of Finland where elevations above sea level are the highest. This dividing line is called the highest shoreline and marks the boundaries between sub-aquatic and supra-aquatic terrain. The highest shorelines are located at a present altitude of about 220 meters above sea level (m a.s.l.) in northern Finland and 100 m a.s.l. in south-east Finland (Eronen 1990; Tikkanen & Oksanen 2002).

1.3. The role of geomorphology in forest site productivity and in water and nutrient fluxes

Geomorphology can be seen as a part of forest site productivity, because landform and morphometrical properties partly determine the fertility of the site. Important fertility-affecting variables connected to geomorphology are sedimentation processes and sediment quality, which affect particle size distribution and the water retention of soil (Ilvessalo 1933; Viro 1962; Lipas 1985; Tamminen 1991; 2000). An increase in the proportion of fine sediment texture usually enhances site fertility, which is due to the increasing amount of mineral nutrients available for trees (Hölscher et al. 2002). Landforms are characterized by their size, elevation, slope gradient, and aspect at each part. Incoming solar radiation, which is one of the main issues controlling tree growth, is affected by landform morphometry (Poso & Kujala 1973; Stage 1976). Solar radiation affects the photosynthesis and the temperatures of a site, which is further affected by the elevation (Viro 1962; Linderholm & Linderholm 2004). Tamminen (1991; 1993) found a negative correlation between tree height and the elevation of a site, which is due to decreasing temperature sum during the growing season. The latitude coordinate showed the same effect (Viro 1962). Tamminen (1991) also found that the slope gradient had a positive effect on tree height growth, especially for Scots pine; however, aspect was not relevant. Aspect and slope also contribute to the distribution of precipitation, evaporation, and transpiration (Spurr & Barnes 1980), which shows the importance of landform position in a landscape.

Soil properties and topography control the water and nutrient supply to trees, and they can be depicted in part by means of geomorphology and groundwater level (Tamminen 1991). For example, for drumlins, where the basal till cover on the bedrock is typically rather thin with low hydraulic conductivity, the formation of a near-surface water flow is more common than for sandy glaciofluvial eskers with permeable soil. Usually, the forest site productivity of a landform increases downhill slopes, because there, trees may utilize more water and nutrients than in locations near the catchment border or at convex morphometry (Poso & Kujala 1973; Viessman et al. 1989). The distribution of surface and ground water flow depends on the hydraulic properties and topography of the site as well as on soil thickness and bedrock (Miller et al. 1990; Youngs 1991; Daniels & Hammer 1992; Iwata et al. 1995). Forest site productivity can be derived from tree height and age, which are also controlled by the influences of environmental and climatic conditions on geomorphological landforms (Heikurainen 1959; Kuusela 1977; Tamminen 1993; Bolstad et al. 1998; Kayahara et al. 1998; Dorner et al. 2002; Rivas et al. 2004).

Biogenic landforms are also determined by their site fertility type and the climatic conditions (Heikurainen 1959; Kuusela 1977; Keltikangas et al. 1986; Ritari & Nivala 1993). Site fertility on peatlands depends on the biogeochemical processes within the landform. The nutrient status can be considered as a local factor that affects forest site productivity in peatlands (Kaunisto & Pietiläinen 2003; Pietiläinen et al. 2007). Water and thus nutrient inflow to peatlands can occur from rainfall, surface runoff from adjacent mineral soils, or groundwater. Nitrogen (N) availability differs with regard to other nutrients, because some microbes can utilize nitrogen straight from the atmosphere (Laiho & Alm 2005). Nitrogen deficiencies, however, especially in Scots pines growing on peatlands, are very typical (Reinikainen et al. 1998).

1.4. Aims of the study

Four questions were addressed in this thesis to study forest site productivity and the spatial arrangement of catchment properties (Fig.1).

1. Is it possible to explain forest site productivity as a function of phytogeomorphological site variables (I)?
2. Does the peat nitrogen concentration explain forest site productivity in drained biogenic areas (II)?
3. How does geomorphology affect the spatial arrangement of catchment properties and what is the variation of the properties in a large catchment population when described in terms of typical water flow paths (III)?
4. How does artificial peatland drainage affect the spatial distribution of catchment properties described with typical water flow paths (IV)?

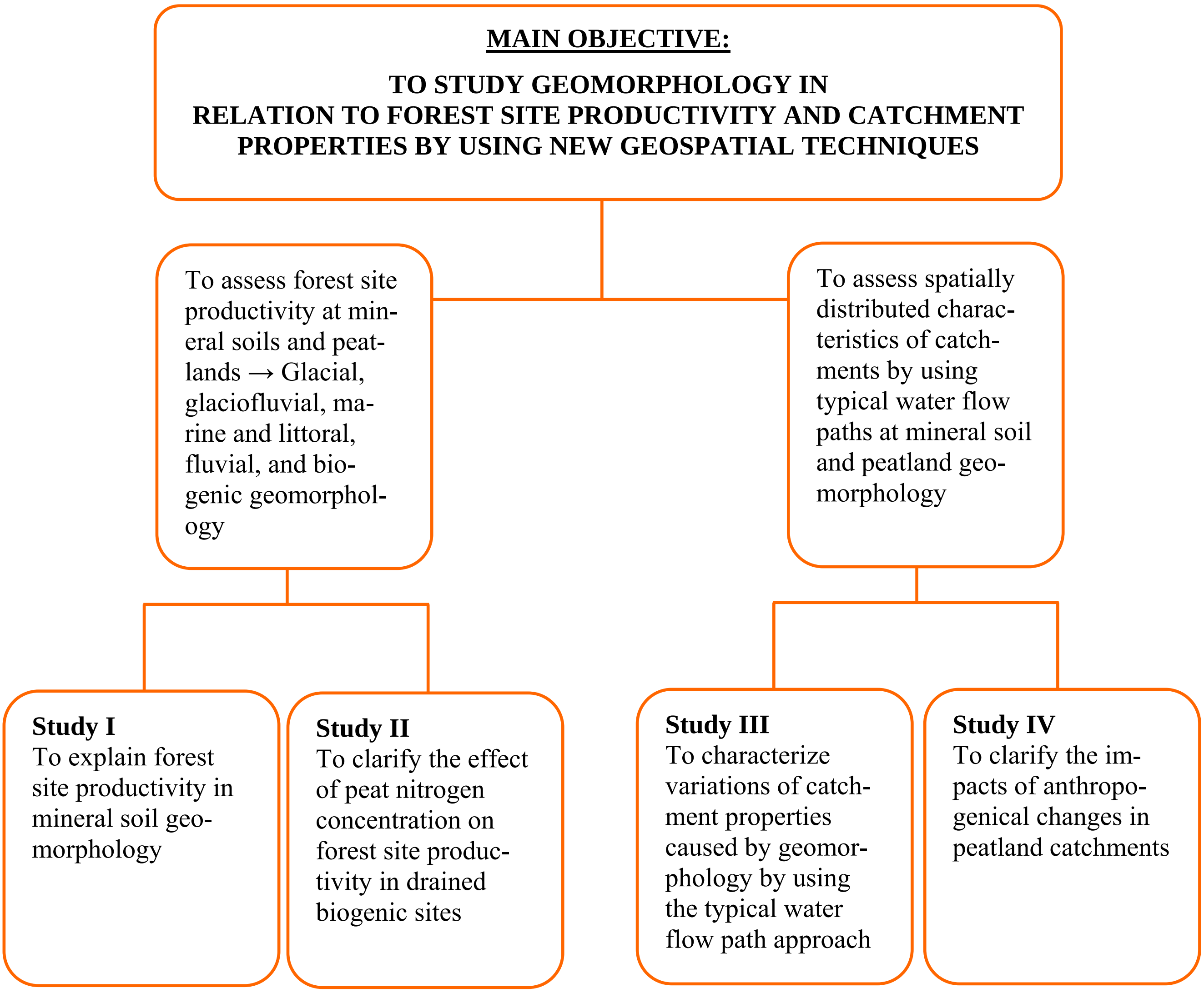


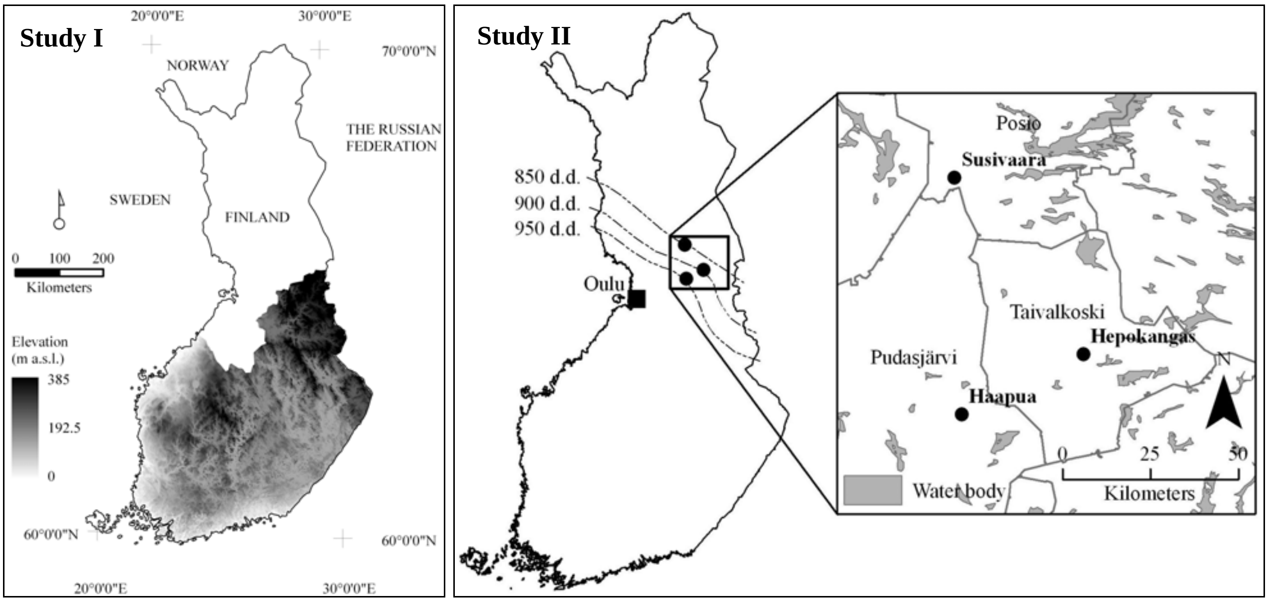
Fig. 1. Flow chart depicting the general aims of this study.

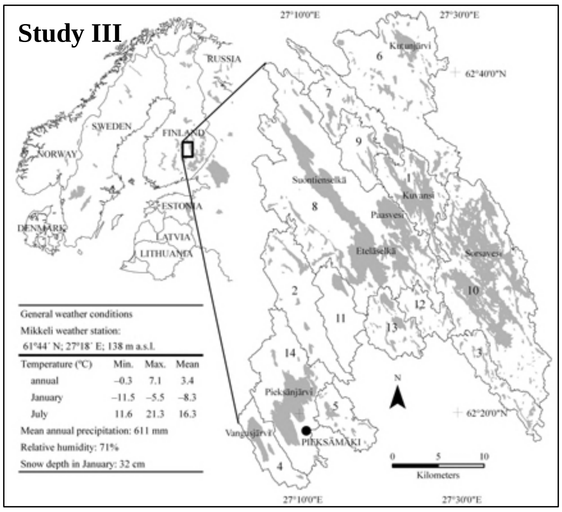
2. Material and methods

2.1. Study areas

The study areas are situated in southern (I), central (I, III, IV), eastern (IV), and northern (II) Finland (Fig. 2). The common relief of the studied parts of Finland is highly variable from south to east and north (I, Fig. 1 and II, Table 1). Precipitation in the northern study area is 600 mm, and that in the south is over 700 mm. The annual temperature sum decreases from south to north (1372 to 828 dd) (I and II, Table 1). The bedrock in the southern part of the study area consists mainly of Svecofennidic schists and Rapakivi granites. In the eastern part, basement gneisses and Karelidic schists dominate. The central and western parts contain Orogenic plutonic rocks, and the northern study sites hold granodiorites and gneisses of the Archean basement complex (Simonen 1987). While the southern and southwestern parts are dominated by clayey soils, sandy soils become more common towards the east and north. Peat deposits are also common all over the study area (Haavisto et al. 1987). Boreal coniferous forests cover about 70% of the total area of Finland. The vegetation types in the study areas vary from rich to dry heath types (Hämet-Ahti 1988). The original peatland site types in study II ranged from low sedge bogs (with *Sphagnum fuscum* hummocks) to herb-rich fens (Huikari 1952).

Study I covered approximately the southern half of Finland. Study II researched three drained peatlands from the municipalities of Posio (Susivaara), Taivalkoski (Hepokangas), and Pudasjärvi (Haapua) in northern central Finland. Study III examined 14 third-order catchments that were further divided into 782 head-water catchments in central Finland, and study IV concentrated on three third-order catchments (Mujejärvi, Tuomiojärvi, and Suihkolanjoki) in eastern and central Finland (Fig. 2).

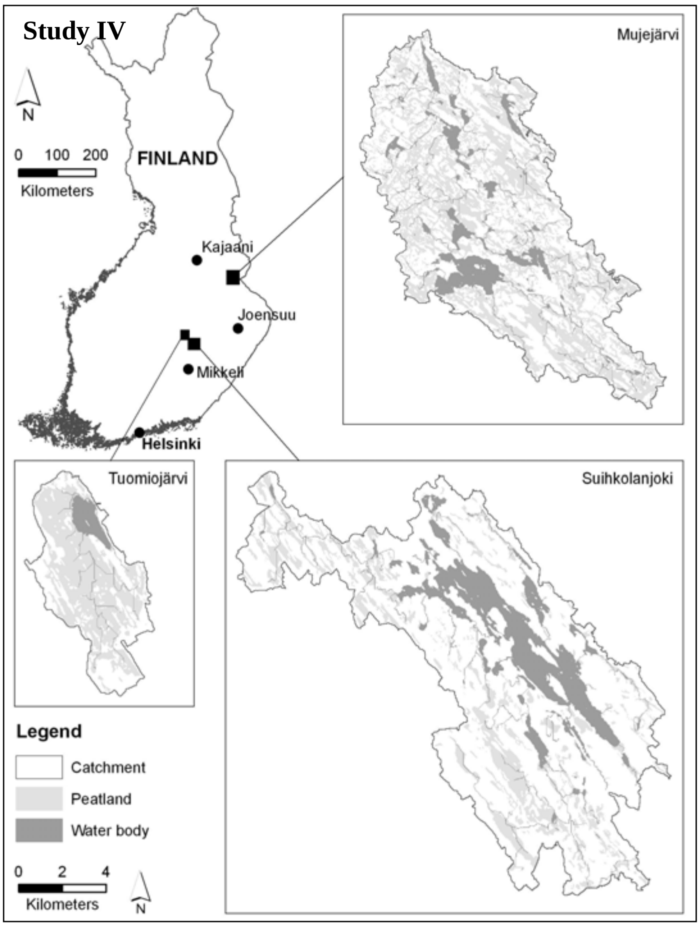




General weather conditions
Mikkeli weather station:
61°44´ N; 27°18´ E; 138 m a.s.l.

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



Study I: Elevations of the research area (a digital elevation model ©National Land Survey of Finland).
Study II: Three experimental fields in northern central Finland. Temperature sums (d.d.) between 1961–1990 (Ritari & Nivala 1993).
Study III: Locations of the 14 studied third-order catchments and information about the climatic conditions between 1971–2000 (Drebs et al. 2002).
Study IV: Locations of the three studied catchments.

Fig. 2. Locations and general information on the research areas in Finland.

2.2. Geomorphological interpretation (I–IV)

The geomorphological landforms in study I were interpreted by using raster-based contour line data with a scale of 1:20 000, geomorphological maps (Tikkanen 1981; 1989; Fogelberg & Seppälä 1986; Rönty 1999; 2002), and raster-based soil maps (Haavisto et al. 1987). Geomorphological and soil maps with a coarse resolution (i.e., a scale of 1:1 000 000) were used as a reference only to place the sample plots on map and to get a general overview of the area. Specific geomorphological interpretation was done with detailed maps. The following four relief types were considered: glacial, glaciofluvial, marine/littoral, and fluvial (I, Table 3 and Fig. 3). The most dominant relief type was glacial. Among the glacial landforms, the most frequent ones were those of undulating basal till and flat basal till. Drumlins were also relatively common. Other types of moraines were relatively few, and De Geer-moraines occupied only a small area. The glaciofluvial was the second most dominant relief type. Flat surfaces of glaciofluvial deposits were the most frequent landform in the glaciofluvial areas. Eskers and fine-sediment ice-marginal landforms were also found, whereas kames and sandurs were rare. The third relief type was marine and littoral, containing two landforms: fine-sediment plain and beach ridges. The plains appeared in areas close to water bodies where the water level has been stable for a long time. From the fluvial relief type, erosional valley and depositional plain landforms typically occur near rivers. However, their occurrence was rather limited.

In paper II, drained peatlands were studied. Three gently inclining biogenic areas (Susivaara, Hepokangas and Haapua) were mapped for the study (II, Table 1). Study III was completed in a drumlin field. The drumlins were mapped by using 1:20 000 raster-based contour maps. A DEM with a 25 m resolution was used to calculate hillshades, slopes, and aspects in order to identify the drumlins on the map. The geomorphological map of Finland (Fogelberg & Seppälä 1986) was also exploited. In total, 600 drumlins were detected within the study area (III, Fig. 2 and Table 1). Drumlins also dominated in the three third-order catchments studied in paper IV. At the Mujejärvi catchment, geomorphological landforms were mapped for interpretation by using maps and a DEM (Korkalainen 2002). The Tuomiojärvi catchment was situated within the study III area and the Suihkolanjoki catchment close to the southern part of the Tuomiojärvi catchments.

2.3. Forest data on site productivity (I and II)

The Finnish Forest Research Institute provided the forest data of the Ninth Finnish National Forest Inventory (NFI9) conducted between 1996 and 2003 for study I. In the NFI, sample plots are located as systematic clusters (Tomppo 2000), and every fourth sample cluster is permanent and used for re-measurements. Each permanent cluster has ten sample plots, while each temporary cluster has 14 plots. These clusters are defined by using the grid lines of the Finnish coordinate system (Tomppo 1998), whose interval in both north–south and east–west directions is six km. The cluster side length is 1750 m, and the distance between each sample plot inside a cluster is 250 m (I, Fig. 2).

As permanent plots have no data on tree ages from increment boring, all the sample plots used for this study were temporary ones. Only areas with upland mineral soils were chosen. Trees from the two most dominant tree strata were used, for in the lower strata, the competition between trees would mask the effects of forest site properties. Trees with major defects were excluded. Scots pine and Norway spruce with the ages of 30 to 110 yrs were included in the analysis, for within this range and according to study I, the relationship between tree height and age was nearly linear. The number of sample plots for Scots pine was 4151 (3053 unsorted soils and 1098 sorted soils) and that of Norway spruce 4795 (3792 unsorted soils and 1003 sorted soils).

For study II, forest data was provided by the Finnish Forest Research Institute. Scots pine stands were measured at Haapua and Hepokangas in the autumn of 1999 and at Susivaara in the autumn of 2004 by using 20 m × 20 m grids within circular sample plots with a radius of seven meters. The ages and diameters at breast height ($d_{1.3}$) and the total height of the 1687 sample trees were measured. Their stand volumes were calculated by using the equations described by Heinonen (1994). The average stand heights were calculated with reference to the sample trees.

2.4. Explanatory variables on forest site productivity (I and II)

In study I, forest site productivity was expressed as tree height at a known age. The tree species of this study were Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* [L.] Karst.). Forest site productivity was explained as a function of phytogeomorphological site variables. These variables were grouped into two: Group 1 with seven variables describing the geographical conditions of sites, including climate, and Group 2 with eight variables describing the local morphometric and soil properties (Table 1). The site fertility type, taken from field surveys of the NFI9, was included into the study. In study II, there was one explanatory variable provided by the Finnish Forest Research Institute: the total peat nitrogen concentration, also taken from field surveys, on the height and volume of Scots pine (*Pinus sylvestris* L.) stands.

Table 1. Phytogeomorphological site variables used in study I.

Group 1 variables:	Group 2 variables:
latitude coordinate (km)	elevation (meters a.s.l.)
longitude coordinate (km)	slope (degrees)
total annual temperature sum with threshold +5°C	aspect (degrees)
lake index (%)	calcium (Ca) content of the soil (%)
sea index (%)	the highest shoreline of the Baltic Sea
length of the growing season (days)	relief type
radiation index (kJm^{-2}growing season^{-1})	geomorphological landform
	catchment area

Fig. 3. is a schematic representation of a two-dimensional drumlin cross-section along the length axis. It shows the main processes of geomorphological, morphometrical, and soil properties on and in soil. It also displays some explanatory site variables used in studies I and II.

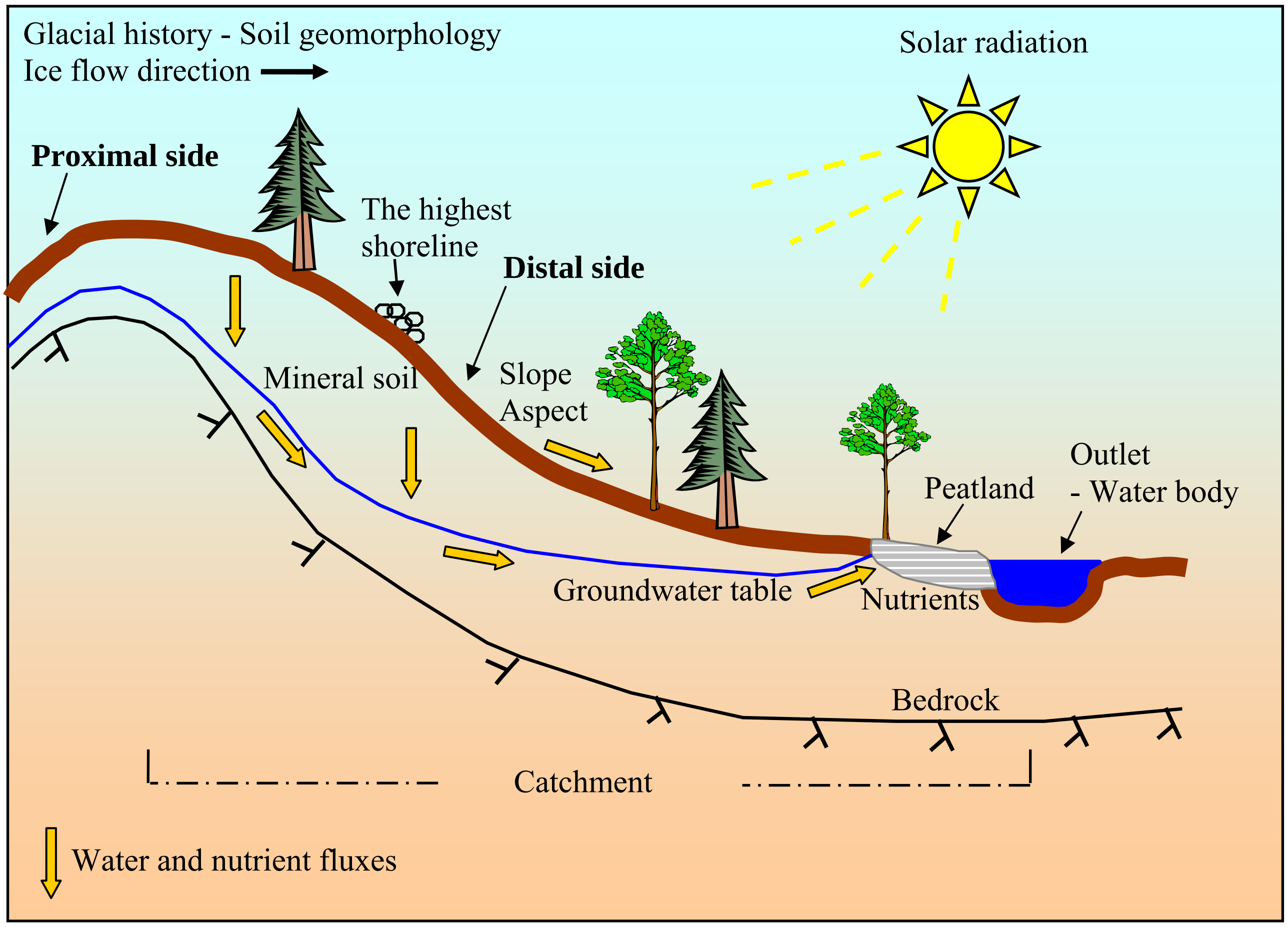


Fig. 3. Schematic drumlin cross-section and some site variables used to explain forest site productivity.

2.5. Regression analysis on forest site productivity (I and II)

Linear regression analysis (Weisberg 1985; Shaw & Wheeler 1997) was used to describe occurrences of significant relationships between the phytogeomorphological site properties and forest site productivity. In study I, the Schumacher (1939) model was used to explain tree height from tree age and the phytogeomorphological site variables described in chapter 2.4. The Schumacher model was used because it is a common and widely-used model for predicting tree height with regression equations. Categorical variables were used here as dummy variables. The mathematical formula derivation is presented in study I (equations 1−4). The final regression model for tree height is

$$\mathit{tree\ height} = c_0 + c_1 x_1 + \ldots + c_i x_p + b_1 A^{-1} + e\,, \tag{1}$$

where c_0 and b_1 are constants, $c_1 \ldots c_i$ are regression coefficients, $x_1 \ldots x_p$ are phytogeomorphological site variables, A is tree age at breast height (1.3 m) and e is residual.

In study II, regression analysis was applied to explain the Scots pine stand height and volume as a function of the total peat nitrogen concentration.

2.6. Use of a DEM in the description of morphometry (I, III, and IV)

The morphometrical parameters were derived from a DEM with a 25 m resolution by using spatial analysis tools (Hoersch et al. 2002; Finlayson & Montgomery 2003; Ayalew & Yamagishi 2004; Chau et al. 2004). The parameters defined directly from the DEM were elevation (Tikkanen 2002; Tikkanen & Oksanen 2002; Hättestrand et al. 2004), slope (Finlayson & Montgomery 2003), and aspect (Zhou & Liu 2004). Morphometrical parameters permit various modeling applications in earth sciences (Tucker et al. 2001; Tikkanen 2002), hydrology (Jones 2002), and ecology (Luoto & Heikkinen 2003). Morphometrical parameters are also used in morphological classification (Walsh et al. 1998).

2.7. Catchment analyses (I, III, and IV)

The catchments (I, III, and IV) were determined by using a DEM with a 25 m resolution and raster data operations with hydrological modeling tools (Jones 2002; He 2003; Ko & Cheng 2004). Catchment analysis uses algorithms of 3 × 3 cell matrices (Jenson & Domingue 1988) and requires three datasets in raster format:

(1) A filled elevation grid, where pits are filled by increasing the elevations of the cells within each depression to the level of the lowest cell on the depression boundary (Jenson & Domingue 1988; Tucker et al. 2001). A depression is a cell or cells surrounded by higher elevation values. Depressions are cells of internal drainage. They can be natural, such as glaciated potholes, but usually they are imperfections in the DEM (MacMillan et al. 2000; Chang 2002).

(2) A flow direction grid that shows the direction of water draining out of each cell from an elevation grid (Tucker et al. 2001). This is an iterative procedure, and in each iteration, the cells are assigned a flow direction to one of the cells in the 3 × 3 cell matrices (Jenson & Domingue 1988). The most common method for determining a cell's flow direction from its source cell is to find the steepest distance-weighted gradient in relation to one of its eight surrounding cells (D8 method) (Jenson & Domingue 1988; Jones 2002; Oksanen & Sarjakoski 2005; Sørensen et al. 2006). For the four nearest neighbours, the slope gradient is calculated by dividing the elevation difference between the centre cell and the neighbour cell by one, and the four corner cells by 1.414. This method does not allow the flow to be distributed to multiple cells. Only one direction cell is possible. If the descent to all adjacent cells is the same, the neighborhood is enlarged until the steepest descent is found (Chang 2002).

(3) A flow accumulation grid defining for each cell the number of cells that drain into it. It is quite common that cells having high accumulation values are stream channels or potholes. Instead of a value of zero, the cells are usually located in hills or ridgelines (e.g., drumlin top). Therefore, the drainage network can be derived from the accumulation grid by using a threshold accumulation value. Flow accumulation is used for defining catchments, either by using the user-defined minimum grid size to delineate it, or by deriving it from any starting cell in accordance with the threshold (Jones 2002).

2.8. Water flow path approach at catchment scale (III and IV)

The spatial arrangement of catchment properties in studies III and IV were characterized by using the typical water flow path approach from the water divide to the receiving water body. The properties of the typical water flow path included length, surface slope, elevation, relative width, and soil type (mineral soil and peatland). Based on the typical water flow path, the three-dimensional catchment domain was simplified into a vertical, two-dimensional characteristic profile, where hydrological and nutrient transport models operating at a hillslope scale can be implemented (Laurén et al. 2005; Koivusalo et al. 2006; Kokkonen et al. 2006; Laurén et al. 2007). Determining the surface geometry of a typical water flow path, i.e., length and slope, is based on analyses of the catchment DEM and on the mapped water body locations within the study areas (III and IV).

The distance along the water flow path from any grid cell to the receiving water body cell was computed for all cells in the studied catchments by following the water flow path until the path intersected a water body cell. The elevation difference between each start cell and its receiving water body cell was also recorded. This computation produced the surface geometry of the steepest water flow paths. For class variables, such as soil types, average values at distance intervals cannot be computed. Thus, soil type values were assigned to the characteristic profile according to their prevalence at a given distance interval from a water body. The soil data used in this thesis was a raster-based dataset in a scale of 1:20 000. In study III, the soil types along the steepest water flow paths were categorized into mineral soils, fine soil texture, peatlands, and thin peat layers (0.4–0.9 m depth) on mineral soil. In study IV, only mineral soils and peatlands were separated.

A two-dimensional catchment description can account for a 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 at a given distance interval. This was identified by counting the number of cells residing at each distance interval along the water flow paths. The distribution of mineral soil and peatland areas along the water flow paths were determined by counting cells that fall within mineral soil and peatland masks.

The typical water flow path was divided into a number of sections, each of which represented the distance to the receiving water body at intervals of 25 m. The average elevation of the cells residing in one section (i.e., at a given distance interval) determined the elevation of the section. The fraction of cells from all the cells belonging to a catchment determined the width of the section, and the prevalent properties of the cells within the section determined the soil type. However, in study III, the last section included a class of 1000−2326 m distance from the water body, and in study IV, the typical water flow path was cut off at the distance where 95% of the catchment area is covered. This was done because only a few individual water flow paths existed near the catchment divide, and therefore, the number of cells decreases in the sections near the upslope end of the water flow paths causing unrealistic elevation fluctuations in the tail of the typical water flow path.

The properties of the typical water flow paths were first analyzed, neglecting the ditches in the peatlands (III and IV). Then, the typical water flow paths were determined with the ditches read from basic maps (IV). In study III, 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 & Taper 2002). Variance component analysis was used, because it allowed comparisons of small-scale and large-scale variations of catchment populations. In addition, the MINQUE method was utilized, because of its considerable flexibility with respect to the form of models that were fitted to the catchment data.

Fig. 4 shows the main processes for water and nutrient fluxes in a catchment and the concept of the steepest water flow path approach.

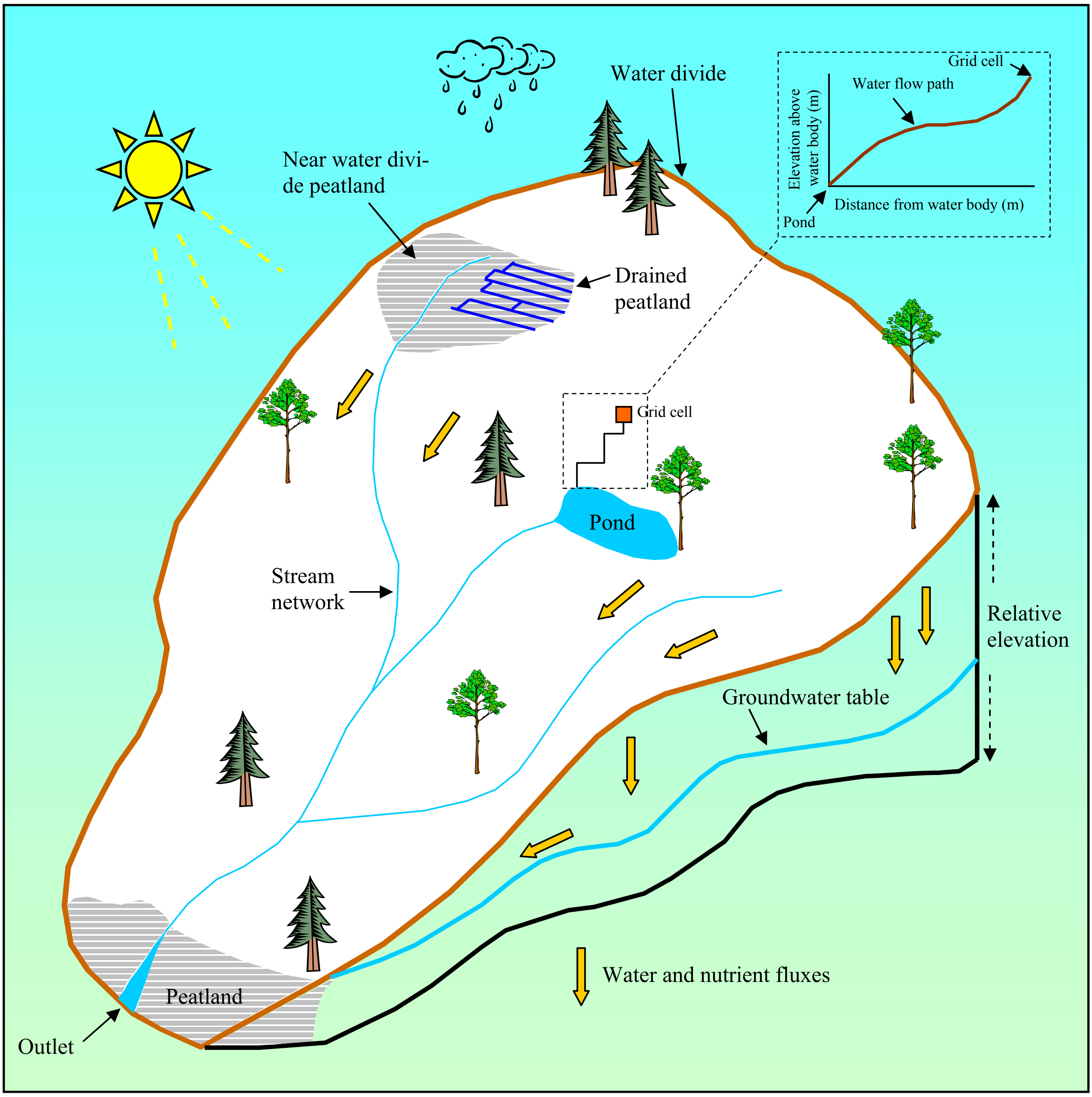


Fig. 4. Schematic catchment presentation, water and nutrient fluxes, and concept of the steepest water flow path approach. Water flow paths were computed for all grid cells within a catchment.

3. Results

3.1. The effect of phytogeomorphological properties on forest site productivity (I and II)

The phytogeomorphological site variables affected forest site productivity. Steep slope, southerly aspect, long growing season, high temperature sum, high lake and radiation indices as well as a high total peat nitrogen concentration increased forest site productivity. The northerly latitude coordinate, the high elevation of a site, and the high sea index, however, decreased the productivity (I, Table 4 and II, Figs. 3 and 4). The latitude coordinate, the length of the growing season, and the temperature sum were the best individual phytogeomorphological site variables to explain forest site productivity. However, the site fertility type, taken from field surveys, increased the reliability of the results of forest site productivity (Table 2). Neither the relief nor the landform type and the catchment area significantly affected forest site productivity.

Table 2. Estimated individual regression parameters for Scots pine and Norway spruce for unsorted and sorted soils.

		Scots pine, unsorted soil				**Scots pine, sorted soil**				**Norway spruce, unsorted soil**				**Norway spruce, sorted soil**			
	Variable	Value	Std. err.	R^2	σ_E	Value	Std. err.	R^2	σ_E	Value	Std. err.	R^2	σ_E	Value	Std. err.	R^2	σ_E
	A^{-1}	-19.6924	0.4678	0.367	0.1933	-20.5979	0.8296	0.359	0.1946	-20.0774	0.5308	0.274	0.1965	-20.2650	1.0004	0.290	0.1870
Group 1	*LAT*	-4.767E-04	2.341E-08	0.443	0.1814	-5.475E-04	3.844E-08	0.459	0.1788	-5.751E-04	2.732E-08	0.350	0.1859	-4.822E-04	4.870E-08	0.353	0.1785
	LONG	7.620E-05	2.595E-08	0.369	0.1931					7.728E-05	2.597E-08	0.275	0.1963	1.048E-04	4.722E-08	0.293	0.1866
	TS	5.892E-04	2.795E-05	0.447	0.1807	7.291E-04	4.783E-05	0.471	0.1768	7.318E-04	3.469E-05	0.350	0.1859	6.032E-04	6.558E-05	0.345	0.1796
	LAKE	3.247E-03	2.868E-04	0.393	0.1894	3.585E-03	5.203E-04	0.385	0.1906	3.310E-03	3.069E-04	0.295	0.1936	2.556E-03	6.110E-04	0.302	0.1854
	SEA	-2.215E-03	3.769E-04	0.374	0.1923	-1.017E-03	4.582E-04	0.362	0.1943	-2.458E-03	3.445E-04	0.283	0.1952	-3.544E-03	5.683E-04	0.316	0.1835
	GS	5.910E-03	4.180E-04	0.406	0.1873	6.864E-03	6.607E-04	0.416	0.1858	6.223E-03	4.649E-04	0.306	0.1920	5.200E-03	8.105E-04	0.317	0.1833
	RI	5.519E-05	1.089E-05	0.372	0.1926	6.803E-05	1.901E-05	0.366	0.1936	2.652E-05	9.658E-06	0.275	0.1963				
Group 2	*ELEV*	-7.144E-04	6.186E-05	0.394	0.1893	-9.293E-04	1.082E-04	0.399	0.1885	-3.732E-04	6.527E-05	0.280	0.1957				
	SLOPE	7.272E-03	1.122E-03	0.376	0.1921	1.260E-02	1.998E-03	0.381	0.1913	9.688E-03	9.707E-04	0.292297	0.1940	8.911E-03	2.109E-03	0.301797	0.1854
	ASPECT	2.821E-04	6.235E-05	0.371	0.1927	4.498E-04	1.009E-04	0.37	0.1929	1.625E-04	5.860E-05	0.275166	0.1963				
	CA	-1.129E-01	5.696E-02	0.374	0.1916												
	SHORE			0.369	0.1931			0.372	0.1928			0.276632	0.1961			0.292134	0.1867
	-sub	5.5580	9.182E-03			5.5654762	1.62E-02			5.6709	1.013E-02			5.7159441	1.911E-02		
	-supra	5.5333	8.231E-03			5.4983691	1.43E-02			5.6403	7.803E-03			5.6799377	1.811E-02		
	FOREST			0.553	0.1626			0.541	0.1647			0.43768	0.1729			0.427032	0.1680
	-SC $_1$	5.7530	9.72E-03			5.7360	1.728E-02			5.7710	5.756E-03			5.7898	1.122E-02		
	-SC $_2$	5.5875	8.30E-03			5.6301	1.523E-02			5.5993	9.054E-03			5.6384	1.806E-02		
	-SC $_3$	5.7291	-1.42E-01			5.5003	1.086E-02			5.3823	1.983E-02			5.4501	3.773E-02		
	-SC $_4$	5.9443	-3.57E-01			5.2897	2.254E-02										
	-SC $_5$	6.0219	-4.34E-01			5.4147	9.554E-02										

Note: The number of records for Scots pine was 4151 and for Norway spruce 4795. Value=coefficient, Std. err.=standard error of the regression coefficient. R^2=Adjusted R Square, σ_E=standard error of the estimate. Tree height is a dependent variable, the others are independents. A^{-1} is inverse of tree age (yrs^{-1}.) form function, *LAT*=latitude (km), *LONG*=longitude (km), *TS*=total annual temperature sum with threshold +5°C, *LAKE*=lake index (%), *SEA*=sea index (%), *GS*=length of the growing season (days), *RI*=radiation index (kJm^{-2}growing season^{-1}), *ELEV*=elevation (meters a.s.l.), *SLOPE* and *ASPECT* (degrees), *CA*=Calcium content of the soil (%), *SHORE*=the highest shoreline of the Baltic Sea, *SC*=fertility class (for Scots pine *1*=grove and grove-like, *2*=damp, *3*=dryish, *4*=dry, *5*=barren, rocky land, sands and alluvial land and for Norway spruce *1*=grove and grove-like, *2*=damp, *3*=dryish, dry, rocky land, sands and alluvial land.

The best combinations of the phytogeomorphological site variables and the tree age and their effects on forest site productivity are presented in models 1–5 in study I, Tables 6–8. Model 1 shows the regression between tree age and tree height. In Model 2, analyses were done for seven Group 1 variables. This analysis gave 16.6–17.9 dm standard errors. In Model 3, some Group 1 and Group 2 variables were analyzed together, which only slightly decreased the standard errors. Thus, Group 2 has much weaker effects on forest site productivity than Group 1. Model 4 analyzed the Group 1 variables with the site fertility types, yielding a lower standard error (14.3–15.9 dm). In Model 5, The Groups 1 and 2 variables and the site fertility types were analyzed together, but that did not significantly reduce standard errors. The results for Norway spruce with sorted soils were common to Models 4 and 5. The values of the standard error indicated that the phytogeomorphological variables generally explained the forest site productivity for Scots pine better than that of Norway spruce.

An example application was conducted for Norway spruce with an age of 70 years, growing on unsorted soil in central Finland, by using the parameter values of Model 3, as shown in Table 6 (I). This revealed that trees on a 20-degree slope were 1.5 m higher than trees on a 5-degree slope, trees on south-facing slopes were 0.5 m higher than trees on north-facing slopes, and trees with 0.5% soil Ca-content were 1.5 m higher than trees with a soil Ca-content of 0.1%. An example application was also conducted for sorted soils (Model 3). It showed that trees on a 20-degree slope were 2.0 m higher than trees on a 5-degree slope, and a 10% lake index produced 0.8 m higher trees than a 1% lake index.

In an all three biogenic areas of study II, forest site productivity improved with increasing peat nitrogen concentration. At Haapua and Hepokangas, the relationship between peat nitrogen and forest site productivity was strongest. According to the trendline as seen in II, Fig. 3 and Fig. 5 below, the stand height (about 140 dm) and the volume (about 190 m3/ha) were highest at Haapua when the peat nitrogen concentration rose up to 3.0%. At Hepokangas, the stand height was about 90 dm and the volume 70 m^3/ha when the N concentration was highest (2.8%). At Susivaara, the stand height was also about 90 dm and the volume at 80 m^3/ha at the highest level of N concentration (2.5%). However, a few high individual stand height and volume values were found even under a level of 2.0% N concentration in all three study areas. Fig. 5 represents the relationships between peat nitrogen concentration and forest site productivity in terms of the average Scots pine stand volume. Cf. II, Fig. 3 and Table 3.

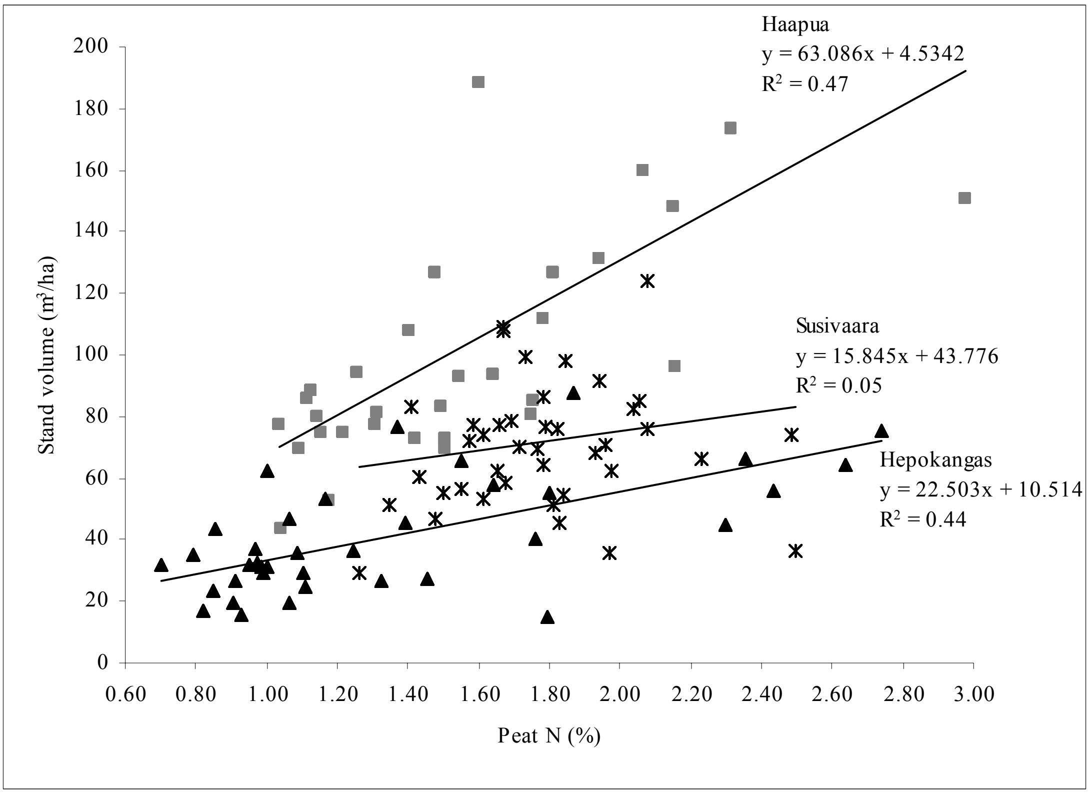


Fig. 5. Relationships between peat nitrogen concentration and average Scots pine stand volume by sample plots.

3.2. The effect of geomorphology on catchment properties (III and IV)

In studies III and IV, drumlin landforms characterized the shape of the typical water flow paths. In the drumlin ridges, the steepest slopes were situated at the proximal side and the more gentle slopes at the distal side. The flat areas between the drumlins were typically dominated by peat deposits. The drumlins in the study catchments were clustered (III, Fig. 2) with varying size and form (III, Table 1). The number of drumlins in each catchment varied, depending on their position in the landscape.

The elevation of the typical water flow path profiles near the water body were low (Fig. 6 and IV, Fig. 3), followed by steeper slopes. Depending on the changing number of drumlins and on their asymmetric form, the typical water flow path variation within the studied 782 head-water catchments was large in comparison to the variation between the 14 third-order catchments (Fig. 6). Diverging hillslope profiles were frequently formed into catchments characterized by the drumlin field, i.e., its topography was dominated by drumlin peaks and flat peat areas between them, showing that a substantial area of the catchments was concentrated near the receiving water body (III, Fig. 4). Anthropogenic effects, i.e., peatland drainage, were found to change the catchment properties within drumlin fields. Drainage decreased the length and elevation of the typical water flow path (IV, Fig. 3) and drastically increased the area near the water body: at Mujejärvi 40.0%, at Suihkolanjoki 17.1%, and at Tuomiojärvi 60.7% of the catchment area was closer than 25 m from a water body (Fig. 7). After drainage, almost all peatlands were concentrated next to the receiving water body (IV, Figs. 5B–7B): at Mujejärvi 87.1%, at Suihkolanjoki 75.4%, and at Tuomiojärvi 98.9% of peatlands were no farther than 25 m from the water body.

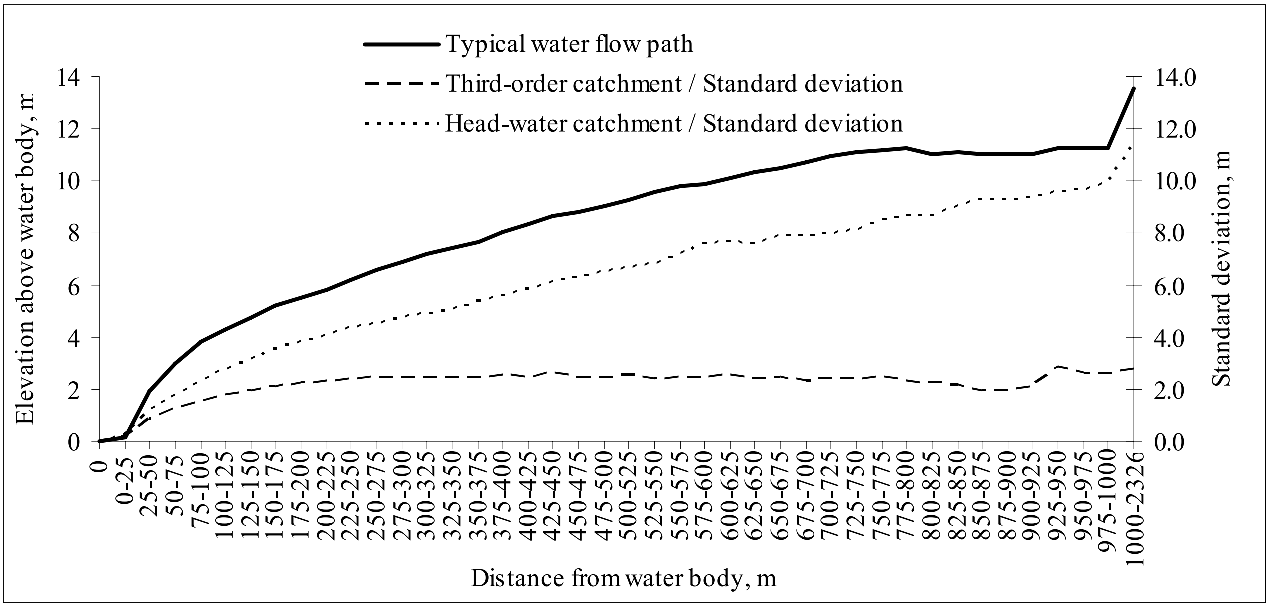


Fig. 6. The typical water flow path and standard deviations between 14 third-order catchments (large-scale catchment variation) and within 782 head-water catchments (small-scale catchment variation) as average values within 25 m sections along the water flow path.

Because of the drumlin landforms, mineral soils dominated throughout the typical water flow path, whereas peatlands represented a smaller proportion (III, Figs. 5–7). Even though the peatlands were rather evenly distributed along the typical water flow path, most of them were situated close to the water body, where, correspondingly, the share of mineral soil was smallest. The characteristics for the average head-water catchment in a drumlin field were also calculated (III, Fig. 8) 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 paths 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.

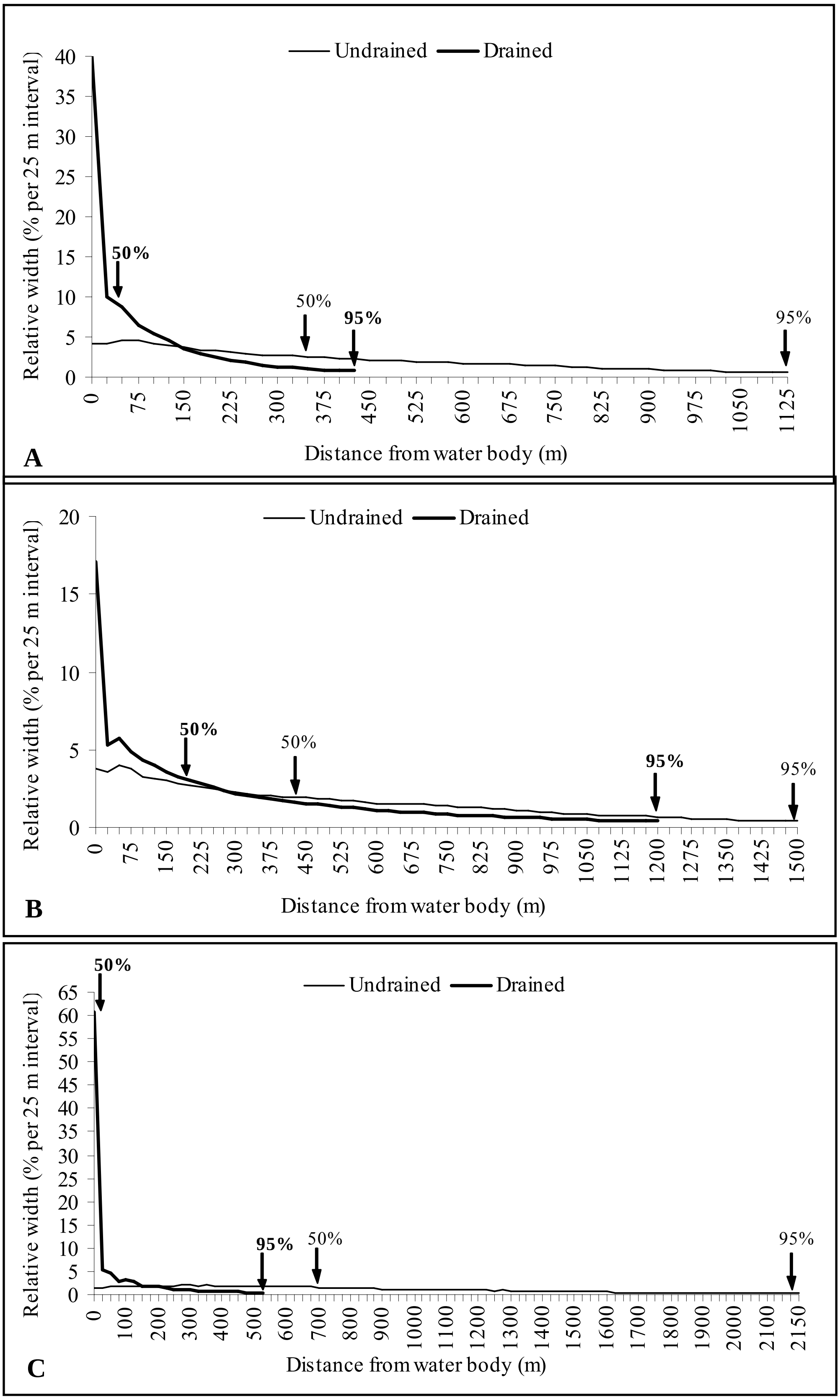


Fig. 7. Relative widths of the profiles (i.e., the proportion of a catchment area at a given distance interval) at the Mujejärvi (A), Suihkolanjoki (B), and Tuomiojärvi (C) catchments in undrained and drained conditions. Width distribution is shown as a function of distance along the typical water flow path in 25 m distance intervals. The numbers show the proportions (50% and 95%) of the catchment area to be located closer to a water body than the distance at the arrow tip.

4. Discussion

Although phytogeomorphological site variables were found to affect forest site productivity, some uncertainties arose during the analyses. Geomorphological classification requires a simultaneous consideration of large areas and small-scale details of the various landforms. Landforms are different in their size and form. Thus, especially small geomorphological landforms without any specific form are difficult to interpret from maps. Field work, as noticed in studies I and II, was found to improve the reliability of the results added to cartographic landform interpretation and computer aided modeling. Therefore, data from field surveys is highly valuable and should be incorporated into phytogeomorphological studies. Morphometrical and catchment-scale analyses from a DEM are dependent on the spatial resolution of the data. A resolution of 25 m may be too coarse for a detailed morphometrical description. In the near future, a DEM with a resolution of ten meters will become available (Valtakunnallisen… 2006) and may increase the reliability of the geomorphological and catchment-scale methods used in this study. Problems may occur also in determining catchment boundaries, because anthropogenic changes, such as road construction and drainage, change natural catchments. However, despite the presented uncertainties, the results of this study have revealed a new understanding of how to use geomorphology in the analysis of forest site productivity and catchment properties. The use of large datasets increased the plausibility of the results.

From all the phytogeomorphological variables, slope increase had a positive effect on forest site productivity, whereas aspect had only a minor effect. This is in accordance with Tamminen (1991). However, Roiko-Jokela (1980) observed that the slope did not affect the tree growth. Worrell (1987) noticed that tree productivity was highest on north to east facing slopes. Poso & Kujala (1973) showed that southwest, west, and northwest aspects produced the greatest tree productivities. Solar radiation reaching the soil is related to latitude, slope, and aspect affecting the temperature conditions on the site (Spurr & Barnes 1980; Shuttleworth 1992). The latitude coordinate, the length of the growing season, and the temperature sum were the best phytogeomorphological variables to explain forest site productivity in this study. Koivisto (1970) and Roiko-Jokela (1980) reported a similar dependency. The results showed that the forest site productivity was lower in the north than in the south. Longer growing seasons and higher temperature sums represent more positive climatic conditions in southern Finland than in northern Finland (Viro 1962; Koivisto 1970; Tamminen 1991; 1993; 2000).

This study showed that an increasing total peat nitrogen concentration had a positive effect on forest site productivity in low temperature sum regions. Heikurainen (1959), Kuusela (1977), Keltikangas et al. (1986), and Ritari & Nivala (1993) showed that the regional climatic conditions affected the growth of trees on drained peatlands. In this study, the temperature sum of 950 d.d. at Haapua was adequate for an increasing forest site productivity, which was comparable to the results of Moilanen (1993). In contrast, at Hepokangas and Susivaara, at the temperature sum levels of 900 d.d. and 850 d.d., forest site productivity was lower. However, the forest site productivity at Susivaara (290 m a.s.l.) was higher when compared to Hepokangas (240 m a.s.l.). More favorable local climate conditions and a higher nitrogen concentration in the peat may have increased the forest site productivity at Susivaara when compared to Hepokangas. In the low temperature sum regions, nutritional aspects and the high elevations of the sites substantially affected forest site productivity.

The proximity of lakes increased forest site productivity. Non-saline lake water provides permanent water resources for trees. The sea index, however, decreased forest site productivity. Worrell (1987) found that in Britain tree productivity was higher in inland than in coastal areas. The sea affects climatic factors such as windiness near seashores (Ojansuu & Henttonen 1983). Moreover, rockiness and stoniness usually increase near seashores, which restricts tree growth (Viro 1958; Kuusela 1977). It was also found, in agreement with Kuusela (1977), that forest sites near the sea were flatter and lacked fertile soils, which may also have a negative effect on tree growth (Tamminen 1991). Kuusela (1977) concluded that the low tree productivity in seashore areas could be caused by the lack of water resources as a consequence of the shorter accumulation time for soil organic matter on recently uplifted coastal terraces.

In this study, the high elevation of a site has shown to decrease forest site productivity. Koivisto (1970) noticed that high elevations negatively affected the tree growth for Norway spruce. Worrell (1987), on the other hand, found that, in Britain, tree productivity decreased by three to four m^3/hectare with every 100 m elevation increase because of changes in the climatic conditions and in soil properties. The average Environmental Lapse Rate (ELR) in the troposphere is an air temperature decrease of 0.65° per 100 m rise in elevation. In the current study, the effect of elevation was clear for Scots pine, whether growing in mineral soils or drained peatlands, but not for Norway spruce. In general, the unexplained tree height variation of Norway spruce was greater than that of Scots pine, suggesting that other sources of variation may mask the effect of elevation. For example, the height growth of a young Norway spruce may be rather slow because of suppressing tree strata. The period for slow growth may vary, depending on the competition among trees and vegetation as well as on the tending of the forest (Ilvessalo & Ilvessalo 1975). High elevations are also areas at risk to snow damage (Hyvän metsänhoidon… 2006). This was found in the Scots pine stands growing in drained peatlands in northern central Finland, in which many trees suffered from snow load damage. The risk is high, especially in Scots pine stands, because of their asymmetric and broad crowns (Autio & Colpaert 2005).

The size and form of drumlin landforms were characterized by catchment properties, expressed as two-dimensional typical water flow path profiles. Although typical water flow path studies are scarce in literature, some of the characteristics discovered can be considered to be typical of drumlin landforms. The large within-catchment variation of the typical water flow path elevation, as found from 782 studied head-water catchments, may originate in the asymmetric form of the drumlin peaks, the steepest slopes of which are at the proximal side of the drumlin ridge, while the distal side is characterized by gentle slopes. The hillslope gradient is primarily controlled by the geomorphological settings of the catchments (Bogaart & Troch 2006). The topography of the typical water flow path profile close to the water body was nearly flat, and thus, 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). These riparian areas are probably annually washed by spring floods, which make them vulnerable to nutrient leaching.

The categorization of soil types showed that peatlands existed along the entire length of the typical water flow path, rather than that they would mainly concentrate close to the water body. Rodhe & 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. Crave & Gascuel-Odoux (1997) observed that elevation difference within a catchment correlates negatively to soil moisture. They also found that the soil moisture status was more variable in lower than in higher elevations.

The changes in the catchment properties caused by anthropogenic drainage were remarkable. Drainage changed the profile geometry and composition and increased the area close to water bodies. Drainage has also been found to increase nutrient loads transported to water bodies (Ahtiainen & Huttunen 1999). Part of this effect can be understood as a result of the increased near-stream catchment area represented here. A short water flow path in the catchment results in a short residence time of water and decreases the buffering capacity of the catchment (Cirmo & McDonnell 1997). The total load to watercourses increases, for when the nutrient load has entered ditches, the means for controlling the load are scarce. It is, however, possible to channel the water from the ditches to a peatland buffer area, which can reduce nutrient loading (Silvan et al. 2004).

The compilation of characteristics of an average catchment was based on the results of the proportions of peatlands and mineral soils along a typical water flow paths studied from 782 head-water catchments. Although the 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.

The results of this study can be utilized when determining forest site productivity in southern and central Finland, using the presented regression models. It is also possible to assess fertilizing and stand regeneration of drained biogenic areas in high latitudes and low temperature sum areas. The typical water flow paths can be used when 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), Kokkonen et al. (2006), and Laurén et al. (2007). It is furthermore possible to estimate the fraction of a catchment area situated at a certain distance along the typical water flow path from a water body. This area estimate could be used when calculating the costs of restricting forestry operations for purposes of water protection.

5. Conclusions

Based on the results, the following conclusions were deduced:

1. Phytogeomorphological site variables were found to be relevant for the assessment of forest site productivity, represented by the height of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* [L.] Karst.). The phytogeomorphological site variables were divided into two groups (Table 1), of which the latitude coordinate, the length of the growing season, and the temperature sum were the most significant variables for explaining forest site productivity. It was noticed that most of the site variables explained the forest site productivity of Scots pine better than that of Norway spruce. This may reflect the fact that Scots pine forests tend to occur in dry and less fertile sites, where even a slight decline in external environmental conditions may significantly disturb tree growth.

2. The total peat nitrogen concentration had a positive effect on forest site productivity that is expressed as the height and volume of Scots pine (*Pinus sylvestris* L.) stands growing on drained biogenic areas. This study was completed in areas where low temperature sums normally restrict tree growth. However, it was found that forest site productivity increased with an increasing total peat nitrogen concentration, even in areas of low temperature sums and high elevations.

3. The typical two-dimensional water flow path approach provided a new perspective to assess the spatial arrangement of catchment properties within a drumlin field. The differences in size and form of drumlin landforms and the flat peat areas between drumlin peaks within the study catchments characterized the shape of the typical water flow path profile. Variation within the 782 head-water catchment population was large, resulting from the landform properties within the catchments.

4. Peatland drainage had a strong effect on the spatial arrangement of catchment properties in this study. Drainage changed the typical water flow path geometry and composition and increased the area close to water bodies. Drainage also concentrated almost all peatlands near the receiving water body.

This thesis is a quantitative representation of the usefulness of geospatial methods to assess geomorphology in regard to forest site productivity and catchment properties. The study showed that by using new methods and introducing new perspectives, it was possible to connect the traditional geographical research field with other scientific fields, especially with forest sciences, and thus, to produce convergent multidisciplinary research. Innovative geospatial methods and applications for utilizing DEMs and other spatial data are nowadays developing rapidly. This also provides great possibilities for developing new ideas of studying geomorphology for different purposes. For this study, it was already possible to analyze an immense amount of phytogeomorphological and catchment-scale variables of relatively large study areas straight from the DEM and other digital data. Overall, it was concluded that phytogeomorphological site variables affected forest site productivity and that the typical water flow path approach was usable to analyze the spatial arrangement of catchment properties. The thesis also presented several practical fields in which the results of this study can be utilized. In future, it would be important to expand this type of geomorphological studies to larger areas that may further specify the results achieved in this research. In this study, the main geomorphological landform was the drumlin. Future analyses should also incorporate other geomorphological landforms.

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