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Samuli Joensuu

VANTAAN TUTKIMUSKESKUS

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Academic dissertation

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VANTAAN TUTKIMUSKESKUS – VANTAA RESEARCH CENTRE

Opponent Prof. **Leena Finér**
University of Joensuu
Faculty of Forestry

Reviewers Doc. **Lars Lundin**
Swedish University of Agricultural Sciences
Department of Forest Soils
Uppsala, Sweden

Prof. (emer.) **Eero Paavilainen**
Finnish Forest Research Institute
Vantaa Research Centre

Supervisor Dr. **Erkki Ahti**
Finnish Forest Research Institute
Vantaa Research Centre

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Author's address Samuli Joensuu
Forestry Development Centre Tapio
Soidinkuja 4
FIN-00700 Helsinki
Tel. +358 9 1562 432, fax: +358 9 1562 232
e-mail: samuli.joensuu@tapio.mailnet.fi

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Abstract

Joensuu, S. 2002. Effects of ditch network maintenance and sedimentation ponds on the export loads of suspended solids and nutrients from peatland forests

Even if forestry is not the major source of diffuse loading to watercourses in Finland, it is important in headwater areas. Regarding water protection, forest drainage, and today, ditch network maintenance are considered the most harmful measures in Finnish forestry. This thesis deals with the effects of ditch network maintenance on runoff water quality from peatland forests. The study is based on a relatively large number of paired catchments consisting of a control and a treated area that had been calibrated before treatment.

The characteristics of runoff water from old ditch networks in peatland forests were first studied. The study is based on 75 peatland drainage areas located in pairs in different parts of Finland during a 1 – 3 year period (1990–1993). In a second phase of the study, ditch network maintenance was carried out in one of the areas in each pair of catchments (40) in 1991–1993. The other area in each pair of catchments was left untreated and is used as a control. Catchment characteristics were used to explain changes in runoff water quality. Export loads were calculated from observed concentrations and discharge. Additionally, discharge data produced by the Finnish Environmental Administration were used. The effects of sedimentation ponds on the concentrations and export loads of suspended solids (>1.2 μm) were examined in 37 of the catchments installed at the time of ditch maintenance. About half of the ponds functioned well or satisfactorily as regards retention of suspended solids. In part of the ponds the concentrations of suspended solids increased immediately after construction but then declined. This was attributed to erosion of the pond walls. The retention of nutrients in the ponds was negligible.

The long-term effects of ditch network maintenance on runoff water quality were studied. For this purpose, the characteristics of runoff water were monitored during six years after treatment in 23 of the 40 catchments. The effects of ditch network maintenance on the increased concentrations of suspended solids and a few nutrients were still significant six years after treatment. For individual catchments, the duration of change was largely dependent on soil characteristics.

Finally, the possibilities and problems connected to a data originating from an exceptionally large set of catchments situated in different parts of Finland are discussed. Varying site characteristics are used to explain the variation in runoff water quality. By using data from a large number of sites, good representativity of the relationships between water quality variables and site characteristics are thrived at. Compared with traditional hydrological research with a few catchments and more continuous and accurate data, the data of this study is less suitable for estimating changes in an individual catchment.

Key words: catchments, ditch network maintenance, element concentrations, forest drainage, nutrient leaching, runoff, sedimentation ponds, water protection, water quality

Seloste

Joensuu, S. 2002. Kunnostusojituksen vaikutus kiintoaineen ja ravinteiden huuhtoutumiseen suometsistä.

Metsiä on ojitettu maassamme järjestelmällisesti yli 90 vuotta. Laaja-alaisinta ojitustoiminta oli 1960- ja 1970-luvuilla, jolloin vuotuinen ojitusmäärä oli huippuvuosina lähes 300 000 hehtaaria. Tällä hetkellä toiminta on keskittynyt vanhojen ojitusalueiden kunnostamiseen. Valtioneuvoston hyväksymän, vuoteen 2010 ulottuvan Kansallisen metsäohjelman mukaan vuotuisena tavoitteena on kunnostaa ojitusalueita 110 000 hehtaaria. Metsäojituksella ja lannoituksella on lisätty puuston määrää ja kasvua turvemailla. Kolmannen valtakunnanmetsien inventoinnin (1951 – 1953) jälkeen suometsien puuston tilavuus on lisääntynyt runsas 200 miljoonaa kuutiometriä ja puuston kasvu soilla on lisääntynyt 1950-luvun alusta yli 10 miljoonaa kuutiometriä.

Vaikka Suomessa metsätalous ei olekaan kaiken kaikkiaan vesistöjen suuri kuormittaja, metsätaloudella on paikallisesti paljon merkitystä pienille latvavesistöille erityisesti alueilla, joissa metsätalouden osuus elinkeinona on suuri. Yleisesti arvioidaan, että metsätalouden toimista erityisesti metsäojitus ja nykyisin puolestaan kunnostusojitus aiheuttavat suurimmat kuormitushaitat vesistöille.

Tämä väitöskirja kokoaa yhteen niitä tuloksia, joita on saatu viime vuosikymmenen alussa aloitetusta tutkimuksesta, jossa selvitetään kunnostusojituksen aiheuttamia vedenlaadun muutoksia. Tutkimuksessa on laajasti sovellettu kalibrointijakso-vertailualueparimenetelmää. Osa tutkimusalueista toimi lyhyen kalibrointijakson jälkeen vertailualueina ja osalle alueista tehtiin kunnostusojitus.

Tutkimuksessa tarkastellaan vanhoilta ojitusalueilta valuvan veden laatua. Tarkastelu perustuu 75:een eri puolilta Suomea valittuun vanhaan metsäojitushankkeeseen, joiden valumaveden laatua seurattiin 1 – 3 vuoden ajan. Kunnostusojituksen vaikutusta valumaveden laatuun tarkastellaan edellä mainitusta aineistosta 40 ojitusalueella, jotka kunnostusojitettiin tutkimuksen kuluessa 1991 – 1993. Muilla alueilla, joille kunnostusojitusta ei tehty, jatkettiin samanaikaista vedenlaadun seurantaa, ja alueita käytettiin kunnostusojitusalueiden vertailualueina.

Kunnostusojituksen aiheuttamaa muutosta valumaveden ominaisuuksiin selitetään aluetekijöillä. Maatumattoman turpeen osuus ojaprofiilissa selitti parhaiten valumaveden kokonais- ja ammoniumtyppipitoisuuden lisääntymistä kunnostusojituksen jälkeen. Fosforipitoisuuden lisääntymistä taas selittivät kalibrointijakson valumaveden fosforipitoisuus ja hienojakoisen kivennäismaan osuus ojaprofiilissa. Maaperän lajitekoostumus selitti parhaiten kiintoainepitoisuuden muutosta. Tutkimuksessa arvioidaan kunnostusojituksen aiheuttamaa kiintoaines- ja ravinnekuormituksen muutosta käyttäen virtaaman estimaattina tutkimusalueilta näytteenoton yhteydessä mitattua virtaamaa. Lisäksi käytettiin vesihallinnon ylläpitämien pienten valuma-alueiden virtaamahavaintoja.

Tutkimuksessa tarkastellaan laskeutusaltaita vesiensuojelun esimerkkinä kunnostusojituksessa. Aineistona on 37 kunnostusojituksen yhteydessä ojitusalueelle kaivettua laskeutusallasta. Johtopäätöksenä todetaan, että noin puolet näistä altaista toimi hyvin tai kohtalaisesti. Muutamasta altaasta lähti alkuvaiheessa jopa enemmän kiintoainesta liikkeelle kuin niihin tuli. Ojitusalueen koko, laskeutusaltaan tilavuus, kiintoainepitoisuus ja maksimivirtaama selittivät yli 80 % laskeutusaltaisiin kertyvän kiintoaineksen määrän vaihtelusta. Tutkimus osoittaa, että laskeutusaltaat toimivat lähinnä kiintoaineksen ja siihen sitoutuneiden ravinteiden pidättäjinä. Liukoisia ravinteita altaat eivät näytä pidättävän.

Työssä tarkastellaan myös kunnostusojituksen pitkäaikaisvaikutuksia valumaveden laatuun 23 alueella, jotka valittiin alkuperäisestä 40 alueesta. Seurantajakson pituus oli kuusi vuotta. Tuloksissa todetaan, että kunnostusojituksen vaikutukset näkyvät kiintoainespitoisuuden ja eräiden ravinteiden lisääntymisenä vähintään kuusi vuotta. Vaikutuksen kesto riippuu maaperän ominaisuuksista.

Työssä on käytetty hydrologisiin tutkimuksiin poikkeuksellisen laajaa valuma-alueparinverkostoa. Tämä on antanut mahdollisuuden tarkastella kunnostusojituksen vaikutuksia suhteessa aluetekijöihin. Sen sijaan perinteisen hydrologisen tutkimuksen mukaiseen yksittäisen valuma-alueen sisäisten prosessien tarkasteluun tämä aineisto ei täysin sovellu.

Avainsanat: valuma-alueet, kunnostusojitus, ravinnepitoisuudet, metsäojitus, ravinnehuuhtoutuma, virtaama, laskeutusaltaat, vesiensuojelu

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Numerous field workers from local Forestry Centres and from the Finnish Forest Research Institute participated into the water sampling. Without their valuable contribution, such a large sampling programme would have been impossible to carry out. The forestry planners from the local Forestry Centres also carried out the inventory of the tree stands and site types at the study areas.

The water samples were analysed in the Central Laboratory of the Finnish Forest Research Institute in Vantaa under the guidance of Ms Arja Tervahauta, Ms Merja-Leena Koskela and Ms Tuija Halonen. Ms Inkeri Suopanki's work in arranging and processing the data and preparation of the figures is also appreciated. Ms Riitta Heinonen (Metla) is thanked for her valuable guidance in the statistical processing of the data. Mr Esa Ärölä (Tapio) made an outstanding work in processing the tree stand data of the study areas. Mr Timo Haikarainen (Metla) prepared maps of the study areas. I thank Dr. Pertti Seuna (Finnish Environmental Institute) who allowed me to use the discharge data from the small catchments database.

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This work has promoted cooperation between different forestry organisations and succeeded bringing research and practical forestry closer together. The experiences gained in different phases of the work were immediately put into practice in training occasions and excursions. In addition, the ditching planners who participated in the study have been able to apply the information gained directly in their every day work.

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Helsinki, October 2002 Samuli Joensuu

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List of articles

This thesis summarises the following publications, which are referred to by roman numbers in the following. All the publications are reprinted with the permission of the publishers.

I Joensuu, S., Ahti, E. & Vuollekoski, M. 2001. Discharge water quality from old ditch networks in Finnish peatland forests. Suo 52 (1): 1–15.

II Joensuu, S., Ahti, E. & Vuollekoski, M. 2002. Effects of ditch network maintenance on the chemistry of runoff water from peatland forests. Scandinavian Journal of Forest Research 17 (3): 238–247.

III Joensuu, S., Ahti, E. & Vuollekoski, M. 1999. The effects of peatland forest ditch maintenance on suspended solids in runoff. Boreal Environment Research 4: 343–355.

IV Joensuu, S. Ahti, E. & Vuollekoski, M. 2001. Long-term effects of maintaining ditch networks on runoff water quality. Suo 52 (1): 17–28.

Joensuu was responsible for major part of the scientific planning and, after suggestions by Ahti, for the experimental layout in studies I, II, III and IV, and for collecting the field data in all studies together with Vuollekoski. Joensuu also performed most of the data analysis and prepaired the first manuscripts in all studies. The final manuscripts for the substudies (I–IV) were jointly prepared by Joensuu and Ahti.

1 Introduction

1.1 Loading of watercourses in Finland: sources

Environmentally important loadings to watercourses usually include inputs of suspended solid material and eutrophifying nutrients such as nitrogen and phosphorus. Inputs of suspended solids are manifested by high concentrations of fine particles, larger particles during high-flow periods, and by sedimentation where and when water flow slows down. In many cases, increased loads of suspended solids and nutrients lead to eutrophication, reduced concentrations of oxygen and negative influences on many species of water fauna, and reduced recreational use of the watercourses (e.g. Marjaaho & Koskinen 1989, Laine & Heikkinen 2000, Laine 2001). Drainage and runoff from agriculture, urban and rural waste waters, industries, forestry and fish farming are the main sources of human loading to watercourses in Finland. The effects of forestry are most clearly observed in headwaters.

According to Kauppila et al. (2001), ca 14% for the total Finnish load of phosphorus and 2% of nitrogen to the Baltic Sea are from forestry. The corresponding figures for agriculture are 30% for phosphorus and 27% for nitrogen. Higher loads of nitrogen caused by forestry have been presented by Kenttämies & Vilhunen (1999). The load of phosphorus from forestry is estimated to be of the same order as that in urban and rural waste waters but that of nitrogen to be 10-fold less (Kauppila & Bäck 2001).

When comparing the potential environmental effects of the forestry measures included in Finland's National Forest Programme 2010 (Maa- ja metsätalousministeriö 1999) with the objectives of the National Water Protection Program, Hilden et al. (1999) estimated that 50% of the proposed reduction in the load of phosphorus from forestry could be achieved by improving water protection associated with peatland ditch network maintenance, i.e. ditch cleaning and complementary ditching. Reaching the remaining 50% phosphorus loading from forestry will depend on the efficiency of water protection in connection with cuttings, soil preparation and other silvicultural measures.

1.2 Finnish peatland forestry

Forests and forestry are important components of the Finnish economy. The share of forestry products to Finnish export revenues is ca 25% and that of the whole forest cluster 30–35% (Maa- ja metsätalousministeriö 1999). According to the 8th National Forest Inventory (NFI) (1986–1994), the total stem volume in Finland is about 1800 million m^3, of which peatland forests account for 25%. The total volume and increment of peatland forests have considerably increased as a result of forest drainage and fertilisation. Since the 3rd NFI in 1951–53, by which most of the ditching of peatlands for forestry had occurred, the total volume of peatland forest stands has increased by more than 200 million m^3. The annual growth of Finnish forests at the time of the 8th

NFI in 1986–94 was estimated at 78 million m^3, 20 million m^3 of which was from peatland forests, a doubling since the 3rd NFI (Tomppo 1998, 1999, Tomppo et al. 2001). By the end of the last century some 520 million € had been invested in forest drainage in private forests and 170 million € in state-owned forests and forests owned by the Finnish forest industry (Metsätalouden kehittämiskeskus Tapio 1997).

Systematic forest drainage has been carried out for more than 90 years in Finland. The first observations on peatland drainage were recorded on sites which were drained for agriculture in the 17th century (Kaitera & Paasilahti 1939, Heikurainen 1960, Tanskanen 2000). The earliest records on the beneficial influences of drainage on forest growth originate from the period 1850–1870, which coincides with the so-called big hunger years in Finland. In order to increase the area of agricultural land, large areas of peatland were drained at the time but later abandoned and left to natural afforestation (Tanttu 1915, Lukkala 1937, Tirkkonen 1952). At the end of the 19th century, forest drainage was limited to sporadic cleaning of natural brooks (Lukkala 1928) and it was not until the beginning of the 20th century that forest drainage started on state forests. By the end of 1926, ca 52 000 hectares had been drained. The first large drainage projects on land owned by forest industry were carried out in the 1910's but forest drainage in private forests had not yet started (Tirkkonen 1952, Holopainen 1957). Actual forest drainage was promoted by the classical studies of Cajander (1906, 1913) and Tanttu (1915) dealing with forestry use and classification of peatlands.

The year 1928 was highly significant for forest drainage in private-owned forests, which represent 2/3 of the Finnish forest area. The Forest Improvement Act (Metsänparannuslaki 140/1928) was accepted by the Finnish parliament that year, through which govermental funding was appropriated for improving the productivity of unproductive private and state forests. After having become operative, this act promoted forest drainage activities and, by the onset of the second world war, the area of peatland drained for forestry purposes was estimated at more than 600 000 hectares (Lukkala 1940, Tapion metsänparannusosaston toimintakertomukset 1929–1939). In the 1940's, forest drainage was retarded by the wars and by the end of 1950, only some 750 000 hectares of peatland had been drained for forestry (Tirkkonen 1952). Forest drainage activity started to revive at the beginning of the 1950's, helped by increased financing through the state budget and technical developments. After the beginning of mechanized forest drainage in the middle of the 1950's, the area annually drained dramatically increased (Tapion metsänparannusosaston toimintakertomukset 1952–61, Aarne 1992).

Forest drainage continued to be lively during the first half of the 1960's, when several forestry programmes to increase the wood production of the Finnish forests were started. Regarding forest drainage, the most important of these were the MERA-programmes (1965–75). During the 10 years of the MERA-programmes, 2.6 million hectares of peatland forests were drained (Holopainen 1965, 1970, MERA Metsätalouden rahoitusohjelma 1964, MERA Metsätalouden rahoitusohjelma II 1966, MERA Metsätalouden rahoitusohjelma III 1969, Uusitalo 1978, Palosuo 1979). The area of peatland and mineral soil wetlands drained for forestry purposes is now estimated at 4.7 million hectares, which corresponds to 18% of the forest land area (Hökkä et al. 2002).

1.3 Ditch network maintenance: extent and targets

Maintenance of deteriorated, old ditch systems was promoted by reforming the Forest Improvement Act in 1987 (Metsänparannuslaki 140/87 1987). At that time, the annual areas of forest drainage had already been considerably reduced from the maximum ca 300 000 hectares in 1969–70 (Finnish Statistical Yearbook of Forestry 1999). Through further reform of the Forest Improvement Act in 1993 (Laki metsänparannuslain muuttamisesta 1278/1992) ditch network maintenance became the main form of forest drainage activity and since 1997, ditching of pristine peatlands is no longer financed by the state (Laki kestävän metsätalouden rahoituksesta 1094/1996, Metsätalouden säädökset 1997, 2000). In this study the term initial ditching refers to the term ditching of pristine peatlands, especially when comparing the effects of ditch network maintenance.

Goverment financing of ditch network maintenance had started already before the reform of the Forest Improvement Act in 1987. In areas closely connected to traditional forest drainage, it had been possible to get partial financing from the state for small-scale ditch cleaning and complementary ditching. In the Metsä 2000 -programme, it was estimated that 120 000 hectares per year of ditch network maintenance would be required to meet targets (Metsä 2000-ohjelma 1985). In 1992, this figure was raised to 150 000 hectares per year until the end of the century (Komiteamietintö 1992:5). However, only ca 75 000 hectares per year of ditch network maintenance was actually carried out during 1990's (Finnish Statistical Yearbook of Forestry 1999). According to the latest National Forestry Programme from 1999 (Maa- ja metsätalousministeriö 1999), 110 000 hectares per year of ditch network maintenance are aimed at during 2000–2010.

1.4 Environmental effects of forest drainage

1.4.1 General

In the first guides for forest drainage, problems dealing with erosion and sedimentation were dealt with from the point of view of the condition of the ditches and their drainage capacity. In the handbooks of forest drainage by Lukkala (1929, 1940, 1948) and Tanttu (1943) for example, sufficient slope of the ditches was emphasized. Attention to excessive erosion was, however, paid at the early stages of forest drainage (Saarinen 1935), and in practical training for forest drainage, technical instructions dealing with erosion problems were also delivered (Lukkala 1940). Even earlier, in the thesis of Kokkonen (1923), the influences of soil frost and the velocity of water flow on the technical condition of the main ditches in agriculture and forestry had been studied. Problems connected with forest drainage, mostly the sedimentation problems of forest ditches, were discussed in several studies (Multamäki 1934, Numminen 1958, Heikurainen 1957, 1959, Antola & Sopo 1966, Timonen 1971, 1983). In field inspections of forest drainage the main emphasis was on a good drainage capacity of the ditches (Heikurainen 1958, Keskusmetsälautakunta Tapio 1966, 1972, 1974, 1980).

The principles of environmental protection related to forest drainage were included at the end of the 1960's (Tapio 1970), when there was lively debate about flooding and erosion caused by forest drainage (Vesihallitus 1970). Also, the loan agreements between Finland and the International Bank of Reconstruction and Development required that watercourses were not to be harmfully effected by forest drainage (Loan Agreement... 1972, Metsähallitus 1973). Promotion of water protection in forestry was repeatedly a question of interest by the water protection authorities in the 1980's (Vesihallitus 1983) and in the silvicultural recommendations for private forestry (Ohje vesiensuojelusta ... 1984, Yksityismetsien ympäristönsuojelu 1984, Vesiensuojelutoimenpiteet metsäojituksessa 1987, Metsänhoitosuositukset 1989). Water protection in private forests was improved through the renewal of instructions for water protection (Joensuu & Kokkonen 1992) and by including water protection in the planning of ditch network maintenance projects. The importance of water protection has been further emphasised in the latest recommendations dealing with forestry, especially ditch network maintenance, and in the instructions for field inspection of forestry operations (Metsätalous ja ympäristö 1994, Hänninen et al. 1996, Joensuu 1999, Hartikainen et al. 2001).

The first studies dealing with the environmental effects of forest drainage were started in the early 1970's (Heikurainen et al. 1978). In the 1980's, environmental observations in connection with forest drainage were carried out in a few individual areas (Heikurainen et al. 1978, Kenttämies 1980, 1981, 1987). The monitoring of several forest brooks in catchments subject to various forestry measures in Nurmes, Northern Carelia since 1978 is the oldest study in Finland dealing with the effects of forestry on watercourses (Ahtiainen 1988, 1990, Ahtiainen et al. 1988, Ahtiainen & Huttunen 1995, 1999, see Starr & Päivänen 1982).

In a ministerial committee report from 1987, environmental problems caused by forestry and peat harvesting were evaluated and several proposals for water protection and future research were made (Komiteamietintö 1987:62). In 1990, a national five-year research programme, METVE, aimed at finding out the effects of forest drainage, ditch network maintenance, cuttings, site preparation connected with reforestation after clear-cutting and fertilisation on runoff quality and possible problems on the water courses was started (Kenttämies & Saukkonen 1996). Commissioned by the Forest-2000 programme, Ahti (1990) summarised the environmental impacts of forestry. The environmental problems caused by forestry were further examined by a working group set up within the Forest-2000 programme (Metsä 2000 -ohjelman ... 1991), and several methods and principles for preventing damage to the environment caused by forestry were suggested.

Forest-, forest improvement- and nature conservation acts were revised in late 1996 (Metsälaki 1093/1996, Laki kestävän metsätalouden ...1094/1996, Luonnonsuojelulaki 1096/1996, Metsätalouden säädökset 1997, 2000). In addition, many essential revisions were made to the water legislation during the last decade, and the Environmental Protection Law was given in 2000 (Vesilaki 264/1961, Laki vesilain muuttamisesta 1041/1991, 88/2000, Ympäristönsuojelulaki 86/2000). National criteria for forest certification have been prepared (Suomen metsäsertifioinnin... 1998), which also contain standards for peatland forest ditch maintenance. In preparing the national forestry plan for upto 2010, Finland's National Forest Programme 2010, the environmental impacts of the programme were assessed (Hildén et al. 1999). Special attention was paid to how the aims of the National Water Protection Programme for 2005 would be affected. The aim of the Water Protection Programme is to improve, among other things, the condition of the Baltic Sea, which would require that forestry reduces its 1993 nitrogen and phosphorus loads by 50 % by the year 2005 (Valtioneuvoston periaatepäätös ... 1998, Vesiensuojelun toimenpideohjelma vuoteen 2005 1999).

1.4.2 Hydrological effects of forest drainage and maintenance

The hydrological effects of forest drainage have been extensively studied (Baden & Eggelsmann 1964, Mustonen & Seuna 1971, Heikurainen 1971, 1974, 1980a, 1980b, Karsisto 1974, Ahti 1975, 1987, Heikurainen et al. 1978, Kytövuori 1979, Seuna 1981, 1982, 1988, Kenttämies 1981, 1987, Kenttämies & Laine 1984, Laine 1984, Hynninen & Sepponen 1983, Ahtiainen 1988, 1990, Verry 1988, Rekolainen 1989).

The evaporation dominated hydrology of pristine peatlands is drastically changed by forest drainage – evaporation decreases, runoff increases and the water table is lowered. The lowering of the water table increases the water storage capacity of the peat. Annual runoff and spring (snowmelt) high flows are increased by ditching (Seuna 1981, 1987, 1988, see also Starr & Päivänen 1986) and evapotranspiration decreased (Ahti 1988). The maximum annual runoff occurs during the first years after drainage (Kytövuori 1979, Heikurainen 1980b, Sallantaus 1983). Summer runoff peaks and minimum flows are considerably increased as well. The changes in runoff caused by forest drainage are gradually eliminated with the development of the tree stand and, in many cases, being negligible after 20 years (Seuna 1981, 1988, Starr & Päivänen 1986). Runoff from drained peatland forests peaks during the snowmelt period. The discharge is accelerated by the ditch network but the developing tree stand retards the snowmelt (Ahti 1975, Ferda & Novak 1976, Mansikkaniemi 1985, Mansikkaniemi & Kotilainen 1986). However, the long-term monitoring of runoff from drained peatland sites are limited to few sites. In the Suopuro catchment, included in the Nurmes-Project, no increase in the annual runoff was observed during the first 14 years of observation (Alatalo 1999).

The aim of ditch network maintenance is to maintain the drainage capacity of the original ditch network. Because of this, it has been argued that the hydrological effects of ditch network maintenance should be evaluated by comparing them not with the hydrology prevailing immediately before the maintenance operations but against the hydrology of the undrained state, i.e. pristine peatland.

The hydrological effects of ditch network maintenance have very little been studied. According to Ahti et al. (1995a), the effect of ditch network maintenance on runoff is partly dependent on whether the ditches are cleaned or whether drainage capacity of the ditch network is restored through complementary ditching. Increasing ditch depth does not much influence the fast forms of runoff (surface flow and interflow) and therefore the influence on discharge peaks is small. However, increased runoff peaks may be created when complementary ditching is carried out because of increased channel density and faster flow of surface waters into the ditch system (Ahti et al. 1995a).

1.4.3 Effects of drainage and ditch maintenance on erosion

Ditch bank erosion and increased concentrations of suspended solids are immediate changes caused by ditch network drainage (Heikurainen et al. 1978, Ahtiainen 1990). Because of comparatively low discharge, erosion and transport of suspended solids in the individual drainage ditches are low but the risk is greater in the main ditches that collect runoff water from larger areas (Kokkonen 1923, Sallantaus 1987).

The load of suspended solids following the initial ditching depends on the water store of the peatland, the degree of decomposition of the peat layer, weather conditions during digging, and the amount of water entering the ditch (Sallantaus 1987). High concentrations of suspended solids in runoff water have been observed during high-flow periods following the digging operations and during spring snowmelt (Sallantaus 1986, 1987).

If the peat deposit is thin, the base of the ditch may reach underlying mineral soil. Mineral soil susceptible to frost heaving, such as silt and fine sand, are more easily eroded than poorly decomposed peat. However, the erosion of the mineral subsoil may increase the loads of organic suspended material through the collapse of the ditch banks. Mud and decomposed peat are also easily eroded (Kokkonen 1923).

Increases in the concentrations of suspended solids following the initial ditching have been reported in several studies (Heikurainen et al. 1978, Kytövuori 1979, Kenttämies 1981, 1987, Kenttämies & Laine 1984, Sallantaus 1984, Ahtiainen 1988, 1990, Ahtiainen & Huttunen 1999). According to Ahtiainen (1990), concentrations of suspended solids in recipient streams after peatland forest drainage were 7–10-fold compared with controls and attributed the large difference in concentrations to erosion of mineral soil material.

Hynninen and Sepponen (1983) observed main ditch concentrations of suspended solids reaching 2800 mg l^{-1} after ditching. The highest concentrations occurred during high-flow periods and were attributed to the erosion of the banks of the main ditches. Hynninen and Sepponen (1983) have also reported long-term channel erosion after ditching in the catchments Syväoja and Hiekkaoja, which are tributaries to Nuoritta-joki-river. Heikurainen et al. (1978) attributed high concentrations of suspended solids to heavy rainfall. In ditches reaching down into mineral subsoil, high concentrations of suspended mineral solids for long periods have often been observed (Heikurainen et al. 1978, Konstantinov & Suhorukova 1980).

Although raised concentrations of suspended solids are regularly observed during and immediately after ditching, they are considerably reduced within a few hours (Heikurainen et al. 1978). But increased concentrations of suspended solids have been observed to persist for five years (Kenttämies 1980, 1987) and for up to 14 years after ditching (Alatalo 1999). In peat harvesting areas, only organic material is usually eroded (Sallantaus 1983, Heikkinen 1990a, Ihme et al. 1991a and b, Ihme 1994, Kløve 1998).

The effects of ditch network maintenance on the concentration of suspended solids in runoff water are similar to the effects of the initial ditching (Ahti 1990, Ahti et al. 1995b, Manninen 1995, 1998, 1999). The deformation of the old ditches makes it easier to identify areas which are susceptible to erosion than it was when planning the initial ditching (Ahti 1990). However, the increased decomposition of peat in the walls and bottoms of the ditches and peat subsidence, mean that the risk for erosion is greater in connection with maintaining old ditch networks than digging new ones (Sallantaus 1987, Komiteamietintö 1987:82).

Natural erosion in Finland is insignificant. The distribution of annual precipitation is rather even, rain intensities are rather low, and the soil is frozen for part of the year. Most of the erosion occurs during high flows caused by snowmelt and autumn rains. Soil erosion from ploughed agricultural land during snowmelt (Mansikkaniemi 1982) is probably much greater than from forested peatland areas undergoing ditch maintenance. According to Rekolainen (1993), erosion from fields is closely connected to slope and soil texture. The erosion of clayey soils is decisive for the total loading of clay and particulate P to water courses (Turtola & Paajanen 1995, Turtola 1999).

1.4.4 Forest drainage effects on runoff, nutrient concentrations and acidity

Estimation of the loads from agriculture and forestry into the watercourses is more difficult than for urban and industrial loads, which usually come from point sources (Rekolainen 1993). The loadings from forestry today are mainly related to maintenance of ditch networks, wood harvesting, site preparation for regeneration and forest fertilisation (Kenttämies & Saukkonen 1996, Kauppila et al. 2001). Nitrogen loads from peat production areas are larger than from harvesting forestry areas (Heikkinen 1990a).

The initial ditching of pristine peatlands has been shown to mobilise nitrogen, phosphorus, organic material and iron to watercourses (Heikurainen et al. 1978, Hynninen & Sepponen 1983, Sallantaus 1984, 1988, 1995, Ahtiainen 1988, Hynninen 1988).The increase in N loads was mainly due to mineral nitrogen. Hynninen and Sepponen (1983) reported raised concentrations of NH_4–N after initial ditching within the catchment of Nuorittajoki river. The highest concentrations were 18-fold those in pre-treatment times. In the brook systems of the Kiiminkijoki river, the highest NH_4–N concentrations were associated with the oldest forest drainage sites. In water samples taken downstream from sites that had been drained three years earlier, the concentration of NH_4 averaged 0.45 mg l^{-1}. The leaching of mineral nitrogen is considered a long-term phenomenon, which reaches its maximum several years after ditching (Hynninen & Sepponen 1983, Alatalo 1999). Increased concentrations of NH_4–N after initial ditching were also observed in the Nurmes study in North Carelia (Ahtiainen 1988, 1990) and in studies carried out in central and northern Sweden (Lundin 1988, 1992, 1996).

In the studies by Lundin (1992, 1996) increased concentrations of NO_3–N after the initial ditching of an eutrophic sedge mire were also observed. Most of the NO_3–N leaching took place during high-flow periods in spring and autumn. A similar NO_3 leaching response after initial ditching was also observed in the study by Hynninen & Sepponen (1983) carried out in northern Ostrobothnia.

For example, Kubin (1987, 1995, 1998) observed raised concentrations of NO_3 in both surface waters (runoff) and ground water after the heavy site preparation (deep ploughing) for forest regeneration at mineral soil sites. He observed concentrations of several hundred mg l^{-1} NO_3–N in surface water after treatment but concentrations had returned to pre-treatment levels after five years. In ground water, the reaction of the NO_3–N concentration was delayed but it lasted over 10 years.

The initial ditching of peatlands has been shown to cause an immediate increase in the loads of total phosphorus in several studies (e.g. Heikurainen et al. 1978, Kenttämies, 1980, 1981, 1987, Kenttämies & Laine 1984). A major part of the increase was due to particulate phosphorus (Kenttämies 1987, Ahtiainen 1990, Pietiläinen & Rekolainen 1991).

The effects of ditching on pH are less clear than for nitrogen and phosphorus. Hynninen and Sepponen (1983) reported a statistically significant increase in the pH of brook water at one of their sites of 0.9 units. Kenttämies (1981) also observed slight increases in runoff pH after initial ditching. Sallantaus (1986) reported no increase in runoff pH in his study. In the Nurmes-study, runoff pH slightly decreased during the digging operations, but the median pH value during the three years following treatment was 0.5 –1.0 units higher than during the pre-treatment period (Ahtiainen 1988, 1990, Ahtiainen & Huttunen 1999). The initial decrease in pH was attributed to the increase in runoff connected with the decrease in the water store of the peatland (Ahtiainen 1990).

A slight decrease in the concentration of organic carbon after initial ditching was observed by Kenttämies (1987). Ahtiainen (1988, 1990) reported an initial increase in the concentration of organic carbon after ditching followed by decline. Heikurainen et al. (1978) found no difference in the concentrations of organic matter in runoff between pristine peatlands and peatlands that had been drained 20 years earlier. A similar result from Sweden was reported by Bergqvist et al. (1984). Concentrations of organic carbon in percolation water from deep peat layers are low (Lundin 1996). According to Hemond (1990) and Mulholland et al. (1990), the surface soil layer containing much organic material seems to be the source of the organic carbon in surface waters. Instead, the deeper soil layers appear to be sinks of organic carbon. Also, the adsorption of organic carbon in the mineral soil has been considered to largely control the transport of organic carbon, and even to reduce the concentrations of organic carbon in surface waters (Hemond 1990, Vance & David 1991, David et al. 1992). Kortelainen (1993a) found that the proportion of peatland cover explained 53% of the variance in dissolved organic carbon (DOC) concentrations in the runoff from cathments in northern Finland (see also Moore 1987, Eckhart & Moore 1990, Kramer et al. 1990).

Long-term monitoring data show that the concentrations of organic matter in Finnish rivers and lakes between 1962 and the 1980's remained unchanged (Laaksonen & Malin 1980, 1984), even though there was much drainage for forestry going on in the period too. Comparing long time series (1911–1931 and 1962–1979) from river systems of northern Finland, Alasaarela and Heinonen (1984) reported clear decreases in the concentrations of dissolved organic matter. In North-American brooks originating from catchments dominated by peatlands, DOC concentrations varied between 10 and 60 mg l^{-1} (Thurman 1985).

High concentrations of iron in the brooks and rivers of northern Ostrobothnia catchments which included both undrained and drained peatland areas have been observed in several studies (Haapala et al. 1976, Heikkinen 1985). The authors suggested that the high concentrations were mainly due to organic-iron complexes originating from minerotrophic peatlands. Heikkinen (1985) observed increases in the concentrations of iron and DOC during low-flow periods in the summer when water flow is dominated by that from deeper, partly anaerobic peat layers.

However, increases in iron concentration have not always been found. In the study by Hynninen & Sepponen (1983), iron concentration in runoff did not increase after the initial ditching. Insignificant changes in iron concentrations after initial ditching have been observed in several other studies (e.g. Bergqvist et al. 1984, Ahtiainen 1990). In the Nurmes-study, high iron concentrations following ditching were observed during low-flow periods, but the differences between the pre-treatment and the post-treatment periods were not statistically significant (Ahtiainen 1990).

Aluminium concentrations in runoff water did not increase after ditching in the Nurmes-study (Ahtiainen 1988, 1990) but did in Swedish studies (Lundin 1988, 1996). Ahtiainen (1990) did, however, report increased concentrations of potassium, calcium and magnesium during the first three years after ditching. Corresponding changes have also been observed in Swedish studies (Bergqvist et al. 1984).

1.5 Water protection and forest ditch networks maintenance

1.5.1 Water protection methods

Water protection is a crucial aspect of the present directions on ditch network maintenance. The most important aim is to reduce the load of suspended solids and their associated nutrients (e.g. Enso-Gutseit Oy 1994, Hänninen et al. 1996, Metsähallitus 1997, Joensuu 1999, Hyvän metsänhoidon suositukset 2001). Minimizing the loads of suspended solids is primarily achieved by reducing the risk of erosion and preventing eroded material from reaching watercourses as effectively as possible.

In planning a ditch maintenance project, protection of groundwater, aquifers, pristine brooks, ponds, and springs within or in the immediate vicinity of the ditch network is aimed at. It is important to identify, where the drainage waters are to be conducted and where water protection structures such as sedimentation ponds or overland flow areas should be situated. Ditches that are eroded are usually left unmaintained to avoid further erosion; they are usually also deep enough for flow. No maintenance measures are made to the main ditch if its water conducting capacity is considered to be good enough, as is usually the case. Low-lying shore areas susceptible to flooding are usually left untouched because of the risk of erosion during high water levels.

As mentioned in chapter 1.4.3, ditch erosion is determined mainly by discharge, ditch slope, velocity of water flow and soil characteristics. The flow of water can be slowed down and retention of coarse suspended solids increased by reducing ditch slope, by leaving uncleaned ditch sections and by constructing bottom weirs.

Conducting water over peatland to allow infiltration has earlier been used for the purification of urban waste waters (Surakka & Kämppi 1971) and long been used by the fuel and garden peat harvesters (Ihme 1994). The method has proved particularly efficient in retaining suspended solids and particulate nutrients (Kent 1987, Kadlec 1987, Ihme 1994). Solutions based on overland flow such as small scale overland flow areas, buffer zones and riparian zones (Sallantaus et al. 1998, Joensuu 1999) are applied in connection with ditch network maintenance. Overland flow has also been successfully used in connection with heavy site preparation treatment in northern Finland (Kubin et al. 2000).

Sedimentation ponds have been used for more than two decades in peatland forestry for water protection and even longer in peat harvesting areas (Sallantaus 1983, Hannon & Coffey 1984, Selin & Kaunismaa 1985, Selin & Koskinen 1985, Ihme 1991a). The sedimentation technique is videly used in the purification of waste waters. Particles settle downwards in a liquid if their density is greater than that of the liquid. In sedimentation ponds the flow of water is slowed down to allow suspended solid particles to settle to the bottom of the ponds. The sedimentation of the particles depends on their physical characteristics and on the ratio between their settling velocity and the velocity of the water flow. The settling velocity of fine soil particles such as clay and fine silt is too low to allow sedimentation in practical sedimentation ponds (Aho & Kantola 1985).

Sedimentation pits and ponds are constructed to prevent eroded suspended material from entering watercourses. Runoff entering sedimentation ponds slows the flow of water allowing the suspended particles to sediment. The effectiveness of sedimentation ponds in connection with forest drainage has been studied by Sallantaus and Pätilä (1983), Sallantaus (1986) and Joensuu (1990a, 1990b, 1992, 1994), and in connection with peat harvesting in severd studies (Koskinen 1983, Aho & Kantola 1985, Sallantaus 1983, 1986, 1987, Selin & Kaunismaa 1985, Selin & Koskinen 1985, Ihme et al. 1991a, Wynne 1992).

Various new techniques for water protection in connection with peat harvesting have been developed such as pumping runoff water into special infiltration sites, where the water infiltrates into the mineral soil, and evaporation basins (Selin & Marja-aho 1992, Kløve 1994, 2000a, Savolainen et al. 1996). More sophisticated clarification techniques, such as electrochemical or chemical precipitation treatment, cannot be used in forestry because of the dispersed nature of forestry, the need of external energy and regular service. Techniques requiring external electric energy have been applied to some specific peat harvesting sites and agricultural sites (Savolainen et al. 1996, Aura 2000).

1.5.2 Water protection responsibilities

The most important tasks in planning a forest ditch maintenance project are to clear-up any environmental damage caused by the ditching and to plan measures for reducing them. The planning and the implementing organisations are responsible if harmful effects are due to errors in the planning and implementation of the project. Otherwise, the landowners or other parties directly benefiting have the general responsibility for any harmful effects to watercourses caused by the peatland forest ditch maintenance (Joensuu 1999).

The official administration of the practical environmental and water protection is assigned to the regional environmental centres and officials. There are also three environmental license offices that may give environmental permits for ditch maintenance (Ympäristönsuojelulaki 86/2000).

In 1983, the Central Forestry Board Tapio and the National Board of Forestry reached an agreement with the National Board of Waters that they would send forest drainage plans prepared by their regional organisations to the regional Environment Centres for their information. This practice still continues. Since1992, a water protection plan has been prepared for every new peatland forest ditch maintenance project. The regional Environmental Centres and the planners of ditch maintenance work, i.e. the regional Forestry Centres and the National Board of Forestry, negotiate over the best ways of arranging the water protection aspects (Joensuu 1999). In addition, the environmental authorities may perform random field inspections of the quality of the water protection measures taken.

The Forestry Development Centre Tapio also performs random inspectations (Hartikainen et al. 2001) as does the National Board of Forestry (Rissanen 1999). Water quality protection in connection with ditch maintenance in peatland forests is also one of the criteria in the Finnish forest certification system (criteria 25–28) (Suomen metsäsertifioinnin... 1998).

1.6 Hydrological studies and methodological basis

1.6.1 Water quality

Forest ditch maintenance techniques and methods should be based on scientific research. Because the water balance of a site is altered by forest drainage and cuttings, all-year-round and long-term hydrological monitoring and research is needed to study their effects on water quality. Often the results are site specific and a representative number of sites are needed in order to make generalisations. However, by increasing the number of areas to be monitored, the research becomes more expensive and difficult to carry out. The variation also increases which might be difficult to explain.

By regular monitoring of large river systems, the loading effects of agriculture and forestry can be estimated. However, it is difficult to separate the loads of agriculture and forestry from each other, and from natural background loading (Rekolainen et al. 1992).

In Finland, a network of small catchments has been monitored for more than 40 years (Mustonen 1965). The material has been mainly used to study the loads from agriculture to watercourses but the network has also been used for estimating hydrological changes and loads caused by forestry (Seuna 1981, Saukkonen & Kortelainen 1995, Kortelainen et al. 1997, 1999, Kortelainen & Saukkonen 1998). The catchments in the network vary a lot in their area and land use, and are not much affected by point sources of pollution. Consequently, the network is well suited to study the effects of agriculture and forestry land use on stream water quality. As the hydrological monitoring started in the 1950s and the water quality monitoring in the early 1960s, they are a unique source of long-term data on water quality. However, because of the mixed land use in many of the catchments, it is difficult to separate the effects of various agriculture and forestry practices (Rekolainen 1989, Bengtsson 2000).

Leaching experiments in which individual fields have been divided into experimental plots or strips have been used to estimate the loads from agriculture (Rekolainen et al. 1991, Ekholm 1998, Turtola 1999). The purpose of these layouts was for studying the loading effects of individual agricultural measures, but they can also be used for studying the loading effects of agriculture in general. Lysimeters are used for studying the effects of soils characteristics, fertiliser levels, irrigation and other factors on leaching. Lysimeters are soil profiles of fixed surface isolated from their surroundings by steel or plastic walls from which the infiltrating and percolating water is collected to determine leaching (Rekolainen et al. 1991, 1992).

To avoid the need for long-term monitoring, the effects of ditching and stand treatments may be studied by simultaneous comparisons of sites that represent different stages of development after treatment or different intensities of treatment (e.g. Baden & Eggelsmann 1964, Heikurainen 1976, Heikurainen et al. 1978). Such an approach assumes that the sites were initially similar. This assumption can be more easily made if the study areas are small and therefore homogenous. However, if the areas are too small they have zero-runoff periods, especially during summer.

1.6.2 Representability of data

Traditionally hydrological studies in Finland have been based on long-term monitoring or comparisons of long-term data from treated and control areas (e.g. Sallantaus 1986, Ahtiainen 1990, Kortelainen 1993b, Finér et al. 1997). However, only a few paired catchments, which have represented certain specific site types or certain conditions in general have been studied. Because of this, the direct applications of the empirical data from such studies are limited. Because of the limited number of catchments, the geographic representability of the data often remains poor, and does not allow statistical analysis of geographical differences.

In most studies dealing with hydrological changes and changes in nutrient loads, problems connected to the experimental layout are present. Ahti (1987) has dealt with some of these difficulties as follows:

"Part of the difficulties in interpretation of the data is connected with experimental layout. Scientifically the most precise method, the control basin method, is based on basins large enough to include a natural runoff channel. In large basins, on the other hand, uncontrolled changes during data collection are more probable than in small basins. Second, in spite of the fact that the control basin eliminates the variation caused by long term climate variation, the possibility always exists that the period of observation does not include vital parts of the climatic continuum. Consequently, very long periods of observations are necessary for each pair of basins if reliable conclusions are aimed at."

Huikari et al. (1966) and Ahti (1987) studied the hydrological effects of forest drainage by simultaneous comparisons of runoff from sites with varying drainage intensity. In these studies, no control area was included. Instead, the runoff of pristine peatland was extrapolated from the relationship between drainage intensity and runoff. To cover the climatic variation in time, long-term data was necessary even if the layout of simultaneous comparisons was applied.

Ahtiainen et al. (1988), Päivänen and Ahti (1988), Lundin (1988), Ahti et al. (1995a), Prévost and Plamondon (1999) and Prévost et al. (1999) used the paired-catchment method in their studies. The paired-catchment method has also been used in this study. The number of paired catchments was, however, larger than in most earlier studies. Because it could be assumed that, with exception of the runoff connected to an immediate decrease in the water store, ditch network maintenance has no essential effects on runoff (e.g. Ahti et al. 1995a), hydrological monitoring was limited to manual runoff observations in connection with sampling. The variation of site characteristics was increased by the relatively large number of catchments included in the study. The variation of site characteristics was then used for interpreting the changes in runoff water quality after ditch network maintenance.

Because of the fact that the resources are normally limited, studies based on a large number of experimental sites usually have to concentrate on a few essential variables only, and many variables of interest have to remain unobserved. In spite of this shortcoming, the layout of this study provides the possibility to estimate the magnitude of the environmental effects of forestry on a strictly empirical basis. The layout gives satisfactory information on the environmental effects of different forestry measures in different parts of the country.

In this study, a short calibration period was used. Because rather long pre-treatment periods with dry and rainy growing periods should be included to get representability of data in time, the reliability of this data might have been decreased due to the short calibration period.

2 Aims

To maintain the favourable soil water conditions created by ditching for tree growth the ditch network has to be maintained. Because of the increasing awareness about the possible detrimental effects to water, there is a need to study the effects of ditch network maintenance. So far, knowledge concerning the environmental effects of ditch network maintenance has been based on information concerning the initial ditching (e.g. Kenttämies & Alatalo 1999).

The aims of this study are:

1) To describe the runoff water quality from peat land forests in which no recent digging operations have been performed (I),
2) To find out how runoff water quality from drained peatland forests is influenced by

site characteristics (I, II, III),

3) To determine the change in concentrations of suspended solids and nutrients in runoff as a result of ditch network maintenance (II, IV),

4) To demonstrate and evaluate the use of averaged data from a large number of catchments to determine changes in runoff water quality caused by ditch network maintenance.

3 Methods and material

3.1 Experimental design

3.1.1 Background

In 1990, a national research programme that included more than 20 research projects (the METVE-project) was started, the aim of which was to study the possibilities to decrease the harmful effects of forestry on the watercourses (Kenttämies & Saukkonen 1996). The projects included studies on modelling the effects of various forestry measures, actions to reduce loads from forestry, monitoring changes in watercourses caused by forestry, effects of forestry on fishing, and the economics of water protection in forestry. The field work for this study was started in connection with the METVE project ”Effect of sedimentation ponds on suspended solids loads after ditch network maintenance”. The study was financed by the Ministry of Agriculture and Forestry, the Finnish Forest Research Institute, Forest Development Centre Tapio, and the regional Forest Centres.

3.1.2 Paired catchments

By examining the planning documents in 1990–1991 ditch network maintenance projects that were to be carried out in private forests, 40 pairs of catchments were chosen for this study (II–III). The geographical emphasis was on southern, central and northern Ostrobothnia, where most of the ditch network maintenance in Finland is carried out. South-western Finland and North Carelia regions were also rather well represented. The northernmost catchments were situated in Tornio. The coverage of the network was low in the Finnish lake district in the south-eastern parts of the country.

Each catchment pair consisted of a treatment area and a control area situated close by (Fig 1a). Five of the control areas are paired with two treatment areas so that, in total, 75 catchments were included. Runoff water quality was monitored in both the treatment and the control areas for at least one year prior to ditch network maintenance in the treatment area (I). The observations in most of the paired catchments were started in 1991 and the ditch maintenance digging operations carried out in 1992 (II,

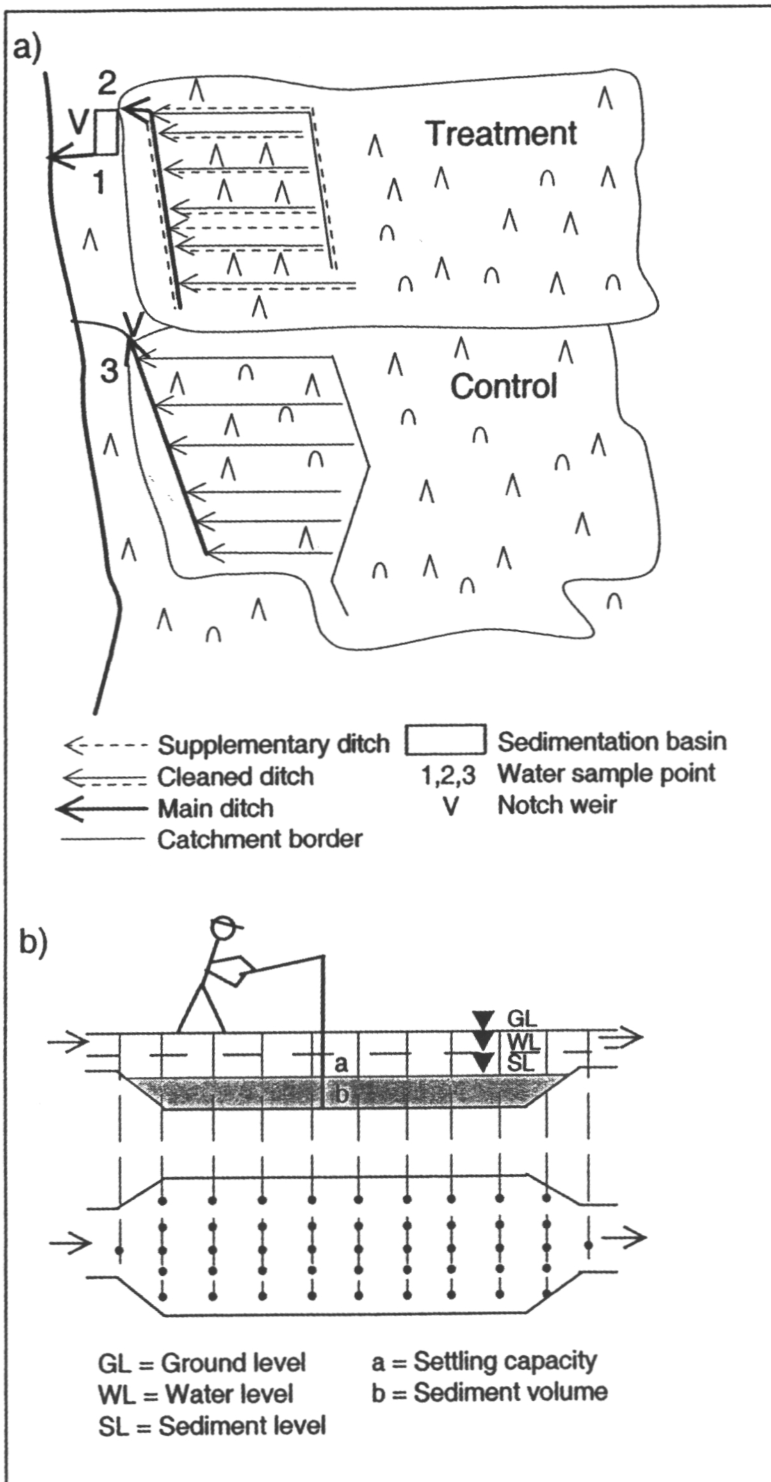

Figure 1. a) Experimental layout in studies II, III and IV. b) The method of determining the volume of the sedimentation ponds.

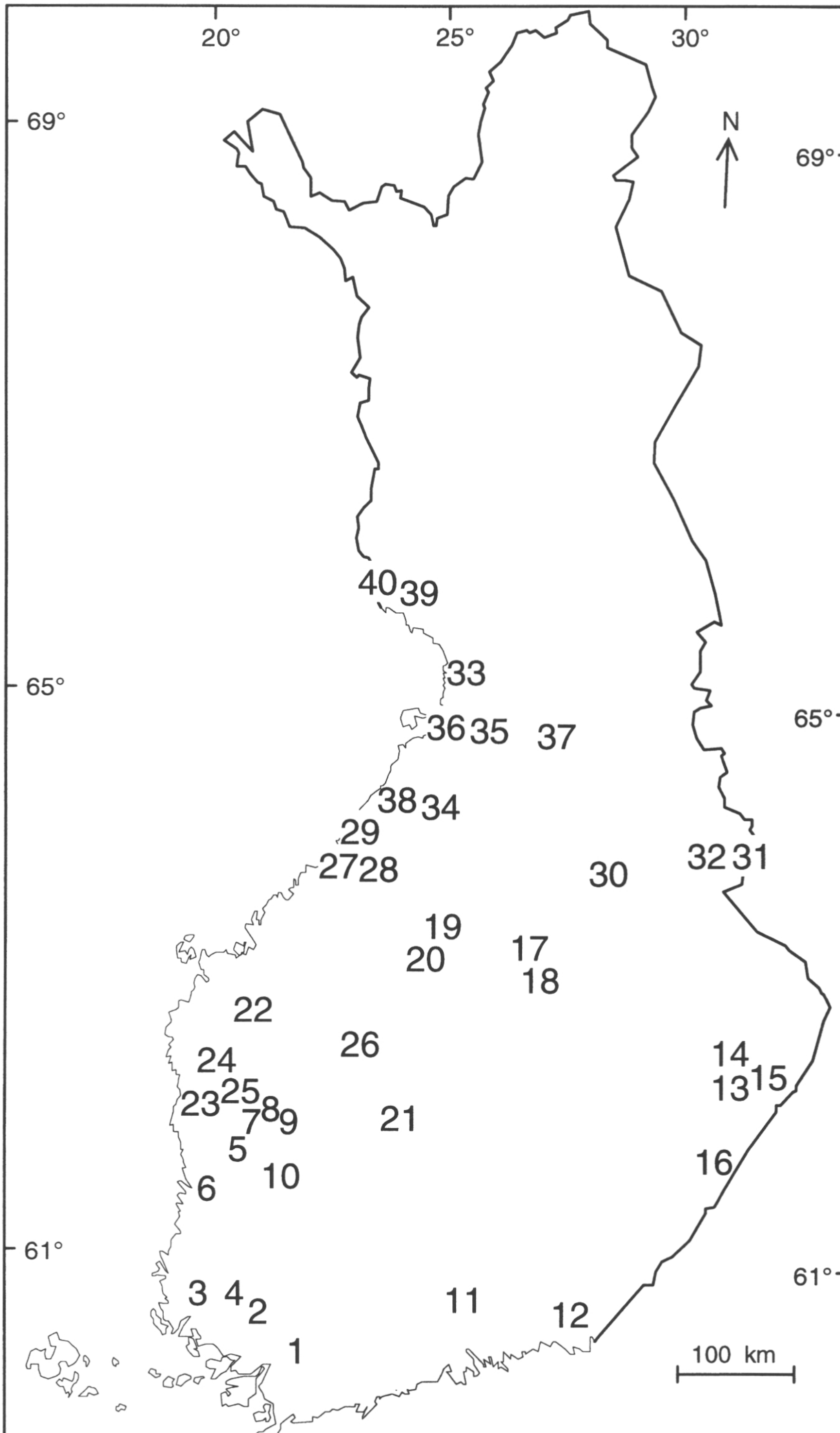

Figure 2. Location of the study areas. The numbers indicate the areas listed in Table 1 and Appendix 1–2.

Appendices 1 and 2). For four sites, the digging operations were performed during the winter 1992–93 and during the early summer of 1993 for 6 sites.

From the original set of 40 paired catchments (Fig. 2, I, II and III) 23 catchments were selected for long-term observation (IV). The selection was based on location, stand characteristics and soil properties such as the thickness of the peat layer and subsoil texture (IV). The 23 selected pairs of catchments were monitored until the end of 1998.

The catchment size in the original set of 40 paired catchments varied between 13 and 202 hectares, with a mean value of 77 hectares. Some two-thirds of the catchments were less than 100 hectares. On average, a treatment area included 35 hectares of ditch network maintenance, 25 hectares of mineral soil sites, and 7 hectares of pristine peatlands or peatland areas without any planned maintenance.

On average, 8.6 km of ditches were either newly cut (complementary ditching) or cleaned within the treatment area. In most cases, ditch cleaning was more used than complementary ditching.

The main characteristics of the treated catchments are briefly described in Appendix 1.

3.1.3 Sedimentation ponds

In connection with ditch maintenance in 37 treated areas, sedimentation ponds were constructed (III). The settling capacity of the sedimentation ponds measured by their water-covered part at the time of digging varied from 0.67 to 5.51 m^3 per catchment area hectare. To estimate the changes in settling capacity, the depth of the ponds were measured as shown in Fig. 1b at least two times per year during the study period (Ahti et al. 1995b). Ponds that filled with sediment during the study were emptied by excavators; the settling capacity being determined before and after emptying.

3.1.4 Water sampling

In all sites, water sampling was carried prior to ditch network maintenance – the pretreatment calibration period (I). The changes in runoff water quality caused by ditch network maintenance could then be estimated by comparing runoff water from the treatment area with that of the control area. (II, III and IV). Sampling was started as early as possible each year, or at the beginning of the spring (snowmelt) high-flow and continued till the freezing of the ditches in autumn. No samples were taken during the winter. The water samples were taken twice a week during the spring high flows, but otherwise weekly.

The samples were taken directly into 500 ml plastic bottles from a sampling point on the main ditch selected to enable sampling from flowing water without stirring the bottom sediment in the ditch. The samples were sent immediately to the Central Laboratory of the Finnish Forest Research Institute in Vantaa. Prior to analysis, the samples were stored at + 5°C. Acidity and electrical conductivity were determined using the standard methods of the Finnish Forest Research Institute (Jarva & Tervahauta 1993). The samples were then filtered (Fibre-glass, pore size 1.2 μm) and the filtrate analysed for concentrations of phosphorus, sodium, potassium, magnesium, calcium, sulphur, aluminium and iron using plasma emission spectrophotometry (ICP-AES, ARL 3580).

Total dissolved nitrogen (N_{tot}), ammonium nitrogen (NH_4^-) and nitrate nitrogen (NO_3^+) concentrations were determined spectrophotometrically with a Tecaton FIA-analyser. Concentrations of dissolved organic carbon (DOC) was determined with a Shimadzu carbon analyser from 1992 onwards. DOC concentrations prior to 1992 were calculated from $KMnO_4$ consumption on the basis of a calibration regression (I, III, IV). The regression equation was derived from parallel measurements of both DOC and $KMnO_4$ concentrations from 714 samples. The filters were dried at 60°C and weighed to determine the amount of suspended solids.

Because of the large number of samples, total dissolved phosphorus was determined by using ICP-AES instead of determining total P spectrophotometrically from unfiltered samples (Vesihallitus 1981, 1984). For comparison, P concentrations were determined from 200 samples using both methods (Jarva & Tervahauta 1993, Nieminen 2000).

3.1.5 Site characteristics

The pre-treatment characteristics of the 75 ditch networks were determined using systematic sampling (I). Ditch depth, ditch width and the condition of the ditch were surveyed on sample plots located systematically along the ditches. Depending on the area of drained peatland, the number of sample plots varied between 22 and 204 per catchment. At each plot, the condition of the ditch was classified into one of the five classes described by Keltikangas et al. (1986). For determining the relationship between site type and ditch water chemistry, the original, pre-drainage peatland site type (Laine & Vasander 1990) of each plot was estimated around the plot centre. Finally, erosion of the ditches and other factors connected with ditch condition were noted. The information concerning initial ditching and fertilization was obtained from records held by the regional forestry authorities.

A second field survey was performed on the treated catchments in 1994. The thickness of the peat layer, the peat type, the the type and thickness of mineral subsoil, the degree of humification of the peat, and ditch depth and width were determined (Maaperän perus... 1994, II, III, IV).

In the third field survey of all 75 catchments in 1994, the tree stands and site types were characterised (Table 1, Appendix 1) in accordance with the TASO forestry planning system (Kinnunen & Ärölä 1993). The mean volume of the tree stands across all catchments and both mineral and peatland stands was 65 m^3ha^{-1}, ranging from 15 to 190 m^3ha^{-1}. The stand volume for the peatland forest stands only averaged 58 m^3ha^{-1}.

3.1.6 Estimation of discharge

After ditch network maintenance, discharge was monitored using simple 90° V-notch (Thompson) weirs made of waterproof plywood. Most basins had been fitted with a weir in 1993. Before maintenance, the order of magnitude of discharge was estimated by measuring the height of the water level in the ditch at sampling. The ditch water level data was used for eliminating the results of water samples taken during zero-discharge periods.

Discharge was calculated from the weir data by using the following equation

Table 1. Some basic characteristics of the treatment areas. Site class (Starr 1986): 1 = Grove and corresponding mire, 2 = Fresh heat and corresponding mire, 3 = Dryish heath and corresponding mire, 4 = Dry heath and corresponding mire, 5 = Barren heath and corresponding mire, 6 = Stone and sand, 7 = No forest land. Period I = 1990-1994, II = 1995-1998. For further details about the study areas, see Appendix 1-2.

Area	Proportion of site class							Mineral soil sites	Proportion of mires	Study period	
	1	2	3	4	5	6	7				
				%				%	%	I	II
1. Sepänsuo	6	23	53	16		2		78	22	X	
2. Kaulanperä	34	49	13		2	2		40	60	X	X
3. Isosuo	2	44	39	15				61	39	X	
4. Vuohensuo		20	49	20	6	6		61	39	X	
5. Pitkäneva		14		70	16			42	58	X	
6. Hirsisuo		47	44	7		2		59	41	X	
7. Paloneva					100			8	92	X	X
8. Alkkia					71	29			100	X	X
9. Porrasneva		2		96	2				100	X	X
10. Kiekonneva			24	76				44	56	X	
11. Pottisuo		2	29	28	37		4	59	41	X	X
12. Liisansuo		50	38	12				60	40	X	
13. Ruskeasuo		25	65	10					100	X	X
14. Alaräme		6	59	33		2		71	29	X	X
15. Purnukorpi		6	32	35	23	2	2	56	44	X	X
16. Mantilansuo	4	31	65					65	35	X	X
17. Honkasuo	46	38	16					78	22	X	
18. Tervasuo	6	44	44	6				50	50	X	
19. Soidinkorpi		8	45	31	14	2		56	44	X	
20. Heinäsuo		9	43	46	2			20	80	X	X
21. Haarasuo		50	32	11	7			75	25	X	
22. Kämppä		32	56	10		2		76	24	X	
23. Vähäoivari				100				4	96	X	X
24. Hautakangas		4		90	6			14	86	X	X
25. Sydänkorvenrämäkkä		2		84	14			12	88	X	X
26. Takkikallio		23	51	17	9			59	41	X	
27. Tupasalo		19	52	27	2			54	46	X	X
28. Korpiala		16	64	18	2			67	33	X	
29. Raippamaanoja		46	54					63	37	X	X
30. Jänissuo	26	50	22	2				68	32	X	
31. Rapasensuo		19	62	19				31	69	X	X
32. Komulansuo		34	58	8				36	64	X	X
33. Käärmekorpi			37	63				12	88	X	
34. Hämäläisneva		6	37	43	14			6	94	X	X
35. Pilpasuo	2	37	40	21				65	35	X	X
36. Isosuonräme		2	76	14	8			64	36	X	X
37. Ruostekorpi		6	55	39				33	67	X	X
38. Ollinneva		8	63	29				58	42	X	
39. Prakunmaa	38	54	6	2				50	50	X	X
40. Kontiojänkä	32	60	8					21	79	X	X

(Huikari et al. 1966, Ahti 1987):

$$Q = 0.0146 * h^{2.5},$$

where

Q = discharge, l s^{-1}

h = height of water level at weir, cm.

In addition to the above discharge observations, discharge data from the so-called "small catchments network" of the Finnish Environmental Administration were used to estimate the loads of suspended solids and nutrients. Because runoff is calculated from external discharge data directly by using catchment area ratios, it is important that the external catchment is situated close to the corresponding experimental catchment, and that the two catchments are as similar as possible as regards relative forest area, site type distribution and land use (Heino et al. 1986). In this study, the two most important variables when choosing the external catchments to be used in runoff estimation were location and the area percentage of forest land. Especially in southern Finland the requirements of close proximity and similar forest percentage were not always satisfactorily. In northern Finland, inaccuracy in runoff estimation was probably caused by to large distances to the external catchments (c.f. Mustonen 1965).

3.1.7 Precipitation

Annual precipitation data from the observation points of the Finnish Meteorological Institute situated close to the experimental catchments were used. The mean distance from the catchments to the nearest rain station did not exceed 10 km.

Mean annual precipitation during the 1990–1998 study period varied between 568 and 727 millimetres. At individual observation sites, the variation range was from 500 to 800 mm. On average, February-March was the driest period (Table 2). After this, the precipitation increased until July-August, from where it decreased towards winter and spring. On average, the study period was a little more rainy than the reference period 1961–1990 (Tilastoja Suomen ilmastosta ... 1991). The year 1992, during which the digging operations in main part of the study areas were performed, was a little more rainy than average. The study period was characterized by slightly higher precipitation during winter and early summer than during the long-term reference period of 1961–90.

Table 2. Monthly mean precipitation from 1990 to 1998 at the meteorological observation stations of the Finnish Meteorological Institute near the study areas (Meteorological Yearbook of Finland 1990-1998) and the comparison to the average of the period from 1961 to 1990 (Tilastoja Suomen ilmastosta ... 1991).

	Year										
Month	1990	1991	1992	1993	1994	1995	1996	1997	1998	X	1961-90
	mm										
January	67.3	41.8	41.2	53.4	50.3	39.8	10.5	34.9	65.6	45.0	36.3
February	70.3	18.4	41.1	18.4	3.8	65.4	31.7	45.3	50.8	38.4	26.0
Mach	42.5	36.0	47.4	30.0	51.2	47.1	21.7	37.1	34.3	38.6	29.5
April	36.2	17.7	40.3	25.9	41.5	31.5	23.6	45.0	12.4	30.5	31.5
May	17.5	46.9	17.5	15.9	22.8	59.5	57.3	24.7	48.3	34.5	36.2
June	38.5	94.4	31.5	56.7	68.0	76.7	54.8	52.9	93.2	63.0	50.3
July	88.8	44.7	88.6	88.0	17.0	52.3	99.7	70.9	120.6	74.5	69.1
August	70.0	74.4	113.0	105.3	59.0	65.3	27.6	33.7	107.4	72.9	78.2
September	33.0	95.1	77.2	28.7	81.3	44.4	24.0	94.2	34.7	57.0	63.0
October	31.5	54.4	61.8	63.8	87.2	71.1	50.8	52.6	91.1	62.7	54.5
November	41.2	75.7	69.8	8.0	37.3	40.3	119.2	47.6	18.5	50.9	51.9
December	43.6	47.4	45.1	74.0	53.9	17.9	54.6	30.6	50.5	46.4	42.3
Total	580.5	647.0	674.5	568.0	573.3	611.3	576.0	566.9	727.4	613.9	568.8

3.2 Estimating the effects of ditch network maintenance

The changes in runoff water quality caused by ditch network maintenance were examined on the basis of element concentrations. To estimate the mean change in concentrations, the concentrations observed in the runoff water from the treated areas were compared with values computed to represent the theoretical non-treated state of the same areas by using the relationship between the treated and control area data during the pre-treatment period. These values are referred to as ”predicted values” in the following sections. The computing of the predicted values and the evaluation of changes are described in more detail in publications II ja IV.

To test the similarity of treated and control catchments, regression models using simultaneous values of different variables during the pre-treatment period were computed for each pair of catchments. The following regression models were used:

$$y = a + bx,$$
$$y = a + b(\log x),$$
$$\log y = a + bx + \varepsilon,$$
$$\log y = a + b(\log x) + \varepsilon$$

where
y = concentration in runoff water from the treated catchment, x = concentration in the runoff water from the control catchment, ε = error term (Beauchamp & Olson 1973).

All four alternative regression models were computed for each pair of catchments and for all water quality parameters. The alternatives of computing predicted values are compared in section 4.2.

3.3 Statistical analysis

The water chemistry in the pre-treatment period (I) and after ditch network maintenance (II, III, IV) was characterised using descriptive statistics, e.g. means and standard deviations. The degree of relationship between variables was determined using Pearson correlation coefficients. The effect of ditch maintenance on the mean concentrations of each element was demonstrated by direct comparison of the pre- and post-treatment averages from the control and treatment areas. The differences between mean pre-treatment and post-treatment concentrations were tested by using Tukey’s test. In estimating the general effects of ditch network maintenance on the quality of runoff water, and when evaluating long-term changes, the Mann-Whitney U-test was used (Anon. 1996, Ranta et al. 1988).

Multiple regression equations relating post-treatment concentrations with pre-treatment concentrations and basin characteristics were constructed on the basis of significant intercorrelations. For estimating the export of elements in mass units, the change in concentrations due to ditch network maintenance was also evaluated on the basis of the difference between predicted and observed concentrations. Because no significant changes in runoff are assumed (Ahti et al. 1995a), the significance of the changes in load is indicated by the significant changes in concentration.

4 Results and discussion

4.1 Compatibility of materials

The concentrations of suspended solids and nutrients in runoff water from peatlands drained for forestry were examined on the basis of three data sets originating from the same set of catchments. First, the water quality of old drainage areas, i.e. the situation preceding the ditch network maintenance was studied on the basis of data from the 75 catchments (I, Fig. 1). Second, the short-term (3 years) effects of ditch network maintenance on runoff water quality were studied after treatments in 40 of the catchments (II, III). Third, the longer term effects of ditch network maintenance were studied during a period of six post-treatment years in 23 catchments selected from the set of 40 catchments above (IV). The compatibility of the short-term effects (40 catchments) and the longer-term effects (23 catchments) was tested by comparing the variables of the two data sets (Mann-Whitney U-test). The differences between the two data sets were not statistically significant (Table 3).

4.2 Evaluation of changes

In paired-catchments studies long pre-treatment calibration periods are preferred. During the calibration period, the relationships between the control area and the area to be treated are established for the important variables. These relationships, which can be simple ratios or more complicated mathematical functions (Ranta et al. 1989), can then be used to estimate hypothetical untreated variable values, so-called "predicted values", for the post-treatment period. When using regression models in producing "predicted values", the reliability of the predictions decreases with increasing deviations of the real observations from arithmetic mean. Regression models are best suited for normally distributed data. A pre-treatment calibration period of at least five years has been considered to be necessary to eliminate random effects caused by climatic variation (e.g. Ahtiainen 1990).

As is typical for runoff and concentration data, the data had skewed distributions, with more low values than high ones (I). The distributions of pH and DOC concentrations were approximately normally distributed while those of NH_4–N and NO_3–N were particularly skewed. Logarithmic transformation of values, however, did not always lead to any increase in the degree of explanation of linear regression models.

Table 3. Comparison of median values of water quality parameters from 40 catchments and a subsample of 23 catchments (Mann-Whitney U-test). Ns= difference not significant, * = $p<0.05$, ** = $p< 0.01$, *** = $p<0.001$. Dimensions: concentrations in mg l^{-1}, electric concuntivity in µS cm^{-1}.

Period	Before maintenance			1st year after maintenance			2nd year after maintenance			3rd year after maintenance		
Water quality parameter	40 areas	23 areas	p-value	40 areas	23 areas	p-value	40 areas	23 areas	p-value	40 areas	23 areas	p-value
N_{tot}	0.67	0.71	0.048 *	0.63	0.63	0.168 ns	0.59	0.55	0.375 ns	0.59	0.59	0.982 ns
NH_4-N	0.00	0.00	0.552 ns	0.028	0.037	0.695 ns	0.025	0.027	0.375 ns	0.028	0.032	0.994 ns
NO_3-N	0.019	0.021	0.201 ns	0.023	0.025	0.098 ns	0.032	0.030	0.848 ns	0.029	0.029	0.961 ns
DOC	27.3	28.9	0.134 ns	22.4	22.3	0.279 ns	20.9	20.0	0.730 ns	21.2	21.0	0.988 ns
SS	2.3	2.4	0.838 ns	11.5	9.8	0.677 ns	8.2	7.4	0.915 ns	7.8	7.5	0.976 ns
EC	36.3	37.4	0.417 ns	40.1	42.4	0.218 ns	41.0	40.2	0.554 ns	39.6	39.8	0.993 ns
pH	5.52	5.49	0.935 ns	6.45	6.47	0.983 ns	6.43	6.43	0.416 ns	6.38	6.35	0.984 ns
Na	1.84	1.64	0.682 ns	2.38	2.33	0.898 ns	2.31	2.17	0.938 ns	2.25	2.23	0.974 ns
K	0.43	0.42	0.106 ns	0.75	0.74	0.016 *	0.78	0.77	0.355 ns	0.77	0.77	0.982 ns
Ca	2.63	2.92	0.431 ns	3.28	3.54	0.063 ns	3.28	3.49	0.289 ns	3.23	3.21	0.981 ns
Mg	1.08	0.99	0.419 ns	1.50	1.48	0.179 ns	1.48	1.34	0.434 ns	1.47	1.42	0.996 ns
Al	0.39	0.32	0.903 ns	0.42	0.32	0.746 ns	0.34	0.27	0.736 ns	0.32	0.27	0.966 ns
Fe	1.18	1.20	0.947 ns	1.37	1.50	0.104 ns	1.21	1.39	0.369 ns	1.22	1.25	0.989 ns
S	1.50	1.27	0.547 ns	1.44	1.35	0.438 ns	1.61	1.38	0.849 ns	1.42	1.41	0.980 ns
P_{tot}	0.045	0.48	0.236 ns	0.050	0.054	0.143 ns	0.041	0.044	0.275 ns	0.038	0.041	0.992 ns

For each variable, predicted values based on regression models (Chapter 3.2) were constructed for all 40 treated catchments and used to predict values in study (III; Fig. 6, 7 and 8). In study (II), the predicted values were calculated using the control-treated area ratios of the variable means during the pre-treatment period. Rather similar values

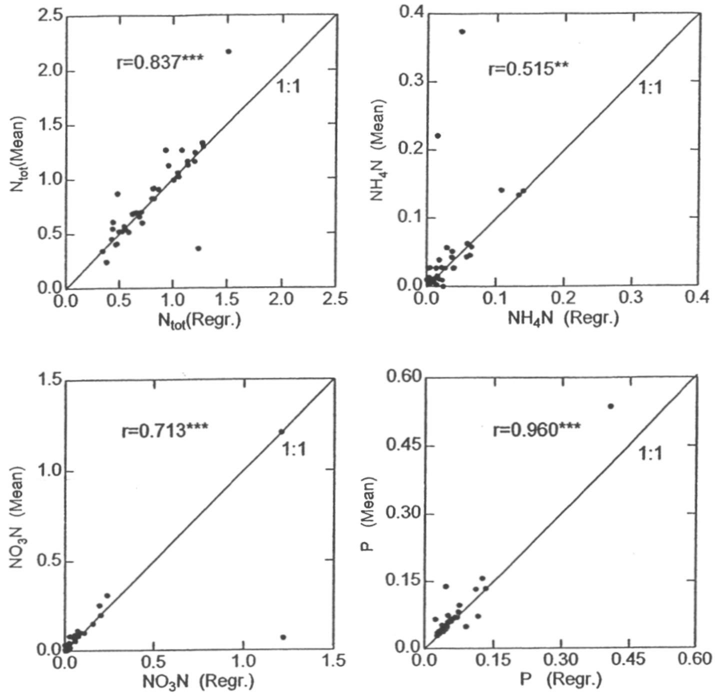

Figure 3a. Compatibility of two principles of predicting "non-treatment" concentrations of N_{tot}, NH_4–N, NO_3–N and P_{tot}. Vertical axis: predicted values based on pre-treatment differences between mean concentrations from control and treatment areas; horizontal axis: predicted values based on pre-treatment regressions between simultaneous observations from control and treatment areas.

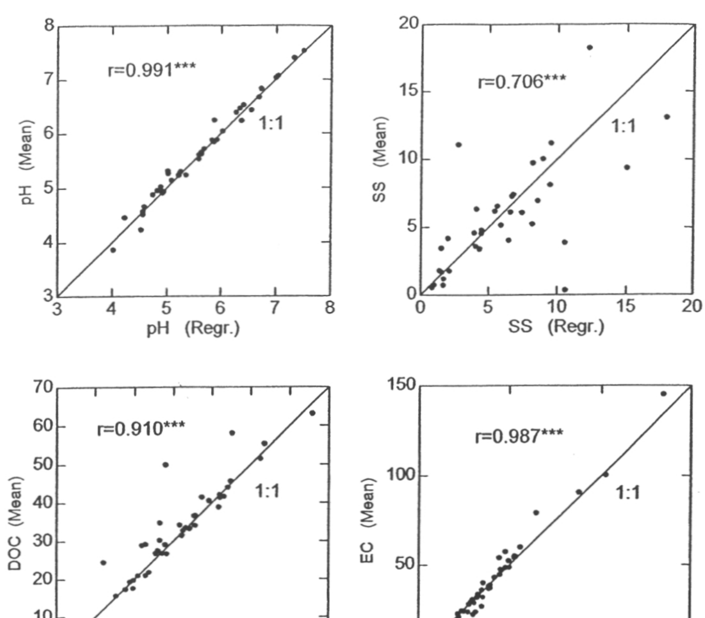

Figure 3b. Compatibility of two principles of predicting "non-treatment" values of pH, electric conductivity, and concentrations of suspended solids and dissolved organic carbon. Vertical axis: predicted values based on pre-treatment differences between arithmetic means from control and treatment areas; horizontal axis: predicted values based on pre-treatment regressions between simultaneous obserbations from control and treatment areas.

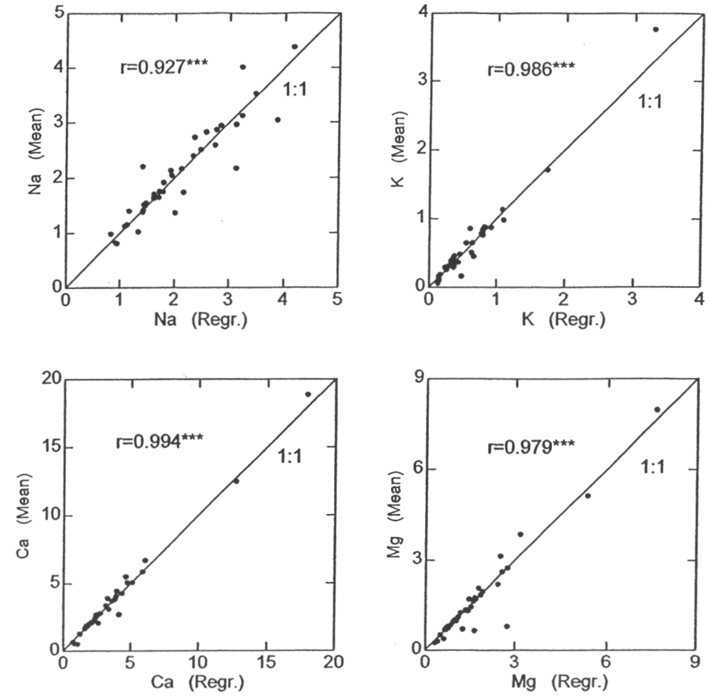

Figure 3c. Compatibility of two principles of predicting "non-treatment" concentrations of Na, K, Ca and Mg. Vertical axis: predicted values based on pre-treatment differences between mean concentrations from control and treatment areas; horizontal axis: predicted values based on pretreatment regression between concentrtations from control and treatment areas.

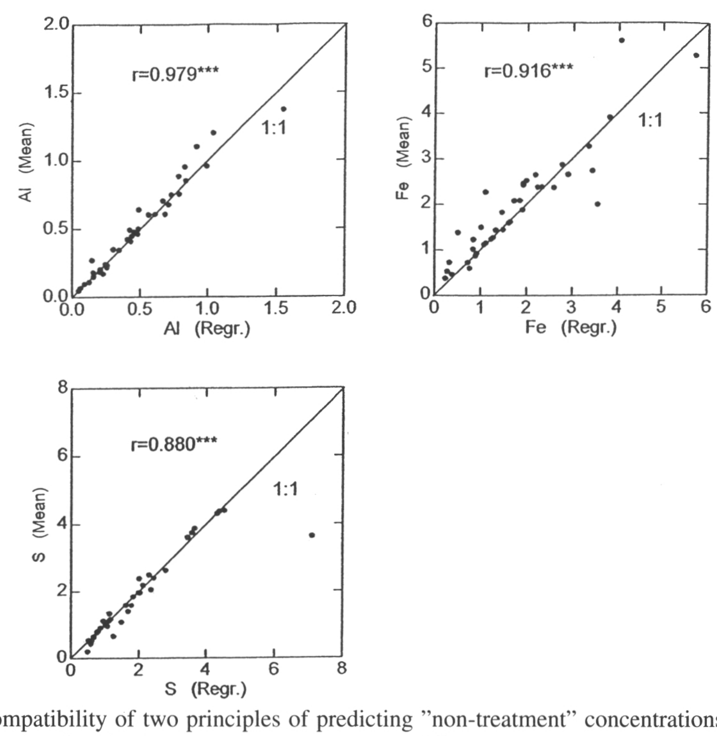

Figure 3d. Compatibility of two principles of predicting "non-treatment" concentrations of Al, Fe and S. Vertical axis: predicted values based on pre-treatment differences between mean concentrations from control and treatments areas; horizontal axis: predicted values based on pre-treatment regressions between concentrations from control and treatment areas.

were arrived at using both methods of prediction (Fig. 3 a-d). As could be expected from their skewed distributions, the largest differences between the two prediction methods occurred for NH_4–N and NO_3–N. The values for pH and DOC (Fig. 3b) were close for both prediction methods.

4.3 Load estimates

In paper (III), runoff from old ditch systems and freshly-maintained ditch systems were compared. No major changes in runoff caused by ditch network maintenance could be observed. Because of the deeper watertable, lateral water flow from the soil profile into the ditches probably occurs deeper in the peat profile than before ditch network maintenance and results in changes in the chemical characteristics of runoff water.

In estimating annual loads, both direct runoff observations and runoff data from adjacent small catchments were used (Chapter 3.1.6., II). Generally there were no major differences between the annual loads estimated on the basis of the two runoff data sets (Table 4). As expected, the greatest differences occurred in the loads of NH_4 and NO_3 during the pre-treatment period.

Table 4.Mean annual loads before ditch network maintenance and during three years after it by two methods of estimation. Load 1 = load estimate based on mean monthly concentrations and mean monthly discharge estimates from all catchments (II); load 2 = load estimate based on mean monthly concentrations of individual catchments and corresponding discharge data from the nearest "small catchments".

	Mean annual load kg ha^{-1} a^{-1}							
	Before		1st Year		2nd Year		3rd Year	
Element	Load 1	Load 2	Load 1	Load 2	Load 1	Load 2	Load 1	Load 2
N_{tot}	2.0	2.2	2.0	2.0	1.8	1.8	1.9	1.8
NH_4-N	0.093	0.110	0.29	0.29	0.28	0.25	0.29	0.24
NO_3-N	0.19	0.39	0.25	0.28	0.25	0.26	0.24	0.24
DOC	82	78	65	62	62	57	65	62
SS	11	11	268	232	89	103	75	53
Na	5.5	5.7	7.6	7.3	6.7	6.5	6.8	6.6
K	1.6	1.8	2.9	2.6	2.4	2.4	2.4	2.4
Ca	8.8	9.7	11.8	11.4	10.2	11.3	10.6	12.8
Mg	3.9	4.4	5.8	5.5	4.7	5.3	4.6	5.3
Al	1.4	1.3	3.8	2.8	1.8	1.7	1.6	1.6
Fe	3.8	3.9	5.5	4.6	3.8	3.4	3.9	3.6
S	5.9	5.5	5.6	5.2	6.1	5.7	6.2	5.6
P_{tot}	0.15	0.13	0.16	0.14	0.12	0.11	0.14	0.11

4.4 The effects of ditch network maintenance

4.4.1 Nitrogen

In the Nurmes study in Northern Carelia, pre-treatment concentrations of total nitrogen varied between 386 and 502 μg l^{-1} (Ahtiainen 1990). In the study by Kauppi (1979), the smallest concentration of total nitrogen was 230 μg l^{-1}. In forest-dominated catchments, median concentration of N_{tot} varied between 180 and 900 μg l^{-1} (Kortelainen et al. 1997). In the study by Bergqvist et al. (1984), N_{tot} concentrations varied between 300 and 600 µg l^{-1} and in those by Kenttämies (1980, 1981, 1987) between 427 and 518 µg l^{-1}.

A slight decrease in the across-site mean concentrations of N_{tot} was observed during the first three years after ditch network maintenance in this study (II). The decrease could still be seen six years after ditch maintenance in the 23 site data set (IV). This result differs from earlier studies (e.g. Ahtiainen & Huttunen 1999, Manninen 1999), who reported an increase in N_{tot} concentrations. However, some of the study catchments in this study did show an increase. Post-treatment N_{tot} concentrations were best explained by pre-treatment concentrations and the occurrence of poorly humified peat (H1–5) in the ditch profiles (II).

The average of site median N_{tot} concentrations were higher in this study than the median values reported for 13 peatland-dominated forested catchments by Saukkonen and Kortelainen (1995) and Kortelainen et al. (1997). The pre-treatment N_{tot} concentrations in this study were similar to those reported by Rekolainen (1989) for forest-dominated catchmentes but slightly lower than those for old drained peatlands reported by Kenttämies (1980, 1981).

The load of N_{tot}, in general, showed a slight decrease after ditch maintenance (Table 3, II). The annual loads per catchment hectare were similar or slightly higher than the value (1.8 kg ha^{-1} a^{-1}) reported for the Nurmes study (Ahtiainen 1990). The annual load of N_{tot} from peatland-dominated small forested catchments was estimated at 1.6 kg ha^{-1} a^{-1} by Kortelainen & Saukkonen (1998). The loads from peat harvesting areas (10–15 kg ha^{-1} a^{-1}) and agricultural land (7–20 kg ha^{-1} a^{-1}) are ten-fold (Rekolainen 1989, Kløve 2000b) those from drained peatlands and ditch maintenance areas.

Increases of NH_4–N concentrations in runoff water of between 0.03 and 0.09 mg l^{-1} after initial ditching have been reported (Bergqvist et al. 1984, Lundin 1988, Ahtiainen 1990). According to Manninen (1998,1999), the immediate increase in NH_4–N concentrations related to ditch network maintenance was greater than after the initial ditching and remained high during the whole 5-year post-treatment period. In this study, the across-site mean change in NH_4–N concentrations over the first three post-treatment years was as an increase of 0.051 mg l^{-1} (II). The effect could still be seen after 6 years (IV). In addition to the pre-treatment concentrations, the increase in the NH_4–N concentrations was best explained by the occurrence of poorly humified peat (H1–5) in the ditch profile, as with N_{tot} (II). Compared with the pre-treatment period, the mean NH_4–N load increased three-fold during the first three post-treatment years (Table 3).

The adsorption of ammonium in peat is one of the most important processes controlling mineral nitrogen loads from peatlands (Bastian & Benforado 1988). At pH 7 or lower, mineral nitrogen in peat water mostly occurs as NH_4^+ ions (Lance 1972). According to Lance (1972), anaerobic conditions are required for adsorption of NH_4^+ by peat. However, the NH_4^+ ions can be mobilized into soil water or taken up by plants and microbes through ion exchange reactions. The increase in the air content of the upper peat layers after ditch network maintenance would lead to the observed mineral concentrations of NH_4–N in runoff water.

The effect of ditch maintenance on NO_3–N concentrations in runoff water was less clear. The effect was difficult to establish because of a significant difference in the mean pre-treatment concentrations between the control areas and the treatment areas. In the Nurmes study, an increase in NO_3–N concentrations was observed in both of the two catchments in which initial ditching was performed (Ahtiainen 1990). However, the Nurmes-study results clearly differ from those reported by Bergquist et al. (1984) and Lundin (1988). Manninen (1999) observed raised NO_3–N concentrations after ditch network maintenance only during high-flow periods especially in April-May.

In general, the concentration of mineral nitrogen ($N_{min} = NO_3–N + NH_4–N$) in runoff water was higher after ditch network maintenance and remained higher than in the control catchments during the whole post-treatment observation period. In the study by Manninen (1999), the share of mineral nitrogen from total nitrogen doubled after ditch network maintenance. The share of mineral nitrogen also increased in this study. Prévost and Plamondon (1999) reported an increase in mineral nitrogen concentrations in runoff water of 320% after forest drainage. In this study, the concentration of organic nitrogen ($N_{tot} – N_{min}$) significantly decreased after ditch network maintenance and remained lower than in the control catchments during the whole six year post-treatment period studied (IV).

4.4.2 Phosphorus

Mean and median P_{tot} concentrations calculated from all individual samples in the pre-treatment data were higher than reported in many earlier reports (Heikurainen et al. 1978, Kenttämies 1987, Saukkonen & Kortelainen 1995, Kortelainen & Saukkonen 1998). The highest pre-treatment P_{tot} concentrations were observed during the low-flow periods in July and August (I). The post-treatment concentrations of P_{tot} exceeded those of the pre-treatment period in both the control catchments and the treated catchments. But during the first post-treatment year, no clear influence of ditch network maintenance could be observed. During the second and third post-treatment year, concentrations of P_{tot} were slightly lower than in the control catchments. The same was true in the longer-term data, but significant differences did not occur until during the fifth and the sixth post-treatment year (IV).

The annual load of dissolved P_{tot} averaged 0.12 kg ha^{-1} a^{-1}, and did not increase after ditch network maintenance (Table 3). In contrast, both Ahtiainen (1990) and Kenttämies (1987) reported an increase in P_{tot} concentrations after initial ditching. However, these increases were probably due to particulate phosphorus as the analysis had been done on unfiltered samples. Manninen (1999) found the concentrations of particulate phosphorus in runoff water to clearly increase immediately after the maintenance of old ditch systems. But later, the concentrations became lower than in the pre-treatment period.

The fact that dissolved P_{tot} was determined in this study may explain why no major changes in the export loads of phosphorus were observed. The difference in P concentration between filtered P_{tot} determined with ICP and unfiltered P_{tot} determined spectrophotometrically from 200 water samples originating from 31 of the catchments showed an increase with concentrations (Fig. 4). The difference was over 40% at high concentrations.

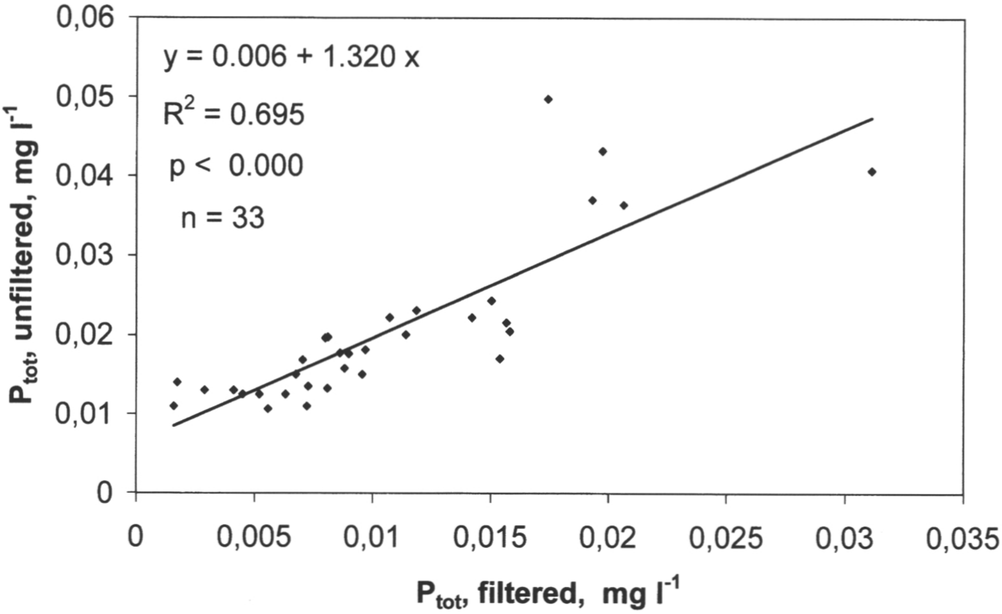

Figure 4. Comparison of P_{tot} concentrations determined spectrophotometrically from unfiltered samples (vertical axis) and from filtered samples by using ICP (horizontal axis).

In the data presented by Kortealainen and Saukkonen (1998) for small peatland-dominated forested catchments, the annual load of total P was 0.09 kg ha^{-1} a^{-1}. Studying export loads from peat harvesting areas, Kløve (2000a) reported mean annual P_{tot} loads of 0.23 kg ha^{-1} a^{-1}, which is more than double the load estimates of this study but matches the values presented by Sallantaus (1983).

According to Ekholm (1998), most particulate P is slowly soluble and therefore, not readily available for algae and other organisms. Only 10% of the particulate phosphorus originating from agriculture has been estimated to be readily available "reactive phosphorus" (c.f. Turtola 1999).

In this study, post-treatment P_{tot} concentrations were best explained by the pre-treatment P_{tot} concentration and the occurrence of fine mineral soils in the ditch profiles (II). According to studies dealing with the environmental effects of agriculture, the major part of the particulate phosphorus in runoff from clay soils is bound to suspended clay particles (Turtola & Paajanen 1995, Turtola 1999, Uusitalo et al. 2001).

4.4.3 Dissolved organic matter, suspended solids and pH

In brown-colored inland waters, humic substances are the main constituents of dissolved organic matter (Thurman 1985). Peatlands are the main source of organic matter for surface waters (Mulholland & Kuenzler 1979, Hovi 1988, Hemond 1990, Mulholland et al. 1990, Kortelainen 1993b). In runoff from mineral soils, concentrations of organic carbon are considerably lower than in waters originating from peatlands (Hemond 1990). To express the concentration of organic matter in waters, the consumption of $KMnO_4$, chemical oxygen demand (COD), color and total or dissolved organic carbon (TOC, DOC) are used. The concentrations obtained by the different methods strongly correlate with each other (Kortelainen 1993a, 1993b). In this study, pre-treatment DOC concentrations, determined from filtered samples, averaged 29.8 mg l^{-1}.

DOC concentrations were at their lowest during spring high flows and at their highest in autumn. Concentrations increased linearly towards the autumn both before and after ditch network maintenance (II). Heikkinen (1990b) found DOC concentrations to be slightly lower during the midsummer low-flow period (see also Kauppi 1979).

In the 40 catchment data set that covered the first three post-treatment years (II), the mean concentration of DOC was 29.9 mg l^{-1} before ditch network maintenance and 23.5 mg l^{-1} afterwards. In the longer-term data set of 23 catchments (IV), pre-treatment DOC concentrations averaged 31.0 mg l^{-1} and post-treatment concentrations 23.3 mg l^{-1}.

During the pre-treatment period, no statistically significant difference between control and treated catchments in DOC concentrations was observed. During each post-treatment year, however, the differences in mean DOC concentrations between control and treated catchments were statistically significant ($p<0.001$). In the data presented by Kenttämies (1987) and Ahtiainen (1988), a slight increase in the concentrations of DOC immediately after initial ditching was observed. In the next year, the concentrations of DOC decreased. In the study of Ahtiainen (1988), the immediate increase in DOC concentration might have resulted from the runoff water flowing through an undrained and saturated protection zone. In a number of studies dealing with the effects of overland flow on water quality, increases in the DOC concentrations have been observed (Ihme et al. 1991b, Finnish Forest Research Institute, unpublished data).

The mean and median suspended solid concentration values calculated from all pre-treatment samples (N=2818) were 4.9 mg l^{-1} and 2.4 mg l^{-1}, respectively (I). The highest monthly mean concentration occurred in July (7.8 mg l^{-1}) and the lowest in October (2.1 mg l^{-1}) and April (2.7 mg l^{-1}). The concentrations of suspended solids were increased by the ditch network maintenance. In all treated catchments, high concentrations were observed during the digging operations and during the following spring high flow. The highest concentrations exceeded 2000 mg l^{-1} in some catchments (III). Elevated concentrations of suspended solids were still observed six years after treatment (IV).

In the Nurmes study, where the water samples were taken from natural brooks (Ahtiainen 1990), no major increases in the concentrations of suspended solids were observed before the spring high flow period following initial ditching. High concentrations were occasionally observed after heavy summer rainfall, however. Kenttämies (1980) reported similar results.

In the Suopuro catchment of the Nurmes study, most of the suspended solid material was mineral soil and originated from the ditch bottoms. Mineral and organic suspended solids were not distinguished in this study, but it can be assumed that the suspended solids were of inorganic origin because most ditches cut into the mineral subsoil. The changes in the concentrations of suspended solids are discussed in more detail in Chapter 4.5.

The mean pre-treatment runoff water pH was 5.61, and ranging from 3.89 to 7.63 (I). The pre-treatment pH values were similar in the control and treated catchments (II, IV). Immediately after ditch network maintenance, the mean pH value was elevated by 0.6 units and was still 0.3 units higher six years after treatment than during the pre-treatment period. The change was further emphasized by a simultaneous pH decrease in the control areas (IV). In a case study of the Kloten project (Ramberg 1981), in which the treatment resembled the ditch maintenance of this study, the pH of runoff water increased by 0.9 units during a post-treatment period of two years. In that treatment, the ditches were cleaned to a depth of 1 m and into mineral subsoil. In the studies of Manninen (1998), the mean pH value of the runoff water from the Ruunusuo study area was 0.8–0.9 units higher during the first two years after ditch network maintenance than the pre-treatment values. Raised pH values after initial ditching have been reported in a number of studies (Hynninen & Sepponen 1983, Bergquist et al. 1984, Kenttämies & Laine 1984, Sallantaus 1986, Ahtiainen 1988, 1990). In the study by Prévost and Plamondon (1999), the pH value of the runoff water was raised by close to one pH unit after forest drainage, and was still higher after five years. According to the authors, the most important reason for the change was a relative increase in that part of runoff which originated from the mineral soil parts of the catchment.

Runoff waters are neutralized by leaching of ammonium in excess of nitrate (Sallantaus 1987). In this study, a long-term increase in the leaching of NH_4^+ after ditch network maintenance could be clearly seen, which may have resulted in the increased pH. However, the increase in pH may partly be due to other factors, such as deeper ditches and runoff into the ditches from deeper soil layers (e.g. Lundin 1996).

4.4.4 Base cations

In peatlands drained about 25 years earlier (I), the mean sodium concentrations in ditch drainage waters from individual catchments varied between 0.73 and 7.00 mg l^{-1}, with an average of 2.29 mg l^{-1}. The corresponding figures for potassium, calcium and magnesium were 0.12–3.47 and 0.58, 0.81–22.2 and 3.81, and 0.32–10.5 and 1.68, respectively. Except for potassium, which showed no seasonal trend, the concentrations of base cations were the highest in middle of the summer.

The concentrations of all four base cations increased immediately after the maintenance measures (II, IV). The differences between treated and control catchments remained statistically significant during the whole post-treatment period of six years (IV). Lundin (1988) and Prévost & Plamondon (1999) have observed increased concentrations of Ca and Mg after initial ditching especially in areas where the ditches cut into the mineral subsoil. Prévost & Plamondon (1999), however, did not observe any increases in K concentrations after drainage and suggested, as Laiho & Laine (1992) that the K concentrations remained unchanged because of effective uptake by the vegetation.

According to Manninen (1999), the concentrations of K, Na, Ca and Mg were respectively 30%, 20%, 50% and 50% higher during the first two years after ditch network maintenance than during the pre-treatment period. In the case of one catchment, Ruununsuo, the concentrations of base cations continued to be high during the whole 5-year observation period following ditch network maintenance.

4.4.5 Iron and aluminium

In several studies the concentrations of iron (Fe) and aluminium (Al) have been observed to increase immediately after initial ditching (Heikurainen et al. 1978, Clausen et al. 1980, Bergqvist et al. 1984, Ahtiainen 1990). In a Swedish study (Bergqvist et al.1984), simultaneous decreases in the concentrations of Fe and organic matter were reported. According to the authors, with the decrease in the concentration of humic acids, the concentration of organically bound iron would decrease as well. The connection between Fe and dissolved organic matter in surface waters has been frequently reported (Koenigs & Hooper 1976, Haapala et al. 1976, Geisy & Briese 1977, Wartiovaara 1978, Heikkinen 1985, 1990a, 1990b 1992). According to Koenigs & Hooper (1976), the soil layer between the aerobic and the anaerobic zones is important for the development of colloids, including organic matter and iron complexes. In this layer, the precipitation of iron with organic substances has also been reported (Puustjärvi 1953). According to Wartiovaara (1978), the increase in Fe concentrations of Finnish river waters in many parts of the country is due to forest drainage.

In this study, large short-term increases in the concentrations of Fe and Al were observed in some catchments after ditch network maintenance (II, IV). Because of these few sites, the mean concentrations of Fe and Al were significantly higher in the treated catchments than in the control catchments in both the 23- and 40 pair catchment data sets during the first post-treatment year. Later, lower concentrations were observed in the treated catchments than in the control catchments (IV).

Manninen (1995, 1998, 1999) reported both increasing and decreasing Fe concentrations after ditch network maintenance. As most Fe is carried into watercourses by organic compounds, decreased Fe concentrations might be connected to decreased concentrations of dissolved organic substances. Manninen (1995, 1999) also reported an immediate 10% increase in Al concentrations in runoff water after ditch network maintenance, which returned close to the pre-treatment levels during the 5-year post-treatment monitoring period.

4.5 Effects of sedimentation ponds

4.5.1 Effects of sedimentation ponds on the load of suspended solids

The concentrations of suspended solids in runoff water from areas subject to ditch network maintenance were reduced in more than half of the sedimentation ponds studied (III). For these ponds (20), the mean reduction was 28%. Averaged over all ponds (37), the concentrations were reduced by 18%, and only for 7 ponds, the reduction in concentrations exceeded 50%. Many of the ponds did not function well during the year of construction, probably because of the collapse of the walls of the ponds, and especially in those sites with fine-textured subsoils (III, Fig. 9). Similar findings have been reported for sedimentation ponds in peat harvesting areas (Ihme et al. 1992).

Higher or equal reductions in the concentrations of suspended solids have been reported for sedimentation ponds in peat harvesting areas (Selin & Kaunismaa 1985, Selin & Koskinen 1985, Ihme et al. 1991a). The measures for water protection are more strict for peat production areas than for forestry, and the sedimentation ponds are therefore usually larger in peat harvesting areas. According to Ihme et al. (1991a), however, seldom more than 30–40 % of the light organic suspended material from peat harvesting areas is retained by the sedimentation ponds during the frost-free period. The forest ditches usually cut into the mineral subsoil, and therefore the suspended solid material includes heavier mineral particles, which settle more easily and are more effectively retained by sedimentation ponds. In runoff water originating from thick-peated ditch maintenance areas, the concentrations of suspended solids are usually relatively low (III).

During high summer, the concentrations of suspended solids are usually low because of low flow, but the share of fine particles is increased (Aho & Kantola 1985, Ihme et al. 1991a). Because of the lower settling velocity of fine particles (Huisman 1973), lower retention of suspended solids in the sedimentation ponds was observed during summer months. Conversely, higher retention of suspended solids by sedimentation ponds in peat harvesting areas have been reported for high-flow periods, during which runoff contains more heavy particles than during low-flow periods (Ihme et al. 1991a). In this study (III), the poor retention of suspended solids originating from areas with fine-textured subsoils during spring high-flow periods is probably due to a combination of a low settling velocity of the fine particles and a high velocity of water flow through the basins.

The suspended solid material retained by sedimentation ponds primarily consists of silt and coarser material. In this study, half of the settling capacity was filled in about 20% of the ponds each year and 2–4 of the ponds had to be emptied during the first year. Some 60% of the variation in pond retention was explained by the area of ditch network maintenance and the settling volume of the pond. Including the concentration of suspended solids in input runoff and maximum discharge in the model enabled more than 80% of the variation in retention to be explained (III).

4.5.2 Effects of sedimentation ponds on dissolved element loads

The effect of the sedimentation ponds on the concentrations of dissolved elements was studied by comparing concentrations of input and output samples in pond (Table 4). The concentration of NO_3–N was statistically higher ($p< 0.05$) in the water flowing out of the pond than in the incoming water, while, the concentration of NH_4 decreased. This would indicate that nitrification was taking place in the pond (Heikkinen et al. 1994). The pH value was 0.05 units higher in outflow than in inflow ($p<0.001$). It appears that, after the pH of the runoff water was increased by ditch network maintenance, the acidity of the runoff is further neutralized in the sedimentation ponds. This is probably due to cation exchange buffering in the pond, as is indicated by higher concentrations of K, Ca and Mg in the outflow than in inflow water.

Table 5. The effects of sedimentation ponds on the concentrations of suspended solids and elements, pH- value and electric conductivity (EC). The differences in concentration medians between runoff water entering and leaving the basin were tested by using Mann-Whitney U-test. Significances: ns = not significant, * = $p<0.05$, ** = $p<0.01$, *** = $p<0.001$. Concentrations are expressed in mg l^{-1} and electric conductivity in µS cm^{-1}.

	Concentration in runoff water entering the pond					Concentration in runoff water leaving the pond					
Material	n	Median	Mean	S_e	S_d	n	Median	Mean	S_e	S_d	p-value
N_{tot}	3797	0.595	0.680	0.006	0.369	3597	0.596	0.671	0.006	0.343	0.737 ns
NH_4-N	3801	0.026	0.103	0.003	0.193	3599	0.026	0.088	0.003	0.161	0.327 ns
NO_3-N	3801	0.027	0.065	0.002	0.135	3600	0.028	0.076	0.002	0.137	0.012 *
DOC	3802	21.3	22.9	0.175	10.8	3600	20.8	22.6	0.180	10.8	0.090 ns
EC	3801	40.2	49.9	0.562	34.7	3598	41.9	50.9	0.587	35.2	0.132 ns
pH	3801	6.39	6.22	0.013	0.821	3599	6.47	6.28	0.014	0.824	0.000 ***
Na	3802	2.28	2.69	0.025	1.55	3600	2.31	2.70	0.026	1.55	0.878 ns
K	3802	0.757	0.972	0.023	1.42	3600	0.795	1.02	0.025	1.52	0.020 *
Ca	3802	3.22	4.40	0.072	4.47	3600	3.39	4.52	0.075	4.52	0.014 *
Mg	3802	1.47	2.04	0.034	2.08	3600	1.57	2.11	0.035	2.13	0.007 **
Al	3802	0.348	0.966	0.071	4.39	3600	0.353	1.07	0.080	4.82	0.737 ns
Fe	3802	1.24	1.79	0.054	3.35	3600	1.19	1.78	0.060	3.59	0.057 ns
S	3802	1.44	2.14	0.039	2.41	3600	1.58	2.19	0.038	2.26	0.006 **
P_{tot}	3802	0.043	0.054	0.001	0.052	3600	0.043	0.053	0.001	0.053	0.877 ns

5 Reliability of results

In this study, runoff water quality from 75 old ditch networks in different parts of Finland was monitored. On 40 of these sites, the effects of ditch network maintenance on runoff water quality were observed during 1 – 3 years. In 37 ditch networks, a sedimentation pond was constructed, the efficiency of which was simultaneously studied. For each of the areas to be treated, a control area was chosen in which runoff water samples were taken at the same time as in the paired treated one. Twenty three sites and corresponding control areas were chosen to study the longer-term (6 years) effects of ditch network maintenance. The data of this study is larger and more comprehensive than in many earlier corresponding studies that often consist of only one or a few catchments but from which conclusions and generalizations have been made. In selecting parameters to describe the characteristics at the sites, those which available to practical forestry were chosen.

The relatively large number of catchments increases the variation in catchment characteristics data. This allows the use of regression analysis in studying the relationships between runoff water quality and catchment characteristics. One of the main objectives of the study was to predict post-treatment concentrations using the catchment characteristics. The present data is large enough for the reliable predictíon of load on an annual basis. For a more detailed analysis, a larger number of experimental sites is needed.

It is difficult to find two catchments that are situated close to each other and have similar runoff water quality to allow direct comparison. For example, the paired Kaulanperä treatment area and the Puistovuori control area (Appendix 2) were rather similar as regards size, topography and site types but different as regards runoff water quality. Even if the method using a calibration period and control areas is supposed to solve this heterogeneity problem, difficulties may turn out in predicting the hypothetical non-treatment values of many water quality variables using regression analysis. This is why comparing of pre-treatment and post-treatment differences of means between treated and control catchments can be as effective as predicting hypothetical non-treatment values of water quality variables as the paired-catchment regression model method.

This study was based on weekly samples collected during the snowless period from a relative large number of sites having a wide geographic distribution except during the spring high-flow period, when samples were taken twice a week. At the same time as the samples were taken, discharge was measured using simple 90° V-notch (Thompson) weirs. The continuous measurement of discharge would have propably increased the accuracy of the export load estimates, but whether this would be of practical consequence is questionable. The comparison of a large number of sites to cover the spatial variation and weekly sampling was considered the best strategy for deriving models for use in ditch network maintenance planning in practice.

Unfortunately, it was not possible to determine the share of organic matter or N_{tot}

out of the suspended solids concentrations. In a few studies (e.g. Hilden et al. 1999, Kenttämies & Vilhunen 2000), the mobilization of nitrogen from organic suspended material has been considered significant for the eutrophication of receiving watercourses. It can be assumed, however, that the loads of suspended solids from ditch network maintenance are mainly of mineral origin.

Acid clays along the Ostrobothnian coast at elevations below 40 m a.s.l., originating from sediments of the postclacial Litorina Sea, may contribute to acid runoff after drainage operations in agriculture and forestry (Palko 1994, Ruokanen 1993, 1995). The occurrence of such clays within the catchments of this study was not inventoried, but no major drops in the pH values were observed after ditch network maintenance in those sites (2) within the coastal region.

In planning a research project such as this one, the balance between costs and representability of sampling in time and space is a common problem. According to Rekolainen et al. (1991), discharge-weighted sampling produces more reliable load estimates than sampling with constant intervals, especially for those water quality variables that are characterized by a large variation in time.

When the project was planned (1989), a large number of water samples was anticipated. In order to ensure that the samples could be filtered in a reasonable time a filter with a pore size of 1.2 µm rather the conventional size 0.45 µm was used. Because the pore size of the filters was larger than conventionally used, the concentration and loads of suspended solids are slightly underestimated compared to other studies.

6 Conclusions

Because of increasing forest ditch maintenance and peat harvesting activities, concern regarding the survival of salmon (*Salmo salar* L.), sea trout (*S. trutta* m. *trutta* L.) and brown trout (*S. trutta* m. *lacustris* L.) in the rivers and streams of northern Finland has been expressed (Laine 2001, Lappalainen & Hildén 1993, Vuori 1995, Vuorinen et al. 1995). The results from this study show that the increased load of suspended solids is the most distinct change in the quality of runoff water after ditch network maintenance. But the role of particulates in the eutrophication processes is poorly known. Changes in the export loads of dissolved elements caused by ditch network maintenance were negligible. The changes in the concentrations of N_{tot} were sporadic, and those of dissolved total phosphorus even decreased after ditch maintenance. A few sites had been recently fertilized and the concentrations of dissolved total phosphorus clearly decreased after the maintenance. The drying of the peat as a result of the maintenance operation probably resulted in the oxidation of Fe, which effectively binds soluble phosphorus (Nieminen 2000).

The national water protection programme aims to decrease the nutrient loads from forested areas in 2005 by 50% from the level of 1993. This aim can to be achieved by reducing the loads of suspended solids through the use of overland flow, i.e. buffer zones and special overland flow areas, and sedimentation ponds. The results from this study (III) demonstrated that when using sedimentation ponds alone, only the coarse fractions of suspended solids can be prevented from leaving the ditch systems after ditch maintenance operations.

In addition to using ponds of sufficient size, the time of construction with respect to the actual ditch maintenance operation is essential for the efficiency of the whole water protection plan. The results from this study suggest that the sedimentation ponds should be constructed at least one year before ditch network maintenance to allow stabilization of pond walls.

The purpose of sedimentation ponds, at present, is to retain suspended solids; they do not retain dissolved nutrients in discharging ditch water. To increase the efficiency of the ponds, the pond structure should be developed to function as a filter zone with vegetation to bind soluble nutrients. To be able to construct these ”riparian sedimentation basins”, further experimentation is needed.

One result from the study was that the concentrations of phosphorus, iron, aluminum and some base cations in runoff water are associated with the presence of fine-textured mineral subsoil. The same has been observed in a number of earlier studies (Heikkinen 1992, Laine & Heikkinen 1999, Lahermo et al. 1996, Turtola 1999).

The drained peatlands in Finland are usually shallow-peated enough to allow the ditches to reach the mineral subsoil, and ditch runoff concentrations of suspended solids are generally higher and remain higher longer than in runoff water from ditches on deep peat after ditch network maintenance (e.g. Heikurainen et al. 1978, Konstantinov & Suhorukova 1980). The results from this study showed that if the ditches cut into fine-textured subsoils, concentrations of suspended solids remained high for at least 6 years. Suspended solids concentrations from areas with coarse-textured subsoils or deep peat return to the pre-treatment levels within 3 – 4 years.

Thus, when planning ditch maintenance projects, the thickness of the peat layer and the texture of the subsoil should be better known. If the texture class of the subsoil is known, and runoff water samples analyzed prior to the digging operations, the concentrations of suspended solids (III) and some nutrients (II) in runoff water can be estimated for a short period immediately after ditch network maintenance using the regression models presented in this study. The simple soil survey procedure used in this (III) study could be further developed and applied in the practical planning of ditch network maintenance.

The clear and long-term (at least 6 years) increase in the pH value of runoff after ditch network maintenance is an interesting phenomenon from the point of view of water protection. Similar results have been reported in earlier studies after forest drainage, but those were individual sites (e.g. Kenttämies 1987, Ahtiainen 1990). Combined with no major changes in annual runoff after ditch network maintenance, this change might have more extensive effects in the watercourses that can be seen today. Thus, ditch network maintenance does not result in the acidification of watercourses, on the contrary.

From the point of view of operational scale forestry, the study provides a more representative picture of the effects of ditch network maintenance on runoff water quality than earlier studies that were based on one or a few individual catchments. It is hoped, that the results of this study will be taken into account by local forest authorities in the near future. It should be mentioned that, in addition to being research objects, many of the experimental areas in this study have been used for excursions and training of those responsible for planning of ditch maintenance projects in private forests.

In operational scale forestry, the discharge from ditch networks has not normally been measured. The simple 90° V-notch weir used in this study might be a cheap enough means of estimating discharge from at least the larger ditch networks. Also, the existing runoff data from the so-called ”small catchments” network, maintained by the Finnish Environment Institute, could be better utilized in estimating expected export load from forest ditch network maintenance areas (Bengtsson 2001).

Many of the results from this study have already been taken into consideration in operational ditch network maintenance instructions. For instance, the recommended area and volume of sedimentation basins have been increased, instructions dealing with the location of the ponds have been changed, sedimentation ponds are not recommended any more if the subsoil is clay or clayey till and if possible, the sedimentation ponds should be constructed in deep peat, i.e. the walls and the bottom of the pond should be in peat (e.g. Savolainen et al. 1996). If the ditches cut into fine-textured subsoils, the retention efficiency of sedimentation ponds is poor, irrespective of pond size. For such sites, water protection methods based on overland flow (buffer zones), or a combined use of overland flow techniques and sedimentation ponds are recommended. The results of this study show that the dimensioning of the sedimentation ponds should be based more on discharge than has been the case so far. Data on the results of using ponds constructed according to the new recommendations are not available but, more research is needed.

In the future, the monitoring and control of environmental effects of agriculture and forestry will become increasingly important (e.g. Rekolainen 1993, Marttila 2001, Vesiensuojelun tavoiteohjelma 2005 1998, Suomen Itämeren suojeluohjelma...2001, Kauppila & Bäck 2001). The water policy directive of the European parliament and Council (Euroopan parlamentin ja neuvoston direktiivi 2000/60/EC) further increases the need for knowledge on the environmental effects of forestry. As regards ditch network maintenance, this study provides a basis for such developments. Among topics for further research are the effects of ditch network maintenance on areas dominated by sulphide-rich clayey and on the leaching of phosphate phosphorus (PO_4–P). Among the methods of water protection, the use of buffer zones and overland flow areas on runoff water quality is not known well enough.

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Appendix 1

Catchment descriptions

In the following, each of the catchments that were subject to ditch network maintenance is shortly described. For description of peatland site types, see Laine and Vasander (1990). Maps of the catchment pairs are presented in Appendix 2.

1. Sepänsuo (commune: Pertteli; 60°26'N, 23°24'E). The total area of the catchment is 62 ha, one third consisting of peatlands or paludified mineral soil sites. Initial ditching was performed on about 18 ha in 1969. Ditch network maintenance was performed on about 18 ha mostly by cleaning the old ditches. The drained area was fertilized in 1975. In total, 1100 kg of N, 570 kg of P and 690 kg of K was applied. About 30% of the catchment area consists of seedling stands, less than 20% are young thinning stands, and more than 20% advanced thinning stands and mature stands. Most of the seedling stands are situated within the ditch systems. More than 50% of the drained area, was originally *dwarf-shrub pine bog*. Morphologically, the drained peatland area is a thick-peated raised bog with poorly decomposed *Sphagnum* peat in the central parts and more humified towards the edges. The mineral soil areas consist of loamy and silty till dominated by Scots pine and Norway spruce. Rocks and boulder areas are characteristic of the area.

2. Kaulanperä (commune: Karinainen; 60°42'N, 22°49'E). This catchment is one of the smallest in the study, 33 ha. Some 40% of the area has had ditch network maintenance. Peat thickness varies from a few centimeters to 0.5 m. The mineral subsoil is clay with pockets of clayey till. The initial ditching was performed in 1956 and practically the same area was subject to ditch network maintenance in 1992; only about 3% of the original drainage area was left without ditch network maintenance. No fertilization has been carried out in the catchment. The original peatland site types were *herb-rich hardwood-spruce swamp, herb-rich sedge hardwood-spruce fen* and *paludified Vaccinium myrtillus spruce forest*. The mean stand volume now exceeds (1994) 190 m^3 ha^{-1} and is dominated by advanced thinning stands of Norway spruce and downy birch.

3. Isosuo (commune: Laitila; 60°49'N, 21°53'E). The total catchment area is 55 ha of which about 45% was drained in 1967. The drained area was fertilized in 1972 with 1600 kg of N, 820 kg of P and 990 kg of K. In addition to the normal ditches with a rather large spacing (about 80 m), narrow ditches dug with a rotary digger at intervals of 10 meters were dug perpendicular to the normal ones. The drainage area is a raised bog with poor site types and sparse tree stands in the centre. The central parts of the bog were still dry, with lichens and dwarf-shrubs dominating the surface vegetation, but secondary paludification had started within the even and low-lying border parts of the bog. Here, the technical condition of the ditch system was considerably impaired by the luxuriant growth of cottongrass (*Eriophorum vaginatum*). The forest area consists of seedling stands, young thinning stands and advanced thinning stands in approximately equal proportion. Some 4% of the mineral soil stands had been clearcut. The mean stand volume of the catchment is 84 m^3 ha^{-1}.

4. Vuohensuo (commune: Yläne; 60°49'N, 22°26'E). The total area of the catchment is 65 ha. In 1965, 28 ha of peatland were drained for forestry and in 1975, complementary ditching was performed, increasing the total length of the ditch network by 10 km. During 1971–80, fertilization was performed on 86 ha, with some stands being repeatedly fertilized. In total, 5600 kg of N, 3400 kg of P and 4800 kg of K was used. About 10 ha of the drained area was afforested in 1976 using planting and spot fertilization. The original site type of the drained area ranged from *low-sedge Sphagnum papillosum pine fen* in the centre to *Vaccinium myrtillus spruce swamps* at the border, with various pine fens between. The oligotrophic character of the site is indicated by the low mean stand volume of 43 m^3 ha^{-1}. The peat layer is thick and consists mainly of poorly decomposed *Sphagnum* peat. Along the borders of the ditch network, the ditches cut into the mineral subsoil.

5. Pitkäneva (commune: Kankaanpää; 61°52'N. 22°22'E). The catchment is 44 ha including 20 ha of drained peatlands. The drainage area partly consists of paludified mineral soil sites with a thin peat layer. The subsoil is compact silty and sandy till. The ditch network includes a few main ditches that collect the waters from the lateral ditches. Bare rock and boulder areas are typical for the mineral soil sites in the catchment. The mean volume of the pine dominated stands is 75 m^3 ha^{-1} . The forest cover is 20% seedling stands, 34% young thinning stands, 25% advanced thinning stands and 10% mature stands. In the 1980's, clear-cuttings, shelterwood cuttings and thinnings were performed on the mineral soil sites. The initial ditching was done in 1964, and in 1973, 4.5 ha was fertilized by spreading 250 kg of N, 180 kg of P and 220 kg of K. Ditch network maintenance (5700 m) was performed on the entire area in 1992 of which more than half were compelementary ditches.

6. Hirsisuo (commune: Noormarkku; 61°34'N, 21°55'E) The total area of the catchment is 134 ha mostly mineral soils. In 1965 38 ha of peatlands were drained. The ditch network maintenance was performed on 17 ha. No fertilizers have been applied. The dominating site type of the peatland area is *Vaccinium myrtillus spruce swamp* with a thin peat layer in places. The ditches partly cut into a clayey and loamy till subsoil. The peat layer consists of moderately or well-humified *Sphagnum-Carex*-peat of varying thickness. The mean volume of the tree stand is 93 m^3 ha^{-1}, which are dominated by seedling stands and young thinning stands. The share of advanced thinning stands and mature stands was 40%.

7. Paloneva (commune: Karvia; 62°10'N, 22°39'E) The catchment area is 31 ha including 30 ha of peatland drained for forestry in 1964. In 1973, 23 ha was fertilized by applying 1070 kg of N, 920 kg of P and 1100 kg of K in total. In 1989, 2.8 ha were clear-cut. Some 16 ha of seedling stands were tended in 1984. The ditch network consists of 8.4 km of ditches, of which 6.6 km were cleaned. The drainage area is thin-peated and the subsoil is dominated by sorted silts, sands and gravels. Three quarters of the stands are advanced seedling stands or young thinning stands. The share of advanced thinning stands slightly exceeds 10%.

8. Alkkia (commune: Karvia; 62°11'N, 22°46'E). The catchment is 79 ha including 66 ha of peatland. In 1965, 48 ha were drained for forestry and in 1977 11 ha were fertilized with 780 kg of N, 470 kg of P and 620 kg of K. In 1983, thinnings on 1.5 ha were made, and in 1990, cuttings connected to natural regeneration on 16 ha were performed. The area subject to ditch network maintenance was 61% of the catchment area. Poorly stocked pristine low-sedge fens still remain on 17 ha, which accounts for the low catchment mean stand volume of 28 $m^3 ha^{-1}$. The major part of the drained peatland is thin-peated. In the northern part of the ditch network, the subsoil is loamy till while that in the southerly part is gravel till.

9. Porrasneva (commune: Kihniö; 62°08'N, 23°07'E). The catchment area is 43 ha including 36 ha of peatland. The catchment borders on esker. The initial ditching (35 ha) was performed in 1969, after which 24 ha were fertilized in 1971. In total, 1250 kg of N, 960 kg of P and 1150 kg of K were applied. Close to half of the catchment area was subject to ditch network maintenance. The mean stand volume is 52 $m^3 ha^{-1}$, with more than 90% of the stands being advanced seedling stands or young thinning stands. The share of advanced thinning stands did not exceed 7% of the catchment area. The peat is generally poorly decomposed Sphagnum peat with abundant remains of dwarf-shrubs.

10. Kiekonneva (commune: Hämeenkyrö; 61°41'N, 23°00'E). The catchment borders an esker area dominated by poor stands of Scots pine. The catchment area is 86 ha, of which 25 ha were subject to ditch network maintenance. About half of the area of drained peatland were not subject to ditch maintenance. In the maintenance area, the mean thickness of the peat layer was only 0.2 m. The mineral subsoil was mostly loam, silt and loamy till. The initial ditching was performed in 1956. No fertilization has been applied. The mean stand volume is 88 $m^3 ha^{-1}$ with more than half of the stands being advanced seedling stands or young thinning stands. The share of mature stands is 40%.

11. Pottisuo (commune: Orimattila; 60°51'N, 25°51'E) The catchment is 75 ha of which 50% consist of thick-peated sites drained for forestry in 1968. At the beginning of the 20th century, peat was taken for cow-house litter. Today, this activity is still to be seen as water-filled depressions. Some 25 hectares of the drained area was fertilized with PK in 1969. In total, about 1000 kg of P and 1200 kg of K was broadcasted. In 1992, thinnings on 2 ha, and in 1993, tending of seedling stands on 12 ha were performed. Morphologically, the drained peatland sites are part of an ombrotrophic raised bog with poorly decomposed *Sphagnum* peats, effective drainage and transformed vegetation in the center and more decomposed peats at the edges. The mean stand volume of the catchment was 111 $m^3 ha^{-1}$. On the drained peatland sites, mean stand volume was only 58 $m^3 ha^{-1}$, however. The share of advanced seedling stands and young thinning stands exceeded 50% of the catchment area and close to one third of the area is covered by mature tree stands.

12. Liisansuo (commune: Vehkalahti: 60°37'N, 27°27'E)). The total area of the catchment is 177 ha, out of which 100 ha are mineral soil sites. Initial ditching covered an area of 78 ha, of which 36 ha were subject to ditch network maintenance. In total, 6 km of old ditches were cleaned and 1.7 km of complementary ditches dug. With the exception of a few ditches at the borders of the maintenance area, the ditches did not cut into the mineral subsoil. The peat layer consists of poorly or moderately decomposed *Sphagnum* peat. The mean volume of the tree stands within the catchment was 116 m^3 ha^{-1}, and 91 m^3 ha^{-1} for the drained peatlands. About 50% of the stands were advanced seedling stands and young thinning stands and the share of mature stands was 20%.

13. Ruskeesuo (commune: Pyhäselkä; 62°28'N, 30°04'E). The catchment is 25 ha, and totally consists of peatland drained for forestry in 1964. Except for some ditches at the borders of the catchment, the peat layer is so thick that the ditches do not cut into the mineral subsoil. The total length of the ditches is 4.5 km. Fertilization has been carried out twice; in 1970 by applying 990 kg of P and 1190 kg of K to the whole catchment area and in 1985, by applying 880 kg of N, 340kg of P and 650 kg of K to 9.5 ha. Three quarters of the tree stands are young thinning stands and 20% advanced thinning stands. The mean volume of the stands over the catchment is 97 m^3 ha^{-1}.

14. Aläräme (commune: Pyhäselkä; 62°29'N 30°04'E). The catchment directly borders the Ruskeasuo (13.) catchment. The catchment area is 60 ha, of which 29 ha were subject to ditch network maintenance. About 50% of the total ditch length were cleaned but some 2 ha of the original drainage area were not subject to maintenance. Because the mean thickness of the peat was 0.4 m, a considerable part of the ditches cut into the mineral subsoil. Advanced seedling stands accounted for 20%, young thinning stands 37% and advanced thinning stands 39% of the catchmenet area. The mean volume of the stands was 87 m^3 ha^{-1}. The initial ditching was performed in 1964 by digging 4 km of ditches. In 1970, PK fertilizer was applied on 12 ha and in 1978, 14.5 ha and in 1985, 8 ha were fertilized with PK fertilizer and urea. In total, 2080 kg of N, 1290 kg of P and 2100 kg of K have been spread.

15. Purnukorpi (commune: Kiihtelysvaara; 62°25'N, 30°18'E). The catchment area is about 100 ha, of which drained peatlands make up 47 ha. The initial ditching was performed in 1968. In 1970, 17 ha were fertilized with PK fertilizer, and in 1983, PK and urea was applied on 9 ha. In total, 820kg of N, 1000 kg of P and 1400 kg of K were used. Ditch network maintenance consisted of ditch cleaning. The peatlands in the catchment form an oligotrophic raised bog complex, in which *cottongrass pine bog* and *dwarf-shrub pine bog* were the main site types. Some 2/3 of the tree stands were seedling stands or young thinning stands and advanced thinning or mature stands accounted for a further 25% of the catchment area.

16. Mantilansuo (commune: Punkaharju; 61°59'N, 29°40'E). The area of the catchment is 64 ha, of which 24 ha were drained for forestry in 1965. In 1986, the ditch network was complemented by digging 420 m of new ditches, and all old ditches were cleaned in connection with this study. In 1971–1972 26 ha of the catchment were fertilized. In total, 1580 kg of N, 950 kg of P and 1260 kg of K were applied. The volume of the tree stands in the catchment averaged 88 m3 ha^{-1} and that on the drained peatlands 58.5 m^3 ha^{-1}. One third of the tree stands were young thinning stands, 25% were advanced thinning stands and various seedling stands and other poorly stocked sites amounted to another third of the catchment area.

17. Honkasuo (commune: Pielavesi; 63°20'N, 26°48'E). The area of the catchment is 54 ha. In 1963, 30 ha was drained for forestry and the whole ditch system was subject to maintenance during the study. More than half of the total ditch length dug in the maintenance operation were complementary ditches. In 1978, 9.4 ha were fertilized with 340 kg of P and 640 kg of K. Mineral soils cover 78% of the catchment and are mainly fertile site types. The peatlands in the catchment are also rather fertile: *tall-sedge fens*. The stands are dominated by mixtures of pine, spruce and birch, with a mean volume of 134 m^3 ha^{-1}. More than half of the stands are advanced thinning stands, and the share of young thinning stands and mature stands are 25% and 6%, respectively.

18. Tervasuo (commune: Pielavesi; 63°12'N, 26°58'E). The area of the catchment is 118 ha. The ditches of the drained area of 69 ha originate from 1947, 1966 and 1985. During this study, 44 ha were subject to ditch network maintenance. No fertilizers have been applied. The volume of mixed stands of pine, spruce and birch in the catchment averaged 163 m3 ha^{-1} and that on the peatland area 147 m^3 ha^{-1}. Advanced thinning stands, mature stands and seedling stands or young thinning stands accounted for 60%, 16% and 25% of the forest, respectively.

19. Soidinkorpi (commune: Pihtipudas; 63°29'N, 25°24'E). The area of the catchment is 163 ha of which 56 ha was drained for forestry in 1960. There are 20 hectares of pristine peatlands. The whole drained area was subject to ditch network maintenance. Mineral soils cover about 30% of the catchment. Spruce swamps, pine mires and treeless fens originally accounted for 6 %, 52 % and 12 %, respectively. The peatlands are of low fertility, characterized by *Eriophorum vaginatum* or *Sphagnum fuscum*. The stand volume on the drained peatlands has thus remained low at 38.5 m3 ha^{-1}. The volume of the pine-dominated stands for the whole catchment averaged 71 m^3 ha^{-1}.

20. Heinäsuo (commune: Kinnula; 63°22'N, 25°12'E). The area of the catchment is 202 ha, of which 102 ha were drained for forestry in 1938 and 1969. The ditch network maintenance was carried out on 23 ha. In 1968, 30 ha were fertilized with 1390 kg of N, 900 kg of P and 1080 kg of K. The minereal soil areas are dominated by Scots pine and are typically of the *Vaccinium vitis-idaea* type. The peatland area is *tall-sedge pine fen* (30%) or *cotton-grass sedge pine fen* (57%). The mean stand volume of the catchment is 64 m^3 ha^{-1}. Half of the forests are advanced seedling stands or young thinning stands, 40% advanced thinning stands and 10% are low-yielding stands.

21. Haarasuo (commune: Keuruu; 62°09' N, 24°48' E). The area of the catchment is 56 ha. The initial ditching was performed in 1965, when 29 ha was drained. In 1970, 15 ha of the ditched area was fertilized with 5800 kg of PK fertilizer and 1450 kg of urea. The nutrient content of that amount was 670 kg N, 580 kg P and 690 kg K. The mineral soil types in the area are mainly *Vaccinium myrtillus and Vaccinium vitis-idaea* site types and on the peatlands, *cottongrass* site types. *Tall-sedge hardwood- spruce swamps* and *tall sedge pine fens* account for over a quarter of the peatland area. *Scots pine* is the dominant tree species but the share of the *Norway spruce* is about a quarter. The volume of the tree stand for the whole catchment area averages 145 m^3 ha^{-1} and that on the peatland area 93 m^3 ha^{-1}.

22. Kämppä (commune: Ylistaro; 62°52' N, 22°27'). The area of the catchment is 150 ha. The surface of the catchment consists of stony hills and peat filled depressions. The drainage consists of single ditches located in the depressions between hills and no regular ditch network exists. The initial ditching was performed in 1962 and covers 48 ha altogether. In 1970, 1.4 ha was fertilized with Urea corresponding to 65 kg of N. The mineral soil areas are mainly *Vaccinium myrtillus* types (40% of catchment). The peatlands are dominated by *tall-sedge pine fens* with *cottongrass pine bogs* accounting for about two thirds of the peatland area. The volume of the tree stands averaged 112 $m^3 ha^{-1}$.

23. Vähä-Oivari (commune: Isojoki; 62°11' N, 21°53' E). The area of the catchment is 49 hectares. The initial ditching of the area was performed in 1969, when 30 ha, well over 60 % of the whole catchment area, were dug. The ditching area is thin-peated and the ditches subject to maintenance cut into silt-fine sandy till. The catchment has low relief and ditch flow rate is low. About 8 ha of the catchment area was fertilized in 1978 with 390 kg N, 230 kg P and 440 kg K. Nearly all the catchment is *cottongrass pine bog* or *dwar-shrub pine bog*. The mean volume of the tree stands is 23 $m^3 ha^{-1}$. About two thirds of the stands are advanced seedling stands with the remaining being young thinning stands.

24. Hautakangas (commune: Kauhajoki; 62°26' N, 21°59' E). The area of the catchment is 88 ha. Initial ditchings has been carried out in 1974, 1979 and 1985 and together covers 70 ha. The relief is flat and covered with thin peat. The subsoil is gravel. In 1976, 22 ha of the ditched area was fertilized with 2130 kg N, 930 kg P and 1120 kg K. Nearly 90 % of the catchment area is *cottongrass pine bogs* and *dwarf-shrub pine bogs*. The mineral soil area is dominated by dry upland forest sites. About 45 % of the forest consists of advanced seedling stands, 30 % are young thinning stands and 13 % advanced thinning stands. The mean stand volume for the catchment is 33 $m^3 ha^{-1}$.

25. Sydänkorvenrämäkkä (commune: Kauhajoki; 62°15 N, 22°20 E). The area of the catchment is 89 ha. The initial ditching was performed in 1969 and covered 69 ha. The ditch network maintenance was performed on the whole initial ditching area. About 45 ha of the catchment area was fertilized in 1971 with PK fertilizer, 1780 kg P and 2140 kg K. About 82 % of the peatland area is *cottongrass pine bogs* or *dwarf-shrub pine bogs* and about 16 % being *Sphagnum fuscum pine bogs*. Advanced seedling stands, young thinning stands and less than one third advanced thinning stands each account for about a third of the forest area. Scots pine is the dominant tree species (75 %) and the mean stand volume for the whole catchment is 50 $m^3 ha^{-1}$.

26. Takkikallio (commune: Ähtäri; 62°40' N, 24°09' E). The area of the catchment is 90 ha. About half of the catchment area is peatland, which was nearly all ditched for forestry in 1966 and then maintained during this research. In 1974, 4 ha were fertilized with 185 kg N, 160 kg P and 190 kg K. About 40 % of the peatland area was sedge-dominated spruce fens and pine fens, one third *cottongrass pine* bogs and one fifth *Sphagnum fuscum pine bogs*. About a half of the forest consists of advanced seedling stands or young thinning stands, nearly one third are advanced thinning stands and 13 % mature stands. Some 80 % of the tree stands are pine dominated and have a mean volume of 65 $m^3 ha^{-1}$.

27. Tupasalo (commune: Kannus; 64°03' N, 23°58' E). The area of the catchment is 26 ha. The ditching area is 15 ha and was all subject to maintenance in connection with this research. The initial ditching was performed in 1965. About 5 ha of the area was fertilized in 1973 with 440 kg N, 210 kg P and 250 kg K. About half of the ditching area is tall-sedge pine fen, some 40 % fuscum-rich or *dwarf-shrub pine bogs* and the rest sedge-dominant spruce fens. About half of the tree stands are advanced seedling stands, 41 % of young thinning stands and 8 % of mature stands. The stands are pine, birch mixed and the mean stand volume for the catchment is 46 m^3 ha^{-1}.

28. Korpiala (commune: Kannus; 64°02' N, 23°59' E). The area of the catchment is 66 ha. A little less than half of the catchment area was ditched for forestry in 1965 and this same area was subject to the ditch maintenance work in this study. About 14 ha of the catchment area was fertilized in 1974 with 370 kg N, 550 kg P and 660 kg K. About half of the peatland area are sedge-dominant pine fens and most of the rest are cotton grass-dominant pine bogs. The mineral soil sites are generally poorer than *Vaccinium vitis-idaea* types. The tree stands are pine dominated, the majority being advanced seedling stand or young thinning stand. The mean stand volume is 57 m^3 ha^{-1}.

29. Raippamaanoja (commune: Kalajoki; 64°07' N, 23°58' E). The area of the catchment is 97 ha. The majority, 83 ha, is an old ditching area, the whole of which was subject to maintenance in connection with this study. No fertilization have been performed in the area. Most, about 88 %, of the ditching area consists of *tall-sedge pine fens and tall-sedge fens*. Nearly half of the tree stands are young thinning stands, less than one third different kinds of seedling stands, and less than one fifth of the tree stand is advanced thinning stands. The mean stand volume for the catchment is 57 m^3 ha^{-1}.

30. Jänissuo (commune: Sotkamo; 63°55' N, 28°07' E). The area of the catchment is 97 ha. The ditching area covers 41 ha and was made in 1968. About 28 ha was subject to maintenance in connection with this study. The catchment contains about 4 ha of pristine peatland. In 1969, 8 ha was fertilized with PK fertilizer, 300 kg P and 360 kg K. The peatlands consist of mostly *herb-rich hardwood-spruce swamps* (19 %), *tall-sedge hardwood spruce fens* (37 %) and *tall-sedge pine fens* (37 %). The mineral soil sites consist mainly of herb-rich and grassy site types. Most of the tree stands are young thinning stands and advanced seedling stands and the mean stand volume for the catchment is 76 m^3 ha^{-1}.

31. Rapasensuo (commune: Kuhmo; 64°01' N, 30°09' E). The area of the catchment is 63 ha. The initial ditching area is 28 ha, from which about 23 ha was subject to maintenance in connection with this study. There are about 17 ha of pristine peatland in the catchment. The initial ditching work was performed in 1968. Fertilizer was applied in 1983 to 19 ha, 870 kg P and 1650 kg K. The peatlands are mostly *tall-sedge pine fens* (64 %) and *cottongrass pine bogs* (27 %). *Vaccinium myrtillus* and *Vaccinium vitis-idaea* types account for most of mineral soil part of the catchment area. The tree stands are mainly advanced seedling stands (29 %) and young thinning stands (39 %) and the mean stand volume for the catchment is 62 m^3 ha^{-1}.

32. Komulansuo (commune: Kuhmo; 64°01' N, 29°59' E). The area of the catchment is 120 ha. There are 82 ha of peatland of which about 49 hectares was diched in 1970. The whole initial ditching area was subject to maintenance in connection with this study. The rest part of the peatland is pristine *low-sedge fen*, from where the water flows to the main ditch of the ditching area. Some 10 ha of the ditching area was fertilized in 1983 with PK fertilizer, 430 kg P and 810 kg K. The mineral soil areas are mostly *Vaccinium myrtillus* types (71%) and *Vaccinium vitis-idaea* types (29%). The peatland areas are dominated by sedge-rich peatland site types (73%). The tree stands throughout the catchment are mainly advanced seedling stands (32.4 %) and young thinning stands (29.7 %) and their mean volume for the catchment is 52 m^3 ha^{-1}.

33. Käärmekorpi (commune: Yli-Ii; 65°21' N, 25°40' E). The area of the catchment is 52 ha and is mostly peatland. The ditched area covers 45 ha, of which about 42 ha have been subject to maintenance in connection with this study. Over 6 ha are virgin peatland. The initial ditching was performed in 1967. No fertilizers have been applied. The mineral soil areas of the catchment consist of dryish site types. *Cottongrass pine bog* and *dwarf-shrub pine bog* (70 %) are the prevalent peatland site types, the rest being sedge-rich fens. The stands are pine dominated (69 %) and the mean stand volume for the catchment is 37 m^3 ha^{-1}.

34. Hämäläisneva (commune:Vihanti; 64°25' N, 25°18' E). The area of the catchment is 38 ha of which 8 ha are mineral soil sites and 30 ha are maintained old ditched areas. The initial ditching was performed in 1968. No fertilizers have been applied. Symptoms of K deficiencis were observed in the peatland pines at the time of ditch maintenance. The mineral soil sites are mainly *Vaccinium myrtillus* (42 %) and *Vaccinium vitis-idaea* types (52 %). *Tall-sedge pine fens* (40 %), *cottongrass-* and *dwarf shrub pine bogs* (46 %) and *Sphagnum fuscum pine bogs* (15 %) are the dominating peatland site types in the catchment area. The tree stand is dominated by pine and the mean stand volume for the catchment is 44 m^3 ha^{-1}.

35. Pilpasuo (commune: Oulu; 64°57' N, 25°46' E). The area of the catchment is 148 ha, most being mineral soil (83 ha). About half of the peatland area has been subject to ditch maintenance in connection with this study. The area of virgin peatland is 17 ha. The initial ditching was performed in 1965. No fertilizers have been applied. The mineral soil sites area are mostly *Vaccinium myrtillus* (42 %) and *Vaccinium vitis-idaea* types (52 %). *Cottongrass pine bogs* and *dwarf-shrub pine bogs* (47 %) have been the dominant peatland site types in the catchment. The tree stand is dominated by Scots pine and the mean stand volume for the catchment is 61 m^3 ha^{-1}.

36. Isosuonräme (commune: Oulu; 64°59' N, 25°40' E). The area of the catchment is 123 ha, one third being mineral soils. The entire area of peatlands is 78 ha of which 58 ha were subject to ditch maintenance in connection with this study. The area of pristine peatland is 14 ha. The initial ditching was performed in 1938. No fertilizers have been applied. The mineral soil sites are mostly *Vaccinium vitis-idaea* types. The peatlands are dominated by sedge-rich site types (78 %). The tree stands in the catchment area are mostly advanced seedling stands (28 %) or young thinning (44 %) stands dominated by Scots pine. The mean stand volume for the catchment is 51 m^3 ha^{-1}.

37. Ruostekorpi (commune: Utajärvi; 64°55' N, 27°15' E). The catchment area is 49 ha and nearly all of the area is drained peatland (46 ha). The initial ditching was performed in 1966 and all was subject to ditch maintenance in connection with this study. Some 28 ha of the catchment area was fertilized in 1987 with NPK fertilizer, 2590 kg N, 1010 kg P and 1900 kg K. The peatlands are dominated by *tall-sedge pine fens* (50 %) or *cotton-grass* and *dwarf-shrub pine bogs* (47 %) while the mineral soil sites are dominated by *Vaccinium vitis-idaea* (65 %) and *Calluna vulgaris* types (24

%). The tree stands in the catchment area are advanced seedling (44 %) and young thinning (35 %) pine-dominated stands. The mean stand volume for the catchment is 15 m3 ha^{-1}.

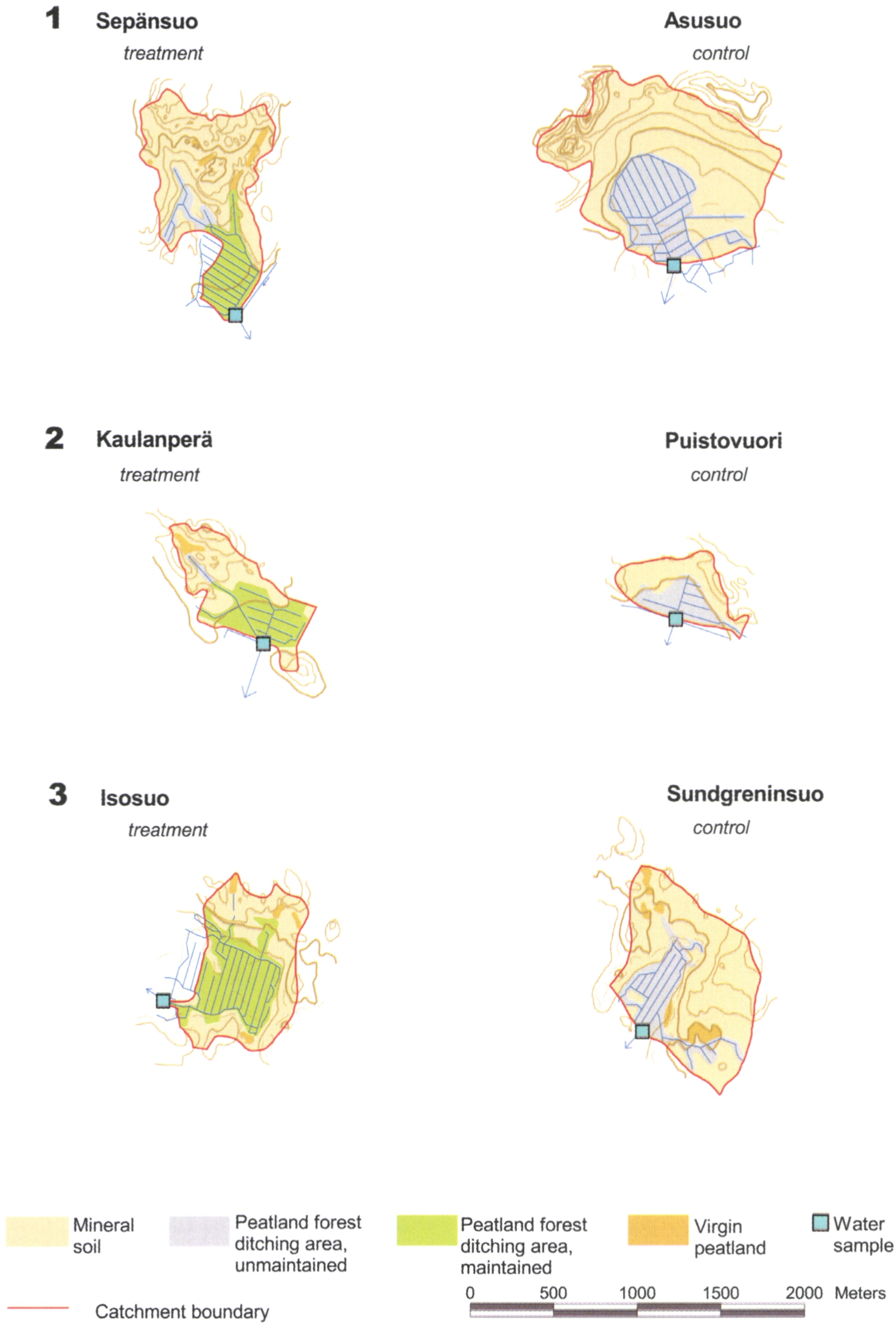
38. Ollinneva (commune: Pyhäjoki; 64°26' N, 24°35' E). The area of the catchment is 53 ha. The ditched area comprises 49 ha and all was subject to ditch maintenance in connection with this study. The initial ditching was performed in 1970. No fertilizers have been applied. The peatlands are dominated by sedge-rich site types (80.0 %) and the mineral soil sites by *Vaccinium vitis-idaea* and *Calluna vulgaris types* (96 %). The tree stands are mostly young thinning stands (53 %) and advanced thinning stands (28 %). Scots pine is the dominant species although the share of birch is quite high (29 %). The mean stand volume for the catchment is 50 m^3 ha^{-1}.

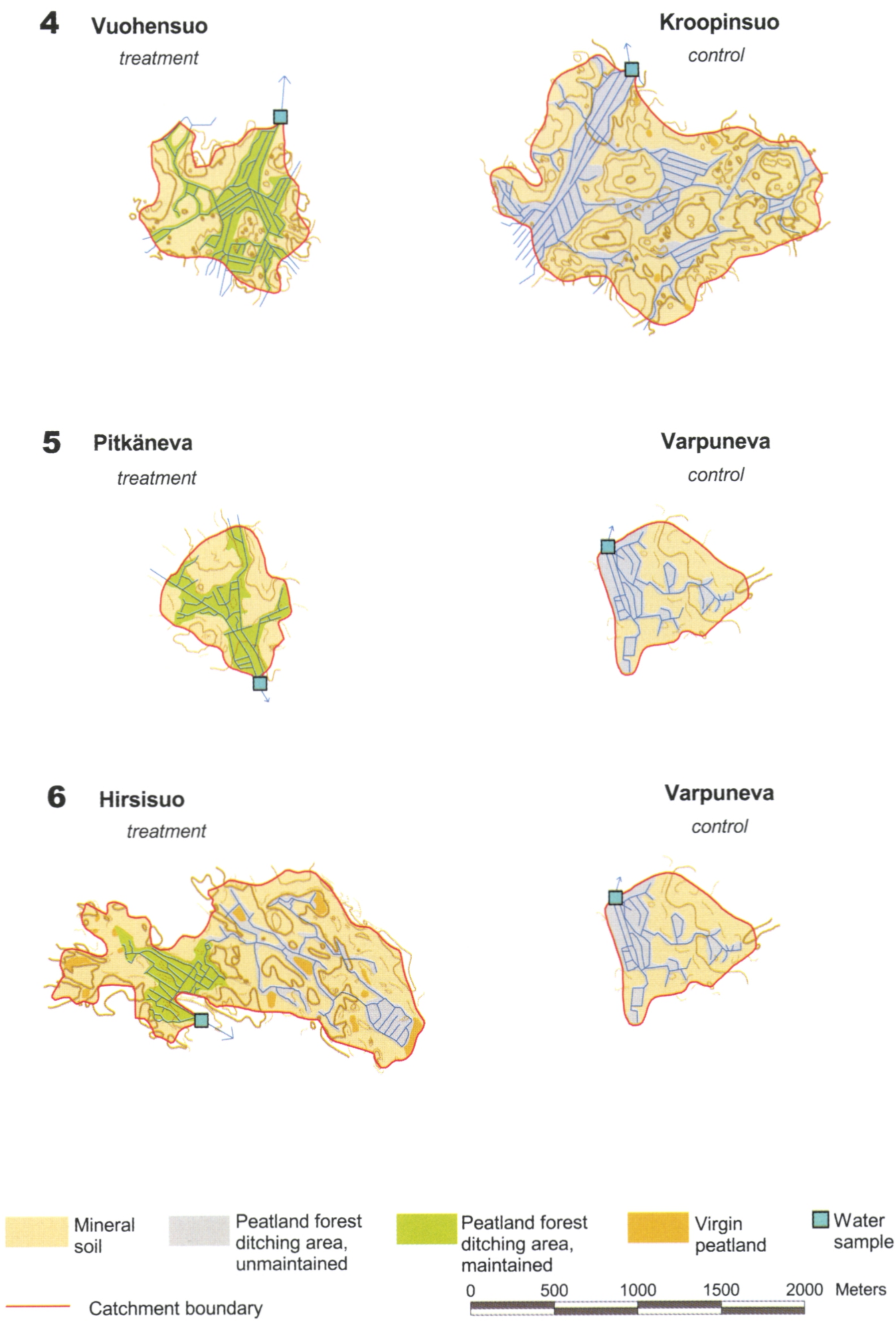
39. Prakunmaa (commune: Keminmaa; 65°55' N, 24°55' E). The area of the catchment is 146 ha and includes 83 ha of peatland (57 %). Most of the peatland area has been ditched for forestry (1965) and subject to ditch maintenance in connection with this study. The area of virgin peatlands is 8 ha. No fertilizers have been applied. The majority (68 %) of the peatlands are *herb-rich hardwood-spruce swamps* and nearly all mineral soil sites are *Vaccinium myrtillus* types (92 %). The stands are dominated by advanced seedling or young thinning stands of mixed spruce, pine and birch composition. The mean stand volume for the catchment is 72 m^3 ha^{-1}.

40. Kontiojänkä (commune: Tornio; 66°00' N, 24°17' E). The area of the catchment is 30 ha, 23 ha of which are drained and the remainder is pristine peatland. The initial ditching was performed in 1970. No fertilizers have been applied. The majority of the peatlands is *herb-rich hardwood-spruce swamp* (41 %) and *tall-sedge hardwood-spruce fen* and *vaccinium myrtillus spruce swamp* (49 %). Young thinning stands account for 40 % of the stand volume and are dominated by spruce. The mean stand volume for the catchment is 104 m^3 ha^{-1}.

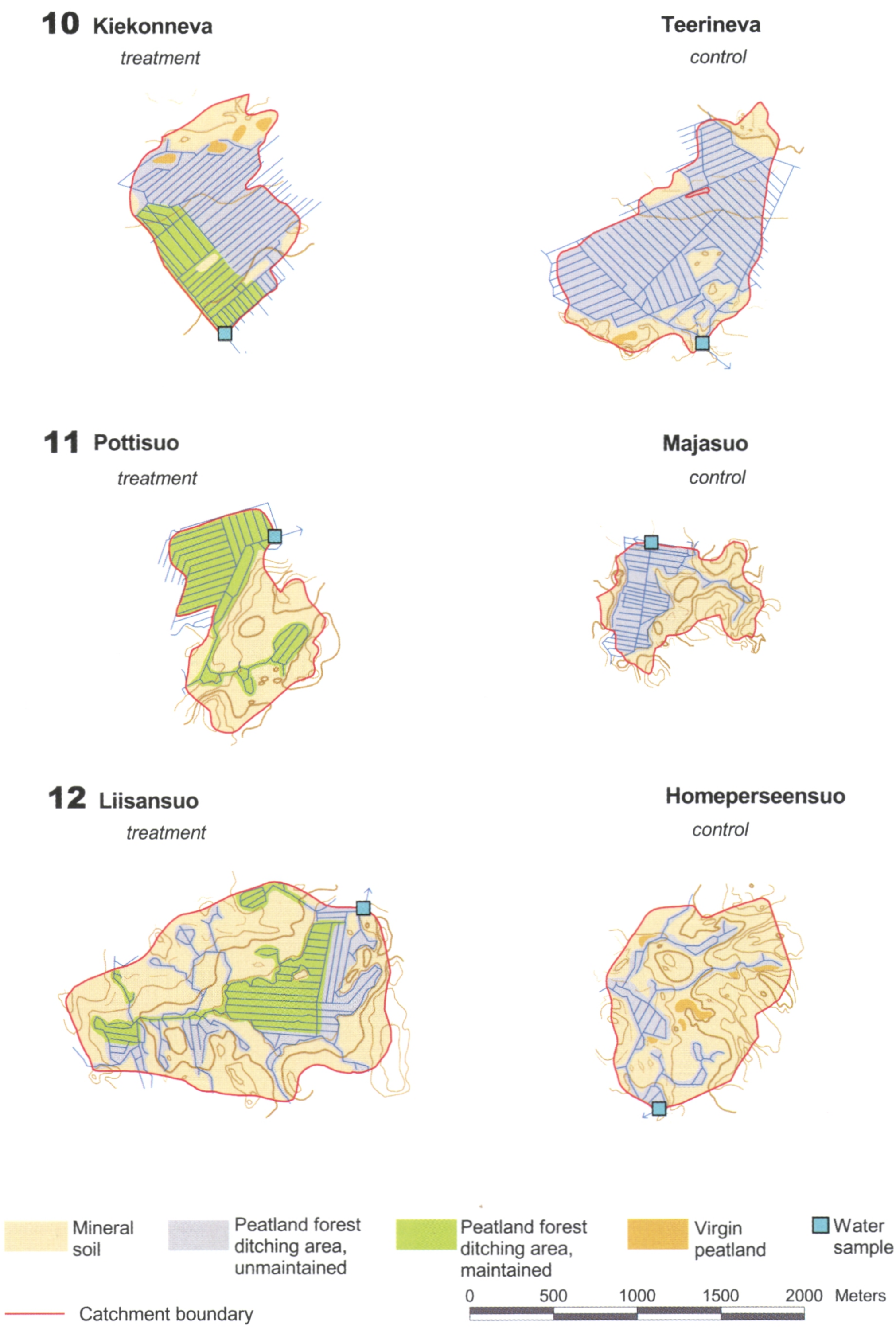
Appendix 2

Maps of the catchment areas




4
Vuohensuo
treatment
Kroopinsuo
control
5
Pitkäneva
treatment
Varpuneva
control
6
Hirsisuo
treatment
Varpuneva
control
Mineral soil
Peatland forest ditching area, unmaintained
Peatland forest ditching area, maintained
Virgin peatland
Water sample
Catchment boundary
0
500
1000
1500
2000
Meters

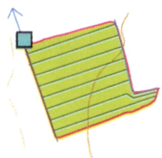

7
Paloneva
treatment
Välisalonneva
control
8
Alkkia
treatment
Välisalonneva
control
9
Porrasneva
treatment
Peltomaa
control
Mineral soil
Peatland forest ditching area, unmaintained
Peatland forest ditching area, maintained
Virgin peatland
Water sample
Catchment boundary
0
500
1000
1500
2000
Meters



10 Kiekonneva
treatment
Teerineva
control
11 Pottisuo
treatment
Majasuo
control
12 Liisansuo
treatment
Homeperseensuo
control
Mineral soil
Peatland forest ditching area, unmaintained
Peatland forest ditching area, maintained
Virgin peatland
Water sample
Catchment boundary
0
500
1000
1500
2000
Meters

13 **Ruskeesuo**

treatment



Mäntylä

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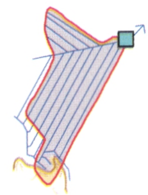
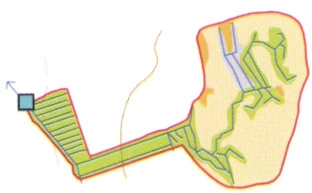


14 **Alaräme**

treatment



Mäntylä

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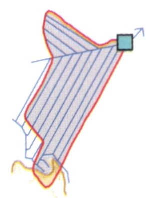
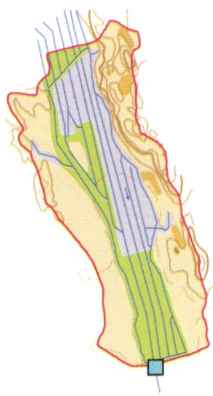


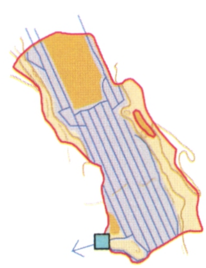
15 **Purnukorpi**

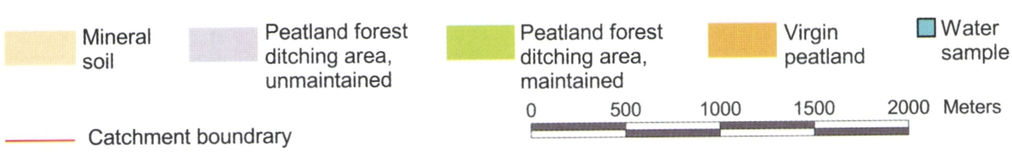
treatment



Laineensuo

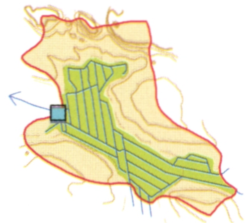
control





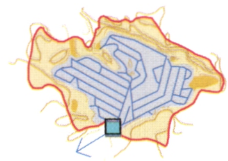
16 Mantilansuo

treatment



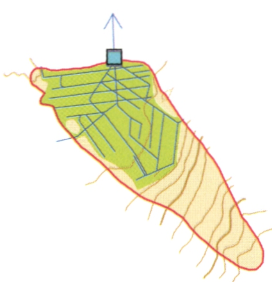
Nenäsuo

control



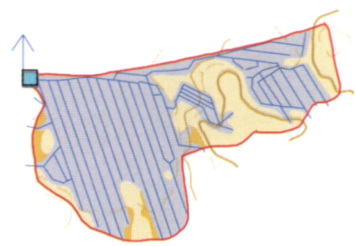
17 Honkasuo

treatment



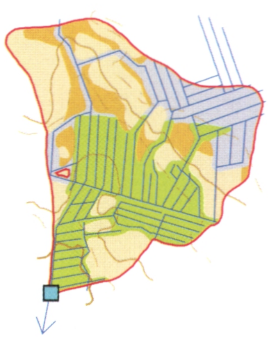
Suurisuo

control



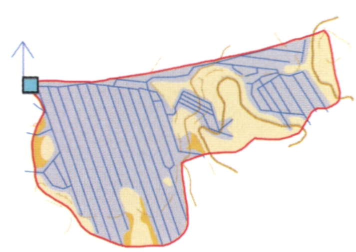
18 Tervasuo

treatment



Suurisuo

control



Mineral soil

Peatland forest ditching area, unmaintained

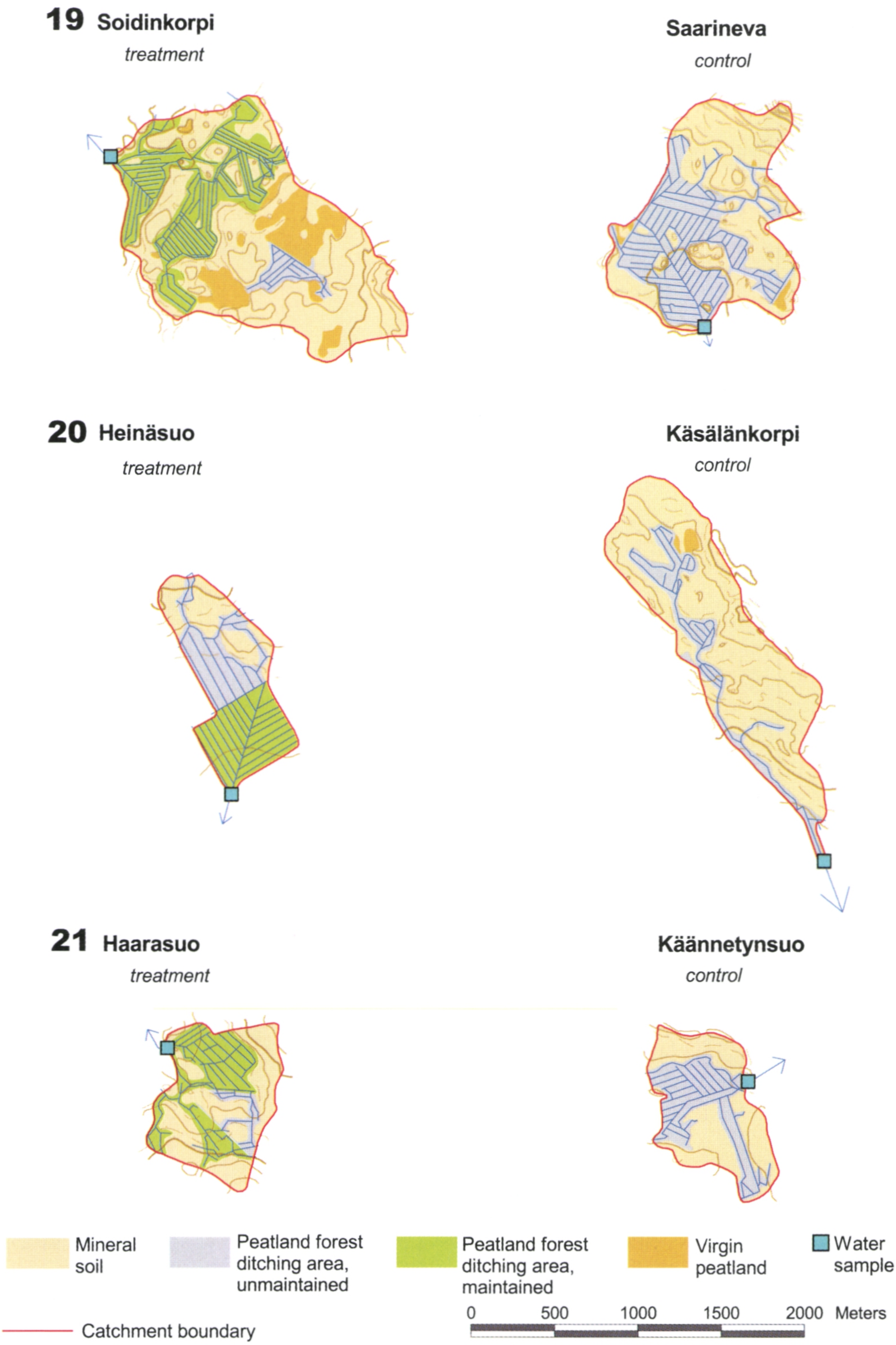
Peatland forest ditching area, maintained

Virgin peatland

Water sample

Catchment boundary

0 500 1000 1500 2000 Meters

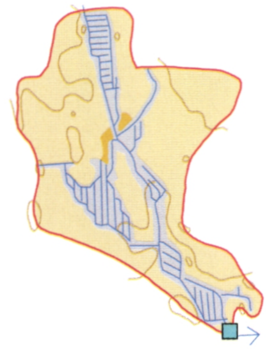

19 Soidinkorpi
treatment
Saarineva
control
20 Heinäsuo
treatment
Käsälänkorpi
control
21 Haarasuo
treatment
Käännetynsuo
control
Mineral soil
Peatland forest ditching area, unmaintained
Peatland forest ditching area, maintained
Virgin peatland
Water sample
Catchment boundary
0
500
1000
1500
2000
Meters

22 Kämppä

treatment

Viitikko

control

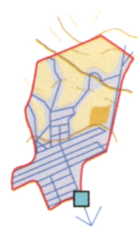


23 Vähä-Oivari

treatment

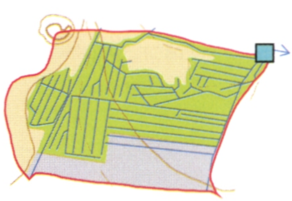
Toristonluoma

control



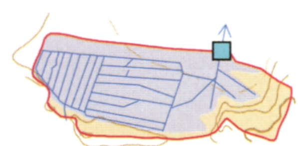
24 Hautakangas

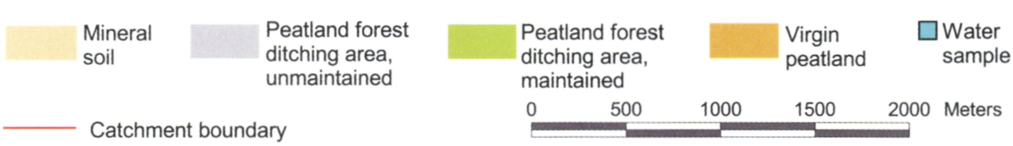
treatment

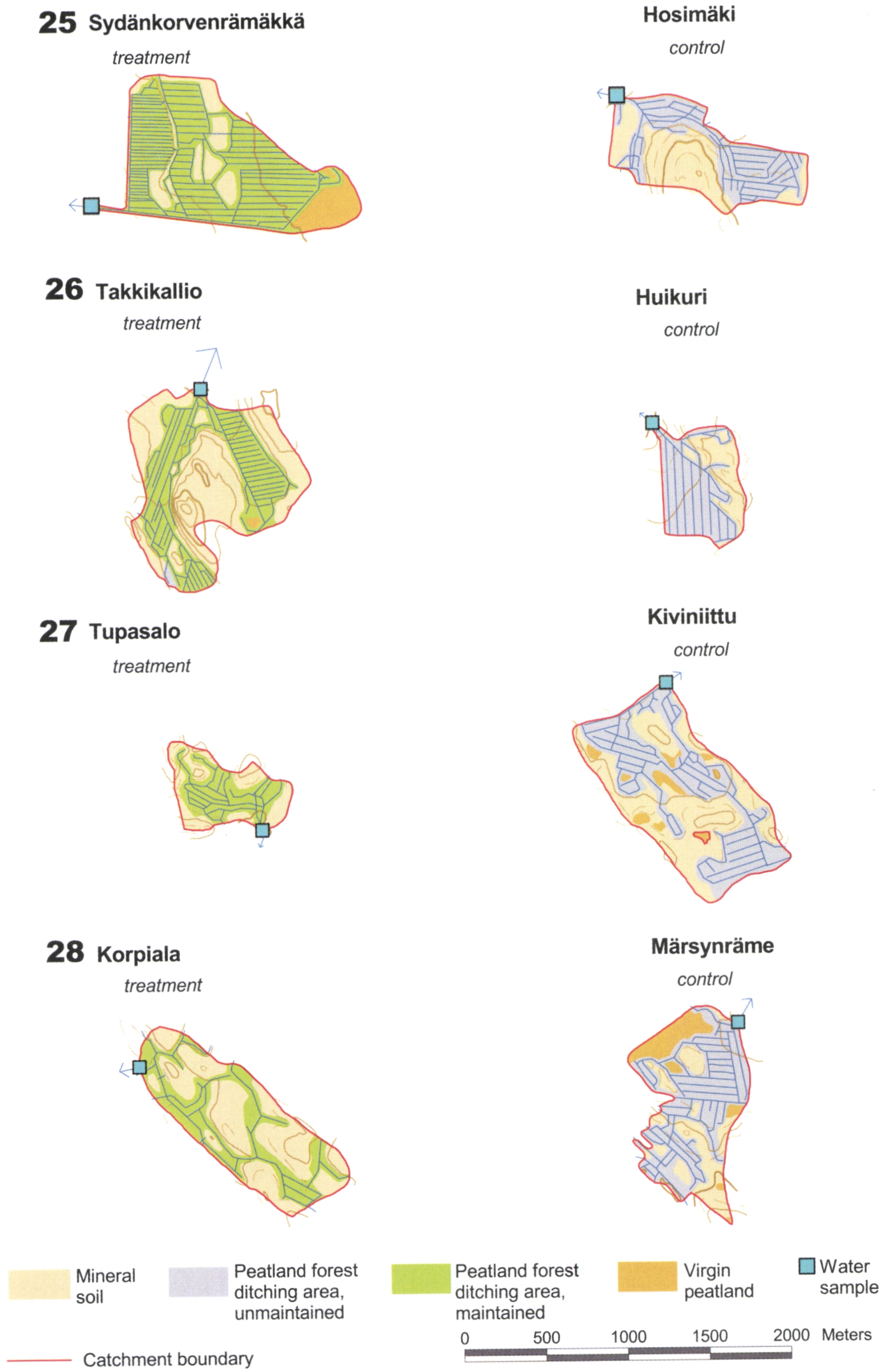


Juurakkoneva

control





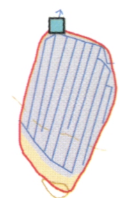

25 Sydänkorvenrämäkkä
treatment
Hosimäki
control
26 Takkikallio
treatment
Huikuri
control
27 Tupasalo
treatment
Kiviniittu
control
28 Korpiala
treatment
Märsynräme
control
Mineral soil
Peatland forest ditching area, unmaintained
Peatland forest ditching area, maintained
Virgin peatland
Water sample
Catchment boundary
0
500
1000
1500
2000
Meters

29 **Raippamaanoja**

treatment

Kannistonräme

control

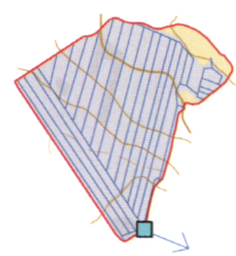


30 **Jänissuo**

treatment

Mustankorvensuo

control

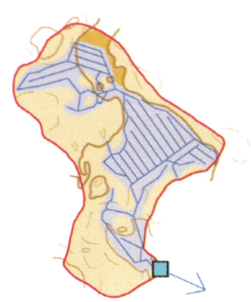


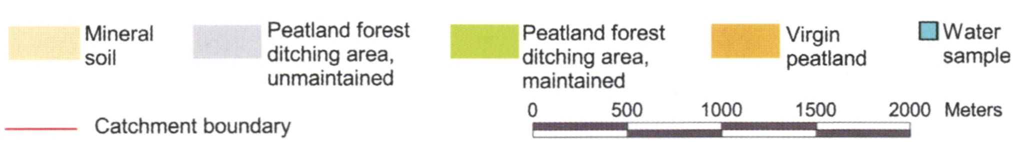
31 **Rapasensuo**

treatment

Lutja

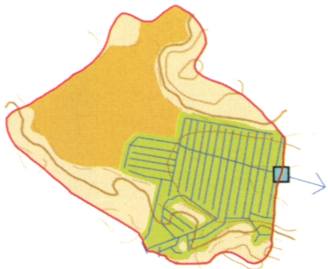
control





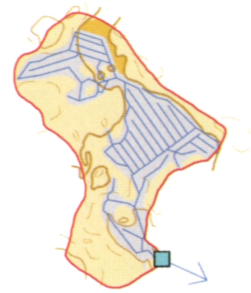
32 **Komulansuo**

treatment



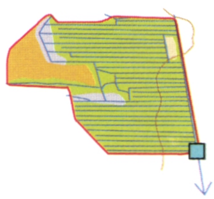
Lutja

control



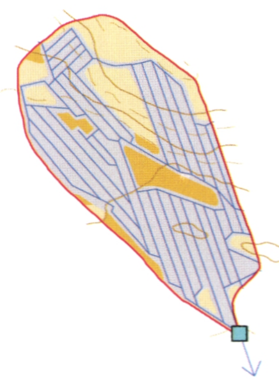
33 **Käärmekorpi**

treatment



Heinisuonsalmi

control

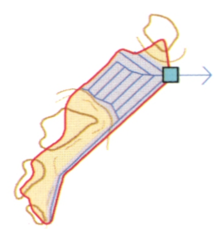


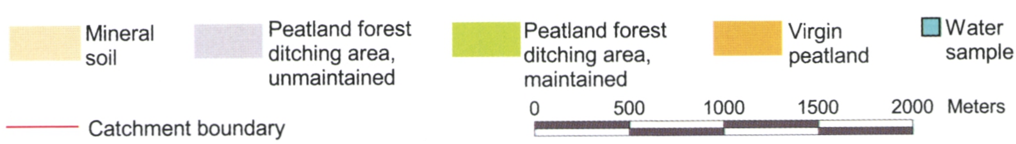
34 **Hämäläisneva**

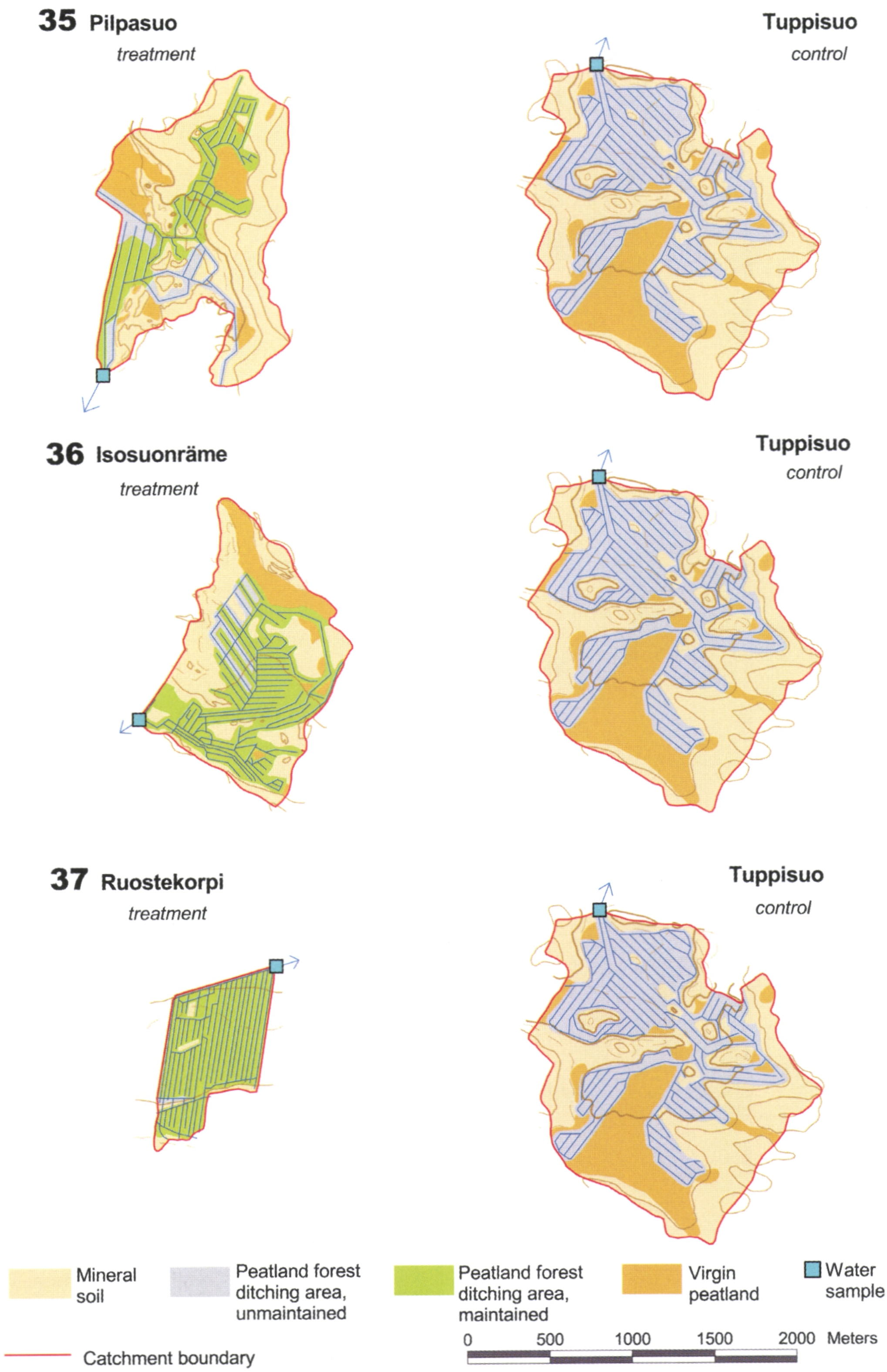
treatment

Lievonkangas

control

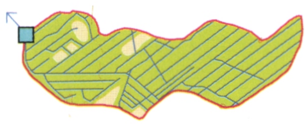





35 Pilpasuo
treatment
Tuppisuo
control
36 Isosuonräme
treatment
Tuppisuo
control
37 Ruostekorpi
treatment
Tuppisuo
control
Mineral soil
Peatland forest ditching area, unmaintained
Peatland forest ditching area, maintained
Virgin peatland
Water sample
Catchment boundary
0
500
1000
1500
2000
Meters

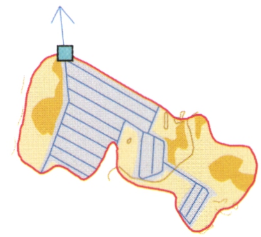
38 **Ollinneva**

treatment



Pöytäpuunneva

control

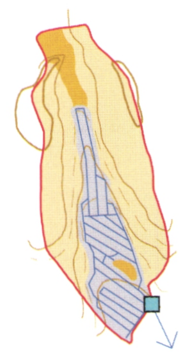


39 **Prakunmaa**

treatment

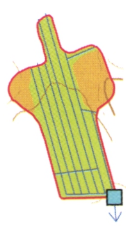
Mykkä

control



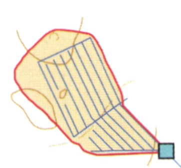
40 **Kontiojänkkä**

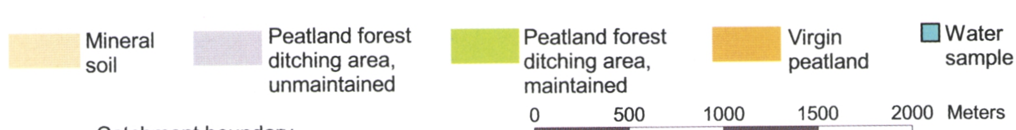
treatment



Pörhölä

control





PAPER I

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Discharge water quality from old ditch networks in Finnish peatland forests

Vanhoilta metsäojitusalueilta valuvan veden ominaisuudet

Samuli Joensuu, Erkki Ahti & Martti Vuollekoski

Samuli Joensuu, Forestry Development Centre Tapio, Soidinkuja 4, 00700 Helsinki (email: samuli.joensuu@tapio.mailnet.fi)
Erkki Ahti & Martti Vuollekoski, The Finnish Forest Research Institute, Vantaa Research Centre, Box 18, 01301 Vantaa

Runoff water from 75 Finnish ditch networks was sampled for chemical analysis in 1990–1992. In total, 2815 samples were analyzed. Higher mean and median concentrations of total dissolved phosphorus were observed than reported earlier. Except for phosphorus, concentration of most elements increased with increasing site fertility. No clear relationship between phosphorus concentration and the site characteristics could be detected. The median concentration of suspended solids in runoff water from old ditch networks was as low as 2.4 mg l^{-1}.

Keywords: ditch networks, peatland forests, water quality

INTRODUCTION

Discharge waters from peatlands are generally more acid and have higher concentrations of dissolved organic matter and nitrogen and lower concentrations of sulphate and base cations than the stream waters from mineral soils (Saukkonen & Kortelainen 1995; Kortelainen & Saukkonen 1998). Low pH-values of peatland ditch discharge water are due to organic acids and thus associated with high concentrations of dissolved organic carbon (DOC) (Kortelainen 1993b, Kortelainen et al. 1997). The production of organic acids in peat adds excessive acidity and organic carbon in the runoff water. Inputs of drainage waters from ditched peatlands can increase the acid load and the loads of phosphorus and nitrogen to water courses (Ahtiainen 1990). However, according to Kenttämies (1987), concentrations of suspended solids, organic carbon, and total nitrogen in the discharge waters from old, already moss covered ditch networks do not differ much from those of drainage waters originating from pristine peatlands.

The aim of this study was, by using extensive sampling in different parts of Finland, to produce a representative description of the quality characteristics of runoff water originating from old ditch networks.

MATERIAL AND METHODS

Catchment characteristics

General description

In total, 75 small forested catchments containing old ditch networks were chosen for the study (Fig. 1). With a few exceptions, all areas were situated in

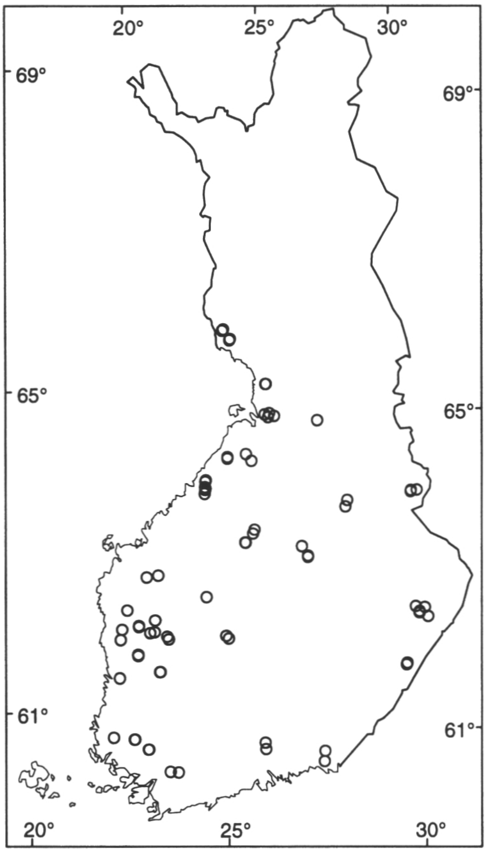

Fig. 1. The location of the 75 old ditch networks used in the study.

Kuva 1. Tutkimuksessa seurattujen 75 vanhan ojaston sijainti.

the southern half of Finland, where annual precipitation in 1961–90 varied between 600 and 750 mm and annual runoff between 250 and 400 mm (Hyvärinen et al. 1995).

When selecting the study sites, only catchments including forestry land (for definition see Finnish Statistical Yearbook of Forestry, p. 343) and forest roads were accepted. In all areas, the samples were taken from the main ditch of the forest ditch network. The size of the average catchment was 77 ha (13–222 ha) and comprised of 39 ha of drained peatland, 5 ha of pristine peatland and 33 ha of upland mineral soil. On average, 80% of the peatland area of a site was dominated by Scots pine and the remainder by Norway spruce. Open (treeless) peatlands accounted for less than 5% of the total peatland area on average. The average site quality class distribution of the catchments, including both peatlands and mineral soil sites, is given in Table 1 and further characteristics in Table 2. For determining the relationships between site type and water chemistry, the original, pre-drainage peatland site type (Laine & Vasander 1990) of each plot was estimated around the plot centerpoint. Finally, erosion of the ditches and other factors connected with ditch condition were noted.

Ditch characteristics

Ditch depth, ditch width and the condition of the ditch were surveyed on sample plots located systematically along the ditches. Depending on the

Table 1. Distribution of forest site quality classes (Huikari 1974) for the average catchment in the study.

Taulukko 1. Valuma-alueiden keskimääräinen ravinteisuusluokkajakautuma Huikarin (1974) luokitusmenetelmällä.

Site quality class *Keskim. ravinteisuusluokka*	Coverage of all sites, % of basin area *Peittävyys,* *% valuma-alueesta*	Coverage of peatland sites, % of peatland area *Peittävyys,* *% suopinta-alasta*
I Grove-like sites – *Lehtomaiset metsät*	-	-
II Herb-rich sites – *Ruohoiset metsät*	5	4
III Myrtillus sites- *Mustikkaiset metsät*	25	13
IV Vaccinium sites – *Puolukkaiset metsät*	35	33
V Calluna sites – *Kanervatason metsät*	30	45
I Cladina sites – *Jäkälätason metsät*	5	5

area of drained peatland, the number of sample plots varied between 22 and 204 per catchment. At each plot, the condition of the ditch was classified into one of the five classes of Keltikangas et al. (1986; class 1 = good ditch quality) for a 40 m ditch section. For the 75 study sites, the mean ditch quality class was 3.5. The width of the ditches averaged 132 cm (range 53–211 cm) and ditch depth 58 cm (34–86 cm).

The abundance of different plant species in the ditch was determined subjectively by using 10% coverage classes. The mean coverage of the most important plants were as follows: *Sphagnum* 48%, *Polytrichum* 14%, *Carex* 7%, *Eriophorum vaginatum* 6%, grasses 5%, and herbs 5% of the ditch surfaces. The most common sedges covering the ditch surfaces were *Carex rostrata, C. rynchospora, C. canescens, C. lasiocarpa* and mostly on the ditch slopes, *Carex globularis*. The most common grass species were *Calamagrostis purpurea, Deschampsia flexuosa, D. cespitosa, Molinia caerulea, Juncus sp, Festuga rubra, Agrostis canina* and sometimes also *Phragmites sp, Phalaris sp,* and *Poa sp*. Among the herb species, *Geranium sp, Gymnocarpium sp, Melampyrum sp, Linnaea borealis*, and *Equisetum sp* can be mentioned. The coverage percents of the dwarf shrubs and the bushes were well over three percent, respectively. Common dwarf shrubs were *Vaccinium vitis idaea, V. myrtillus, V. uliginosum, Ledum palustre, Andromeda polifolia, Empetrum nigrum, Betula nana,* and *Calluna vulgaris*. Small specimens of *Betula pubescens, Betula verrucosa, Alnus sp., Salix sp.* and *Picea abies* were regarded as bushes. On the average 10% of the ditch surfaces were free of vegetation.

Tree stands

Stand characteristics were measured on sample plots located at intervals of $\sqrt{ab}$ metres, in which a = catchment area in m^2 and b = number of plots per area. A minimum number of 50 plots were measured per catchment.

The basal area of the stand was estimated with a relascope. In sapling stands, the stem number instead of basal area was estimated. Stand volume was estimated by species from measurements of breast height diameter and height of the median tree at each of the basal area sample plots.

The catchment means for breast height diameter, stand height, and stand volume were 11.5 cm, 9.5 m, and 72.3 m^3 ha^{-1} (from 9 to 190 m^3 ha^{-1}). The actual site values for stand volume are given in Table 2.

Sampling

Water samples were collected in 1990–1992. The number of water samples per catchment varied from 16 to 83 and averaged 37. In all, 2815–2850 samples were analyzed. The water samples were taken twice a week during the spring high flows, but otherwise weekly. Sampling continued until snowfall and freezing of the ditches in late autumn and no samples were taken in winter.

The samples were taken directly into 500 ml plastic bottles from a sampling point on the main ditch selected to enable sampling from flowing water without stirring the bottom sediment of the ditch. The samples were sent immediately to the Central Laboratory of the Finnish Forest Research Institute in Vantaa. Prior to analysis, the samples were stored at +5 °C.

Chemical analysis

Acidity and electric conductivity were determined using the standard methods of the Finnish Forest Research Institute (Jarva & Tervahauta 1993). The samples were then filtered (Fiber-glass, pore size 1.2 µm).The filtrate was analyzed for phosphorus, sodium, potassium, magnesium, calcium, sulfur, aluminum and iron concentrations using plasma emission spectrophotometry (ICP-AES, ARL 3580). Total dissolved nitrogen (N_{tot}), ammonium nitrogen (NH_4^--N) and nitrate nitrogen (NO_3^+-N) were determined spectrophotometrically with a Tecaton FIA-analyzer. The concentration of dissolved organic carbon (DOC) was determined with a Shimadzu carbon analyzer from 1992 onwards. DOC concentrations prior to 1992 were calculated from $KMnO_4$ consumption (SFS 3036 method) and the regression equation is presented in Fig. 2. This equation was derived from parallel measurements of both DOC and $KMnO_4$ concentrations from 714 samples. The filters were dried at 60°C and weighed to determine the amount of suspended solids.

Table 2. Some basin characteristics according to field observations in 1990-1994 and local forest authorities. (-): not estimated.
Taulukko 2. Tutkimuksessa seurattujen valuma-alueiden ominaisuuksia ja tunnuslukuja vuosina 1990-94 tehtyjen maastoinventointien ja metsänparannussuunnitelmien tietojen perusteella. (-): ei tiedossa.

Name of area *Alueen nimi*	Locality *Sijaintikunta*	Temp. sum *Lämpö-summa* d.d.	Basin area *Val.alueen pinta-ala* ha	Peatland area *Suopinta-ala* ha	Drained peatl. area *Ojitusala* ha	First drain. year *Uudisojitus-vuosi*	Stand volume *Puuston tilavuus* Basin *Va. alue* $m^3 ha^{-1}$	Peatlands *Suot*	Ditch cond class *Ojien kunto-luokka*	Fertiliz. years *Lann. vuodet*	Fertil. area *Lann. ala*
Sepänsuo	Pertteli	1275	62.4	19.6	17.8	1969	90.3	63.5	4.0	1975	14.3
Asunsuo	Kiikala	1261	104.4	27.4	27.4	1967	94.3	64.8	3.2	1972	6.0
Kaulanperä	Karinainen	1266	33.4	15.9	14.9	1956	190.0	-	4.2		0.0
Puistovuori	Karinainen	1276	21.9	9.4	9.4	1956	173.5	-	3.0		0.0
Isosuo	Laitila	1262	54.7	26.5	25.0	1967	83.8	49.8	4.1	1972	20.6
Sundgreninsuo	Laitila	1262	72.9	20.4	17.0	1968	136.2	95.3	2.9	1972	8.9
Vuohensuo	Yläne	1234	65.4	28.4	28.4	1965	43.4	22.7	4.8	1971, 76, 80	86.0
Kroopinsuo	Yläne	1234	174.6	60.2	59.4	1966	39.0	42.2	3.8	1971	51.2
Pitkäneva	Kankaanpää	1156	44.0	20.3	20.3	1964	75.3	84.2	4.0	1973	4.5
Varpuneva	Kankaanpää	1149	48.0	19.3	19.3	1978	57.2	46.3	3.0	1985	1.8
Hirsisuo	Noormarkku	1215	133.5	42.3	38.0	1965	93.2	114.1	3.7		0.0
Paloneva	Karvia	1087	31.3	30.2	30.2	1964	46.8	45.9		1970	23.0
Alkkia	Karvia	1087	79.0	65.7	48.3	1965	28.0	-	3.7	1977	11.0
Välisalonneva	Karvia	1085	53.8	47.2	47.1	1978	50.5	32.9	3.3		0.0
Porrasneva	Kihniö	1098	42.9	36.3	34.6	1969	51.9	51.9	3.4	1971	24.0
Peltomaa	Kihniö	1082	13.3	9.6	9.6	1973	47.5	-	3.7	1974	7.0
Kiekkoneva	Hämeenkyrö	1172	86.1	72.5	70.2	1956	88.4	91.4	2.9		0.0
Teerineva	Hämeenkyrö	1159	110.1	87.5	86.7	1961	52.9	47.6	3.7		0.0
Pottisuo	Orimattila	1275	75.2	35.7	35.7	1968	110.6	57.6	3.5	1969	25.0
Majasuo	Orimattila	1281	46.8	21.5	21.5	1973	66.9	80.8	2.7	1985	20.6
Liisansuo	Vehkalahti	1296	177.0	78.1	78.1	1969	115.9	91.0	3.8	1972	28.6
Homeperseensuo	Vehkalahti	1313	98.6	26.9	24.3	1965	93.9	82.2	3.9		0.0
Ruskeesuo	Pyhäselkä	1123	24.8	24.8	24.8	1964	96.5	96.5	5.0	1970, 85	34.3
Alaräme	Pyhäselkä	1104	59.8	30.6	28.5	1964	86.5	58.2	3.8	1970, 78, 85	34.5
Mäntylä	Pyhäselkä	1132	22.5	21.6	21.6	1967	72.4	70.1	2.9	1970, 83	25.0
Purnukorpi	Kiihtelysvaara	1085	100.2	48.8	46.9	1968	61.4	32.8	3.0	1970, 83	25.8
Laineensuo	Kiihtelysvaara	1092	54.6	40.5	32.0	1974	68.5	45.2	2.7		0.0
Mantilansuo	Punkaharju	1229	64.1	24.4	24.4	1965	87.8	58.5	3.6	1971, 72	26.3
Nenäsuo	Punkaharju	1226	42.1	23.5	22.2	1976	61.5	11.7	3.2	1978	6.0
Honkasuo	Pielavesi	1118	54.1	30.4	30.4	1963	134.7	129.3	3.5	1978	9.4
Tervasuo	Pielavesi	1106	117.9	81.8	68.5	1966	163.0	147.2	4.4		0.0
Suurisuo	Pielavesi	1097	101.5	76.1	73.3	1966	49.1	43.7	3.6		0.0
Soidinkorpi	Pihtipudas	1056	163.0	75.9	55.6	1960	71.1	38.5	3.5		0.0

Continued...

Table 2. Continues

Saarineva	Pihtipudas	1060	105.9	52.3	51.1	1974	68.8	34.2	3.2		0.0
Heinäsuo	Kinnula	1032	202.2	111.8	102.0	1938			3.3	1968	30.0
Käsälänkorpi	Kinnula	1028	104.8	23.8	22.5	1970	21.7	77.1	3.5		0.0
Haarasuo	Keuruu	1152	56.1	28.6	28.6	1965	145.8	93.3	2.7	1970	14.5
Käännetynsuo	Keuruu	1151	50.4	23.7	23.7	1970	140.3	69.6	3.0	1970	10.6
Kämppä	Ylistaro	1111	150.1	49.5	48.2	1962	112.0	61.8	4.2	1970	1.4
Viitikko	Ylistaro	1105	117.9	34.3	33.2	1978	78.7	81.8	3.3		0.0
Vähä-Oivari	Isojoki	1139	48.8	29.6	29.6	1969	24.0	25.0	4.4	1978	7.8
Toristonluoma	Isojoki	1145	32.7	21.7	20.8	1982	107.5		2.9		0.0
Hautakangas	Kauhajoki	1071	87.6	70.2	70.2	1974	33.2	28.6	3.5	1976	22.2
Juurakkoneva	Kauhajoki	1069	56.2	42.3	42.3	1965	29.9	27.7	2.0	1972, 78	28.3
Sydänkorven-rämäkkä	Kauhajoki	1058	89.1	77.8	69.3	1969	49.8	46.5	3.1	1971	44.6
Hosimäki	Kauhajoki	1067	52.0	29.9	29.9	1984	63.1	48.0	2.9		0.0
Takkikallio	Ähtäri	1059	89.7	44.4	43.9	1966	65.1	59.0	3.4	1974	4.0
Huikuri	Ähtäri	1050	31.5	22.6	22.6	1967	9.1	12.6	3.8		0.0
Tupasalo	Kannus	1051	26.2	15.4	15.4	1965	46.3	58.0	4.7	1973	5.3
Kiviniittu	Kannus	1048	85.5	49.6	45.7	1969	47.5	57.9	3.2	1969	20.8
Korpiala	Kannus	1057	66.4	30.1	30.1	1965	32.7	30.1	3.6	1974	13.7
Märsynräme	Kannus	1056	60.8	46.7	39.0	1969	50.8	45.1	3.0	1969	7.2
Valkiaräme	Toholampi	-	49.0	21.0	20.0	-	-	-	-	-	-
Raippamaanoja	Kalajoki	998	97.0	83.1	83.1	1956	57.7	54.8	3.9		0.0
Kannistonräme	Kalajoki	1024	31.0	28.4	28.4	1969	42.6	48.7	3.0	1979	26.0
Jänissuo	Sotkamo	958	97.0	44.9	41.3	1968	75.9	49.4	2.9	1969	7.6
Mustakorvensuo	Sotkamo	978	70.1	66.2	66.1	1968	83.7	81.7	3.7	1969	26.5
Rapasensuo	Kuhmo	928	63.4	45.3	28.0	1968	62.5	39.1	3.5	1983	19.4
Komulansuo	Kuhmo	960	119.9	81.5	45.1	1970	51.7	37.0	3.7	1980	9.5
Lutja	Kuhmo	960	79.0	37.8	36.1	1978	105.3	63.9	3.5	1978	18.8
Käärmekorpi	Yli-Ii	1014	51.9	51.4	45.3	1967	36.7	35.8	2.5		0.0
Heininsuosalmi	Yli-Ii	1011	115.7	94.1	85.0	1967	60.0	57.7	3.4		0.0
Hämäläisneva	Vihanti	1034	38.0	29.8	29.8	1961	44.3	37.9	3.0		0.0
Lievonkangas	Vihanti	1035	24.7	13.3	13.3	1972	137.0	92.8	2.7	1989	8.0
Pilpasuo	Oulu	1019	147.8	65.3	48.1	1965	61.0	51.0	3.8		0.0
Tuppisuo	Oulu	1002	222.0	130.0	90.5	1974	35.9	10.3	3.8	1975	33.0
Isosuonräme	Oulu	1027	122.6	77.6	64.0	1938	50.8	46.6	3.4		0.0
Korpikoskensuo	Oulu	1016	55.0	36.0	36.0	1964	36.5	41.2	3.3		0.0
Ruostekorpi	Utajärvi	969	48.6	46.2	46.2	1966	15.2	13.9	3.6	1987	28.0
Ollinneva	Pyhäjoki	991	52.5	49.4	49.4	1956	50.2	55.3	3.6		0.0
Pöytäpuunneva	Pyhäjoki	994	58.2	36.2	28.8	1962	55.3	40.8	3.8		0.0
Prakunmaa	Keminmaa	976	146.0	82.9	75.3	1965	72.1	97.7	3.7		0.0
Mykkä	Keminmaa	973	78.5	29.0	23.6	1971	98.3	87.9	2.9		0.0
Kontionjänkä	Tornio	973	30.0	30.0	23.2	1970	104.4	83.4	3.5		0.0
Pörhälä	Tornio	971	28.8	24.5	22.2	1978	68.9	76.6	3.1		0.0

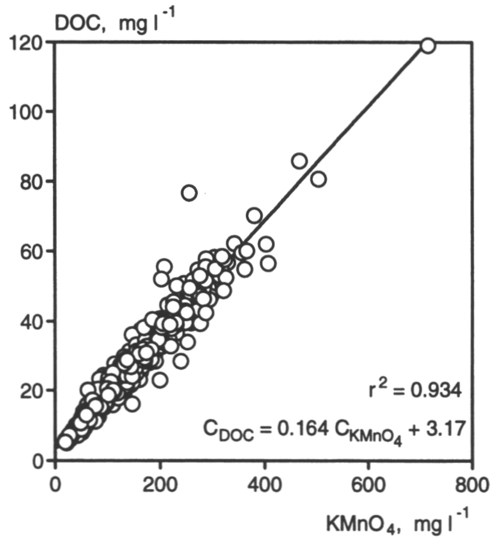

Fig. 2. Linear regression between DOC and $KMnO_4$-consumption. n = 714.

Kuva 2. Orgaanisen hiilen pitoisuuden ja kaliumpermanganaatin kulutuksen välinen lineaarinen korrelaatio. n = 714.

The water quality of the samples was characterised using descriptive statistics e.g. means, deviations, frequency distributions, Pearson correlation coefficient, regression analysis and mean tests. The statistical analysis was performed using the SYSTAT statistical package (SYSTAT 1996).

RESULTS

Ditch water quality

Nitrogen

Site mean total nitrogen concentration ranged from 0.22 to 2.02 mg l^{-1}. The average of all 2820 samples was 0.738 mg l^{-1} (Tables 3 and 4), which is almost double the value reported by Kortelainen et al. (1999) for stream water draining pristine forest land. In addition to the different fractions of N, total N concentrations were positively correlated with the concentrations of potassium, calcium, magnesium and iron (Table 5).

Table 3. Statistical parameters describing the runoff water quality of all samples from 75 forest ditch networks located throughout Finland. n = number of samples, $\bar{x}$ = arithmetic mean, S_d = standard deviation, $s_{\bar{x}}$ = standard error of mean, x_{min} = minimum value, x_{max} = maximum value, Q_1 = lower quartile, M_d = median, Q_3 = upper quartile. All concentrations in mg l^{-1}. SS = suspended solids, EC =electric conductivity, µS cm^{-1}.

Taulukko 3. Eri puolilla Suomea sijaitsevien 75 vanhan ojitusalueen valumavesien ravinnepitoisuudet, kiintoainepitoisuudet (SS), pH ja johtokyky (EC, µS cm^{-1}). n = havaintojen lukumäärä, $\bar{x}$ = keskiarvo, S_d = keskihajonta, $s_{\bar{x}}$ = keskiarvon keskivirhe, x_{min} = havaintojen minimiarvo, x_{max} = havaintojen maksimiarvo, Q_1 = alakvartiili, M_d = mediaani, Q_3 = yläkvartiili. Kaikki pitoisuudet on ilmoitettu mg l^{-1}.

	n	$\bar{x}$	S_d	$s_{\bar{x}}$	x_{min}	x_{max}	Q_1	M_d	Q_3
N_{tot}	2820	0.738	0.386	0.0073	0.090	4.78	0.485	0.670	0.920
NH_4^+-N	2820	0.042	0.115	0.0022	<0.007	1.76	<0.007	<0.007	0.033
NO_3^--N	2821	0.058	0.199	0.0038	<0.002	3.92	<0.002	0.016	0.045
DOC	2820	29.79	13.1	0.236	3.1	92.1	16.7	23.7	32.8
SS	2818	4.90	7.85	0.148	<0.20	148	0.80	2.40	6.0
EC	2820	43.2	24.3	0.457	10.3	232	28.0	37.2	50.1
pH	2821	5.61	1.01	0.019	3.29	8.58	4.81	5.54	6.35
Na	2815	2.25	1.69	0.032	0.137	48.8	1.32	1.79	2.74
K	2815	0.536	0.640	0.0121	<0.01	9.91	0.200	0.402	0.667
Ca	2815	3.65	3.93	0.074	0.455	43.5	1.75	2.52	3.90
Mg	2815	1.62	1.84	0.035	0.187	26.3	0.68	1.07	1.83
Al	2815	0.433	0.296	0.0056	<0.001	2.50	0.207	0.396	0.608
Fe	2815	1.59	1.42	0.0268	0.048	18.6	0.640	1.19	2.07
S	2815	1.89	1.94	0.0366	0.263	68.9	0.89	1.45	2.43
P	2815	0.056	0.0512	0.0001	<0.001	0.596	0.031	0.045	0.066
B	2815	0.0104	0.0093	0.0002	<0.001	0.116	0.0048	0.0091	0.0140

Site mean NH_4-N concentrations varied from 0 to 0.385 mg l^{-1} and the mean concentration of all samples was 0.042 mg l^{-1}. In most runoff water samples the NH_4-N concentration was close to zero, as indicated by the median value (Tables 3 and 4). The highest mean monthly N_{tot} and NH_4-N concentrations occurred in July – August (Fig. 3).

Site mean NO_3-N concentrations varied from 0 to 1.207 mg l^{-1}. Most samples had very low nitrate concentrations, the median concentration of all samples being 0.016 mg l^{-1} (Tables 3 and 4). There was no seasonal trend in the variation of nitrate nitrogen.

Phosphorus

The mean concentration of total dissolved phosphorus calculated from all samples (n=2815) was 0.056 mg l^{-1} and the median 0.045 mg l^{-1}. These values are higher than P_{tot}-values reported earlier for runoff water from peatlands (Heikurainen et al.1978, Kenttämies 1987, Saukkonen & Kortelainen 1995, Kortelainen & Saukkonen 1998). Site mean total phosphorus concentrations varied from 0.026 to 0.458 mg l^{-1} and the median concentration from 0.024 to 0.486 mg l^{-1}. Phosphorus concentrations were highest during the low flow period of July–August and were only weakly correlated with most of the other water quality parameters. There was a statistically significant correlation with organic nitrogen and DOC, though (Table 5).

DOC and pH

The site mean of DOC concentration varied from 6.88 to 47.09 mg l^{-1} and averaged 26.1 mg l^{-1}. The mean DOC concentration calculated from all samples (n=2820) was 29.8 mg l^{-1}. In agreement with what has been reported earlier by Kauppi (1979), DOC concentrations were the lowest during the high water flow period in spring and increased gradually towards autumn. The concentration of dissolved organic carbon correlated positively with total N and organic N concentra-

Table 4. Mean runoff water quality of 75 basins as calculated on the basis of all samples and basin means and medians. Concentrations; mg l^{-1}, SS = suspended solids (mg l^{-1}), EC = electric conductivity (µS cm^{-1}).

Taulukko 4. Valumaveden keskimääräiset kemialliset ominaisuudet 75 vanhassa ojastossa kaikkien näytteiden keskiluvuilla ja ojastokohtaisilla keskiluvuilla ilmaistuina Pitoisuudet mg l^{-1}, SS = kiintoainepitoisuus, EC = sähkönjohtavuus (µS cm^{-1}).

Water quality parameter *Vedenlaatu-muuttuja*	Arithmetic mean of all samples *Kaikkien näytteiden keskiarvo* (n=2815)	Average of basin means *Aluekeskiarvojen keskiarvo* (n = 75)	Median of all samples *Kaikkien näytteiden mediaani* (n = 2815)	Median of basin means *Aluekeskiarvojen mediaani* (n= 75)
N_{tot}	0.738	0.760	0.670	0.732
NH_4-N	0.042	0.039	0.000	0.018
NO_3-N	0.058	0.064	0.016	0.036
DOC	29.8	26.1	23.7	25.2
SS	4.90	4.72	2.40	2.84
EC	43.2	41.7	37.2	38.1
pH	5.61	5.61	5.54	5.56
Na	2.25	2.29	1.79	2.16
K	0.536	0.575	0.402	0.497
Ca	3.65	3.81	2.52	3.71
Mg	1.62	1.68	1.07	1.63
Al	0.433	0.448	0.396	0.432
Fe	1.59	1.60	1.19	1.38
S	1.89	2.04	1.45	1.88
P	0.056	0.061	0.045	0.055

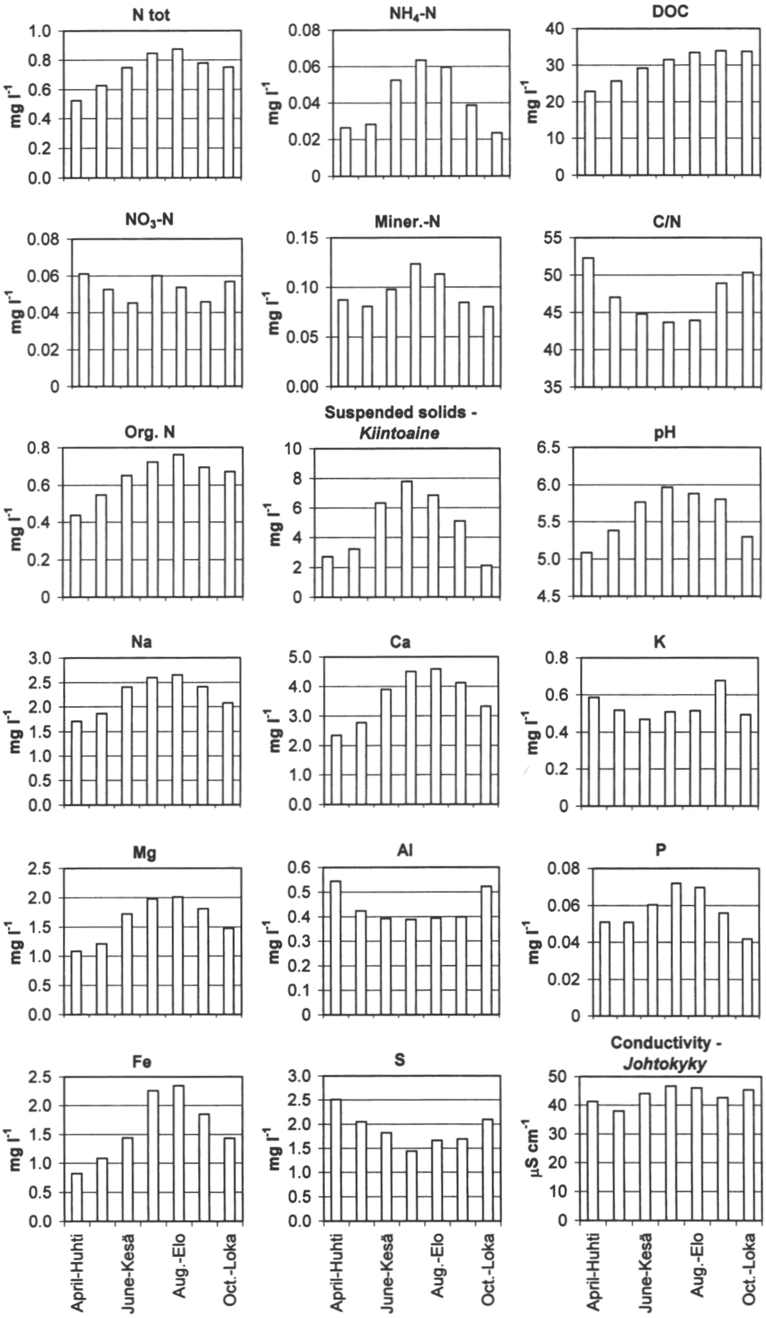

Fig. 3. Mean monthly pH, electric conductivity (EC), element concentrations, concentration of suspended solid material and C/N-ratio in runoff water from old ditch networks.

Kuva 3. Vanhoilta ojitusalueilta valuvan veden ravinnepitoisuuksien, kiintoainepitoisuuden ja liuenneen orgaanisen hiilen (DOC) pitoisuuden sekä pH:n, johtokyvyn (EC) ja hiili-typpisuhteen huhti-lokakuun keskiarvot.

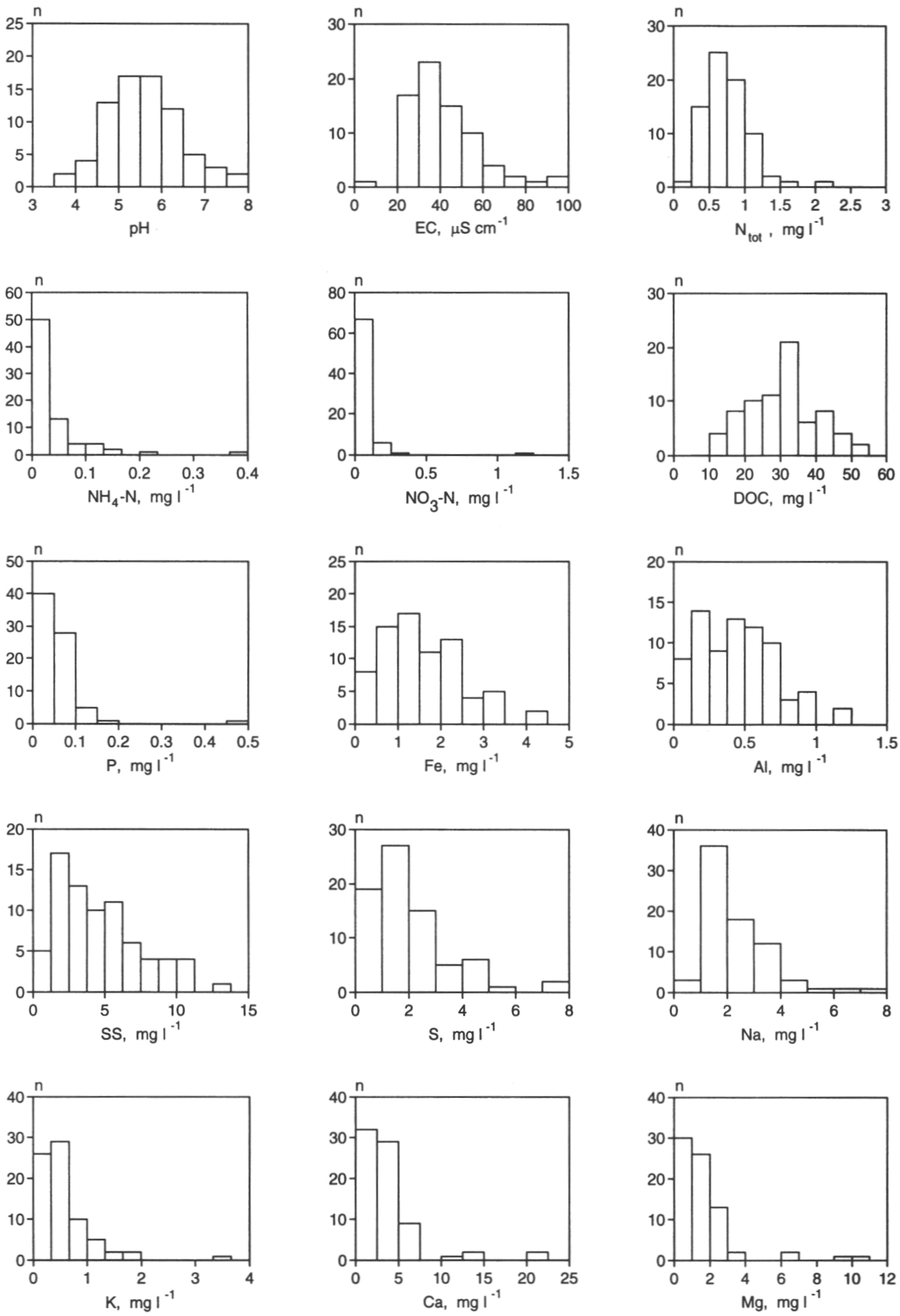

Fig. 4. Distribution of the 75 basin mean values of some water quality parameters.

Kuva 4. Tutkimuksessa seurattujen 75 vanhan ojaston vedenlaatutunnusten keskiarvojen jakaumat.

tions (Table 5).

The average pH-value of all samples was 5.61, and the site mean value varied from 3.89 to 7.63. Using H^+-concentration instead of sample pH, a mean pH value as low as 4.80 was arrived at. The site mean pH values were normally distributed. The average pH value was at its lowest in April (5.08) and at its highest in July (5.95) (Fig. 3).

Suspended solids

The site mean concentration of suspended solids varied from 0.91 to 13.1 mg l^{-1} and averaged 4.72 mg l^{-1} (Table 4). The median concentration of suspended solids calculated from all samples (n = 2815) was 2.40 mg l^{-1}, while the mean value is 4.90 mg l^{-1}, the difference indicated a skewed distribution (Fig. 4). The highest monthly mean concentrations of suspended solids occurred in July (7.77 mg l^{-1}) and the smallest in October (2.13 mg l^{-1}) and April (2.68 mg l^{-1}) (Fig. 3).

Base cations

Site mean concentration of sodium varied from 0.73 to 7.00 mg l^{-1}, with a mean value of 2.29 mg l^{-1}. The corresponding values for potassium were 0.12 to 3.47 mg l^{-1} and 0.58 mg l^{-1}. The site median K concentration was 0.50 mg l^{-1}. The concentration of potassium correlated positively and significantly with the concentration of nitrate nitrogen (r = 0.75; $p<0.001$) and the other cations.

The site mean concentration of calcium averaged 3.81 mg l^{-1} and ranged from 0.81 to 22.2 mg l^{-1}. There was a strong positive correlation between the site mean concentrations of calcium and magnesium (r = 0.95; $p<0.001$).

The site mean concentration of magnesium varied from 0.32 to 10.48 mg l^{-1} with a value of 1.68 mg l^{-1} and a median at 1.63 mg l^{-1}. With the exception of potassium concentrations, which did not show any seasonal trend, the concentrations of base cations were at their highest during midsummer.

Aluminum, iron and sulphur

The site mean concentration of aluminum varied from 0.04 to 1.19 mg l^{-1}, and for iron between 0.14 and 4.49 mg l^{-1}. The site mean concentrations of aluminum and iron were 0.45 mg l^{-1} and 1.60 mg l^{-1}, respectively. The mean concentration of aluminum was at its highest in April and October and that of iron in July–August.

Table 5. Pearson correlation coefficients between site mean values of some water quality parameters in runoff water from old ditch networks. SS = suspended solids, EC = electric conductivity. Statistically significant correlations ($p<0.05$; n = 75) marked with boldface.

Taulukko 5. Eräiden ravinteiden, kiintoaineen, pH:n, hiili-typpisuhteen, ja johtokyvyn väliset korrelaatiokertoimet vanhoilla ojitusalueilla. SS = kiintoaine, EC = sähkönjohtavuus. Tilastollisesti merkitsevät korrelaatiot ($p<0.05$; n = 75) merkitty lihavoidulla tekstillä.

	Ntot	NH_4-N	NO_3-N	Org N	Min N	DOC	C/N	SS	EC	pH	P	K	Na	Ca	Mg	Al	Fe	S
Ntot	1.000																	
NH_4-N	**0.267**	1.000																
NO_3-N	**0.625**	0.031	1.000															
Org N	**0.859**	0.086	0.181	1.000														
Min N	**0.673**	**0.386**	**0.934**	0.198	1.000													
DOC	**0.602**	0.039	–0.049	**0.819**	–0.031	1.000												
C/N	–0.189	–0.083	**–0.312**	–0.030	**–0.318**	**0.520**	1.000											
SS	**0.273**	0.335	0.163	0.175	**0.270**	–0.112	**–0.405**	1.000										
EC	**0.519**	0.040	**0.298**	**0.488**	**0.289**	0.337	–0.150	0.163	1.000									
pH	0.134	0.144	**0.260**	–0.024	**0.291**	**–0.436**	**–0.663**	**0.540**	0.077	1.000								
P	**0.326**	–0.012	0.001	**0.434**	–0.004	**0.404**	0.023	–0.032	**0.425**	–0.193	1.000							
K	**0.594**	0.019	**0.748**	**0.304**	**0.697**	–0.036	**–0.455**	**0.344**	**0.314**	**0.411**	0.100	1.000						
Na	**0.304**	0.092	0.167	**0.274**	0.186	–0.068	**–0.515**	**0.437**	**0.258**	0.610	–0.046	**0.523**	1.000					
Ca	**0.468**	0.068	**0.313**	**0.403**	**0.313**	0.047	**–0.433**	**0.281**	0.346	**0.653**	0.130	**0.446**	**0.470**	1.000				
Mg	**0.468**	0.018	**0.313**	**0.416**	**0.296**	0.055	**–0.438**	**0.320**	**0.345**	**0.667**	0.070	**0.479**	**0.563**	**0.952**	1.000			
Al	–0.068	**–0.276**	–0.107	0.046	–0.197	0.103	0.091	–0.224	–0.027	**–0.478**	0.053	–0.021	–0.108	**–0.358**	**–0.253**	1.000		
Fe	**0.526**	**0.380**	0.073	**0.556**	0.203	**0.368**	–0.158	**0.599**	0.155	**0.229**	0.065	**0.287**	0.473	0.220	**0.241**	–0.120	1.000	
S	**0.365**	–0.073	0.171	**0.392**	0.132	0.117	**–0.342**	0.115	**0.489**	0.117	**0.276**	0.424	**0.393**	**0.380**	**0.419**	0.216	–0.003	1.000

Aluminum concentrations were negatively correlated with pH-value ($r = 0.48$; $p<0.01$) and iron positively correlated with total nitrogen ($r = 0.52$; $p < 0.001$), organic nitrogen ($r = 0.55$; $p<0.001$) and suspended solids ($r = 0.60$; $p < 0.001$).

The mean concentration (n=2815) of S was 1.89 mg l^{-1}. The site mean concentrations (n = 75) varied between 0.50 and 7.52 mg l^{-1} and correlated positively with the concentrations of base cations ($r = 0.38–0.42$, $p < 0.001$). The highest concentrations of S were observed in spring and autumn (Fig. 3).

Relationships between basin characteristics and runoff water quality

The proportion of rich peatland site types was positively correlated with site mean total N concentration ($r = 0.28$, $p= 0.020$). Conversely, the proportion of poor peatland site types correlated negatively with N_{tot} concentration ($r = –0.45$, $p< 0.001$). No clear relationship between P concentrations and site characteristics could be detected.

Site mean pH values were positively correlated with the occurrence of herb-rich peatland site types ($r = 0.48$, $p < 0.001$) and spruce swamps ($r = 0.39$, $p < 0.001$) within the catchment. Calcium concentrations were also positively correlated with the occurrence of spruce swamps ($r = 0.42$, $p<0.001$), and the concentrations of magnesium positively correlated with the occurrence of herb-rich peatland site types ($r = 0.85$, $p< 0.001$) and spruce swamps ($r = 0.54$, $p<0.001$) within the catchment.

DISCUSSION

In order to determine discharge water quality from drained peatland areas typical for Finland we have sampled a large number of sites (75) for a relatively short period of time (1–3 years). Because of the large number of sites compared to long-term but site specific studies we were able to determine the dependence of runoff water quality on site characteristics.

The median concentrations of total N averaged 0.723 mg l^{-1} and were higher than the values reported by Kortelainen & Saukkonen (1995) and Kortelainen et al. (1997) based on 13 peatland dominated catchments. Median concentrations of mineral nitrogen (NH_4^+-N and NO_3^--N) were lower in our material. Mean concentrations of total N and NO_3^--N reported by Rekolainen (1989) fitted well within the ranges observed in our study. Mean total N concentrations in drainage water from old ditching areas (0.427–518 mg l^{-1}) observed by Kenttämies (1980, 1981) were only a little lower than the values we found, and did not differ much from total N concentrations in runoff from natural peatlands. Our total N concentration values were also similar to those reported for untreated Swedish catchments with high proportion of natural peatlands reported by Bergquist et al. (1984) and Lundin (1992), but higher (as also NO_3^--N concentrations) than reported for a study in eastern Finland, both before and after ditching (Ahtiainen 1990, Ahtiainen et al. 1995).

The concentration of phosphorus in runoff water from pristine peatlands in Finland rarely exceeds 0.02 mg l^{-1} (Kenttämies 1980). It appears that forest management increases runoff P concentrations. Median total phosphorus concentrations in this study were higher than reported by Saukkonen and Kortelainen (1995) for small, forested and peatland-dominated and forested catchments in Finland (0.028 mg l^{-1}, range 0.014–0.033 mg l^{-1}). Runoff P concentrations from six pristine catchments varied from 0.012 to 0.033 mg l^{-1} in a study reported by Ahtiainen & Huttunen (1995, 1999). After various forestry measures including ditching and clear cutting carried out in three of the catchments, the mean P concentration varied between 0.020 and 0.142 mg l^{-1} during the first three years. Rekolainen (1989) reported P concentrations in runoff water from small forest dominated catchments in Finland of 0.018 to 0.063 mg l^{-1}.

Ruskeesuo site had the highest mean phosphorus concentration (0.458 mg l^{-1}), which was almost tenfold the mean value of all site mean values. The surface peat layer at Ruskeesuo is poorly humified Sphagnum peat, which normally contains very little iron and aluminium for phosphorus retention (Nieminen & Ahti 1993, Nieminen 2000). The catchment area was fertilized with NPK in 1970, and later, in 1985, one third of it with PK. The high phosphorus concentrations we observed are therefore probably due to the fertilizations.

Fertilization of drained peatlands is known to increase the risk of phosphorus leaching to water courses (Ahti & Paarlahti 1988, Nieminen & Ahti 1993, Saura & al. 1995, Nieminen 2000). Many studies have also indicated that leaching of phosphorus after fertilization of peatlands is a long-term process (Malcolm & Cuttle 1978, Kenttämies 1981, Ahti 1983). In contrast to most other nutrients, runoff P were associated with the occurrence of poor peatland site types within the catchment. These site types are characterized by having oligotrophic *Sphagnum* peat that contain little aluminium and iron. The retention of P in peat is known to be strongly controlled by the amount of Al and Fe (Nieminen 2000). The relatively high mean and median P concentrations observed in this study is thus considered to be also partly due to the lack of retention of P applied in fertilizer. More than half of our study sites had been fertilized at least once during the two decades preceding sampling.

The concentration of dissolved organic material in the discharge water tends to increase with the proportion of peatland in the catchment (Lundin 1988, Saukkonen and Kortelainen 1995). Dissolved organic matter concentrations in runoff do not essentially differ between old ditching areas and pristine peatlands (Heikurainen et al. 1978, Kenttämies 1981, Sallantaus 1994). Laaksonen & Malin (1980, 1984) showed that DOC concentrations did not increase in the Finnish water courses during the decades of extensive peatland forestry ditching activity. In some sites, the concentrations of dissolved organic matter in stream waters have even decreased as a result of ditching operations (Hynninen 1988).

DOC concentrations in our material (site median 25.2 mg l^{-1}) was at the same level as the values of organic carbon measured by Kenttämies and Laine (1984) for drained peatlands, but somewhat higher than the concentrations of total organic carbon reported by Saukkonen and Kortelainen (1995, basin median 20.0 mg l^{-1}). However, Saukkonen and Kortelainen (1995) sampled runoff from forest streams and not from the main ditch on peatland as in our study.

Both the site mean and median concentration of suspended solids (Table 4) were similar to values reported in other studies. According to Kenttämies (1987) the concentration of suspended solids in runoff from peatlands drained 20–40 years ago was 5.08–9.24 mg l^{-1} and 3.32 to 7.78 mg l^{-1} for pristine peatlands. Saukkonen and Kortelainen (1995) reported an average median concentration value of 3.5 mg l^{-1} for catchments with a proportion of peatland cover > 35%. However, our concentrations of suspended solids were higher than those reported for natural brooks in eastern Finland (Ahtiainen 1988, 1990, Ahtiainen & Huttunen 1995).

Discharge waters from peatland catchments are more acid than those from catchments dominated by mineral soils (Rekolainen 1989, Saukkonen & Kortelainen 1995, Kortelainen & Saukkonen 1998). In our data, the site mean pH varied from 3.9 to 7.6. Our median pH value is similar to pH values reported by Heikurainen et al. (1978) and Saukkonen & Kortelainen (1995). We also found a clear seasonal pattern in pH, with highest values in July–August and lowest values in April and October. A similar seasonal pattern has been observed in the pH in natural brooks by Ahtiainen (1990).

As also found in other studies (e.g. Saukkonen & Kortelainen 1995, Kortelainen 1997), pH was positively correlated to the concentration of base cations and negatively correlated to DOC concentrations. The strong positive correlation between the concentration of base cations and the pH-value, and a negative correlation between the concentration of dissolved organic carbon and pH, were also reported by Saukkonen & Kortelainen (1995) and Kortelainen et al. (1997).

The median concentration of iron (1.9 mg l^{-1}) reported by Saukkonen and Kortelainen (1995) from 13 small catchments with a high proportion of peatlands was higher than the site median value (1.38 mg l^{-1}) in our study. Lower iron concentrations (0.7–1.0 mg l^{-1}) have been reported for Finnish catchments comprising of pristine forest land (Kortelainen et al. 1999). The concentrations of aluminum measured in pristine brook waters by Ahtiainen (1990) and in a sedge-rich peatland area in central Sweden (Lundin 1992) were lower than the site mean value in our study.

The concentrations of S observed in this study were considerably higher than the values calculated from the median SO_4 concentrations of Saukkonen & Kortelainen (1995).

With the exception of phosphorus, more nutrients seemed to leach into the ditch waters from catchments dominated by eutrophic peatland site types than from catchments dominated by oligotrophic types. The discharge waters from catchments dominated by rich sites were also less acid.

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TIIVISTELMÄ

Vanhoilta ojitusalueilta valuvan veden ominaisuudet

Tässä työssä tarkastellaan vanhoilta ojitusalueilta valuvan veden laatua. Kirjoitus perustuu 1990-luvun alkupuolella Metsätalouden vesistöhaitat ja niiden torjunta -projektin (METVE) yhteydessä Metsätalouden kehittämiskeskus Tapion, Metsäntutkimuslaitoksen ja metsäkeskusten yhteistyönä keräämään kunnostusojituksen vaikutuksia käsittelevän tutkimuksen kalibrointivaiheen aineistoon (Ahti ym. 1995). Tutkimusaineisto käsittää 75 eri puolilla Suomea sijaitsevaa ojitusaluetta (Kuva 1, Taulukko 2). Kohteet valittiin metsäkeskusten kunnostusojitussuunnitelmakannasta siten, että muut kuin metsätaloustoimenpiteet vaikuttaisivat mahdollisimman vähän alueelta virtaavan veden laatuun.

Kaikilta alueilta otettiin vesinäytteitä metsäojitusalueen laskuojasta. Näytteenottojakson pituus vaihteli vuodesta noin kahteen ja puoleen vuoteen. Kaikkiaan analysoitiin n. 2800 vesinäytettä. Vesinäytteet otettiin yleensä viikottain. Näytteenotto pyrittiin aloittamaan keväällä mahdollisimman varhain. Kevättulvien aikana näytteitä otettiin kaksi kertaa viikossa, tulvakauden jälkeen kerran viikossa. Viikoittainen näytteenotto kesti lumentuloon ja ojien jäätymiseen saakka. Näytteet otettiin virtaavasta vedestä uoman keskikohdalta puolen litran muovipulloon.

Vesinäytteiden analyysit tehtiin Metsäntutkimuslaitoksessa yleisesti käytettävillä standardimenetelmillä (Jarva & Tervahauta 1993). Näyte suodatettiin (1,2 µm) ja suodattimeen jäänyt kiintoaine punnittiin kuivatuksen jälkeen (60 °C). Kemialliset analyysit tehtiin suodatetuista näytteistä. Kokonaisfosfori, natrium, kalium, magnesium, kalsium, rikki, alumiini ja rauta määritettiin ARL 3580 ICP plasmaemissiospektrofotometrillä (ICP). Kokonais- (N_{tot}), ammonium- (NH_4-N) ja nitraattityppi (NO_3-N) määritettiin spektrofotometrisesti Tecaton FIA-analysaattorilla. Veteen liuenneen orgaanisen aineksen määrä määritettiin aluksi kaliumpermanganaatin ($KmnO_4$) kulutuksena ja vuodesta 1992 lähtien orgaanisen hiilen määränä (DOC). Lisäksi näytteistä määritettiin pH ja sähkönjohtavuus.

Tutkimusalueiden ojien kunto kartoitettiin maastossa systemaattisella otannalla. Kartoituksessa mitattiin ojien syvyys ja leveys sekä arvioitiin niiden kunto Keltikankaan ym. (1986) käyttämää menetelmää soveltaen.

Valumaveden keskimääräiset ominaisuudet on esitetty taulukoissa 3 ja 4 sekä kuvissa 3 ja 4. Keskimääräiset kokonaistypen pitoisuudet olivat samaa suuruusluokkaa kuin muissa tutkimuksissa vanhoilta ojitusalueilta raportoidut kokonaistypen arvot. Sen sijaan kokonaisfosforipitoisuus oli korkeampi kuin aikaisemmissa tutkimuksissa on raportoitu. Liuenneen orgaanisen hiilen (DOC) ja kiintoaineen pitoisuudet sekä pH eivät oleellisesti poikenneet aikaisemmissa tutkimuksissa todetuista arvoista. Alueilta, joissa rehevät suotyypit ovat vallitsevia, huuhtoutui fosforia lukuun ottamatta enemmän ravinteita kuin karujen suotyyppien vallitsemilta alueilta. Kasvillisuudeltaan rehevien alueiden valumavesien pH oli myös korkeampi kuin karujen alueiden.

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II

PAPER II

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Effects of Ditch Network Maintenance on the Chemistry of Run-off Water from Peatland Forests

SAMULI JOENSUU[1], ERKKI AHTI[2] and MARTTI VUOLLEKOSKI[2]

[1]*Forestry Development Centre Tapio, Soidinkuja 4, FI-00700 Helsinki, Finland, and* [2]*The Finnish Forest Research Institute, Vantaa Research Centre, P.O. Box 18, FI-01301, Vantaa, Finland*

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Joensuu, S., Ahti, E. and Vuollekoski, M. ([1]Forestry Development Centre Tapio, Soidinkuja 4, FI-00700 Helsinki, Finland, and [2]The Finnish Forest Research Institute, Vantaa Research Centre, P.O. Box 18, FI-01301, Vantaa, Finland). *Effects of ditch network maintenance on the chemistry of run-off water from peatland forests.* Received July 15, 2000. Accepted Dec. 4, 2001. Scand. J. For. Res. 17: 238–247, 2002.

Ditch run-off chemistry of 40 catchments was monitored before and for 2–3 yrs after maintenance of the peatland ditch network and compared with data collected from 34 control catchments. Increases in mean pH, electrical conductivity, and the concentrations of suspended solids and base cations (sodium, potassium, calcium and magnesium) and a decrease in the concentration of dissolved organic carbon were observed. Because of high concentrations in a few areas immediately after the digging operations and during the first post-treatment year in general, the mean concentrations of aluminium and iron also increased. No major changes occurred in the concentrations of total dissolved nitrogen (N) and total dissolved phosphorus. High phosphorus concentrations were observed at a few sites immediately after the digging operations. Concentrations of mineral N, especially NH_4^+-N, increased significantly, while the concentrations of organic N decreased. The largest relative changes in element transport during the 3 yr period following treatment were the increases in the loads of NH_4^+-N and suspended solids. From the point of view of water protection, the loading of suspended solids was considered the most harmful effect of ditch network maintenance. *Key words: ditch water, Finland, open ditches, organic soils, water chemistry.*

Correspondence to: E. Ahti, e-mail: erkki.ahti@metla.fi

INTRODUCTION

Nearly 6 million ha of peatlands and paludifying mineral sites have been drained for forestry purposes in Finland since the 1930s. The annually drained area increased steadily from the middle of the 1950s to 1970s, with a maximum of 294 000 ha in 1969 (Sevola, 1999). Between 1965 and 1990, 1.5 million ha of drained peatlands were fertilized. Phosphorus (P, ~ 40 kg ha^{-1}) and potassium (K, ~ 80 kg ha^{-1}) were the main nutrients added when fertilizing peatland forests. The poorest sites were additionally fertilized with *c.* 100 kg ha^{-1} of nitrogen (N).

Drainage of pristine peatlands has now ceased and the total area of undrained peatlands will remain at 4 million ha. However, maintenance of the existing ditch networks will become an increasingly important aspect of peatland forestry. An average of 75 000 ha of drained peatland forest were subject to ditch cleaning or complementary ditching annually in the 1990s.

Trends in run-off water chemistry after ditch maintenance have been estimated to be similar to those after the original construction of the ditches. The most pronounced change after first ditching is an increase in the concentration of suspended solids (Heikurainen et al. 1978, Kenttämies 1980, Kenttämies & Laine 1984, Prévost & Plamondon 1999). Following ditch network maintenance, an increase in suspended solids concentrations is also accompanied by an increase in the concentrations of mineral N and particulate P as well as an increase in pH, but concentrations of dissolved organic carbon (DOC) decline (Ahti et al. 1995). Manninen (1998, 1999), however, reported no change in DOC concentrations related to ditch maintenance, although concentrations of suspended solids, total P, total N, ammonium and nitrate did increase. According to Manninen (1999), the increase in the total P concentration appears to be connected with the raised concentration of suspended solid material in the discharge water.

This study examines how maintaining ditch networks in peatland forests influences run-off water chemistry and estimates the corresponding changes in loading to recipient waters.

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MATERIALS AND METHODS

Study areas and water sampling

The chemistry of ditch water leaving peatland areas in 40 catchments 1–2 yrs before and for 2–3 yrs after maintenance of the ditch networks was monitored. The digging operations were performed in 1991–1993 according to the original planning performed by the local forestry centres. Control samples were simultaneously taken from the main ditch of 34 otherwise similar catchments situated close to the maintenance areas but in which ditch maintenance was not carried out (Fig. 1, Table 1). The average size of the 74 catchments was 77 ha (13–222 ha) and comprised 39 ha of drained peatland, 5 ha of pristine peatland and 33 ha of upland mineral soil. On average, 80% of the forested peatland area of a site was classified as Scots pine bog or swamp and the remainder as Norway spruce swamp. Open (treeless) peatlands accounted for less than 5% of the total peatland area on average. In most treated areas, both ditch cleaning and complementary ditching were performed. The old ditch systems with 40–60 m ditch spacings and original ditch depths between 0.7 and 0.9 m (Joensuu et al. 2001) were cleaned and/or supplied with new ditches between the old ones by using excavators or hydraulic tractor diggers.

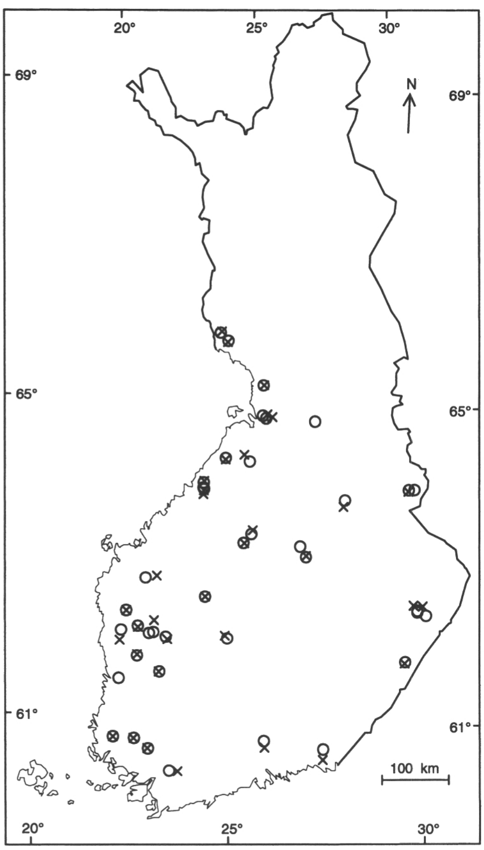

Fig. 1. Map of Finland showing the location of the 34 control catchments (×) and the 40 catchments subject to ditch network maintenance (○).

Table 1. *Mean site characteristics of 34 control and 40 treated areas*

Mean site characteristics	Control areas	Treated areas
Catchment area (ha) (A)	71.3	82.5
Peatlands		
Area (ha) (B)	39.2	48.3
Area (% of A)	55	59
Drained peatlands		
Area (ha)	36.2	43.4
Area (% of A)	51	53
Area (% of B)	66	74
Average year of first drainage	1971	1964
Volume of tree stands (m^3 ha^{-1})		
Whole catchment	71	75
Peatland stands	60	63
Peatland site types (% of B)[a]		
Rich sites	20	24
Medium sites	44	38
Poor sites	36	38
Total fertilization area on peatlands (ha)	9	14
Ditch network maintenance		
Total area	–	33.4
Complementary ditches (km)	–	3.1
Cleaned ditches (km)	–	5.4

[a] The most frequent site types within the classes according to the Finnish site type classification by Heikurainen & Pakarinen (1982): rich sites: eutrophic and herb-rich sites, *Vaccinium myrtillus* spruce swamps, tall-sedge hardwood–spruce fens; medium sites: *Vaccinium vitis-idaea* spruce swamps, *Carex globularis* spruce and pine swamps, tall-sedge pine fens; poor sites: dwarf-shrub pine bogs, cottongrass pine bogs, cottongrass and low-sedge pine fens.

With the objective of relating soil characteristics to run-off chemistry, soil characteristics were studied systematically along the new ditches of the treated areas in 1994. At a minimum of 50 points per site, the depths of the ditch and the peat layer were measured, and subsoil texture, peat type and peat decomposition (von Post) were subjectively determined for the different soil layers visible in the ditch profile. The data concerning fertilization were obtained from the local forestry authorities. According to practice, *c*. 40 kg of P and 80 kg of K, and in the poorest sites, *c*. 100 kg of N was applied per hectare in the areas that were fertilized.

During both the pretreatment and the post-treatment period, the height of the water level in the main ditch was measured at a chosen spot where the water sample was also taken. By 1993, most catchments had been fitted with a simple 90° V-notch weir for manual run-off estimation in connection with sampling. By using the relationship between ditch water level and measured run-off, pretreatment run-off was approximated. Water samples were taken weekly starting during the snowmelt period in spring and continued until freezing in late autumn. No samples were taken in the winter because of low run-off rates and difficulties in sampling. The samples were taken directly into 500 ml plastic bottles from a sampling point on the main ditch selected to enable sampling from flowing water without stirring the bottom sediment of the ditch. The samples were sent immediately to the Central Laboratory of the Finnish Forest Research Institute in Vantaa. Before analysis, the samples were stored for 2–14 days at + 5°C.

Chemical analysis

Electrical conductivity and pH were determined using a combined electrode/conductivity meter (Jarva & Tervahauta 1993). The samples were then filtered and the fibre-glass filters (pore size 1.2 μm) were weighed to determine the amount of suspended solids after drying at 60°C (Joensuu et al. 1999). Concentrations of P, Na, K, magnesium (Mg), calcium (Ca), sulfur (S), aluminium (Al) and iron (Fe) were determined from the filtrates using an inductively coupled plasma emission spectrophotometer (ICP/AES, ARL 3580) and represent total dissolved concentrations. Concentrations of total dissolved nitrogen (N_{tot}), ammonium (NH_4^+) and nitrate (NO_3^-) were determined spectrophotometrically with a Tecaton FIA analyser. The concentration of organic N was calculated as N_{tot}-(NH_4^+-N + NO_3^--N). Concentrations of dissolved organic carbon (DOC) were determined as $KMnO_4$ consumption in 1990–1991 and afterwards directly as DOC with a Shimadzu carbon analyser. For 714 samples, the determination was done by both methods, and the following regression used for converting $KMnO_4$ consumption into DOC concentrations:

$$DOC = 0.164 \cdot C_{KMnO_4} + 3.2; \; r^2 = 0.98 \quad (1)$$

Statistical analysis

The water chemistry was characterized using descriptive statistics, e.g. means, deviations, Pearson correlation coefficient, mean tests and regression analysis. The statistical analysis was performed using the SYSTAT statistical package (Anon. 1996).

The effect of ditch maintenance on the mean concentrations of each element was demonstrated by direct comparison of the pretreatment and post-treatment averages from the control and treatment areas. The differences between mean pretreatment and post-treatment concentrations were tested using Tukey's test.

Multiple regression equations relating post-treatment concentrations with pretreatment concentrations and basin characteristics were constructed on the basis of significant intercorrelations. In this paper, a few equations which may be of use in evaluating the need for practical water protection measures, i.e. using pretreatment data, are presented. For estimating the export of elements in mass units, the change in concentrations due to ditch network maintenance was also evaluated on the basis of the difference between predicted and observed concentrations. The predicted concentrations (= the hypothetical concentrations of the treated areas, if the treatments had not been performed) were calculated using Equation (2):

$$\hat{C}_{treat1} = (C_{Treat0} - C_{Contr0}) + C_{Contr1} \quad (2)$$

where $\hat{C}_{treat1}$ is the predicted concentration for the treatment areas during the post-treatment period if they had not been treated, C_{Treat0} is the measured pretreatment concentration for the treatment areas, C_{Contr0} is the measured pretreatment concentration for the control areas, and C_{Contr1} is the measured post-treatment concentration for the control areas. Monthly export loads were then calculated by multiplying the predicted and the observed mean monthly concentrations by mean monthly run-off of the treated sites. Because no significant changes in run-off were assumed, the significance of the changes in load is indicated by the significant changes in concentration.

RESULTS

Changes in nitrogen concentrations

In the control areas, and before treatment in the sites subject to ditch network maintenance, monthly concentrations of total N varied between 0.5 and 0.9 mg l^{-1} and the highest concentrations occurred in July–August. Mean concentrations of N decreased after ditch network maintenance (Table 2, Fig. 2). The mean concentration of N over the post-treatment study period increased by more than 0.1 mg l^{-1} in nine areas, decreased by more than 0.1 mg l^{-1} in 18 areas and remained within the limits of ± 0.1 mg l^{-1} in 13 areas. According to regression analysis, the overall mean concentration of N during the first 3 yrs after treatment (N_{tot1-3}) was dependent on the pretreatment concentration (N_{tot0}, $p < 0.001$) and the occurrence of poorly decomposed peat at the bottom of the ditch system ($p < 0.001$):

$$N_{tot1-3} = 0.11 + 0.64 \cdot N_{tot0} + 0.0045 \cdot H_{1-5}; \; r^2 = 0.75 \quad (3)$$

where H_{1-5} is the occurrence of von Post degrees 1–5 of humification within each site.

The monthly mean concentration of NH_4^+-N calculated from the combined data of all 40 areas during the pretreatment period varied from 0.02 to 0.07 mg l^{-1}. The highest concentrations occurred in June–August and the lowest in spring and autumn (Fig. 2). The mean annual concentration of NH_4^+-N was more than doubled by the maintenance treatment and the concentration was still higher in the third year after treatment. As for total N, the mean concentration of NH_4^+-N during the first 3 yrs after treatment (NH_4^+-N_{1-3}) was dependent on pretreatment concentration (NH_4^+-N_0, $p < 0.001$) and the occurrence of poorly humified peat at the bottom of the ditches ($p < 0.01$):

$$NH_4^+\text{-}N_{1-3} = -0.0049 + 1.42 \cdot NH_4^+\text{-}N_0 + 0.0012 \cdot H_{1-5}; \; r^2 = 0.60 \quad (4)$$

The response of NO_3^--N concentrations to ditch network maintenance was not as clear as that of NH_4^+-N. Monthly concentrations from treated areas tended to be higher in early spring and late autumn and lower during the summer than pretreatment values (Fig. 2).

The decrease in total N and concurrent increase in mineral N concentrations imply that organic N concentrations decreased as a result of ditch network maintenance.

Changes in phosphorus concentration

Concentrations of total dissolved P did not essentially change as a result of the ditch network maintenance operations (Table 2, Fig. 2). In the first year after ditch network maintenance, P concentrations had increased by more than 0.02 mg l^{-1} in five sites and decreased by more than 0.02 mg l^{-1} in six sites. In the second year, the corresponding numbers of sites were three and six. The most dramatic change occurred in the Ruskeesuo site, where the very high pretreatment concentrations of P (> 0.4 mg l^{-1}) decreased by 0.25–0.30 mg l^{-1} after ditch network maintenance while those in the run-off from the control area increased.

At a few sites, P concentrations increased considerably, especially during the first year after treatment. One of these sites was the Pöytyä site, which was also characterized by high concentrations of suspended solids, Fe and Al. In addition to the pretreatment P_{tot} concentration ($p < 0.001$), the post-treatment P_{tot} concentration (P_{tot1-3}) was related to the occurrence of fine-textured mineral subsoils (Tx_{fine}, $p < 0.001$):

$$P_{tot1-3} = 0.019 + 0.49 \cdot P_{tot0} + 6 \cdot 10^{-4} \cdot Tx_{fine}; \; r^2 = 0.87 \quad (5)$$

Changes in pH, suspended solids and dissolved organic carbon

The most conspicuous qualitative change in run-off water was the increase in the concentration of suspended solids (see also Joensuu et al. 1999). The highest concentrations were observed during the first snowmelt after the maintenance operations (Fig. 2). The mean concentration of suspended solids during the post-treatment period was nearly 10 times higher than the pretreatment period concentrations (Table 2). The increase was closely associated with the total length of the cleaned and the complementary ditches and, as the ditches often reached into the mineral subsoil underlying the peat layer, with the texture of the subsoil (Joensuu et al. 1999). The relationship between the post-treatment concentration of suspended solids and the total length of ditches dug into different types of subsoil could be described by the following equation:

$$SS_{1-3} = -10.6 + 22.7 \cdot L_{ft} + 7.6 \cdot L_{mt} + 4.8 \cdot L_{ct} + 2.6 \cdot L_p; \; r^2 = 0.43 \quad (6)$$

where SS_{1-3} is the mean concentration of suspended solid material during the first 3 yrs after ditch net-

Table 2. *Water chemistry before and during 3 yrs after ditch network maintenance*

Water quality parameter	Area	Before maintenance	1st year after maintenance	2nd year after maintenance	3rd year after maintenance
N_{tot}	M	0.762 ± 0.0109	0.714 ± 0.012**	0.684 ± 0.011***	0.688 ± 0.014**
	C	0.711 ± 0.0094	0.756 ± 0.013	0.674 ± 0.012	0.668 ± 0.016
	M/C ratio	1.07	0.94	1.02	1.03
NH_4^+-N	M	0.047 ± 0.0038	0.103 ± 0.0055***	0.093 ± 0.0054***	0.098 ± 0.0067***
	C	0.038 ± 0.0023	0.035 ± 0.0033	0.023 ± 0.0020	0.021 ± 0.0029
	M/C ratio	1.23	2.97	4.08	4.60
NO_3^--N	M	0.067 ± 0.0058	0.064 ± 0.0053	0.068 ± 0.0035	0.064 ± 0.0036
	C	0.040 ± 0.0023	0.037 ± 0.0029	0.026 ± 0.0021	0.027 ± 0.0040
	M/C ratio	1.68	1.72	2.62	2.35
DOC	M	29.9 ± 0.34	24.3 ± 0.30***	23.1 ± 0.35***	23.2 ± 0.50***
	C	29.4 ± 0.38	34.9 ± 0.59	33.2 ± 0.62	32.0 ± 0.77
	M/C ratio	1.02	0.70	0.70	0.73
Suspended solids	M	5.00 ± 0.21	68.54 ± 7.00***	26.02 ± 2.37**	15.44 ± 1.33
	C	4.85 ± 0.24	4.77 ± 0.22	6.12 ± 0.85	5.08 ± 0.43
	M/C ratio	1.03	14.38	4.25	3.04
Conductivity	M	42.3 ± 0.62	49.3 ± 0.94***	48.5 ± 1.03***	50.6 ± 1.56***
	C	45.0 ± 0.78	44.4 ± 1.05	43.0 ± 1.13	43.6 ± 1.51
	M/C ratio	0.94	1.11	1.13	1.16
pH	M	5.62 ± 0.028	6.30 ± 0.023***	6.27 ± 0.024***	6.17 ± 0.035***
	C	5.62 ± 0.030	5.61 ± 0.034	5.62 ± 0.037	5.67 ± 0.048
	M/C ratio	1.00	1.12	1.12	1.09
Na	M	2.12 ± 0.032	2.90 ± 0.047***	2.72 ± 0.050***	2.68 ± 0.069***
	C	2.39 ± 0.064	2.22 ± 0.053	2.21 ± 0.060	2.29 ± 0.077
	M/C ratio	0.89	1.31	1.23	1.17
K	M	0.55 ± 0.018	1.13 ± 0.064***	0.97 ± 0.031***	0.95 ± 0.028***
	C	0.53 ± 0.017	0.47 ± 0.014	0.53 ± 0.019	0.62 ± 0.025
	M/C ratio	1.05	2.41	1.83	1.53
Ca	M	3.62 ± 0.10	4.33 ± 0.12***	4.26 ± 0.14**	4.56 ± 0.19***
	C	3.83 ± 0.13	3.64 ± 0.14	3.32 ± 0.14	3.32 ± 0.19
	M/C ratio	0.95	1.19	1.28	1.37
Mg	M	1.60 ± 0.046	2.19 ± 0.065***	2.02 ± 0.064***	2.02 ± 0.084***
	C	1.65 ± 0.061	1.57 ± 0.063	1.53 ± 0.070	1.57 ± 0.092
	M/C ratio	0.97	1.40	1.33	1.29
Al	M	0.43 ± 0.009	1.70 ± 0.205***	0.83 ± 0.086	0.57 ± 0.061
	C	0.41 ± 0.008	0.46 ± 0.010	0.48 ± 0.013	0.44 ± 0.016
	M/C ratio	1.05	3.69	1.74	1.31
Fe	M	1.65 ± 0.042	2.30 ± 0.151***	1.72 ± 0.069	1.60 ± 0.065
	C	1.49 ± 0.037	1.83 ± 0.052	1.73 ± 0.073	1.53 ± 0.067
	M/C ratio	1.10	1.26	1.00	1.05
S	M	1.78 ± 0.040	1.94 ± 0.046	2.12 ± 0.059***	2.36 ± *0.146**
	C	2.04 ± 0.071	1.70 ± 0.039	1.68 ± 0.042	1.95 ± 0.082
	M/C ratio	0.87	1.14	1.26	1.21
P_{tot}	M	0.058 ± 0.0017	0.064 ± 0.0019	0.050 ± 0.0014**	0.050 ± 0.0019*
	C	0.053 ± 0.0011	0.061 ± 0.0017	0.059 ± 0.0031	0.049 ± 0.0020
	M/C ratio	1.10	1.05	0.84	1.04

Data are arithmetic means ± SEM of all catchments and individual observations in April–October. Concentrations in mg l^{-1}, electric conductivity in $\mu S\ cm^{-1}$.

M: maintenance; C: control; DOC: dissolved organic carbon.

Significant differences between before and after treatment: ***$p<0.001$, **$p<0.01$, *$p<0.05$.

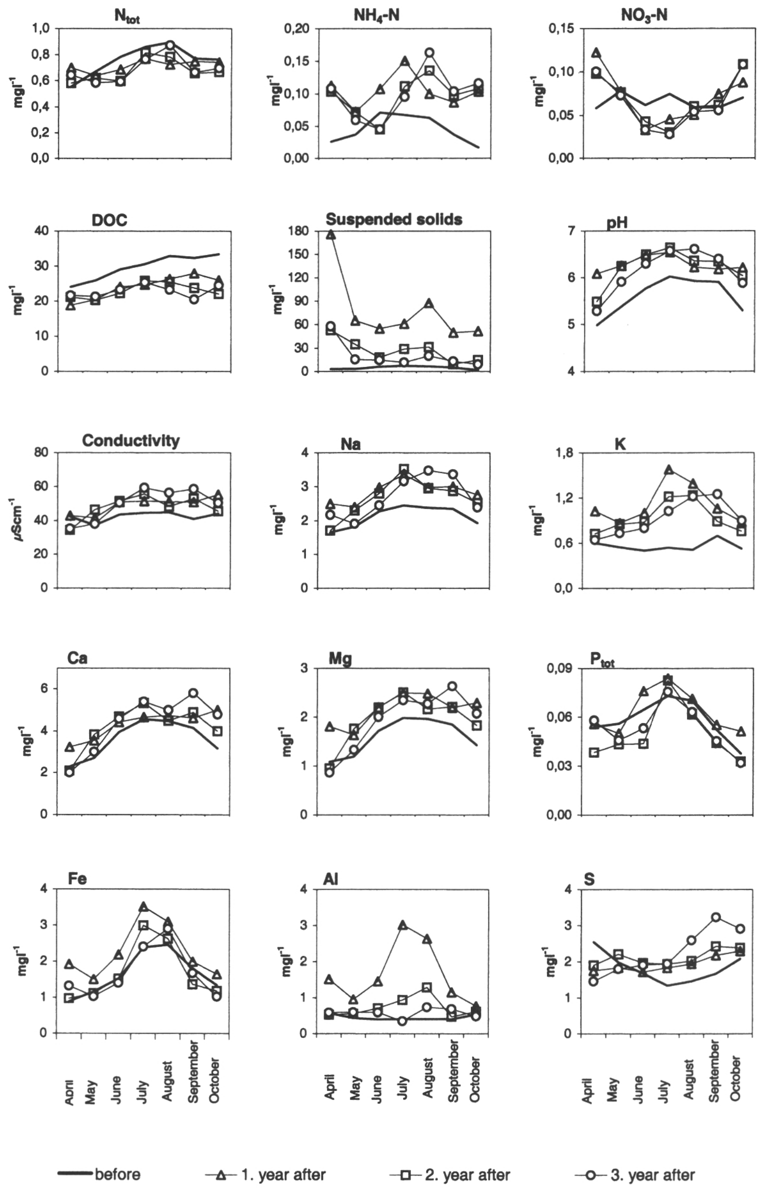

Fig. 2. Water chemistry before and during the three 3 yrs after ditch network maintenance. Mean monthly values over all 40 catchments are shown. DOC: dissolved organic carbon.

work maintenance (mg l^{-1}), L_{ft} is the total length of ditches dug into fine-textured subsoil (clay and fine loam) within each catchment (km) ($p < 0.001$), L_{mt} is the total length of ditches dug into medium-textured (from coarse loam to fine sand) subsoils (km) ($p <$ 0.001), L_{ct} is the total length of ditches dug into coarse-textured (coarse sand and gravel) subsoils (km) ($p = 0.023$), and L_p is the total length of ditches dug into deep peat (km) ($p = 0.210$).

The mean pH value of the run-off water from the treated areas, having been similar to that of the control areas during the pretreatment period, increased immediately after ditch network maintenance from 5.6 to 6.3. Simultaneously, the mean concentration of DOC decreased by more than 10 mg l^{-1} compared with that of the control areas. These clear changes were closely related to pretreatment values but rather weakly related to catchment characteristics such as catchment size, slope, soil type and soil texture.

Changes in the concentrations of base cations, iron, aluminium and sulfur

Concentrations of Na, K, Ca and Mg increased after ditch network maintenance. The change was greatest for K, the average concentration of which more than doubled compared with pretreatment and control values (Table 2).

Concentrations of Fe, Al and S also increased after ditch network maintenance (Table 2, Fig. 2), but the increase was less clear for Fe and S. The largest increase in the mean concentration of Al occurred during the first year after treatment and was primarily due to very high peak concentrations at a few sites. The mean increase exceeded 1.0 mg Al l^{-1} at eight sites and 2.0 mg Al l^{-1} at four sites. At one site the average Al concentrations during the first year after maintenance were 21 mg l^{-1} higher than during the pretreatment period.

Load estimates

Monthly mean export loads of elements other than N, P and C increased after ditch network maintenance (Table 3). In the case of total N and P, the changes in the annual loads were small and, on average, their loads appeared to decrease after ditch maintenance. In spite of increases in the loads of mineral N, the load of organic N decreased sufficiently to cause a decrease in total N.

DISCUSSION

In calculating the effect of ditch maintenance on run-off concentrations it was reasonably assumed that the differences between treated and control area concentrations after treatment would have been the same as those before treatment if the treated sites had not been treated. To calculate the changes in export loads due to ditch network maintenance a further assumption was made: a new water balance, characterized by a lower water table, is achieved very soon after ditch network maintenance and then the run-off

Table 3. *Predicted[a] and observed mean annual loads after ditch network maintenance*

Element	Mean annual load (kg ha^{-1})							Total of years 1–3		
		1st year		2nd year		3rd year				
	Before	Pred.	obs.	pred.	obs.	pred.	obs.	pred.	obs.	Change (% of pred.)
N_{tot}	2.0	2.2	2.0	2.0	1.8	1.9	1.9	6.0	5.7	−5.0
NH_4-N	0.093	0.091	0.29	0.072	0.28	0.047	0.29	0.21	0.86	+310
NO_3-N	0.19	0.19	0.25	0.14	0.25	0.11	0.24	0.44	0.74	+68
Organic N	1.7	1.9	1.5	1.8	1.3	1.7	1.4	5.4	4.1	−24
DOC	82	93	65	93	62	93	65	278	192	−31
Suspended solids	11	12	268	12	89	11	75	34	433	+1170
Na	5.5	5.0	7.6	4.7	6.7	4.6	6.8	14	21	+50
K	1.6	1.6	2.9	1.7	2.4	1.7	2.4	5.0	7.6	+52
Ca	8.8	8.6	11.8	7.4	10.2	7.3	10.6	23	33	+43
Mg	3.9	4.0	5.8	3.5	4.7	3.6	4.6	11	15	+36
Al	1.4	1.5	3.8	1.4	1.8	1.2	1.6	4.1	7.1	+73
Fe	3.8	4.6	5.5	4.1	3.8	3.8	3.9	13	13	0
S	5.9	4.9	5.6	4.7	6.1	5.0	6.2	15	18	+20
P_{tot}	0.15	0.17	0.16	0.17	0.12	0.14	0.14	0.48	0.42	−12

[a] Predicted loads = hypothetical loads from the treated areas, if the treatments had not been performed.
DOC: dissolved organic carbon.

remains much the same as before ditch network maintenance. Ditching of peatlands initially shifts the water balance away from evaporation from the soil surface towards a water balance dominated by run-off (Ahti 1987). With the development of the tree stand, interception and water uptake increase (Vompersky & Sirin 1997), and the water balance gradually becomes dominated by evaporation again, and this time not by evaporation from the soil surface but by interception and transpiration. When the tree stand has become more important than the ditch system in governing the level of the ground water table, the changes in run-off caused by ditch network maintenance would probably be small compared with the effects of first ditching (Ahti et al. 1995, Manninen 1998, 1999). The immediate lowering of the ground water table resulting from ditch network maintenance, by an average of 5–10 cm (Ahti & Päivänen 1997), corresponds to an increase in run-off of only 15–30 mm.

The most conspicuous long-term hydrological change due to ditch network maintenance is an increase in the seasonal variation of the water storage of the peatland and an increase in base flows. Ditch cleaning would not significantly increase high flows. Instead, complementary ditching, which increases channel density, may be expected to increase high flows and annual discharge slightly, but because of the higher evapotranspiration demand of the stands at this stage, the change in total run-off was regarded as negligible compared with the changes in concentration. As regards the change in run-off, this assumption is supported by the empirical data of Ahti et al. (1995) and Manninen (1999).

The changes in water chemistry after ditch network maintenance were similar to those reported earlier for the first ditching of pristine peatlands (Heikurainen et al. 1978, Kenttämies 1981, Kenttämies & Laine 1984, Lundin 1988) and to earlier results on the effects of ditch network maintenance (Ahti et al. 1995, Manninen 1999). Among the observed changes, the most interesting are the rise in pH and the decrease in the concentration of DOC. These changes are probably connected to two factors. First, the pH of soil water is higher in deeper peat layers than in soil water closer to the soil surface (Lundin 1996), and run-off from peatlands with a lower ground water table would have a higher pH. Secondly, because of peat subsidence after the first ditching, the cleaned and the complementary ditches will cut more deeply into the underlying mineral soil, resulting in a higher run-off pH than in the ditch water from the original ditches.

Before treatment, there was a strong positive correlation between DOC and organic N concentrations ($r = 0.83$; $p < 0.001$). The decrease in organic N concentrations after ditch network maintenance was also reflected in clearly decreased DOC and slightly decreased total N concentrations. Increased concentrations of total N were reported by Ahtiainen & Huttunen (1999) after first ditching and by Manninen (1999) after ditch network maintenance. This may be due to the fact that their samples were not filtered before analysis, as was done in the present study.

Ahtiainen & Huttunen (1999) reported suspended solid loads from two basins after first ditching similar to the mean load for the first 3 yrs after ditch network maintenance in this study.

K is a growth-limiting nutrient in most Finnish peatland forests. The clear increase in the leaching loss of K after ditch network maintenance may therefore be of concern from the viewpoint of future tree growth. However, the source of the K that is leached is probably the mineral subsoil or the deeper peat layers rather than the surface peat layer, which contains most of the tree roots.

Run-off P concentrations were not greatly affected by ditch network maintenance. This may at first seem contradictory to the results of earlier studies showing increased P leaching after ditching (Ahtiainen 1988, Manninen 1998). However, in this study the samples were filtered and therefore did not contain particulate P, as did the cited studies. The increased leaching of suspended solids after ditch network maintenance is likely to increase the leaching of particulate P. The major part of particulate P is biologically unavailable (Ekholm 1998) and is therefore unlikely to cause eutrophication of recipient waters. However, for run-off waters from clay soils with very high concentrations of suspended solids, considerable proportions of biologically active particulate P have been reported (Uusitalo et al. 2000).

This report is based on data from 40 treated and 34 control catchments. Because the digging operations were performed in different years (1991–1993), the number of sites contributing to the monthly concentration values and number of months since treatment varied. In spite of this variability, the changes in the treatment average concentrations of suspended solids, DOC, base cations and pH were statistically significant.

Mainly because of sedimentation of suspended solid material at the bottoms of the receiving water courses, which destroys bottom vegetation and breeding habitats of fish and other freshwater animals (Vuori & Joensuu 1996, Vuori et al. 1998), the authors consider the substantial increase in the leaching of suspended solids to be the most adverse effect of ditch network maintenance from the viewpoint of water protection (Binkley & Brown 1992, Nisbet 2001). Although there was an increase in the concentration of ammonium, the changes in the leaching of nutrients are unlikely to cause eutrophication of recipient water bodies. Considering the problems connected with freshwater acidification (Forsius 1992), the decrease in run-off acidity after ditch network maintenance may be regarded as beneficial.

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III

PAPER III

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The effects of peatland forest ditch maintenance on suspended solids in runoff

Samuli Joensuu[1)], Erkki Ahti[2)] and Martti Vuollekoski[2)]

[1)] *Forestry Development Centre Tapio, Soidinkuja 4, FIN-00700 Helsinki, Finland*
[2)] *The Finnish Forest Research Institute, P.O. Box 18, FIN-01301 Vantaa, Finland*

Joensuu, S., Ahti, E. & Vuollekoski, M. 1999. The effects of peatland forest ditch maintenance on suspended solids in runoff. *Boreal Env. Res.* 4: 343–355. ISSN 1239-6095

In 1990–1994, the effect of peatland forest ditch maintenance on the concentration of suspended solids in runoff water was studied in Finland in 37 catchments by using a short pre-treatment period and comparing with 31 control areas. On the average, the concentrations of suspended solids were 4–5 mg l^{-1} in the control areas and in the treatment areas before ditch network maintenance. During a period of 1–3 years after maintenance, the concentration of suspended solids in the water leaving ditch network and entering sedimentation ponds averaged 45.8 mg l^{-1}. The magnitude of the increase depended on the area subjected to ditch maintenance as well as the prevailing soil type at the bottom of the ditches. Measured as 1–3 year averages, only half of the sedimentation ponds reduced the concentration of suspended solids. During the first year after ditch network maintenance, the suspended solids concentration in the water entering the sedimentation ponds averaged 71.3 mg l^{-1} and the water leaving the ponds 58.1 mg l^{-1}. In the second year, the corresponding values were 26.8 mg l^{-1} and 21.1 mg l^{-1} and in the third year, 12.8 mg l^{-1} and 12.4 mg l^{-1}, respectively.

Introduction

During the 20th century, forest drainage in Finland has transformed more than five million hectares of wetland areas into productive forest. Drainage activity reached a maximum in 1970 when 295 000 hectares were drained. Since then, the emphasis has turned from the ditching of new areas to the maintenance of existing ditch networks. Ditch cleaning and digging of supplementary ditches are the new forms of ditching activity in Finland. In 1990–94, 74 000 hectares of drained peatlands on the average were treated in such way (Statistical Yearbook of Forestry 1996).

The effects of draining pristine peatlands on runoff water quality have been studied in a number of experiments (Heikurainen *et al.* 1978, Kenttämies 1980, 1981, Seuna 1982, Hynninen and Sepponen 1983, Sallantaus and Pätilä 1983, Kenttämies and Laine 1984, Ahtiainen 1988, 1990, Ahtiainen *et al.* 1988, Ahtiainen and Huttunen 1995, Sallantaus 1986, 1988, 1995). According to many reports, an increased load of suspended solid material (also "suspended material" by Johansson (1983) and "suspended matter" by Ihme *et al.* (1991b)) is probably the most detrimental effect of initial forest drainage affecting watercourses. High loads are usually associated with the actual ditching work (Heikurainen *et al.* 1978), and even afterwards, high loads can occur during snow melt and other periods of high flow. High concentrations of suspended solids during flood flow periods have been attributed to erosion of the main ditches (Hynninen and Sepponen 1983), and to the direct erosion of bare soil surfaces during heavy rains (Heikurainen *et al.* 1978). Long-term increases in the concentrations of suspended solids have been reported by Heikurainen *et al.* (1978) and Kenttämies and Laine (1984).

In forest ditch networks, the discharge from individual drainage ditches (also called field ditches in peat mining areas; Ihme *et al.* 1991c), usually dug 30–50 meters apart, is often small and therefore erosion and the transport of solid material are low. In contrast, large amounts of water are collected by main ditches and they are therefore frequently subject to considerable erosion. The peat layer often being thinner than the depth of the main ditch, erosion of assorted mineral subsoils was a problem when draining pristine peatlands for forestry.

Only a few reports dealing with the effects of maintaining forest ditch networks on runoff water quality are available (Joensuu 1992, 1997, Ahti *et al.* 1995, Manninen 1995). It has been assumed that the changes in the quality of runoff waters in connection with initial ditching are analogous to those occuring when maintaining old ditch networks, but the magnitude of change would be smaller in the case of the latter.

The main principle of reducing the load of suspended solids to watercourses is to decrease the velocity of the water flow, and thereby increase sedimentation or filtration. In connection with ditch network maintenance, the construction of sedimentation ponds (or sedimentation basins; Ihme *et al.* 1991b) of varying size and form, bottom weirs, and various technical solutions of overland flow can be used to reduce the load of suspended solids.

Although sedimentation ponds are quite commonly used nowadays in peatland forestry, their effectiveness in reducing the concentration of suspended solids from discharge waters is not well known. More intensive and thorough studies have been carried out in peat mining areas (Aho and Kantola 1985, Selin and Koskinen 1985, Marja-Aho and Koskinen 1989, Ihme *et al.* 1991a, 1991b, 1991c, 1992, Ihme 1994). Because of the less intensive nature of peatland forestry, the sophisticated techniques used in peat mining areas can seldom be applied directly in connection with ditch network maintenance.

The main purpose of this study was to find out, how much the concentration of suspended solids in drainage water increases with ditch network maintenance. A secondary aim was to determine, how effective sedimentation ponds constructed in practical forestry are in retaining suspended solids. The effect of ditch maintenance on the load of suspended solids as well as the retention capacity of the ponds were related to catchment characteristics.

Material and methods

In order to obtain a large variation in catchment characteristics and to be able to generalize the results, 37 catchments were monitored (Fig. 1). Assuming minor changes in runoff, the main emphasis in the monitoring was concentrated to the quality of runoff water. The concentrations of suspended solids are dealt with in this paper. Control catchments were used in estimating the change in the concentration after treatments.

The pre-treatment monitoring of six pairs (treatment and control) of drained catchments started in 1990, and the remaining catchments in 1991. Some control areas were used for several treatment areas. The data of 37 treatment areas and 31 control areas from 1990 to 1994 are included in this study. Catchment size of the treatment areas varied from 26 to 217 hectares, with a mean of 83 ha (Table 1). The area subject to ditch network maintenance usually comprised most of the drained peatland area within each catchment and averaged 35 hectares.

Ditch network maintenance was performed in the first six catchments in 1991. The remaining areas were treated in 1992 and 1993, i.e. after a calibration period of one or two years. The digging operations were started by construction of the sedimentation pond in the outlet ditch of the catchment, and then continued by ditch cleaning or by supplying complementary ditches.

During the calibration period, water samples were taken from the outlet ditches of each catchment once a week during the snow-free period, usually from late April until the end of October. After construction of the sedimentation pond, samples were taken from the inlet and outlet ditch of the pond. During the digging operation and spring flood, samples were taken twice a week. The samples were taken into 0.5 l polyethene bottles directly from the ditches by sinking the bottle below the water level. Samples were not taken during dry periods with no apparent water flow. The samples were filtered through 1.0 µm glass fiber filters. The filters were dried at 60 C and weighed for suspended solids.

After ditch network maintenance, discharge was monitored using simple 90 V-notch (Thompson) weirs. Before maintenance, the order of magnitude of discharge was estimated by measuring the height of the water level in the ditch at sampling. In 1993, most basins had been fitted with a weir. The ditch water level data was used for omitting the water samples taken during zero-discharge periods.

To estimate sediment accumulation (= original volume of the pond substracted by current volume of the pond) the volume of the ponds was determined at least twice a year and additionally before and after emptying the ponds. The settling volume was estimated from values of water depth measured at intervals of 0.5 metres along transverses two metres apart over the pond. The variation in the water level of the ponds was taken into consideration by levelling. The settling volumes given in Table 1 were observed immediately after pond construction, and comprised ca. 55% of the total volumes of the ponds.

During 1994, peat depth, peat type and the degree of decomposition (von Post's scale; e.g. Paavilainen and Päivänen (1995)) as well as the texture of mineral subsoil were determined from the ditch profiles at 50 m intervals along the main ditch and mostly at 100 m intervals along the drainage ditches. The aim was to make about 50 observation points per catchment.

Simple linear regression was calculated for the pre-treatment period using simultaneous values from each control and treatment area. With the regression equations, the future "untreated" values of suspended solids concentration were predicted for each treatment area. In addition to using average concentrations, the difference between predicted and measured values was used to indicate the change caused by ditch network maintenance.

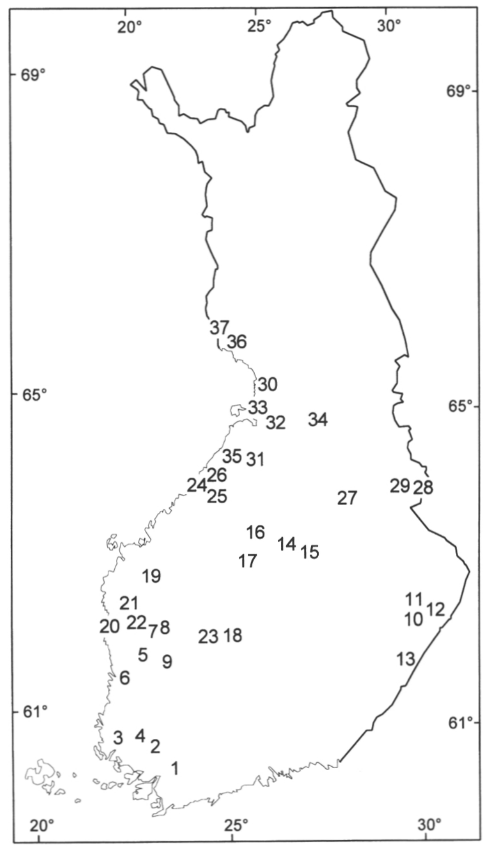

Fig. 1. Location of the study areas in Finland. The numbers indicate the areas listed in Table 1.

Monthly specific loads of suspended solids during the first year after ditch network maintenance were roughly approximated by Eq. 1:

$$LO_{sp} = \frac{kn(q_t Css_t - q_c Css_c)A_{maint}}{A_{catch}} \quad (1)$$

where: LO_{sp} = specific load (kg month^{-1} per treated hectare), $k = 0.0864$; converts mg ha^{-1} s^{-1} to kg ha^{-1} day^{-1}, n = number of days per month, q_t = average monthly runoff from the treatment areas (l s^{-1} ha^{-1}), q_c = average monthly runoff from the control areas (l s^{-1} ha^{-1}), Css_t = average monthly concentration of suspended solids in the water entering the ponds during the first year after maintenance (mg l^{-1}), Css_c = average monthly concentration of suspended solids in the control areas during the first year after maintenance (mg l^{-1}) A_{maint} = ditch maintenance area (ha), A_{catch} = catchment area (ha).

Results

Concentration of suspended material in runoff water after ditch network maintenance

The concentration of suspended solid material in runoff water increased by one order of magnitude after ditch network maintenance (Table 2, Fig. 2a). Even if the change was statistically significant judged by the standard error of mean (Table 2) and the 95% confidence interval of the mean

Table 1. General characteristics of the treatment areas.

No. of catchment	Location of catchment: name of rural district	and coordinates	Catchment area (ha)	Ditch maintenance area (ha)	Reference catchment area (ha)	Pond settling volume (m^3)
1	Pertteli	60 26´N, 23 24´E	63	18	104	84
2	Pöytyä	60 42´N, 22 49´E	34	14	23	40
3	Laitila	60 49´N, 21 53´E	51	28	73	82
4	Yläne	60 49´N, 22 26´E	60	28	171	276
5	Kankaanpää	61 52´N, 22 22´E	41	19	45	105
6	Noormarkku	61 34´N, 21 55´E	136	17	27	116
7	Karvia	62 10´N, 22 39´E	30	30	51	210
8	Karvia	62 11´N, 22 46´E	81	46	51	242
9	Hämeenkyrö	61 41´N, 23 00´E	86	25	109	266
10	Pyhäselkä	62 28´N, 30 04´E	27	27	23	98
11	Pyhäselkä	62 29´N, 30 04´E	57	24	23	70
12	Kiihtelysvaara	62 25´N, 30 18´E	102	21	56	63
13	Punkaharju	61 59´N, 29 40´E	65	25	43	110
14	Pielavesi	63 20´N, 26 48´E	46	31	101	118
15	Pielavesi	63 12´N, 26 58´E	117	43	101	450
16	Pihtipudas	63 29´N, 25 24´E	161	57	106	318
17	Kinnula	63 22´N, 25 12´E	217	23	102	251
18	Keuruu	62 09´N, 24 48´E	57	16	52	98
19	Ylistaro	62 52´N, 22 27´E	149	39	120	424
20	Isojoki	62 11´N, 21 53´E	51	16	41	193
21	Kauhajoki	62 26´N, 21 59´E	148	53	57	435
22	Kauhajoki	62 15´N, 22 20´E	90	70	44	496
23	Ähtäri	62 40´N, 24 09´E	90	43	31	93
24	Kannus	64 03´N, 23 58´E	26	15	83	48
25	Kannus	64 02´N, 23 59´E	66	31	61	90
26	Kalajoki	64 07´N, 23 58´E	98	85	32	158
27	Sotkamo	63 55´N, 28 07´E	101	31	70	387
28	Kuhmo	64 01´N, 30 09´E	65	23	79	193
29	Kuhmo	64 01´N, 29 59´E	119	42	79	171
30	Yli-Ii	65 21´N, 25 40´E	52	42	116	333
31	Vihanti	64 25´N, 25 18´E	37	29	25	128
32	Oulu	64 57´N, 25 46´E	152	40	225	102
33	Oulu	64 59´N, 25 40´E	119	63	225	118
34	Utajärvi	64 55´N, 27 15´E	51	47	30	51
35	Pyhäjoki	64 26´N, 24 35´E	53	50	58	127
36	Keminmaa	65 55´N, 24 55´E	145	59	78	323
37	Tornio	66 00´N, 24 17´E	30	22	26	160

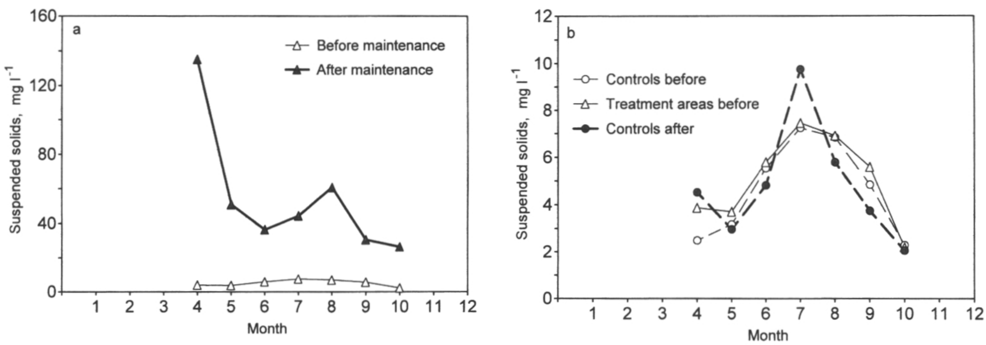

Fig. 2. — a: Mean monthly concentrations of suspended solids in the discharge water before and after ditch network maintenance in 37 catchment areas. — b: Mean monthly concentrations of suspended solids for the control and treatment areas during the pre-treatment period, and for the control areas, also after the treatments. The data of 31 control areas and 37 treatment areas are included.

(Fig. 2a), a large variation in time is revealed by the standard deviation (SD; Table 2). Since the monthly concentrations of the control areas did not differ much from the concentrations of the treatment areas during the pre-treatment period (Table 2), they are presented separately on a larger scale (Fig. 2b). The highest average concentrations of the treatment areas were observed during the first snow melt period following the digging operations (Fig. 3). The variation of the mean concentrations of suspended solids between individual catchments was large (Fig. 4). Obviously, the large standard deviations of Table 2 are due to a large variation both in time and between sites. The median (Md), being much smaller than the mean, as well as the first (Q_1) and the third quartiles (Q_3) show that the values of suspended solids concentration are not normally distributed but strongly

Table 2. Average concentrations of suspended solids ($\bar{x}$, mg l^{-1}) in all runoff samples from 31 control areas and 37 treatment areas in 1990–1994. Number of samples (n), standard deviation (S.D.), standard error of mean ($s_{\bar{x}}$), maximum (x_{max}) values, median (Md), pseudostandard error of median (S.E.) proposed by J. W. Tukey (Dixon *et al.* 1990), first quartile (Q_1), third quartile (Q_3), and the 90% percentile (P_{90}) are included. Because of different years of treatment, the values of the second and the third year after ditch network maintenance include data from a smaller number of catchments than the values from the first year after maintenance.

Period	n	$\bar{x}$	S.D.	$s_{\bar{x}}$	x_{max}	Md	S.E.	Q_1	Q_3	P_{90}
Control areas, pre-tr. period	1123	4.63	6.48	0.193	80.0	2.40	0.173	0.80	6.10	11.1
Control areas, after maint.	1626	4.46	6.40	0.159	55.0	2.10	0.058	0.80	5.33	11.5
Treatm. areas, pre-tr. period	1321	5.04	7.53	0.207	99.2	2.60	0.173	0.80	6.40	12.8
Treatment areas, after maint.										
— first year, entering pond	1189	71.29	251.2	7.29	4914	12.3	0.635	5.50	39.8	139
— first year, leaving pond	1185	58.13	178.6	5.19	3643	11.5	0.433	5.65	37.5	114
— second year, entering pond	848	26.75	77.5	2.66	1248	8.20	0.375	4.20	19.1	49.1
— second year, leaving pond	846	21.09	56.4	1.94	675	8.10	0.375	4.20	16.0	38.3
— third year, entering pond	394	12.84	24.1	1.22	281	7.70	0.548	3.60	13.0	21.9
— third year, leaving pond	394	12.41	23.1	1.16	271	8.10	0.433	3.80	13.1	22.7
— all samples, entering pond	2463	45.82	182.3	3.67	4914	9.60	0.260	4.70	24.0	75.0
— all samples, leaving pond	2457	37.42	130.2	2.63	3643	9.40	0.346	4.80	22.9	66.5

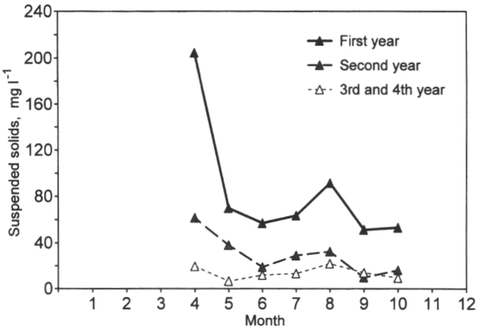

Fig. 3. Mean monthly concentration of suspended solids in different years after ditch network maintenance (37 catchments included). The data from the third and fourth year are merged.

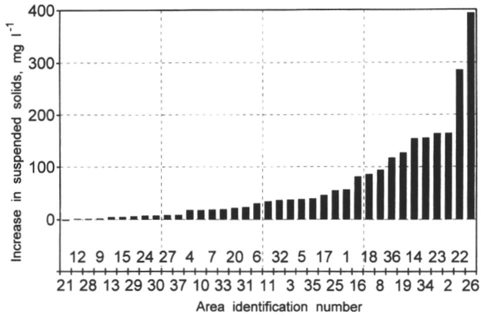

Fig. 4. The increase in the concentration of suspended solids after ditch network maintenance in 37 catchments. Area identification number refers to Fig. 1 and Table 1.

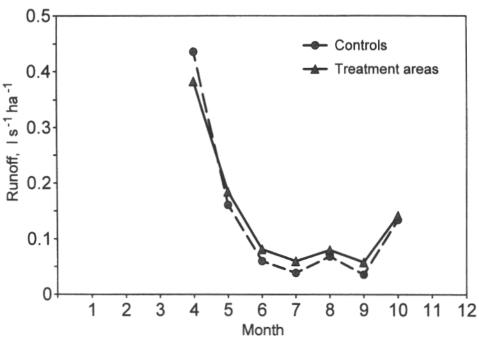

Fig. 5. Mean monthly runoff during the treatment period. The data of 26 control areas and 33 treatment areas are included.

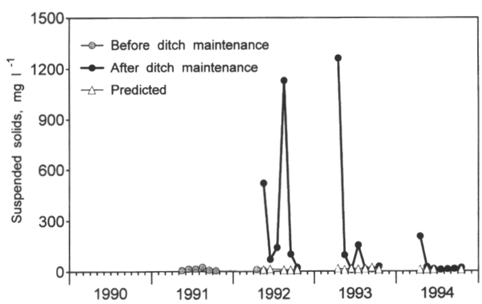

Fig. 6. The effect of ditch maintenance on the suspended solid concentration in the Kalajoki catchment 26 with sand as the predominant subsoil.

dominated by low concentrations.

In the control areas, the highest concentrations of suspended solids were observed in July and August (Fig. 2b). In general, the effect of ditch network maintenance clearly decreased after the first year, but was still conspicious during the second year. Considering that the digging operations were performed in June in almost half of the areas, the mean concentration of suspended solids has remained unexpectedly low during that month (Fig. 3).

The monthly average runoff pattern of the treatment areas did not differ much from the control areas after treatment (Fig. 5). The mean runoff from the end of April to the end of October for 33 of the treatment areas during the whole post-treatment period corresponded to 193 mm of precipitation.

Examples on three main types of effects of ditch network maintenance are displayed in Figs. 6–8. In areas with coarse-textured subsoils, increased concentrations of suspended solids were detected during the digging operation or immediately after it, and during high flow periods in general (Fig. 6). In catchments with fine-textured (clay and silt) subsoils, the concentrations of suspended solid materials were almost constantly higher after ditch maintenance (Fig. 7). In areas dominated by poorly decomposed deep peat or with compact till as subsoil, the increase in the concentration of suspended solids was usually small (Fig. 8).

There was a statistically significant, positive correlation between the concentration of suspended solids in the runoff water entering the ponds and the total length of maintained ditches.

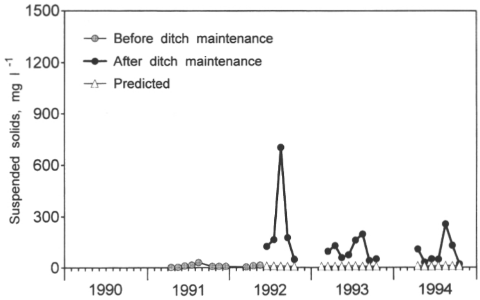

Fig. 7. The effect of ditch maintenance on the suspended solids load in the Pöytyä catchment 2 with clay as the predominant subsoil.

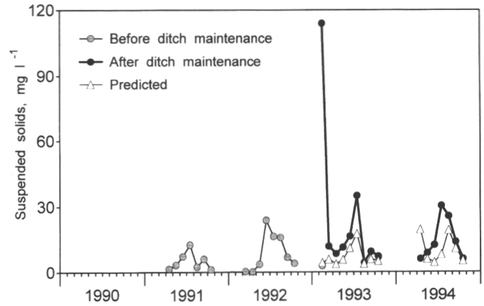

Fig. 8. The effect of ditch maintenance on the suspended solids load in the Yläne catchment 4 with undecomposed peat as the predominant soil type.

Also, the concentration of suspended solids was connected to the subsoil chararcteristics. Combining length of ditches maintained and subsoil texture into four independent variables, the following regression equation can be derived:

$$Css = 26.1L_{ft} + 8.73L_{mt} + 4.98L_{ct} + 2.97L_p - 14.4 \quad (R^2 = 0.49, F = 7.678) \qquad (2)$$

where: Css = mean concentration of suspended solids after ditch network maintenance (mg l^{-1}), L_{ft} = total length of the ditches dug into fine-textured subsoil within each catchment, km ($p < 0.001$), L_{mt} = total length of the ditches dug into medium-textured subsoil, km ($p < 0.001$), L_{ct} = total length of the ditches dug into coarse-textured subsoil, km ($p = 0.042$), L_p = total length of the ditches dug into deep peat, km ($p = 0.212$).

Catchment size, average discharge and slope of main ditch were less significant than L_p.

The effect of ditch network maintenance on load of suspended solids

The concentration of suspended solids was considerably higher during the first year after ditch network maintenance than during the following years (Fig. 3). Using average monthly values of runoff and the first year concentrations of suspended solids, rough approximations of suspended matter loads and specific loads were obtained (Table 3).

Table 3. Approximated monthly loads (LO) of suspended solids during the first year after ditch network maintenance (t = treatment, c = control). Specific load (LO_{sp}) refers to the increase in load per treated hectare. Css = average monthly concentration of suspended solids during the first year after treatment.

Month	Treatment areas				Control areas		
	q_t (l s^{-1}ha^{-1})	Css_t (mg l^{-1})	LO_t (kg ha^{-1})	LO_{sp} (kg ha^{-1})	q_c (l s^{-1}ha^{-1})	Css_c (mg l^{-1})	LO_c (kg ha^{-1})
April	0.382	204.6	67.5*	156.5	0.436	4.02	1.51
May	0.184	69.8	34.4	78.1	0.161	3.39	1.46
June	0.081	57.0	12.0	26.3	0.059	5.90	0.90
July	0.059	63.4	10.0	21.4	0.038	9.63	0.98
August	0.079	91.4	19.3	43.7	0.068	4.75	0.87
September	0.057	51.3	7.6	17.4	0.035	2.88	0.26
October	0.141	53.2	20.1	45.9	0.134	2.11	0.76
Total			170.9	389.3			6.74

* 10 last days of April included

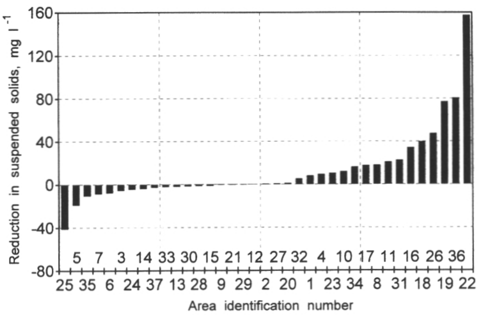

Fig. 9. The distribution of the reduction in the concentration of suspended solids by the sedimentation ponds (37 areas included). Area identification number refers to Fig. 1 and Table 1.

The effects of sedimentation ponds

Reduction in the concentration of suspended solids

During the first year after maintenance the concentrations of suspended solids were reduced by the sedimentation pond in 20 areas and increased in 17 areas (Fig. 9). Averaged over the 37 catchment means of the treated areas, the concentration decreased from 68.7 mg l^{-1} to 56.1 mg l^{-1} (18.3%). For the 17 ponds showing an increase, the concentration increased from 30.0 to 36.6 mg l^{-1} on the average. In the 20 areas, where the concentration was reduced by the pond, the average concentration decreased from 101.5 to 72.6 mg l^{-1} (28.4%).

For 18 catchments out of the 37, the mean concentration of suspended solids in the water entering the pond exceeded 40 mg l^{-1} during the first year after maintenance. Within these 18 catchments, with an average input concentration of 123.2 mg l^{-1}, the pond reduced the concentration of suspended solids by 24 mg l^{-1} on the average. However, the variation within this group of catchments was large: from an increase in suspended solids concentration by 41.2 mg l^{-1} to a reduction of 157 mg l^{-1}.

The efficiency of some ponds was poor during the first year due to the collapse of the pond walls. During the second year, the pond walls stabilized and the sedimentation efficiency increased again (Fig. 10). In most catchments with medium- and coarse-textured subsoils, the sedimentation ponds functioned satisfactorily (Fig. 11).

In catchments with fine-textured subsoils, especially clays, the effect of the ponds was negligible. In the Pöytyä study area (area 2) practically no retention of suspended solids was observed during the whole monitoring period (Fig. 12).

Sediment accumulation

The annual average accumulation of solid material correlated positively with the area of ditch network maintenance, length of ditches dug, pond volume, and concentration of suspended solid material in runoff water entering the pond. Also, the proportion of medium-textured and coarse subsoils within the area correlated positively with the annual accumulation of sediment. Although catchment area, slope of main ditch, and degree of peat decomposition were positively correlated with the annual accumulation of sediment, the coefficients were not significant. The area of ditch network maintenance and pond volume explained more than 60% of the variation in annual accumulation of solid material in the ponds (Eq. 3). When using the concentration of suspended solids in the water entering the pond (C_{in}) and the maximum runoff of the catchment (q_{max}) as independent variables instead of the area of ditch maintenance, more than 80% of the variation could be explained (Eq. 4). The term with the highest F-value in Eq. 4 was C_{in}.

$$V_{acc} = -71.3 + 0.258V_{pond} + 1.999A_{maint} \quad (3)$$
$$(n = 37, R^2 = 0.633, F = 29.3^{***})$$

$$V_{acc} = -66.1 + 0.266V_{pond} + 0.849C_{in} + 0.204q_{max} \quad (4)$$
$$(n = 26, R^2 = 0.803, F = 29.8^{***})$$

where: V_{acc} = annual sediment accumulation, average for several years (m^3 yr^{-1}), V_{pond} = original volume of pond (m^3), A_{maint} = area of ditch maintenance (ha), C_{in} = concentration of suspended solids entering the pond (mg l^{-1}), q_{max} = maximum runoff (l s^{-1} ha^{-1}).

In about 25% of the ponds, only a few cubic

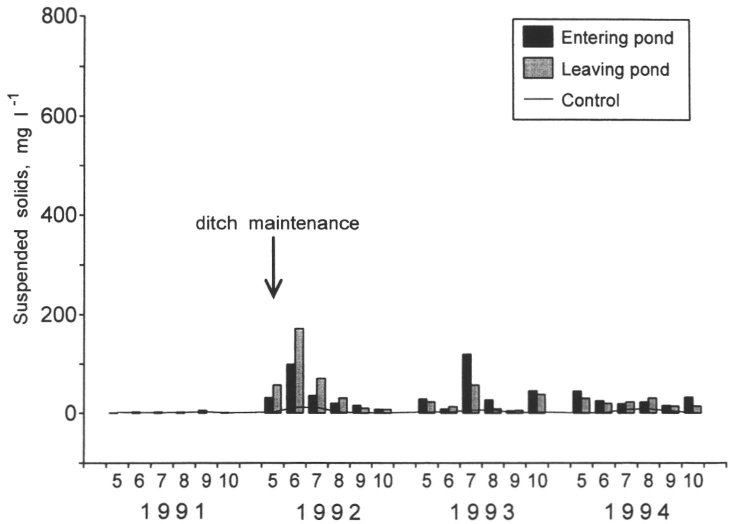

Fig. 10. The effect of the sedimentation pond on the concentration of suspended solids in one of the Karvia catchments (Nr. 8).

meters of sediment were accumulated per year. In contrast, about 20% of the ponds were half filled with sediments after one year and, depending on the year, some ponds were completely filled and required emptying. The pond inlet and outlet difference in suspended solid concentration correlated positively ($r = 0.7$) with the amount of sediment that had accumulated in the ponds annually. Because runoff was measured only during the snow-free period, it was not possible to estimate annual accumulation of sediment on the basis of the difference between inlet and outlet samples. Probably, part of the coarse-textured material that was transported along the bottom of the ditches was not fully represented in the samples.

Discussion

Since ditch network maintenance does not influence runoff, especially the runoff peaks much (Ahti *et al.* 1995, Manninen 1995), the changes observed in the suspended solids load were mainly due to changes in concentration.

Because of the large number of catchments in our study, we regard the average concentrations presented in Table 2 as representative for ditch network maintenance in Finland. Even if high concentrations occurred during the actual digging operation, which usually lasted several weeks, these periods of high concentration were probably so short that they were not to be seen in the averaged data as clearly as the high concentrations during the first spring maximum flow after ditch network maintenance.

The increase in the concentration of suspended solids after ditch network maintenance found in this study resembled the values reported by Ahtiainen *et al. (1990)* for initial ditching. The concentrations of suspended solids prior to ditch network maintenance were close to those reported for pristine peatlands by both Ahtiainen *et al.* (1990) and Seuna (1982). The discharge of suspended solids from a catchment of 5 600 hectares in northern Finland, of which 17% was drained for forestry, increased by 62–105 kg ha^{-1} yr^{-1}, which corresponds to a specific load of 365–618 kg ha^{-1} yr^{-1} (Seuna 1982). In a separate experiment in the same area, the discharge of suspended solids was as much as 2 300 kg ha^{-1} during the first spring flood after ditching.

Hynninen and Sepponen (1983) studied the effects of initial ditching in brooks and tributories of river Kiiminkijoki in northern Ostrobothnia. High concentrations and loads of suspended solids were detected in part of the brooks, but in most cases, the changes were short-lived. In the case of Syväoja brook, with a catchment of 11.6 km^2 out of which 41% was drained in 1973, high concentrations of suspended solids were still observed

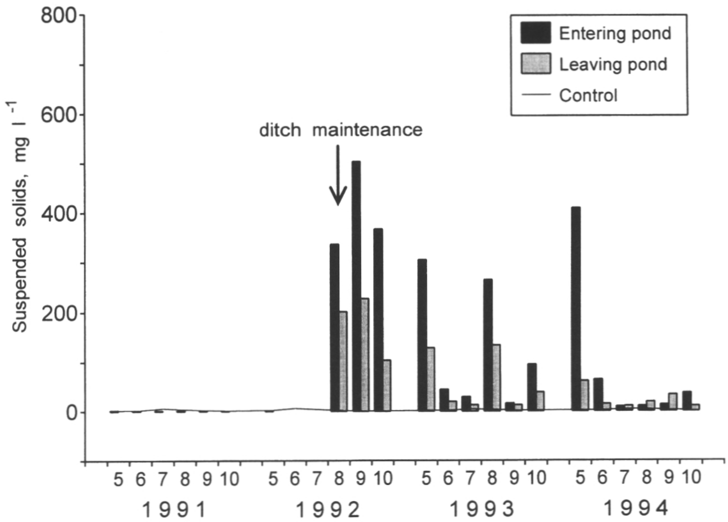

Fig. 11. The effect of the sedimentation pond on the concentration of suspended solids in one of the Kauhajoki catchments (Nr. 22), typical of medium- and coarse texture subsoils.

during the rainy summer of 1974: the mean concentration was as high as 395 mg l^{-1}. Even higher concentrations between 378 and 647 mg l^{-1} were observed during the first spring flow after ditching in 1973 (Hynninen and Sepponen 1983).

As a whole, the changes in the concentration of suspended solids in runoff water after ditch network maintenance appear to be of the same order of magnitude and duration as after ditching of pristine peatlands. The average concentrations of suspended solids from peat mining areas appear to be of the same order of magnitude as in runoff waters from peatland forests during the first year after ditch network maintenance (Selin and Koskinen 1985, Ihme *et al.* 1991a, 1991b, 1991c, Ihme 1994). However, in peatland forests the high concentrations of suspended solids are likely to decline in a few years, as in peat mining areas, high concentrations will probably occur as long as the mining activity continues. It is probable, also, that a greater part of the suspended material is of mineral origin in the runoff water coming from peatland forests than from peat mining areas.

Even if the arithmethic means of suspended solids concentrations instead of averages weighted by discharge (e.g. Ahtiainen *et al.* 1990) were used in this study, both the concentrations and the approximated loads of suspended solids for the control areas appear to be of the same order of magnitude as prior to ditching in the catchments of Ahtiainen *et al.* (1990). Consequently, we consider the rough load estimates in Table 3 to be of the right order of magnitude. The effect of using mean concentrations weighted by discharge for each observation remains to be demonstrated by a detailed analysis of individual catchments.

The efficiency of sedimentation ponds in reducing the concentration of suspended solids in sites used for peat mining (Selin and Koskinen 1985, Ihme *et al.* 1991b) have varied both between sites and in time. Ihme *et al.* (1991b) reported a variation range from an annual increase of 216% to an annual reduction of 73% by different sedimentation ponds in different years in Kurunneva peat mining area, Central Finland.

In Ireland, the effectiveness of sedimentation ponds to retain suspended solid materials originating from peat mining areas has been monitored for a considerable period of time (Hannon and Coffey 1984, Wynne 1992). According to the results of these studies, correctly sized sedimentation ponds are capable of retaining over 90% of the solid material entering the pond. As in this study, the retaining capacity of the ponds appears to increase with increasing concentration of suspended solids. At low concentrations, especially in areas with undecomposed peat, the concentration of suspended solid material in the water leaving the pond was greater than that of the water entering it.

In this study, ca. 60% of the annual accumula-

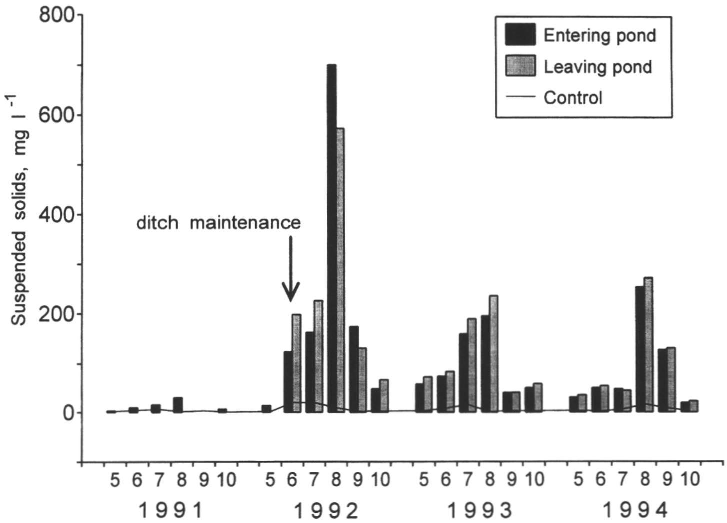

Fig. 12. The effect of the sedimentation pond on the concentration of suspended solids in the Pöytyä catchment 2 with predominant subsoil of clay.

tion of suspended solids could be explained by pond volume and area of ditch network maintenance. The significant positive correlation found between average annual accumulation of sediments and pond size indicates that our ponds were too small on the average.

Since the maximum discharge is largely determined by basin area and erosion is determined by the discharge, it was expected that the suspended solids concentration after ditch network maintenance would be closely related to total catchment area. However, ditch network maintenance area was more closely related to both the concentration of suspended solids in the runoff water and to sediment accumulation than the total area of the catchment. This might be connected to some other catchment characteristics influencing maximum discharge than catchment area. It might also imply the existence of errors in determining the catchment area or measuring runoff.

Because the peat layer subsides after ditching, and due to enhanced decomposition, the future risks of erosion may even be greater in connection with ditch network maintenance than with the initial operation. This further emphasizes the importance of water protection.

We have shown how much the load of suspended solids caused by ditch network maintenance can be reduced by using sedimentation ponds sized and constructed according to the guidelines for water protection applied in Finland in 1992. In areas with fine-textured subsoils, methods of water protection other than sedimentation ponds should be used.

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PAPER IV

IV

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Long-term effects of maintaining ditch networks on runoff water quality

Kunnostusojituksen pitkän ajan vaikutus valumaveden ominaisuuksiin

Samuli Joensuu, Erkki Ahti & Martti Vuollekoski

Samuli Joensuu, Forestry Development Centre Tapio, Soidinkuja 4, 00700 Helsinki (email: samuli.joensuu@tapio.mailnet.fi)
Erkki Ahti & Martti Vuollekoski, The Finnish Forest Research Institute, Vantaa Research Centre, P.O. Box 18, 01301 Vantaa

The effects of ditch network maintenance on runoff water quality was studied at 23 sites in different parts of Finland. The study included a calibration period of 1–3 years before maintaining the ditches and six years after. No observations were made during winter. After ditch maintenance, which involves either cleaning of old ditches and/or digging of complementary new ditches, the concentrations of suspended solids in runoff water increased immediately. At sites where the ditches cut into fine-textured subsoil, runoff continued to have increased suspended solids concentrations throughout the whole six-year period. However, if the bottom of the ditches consisted of coarse mineral subsoil or peat, the annual mean concentration of suspended solids returned to pre-treatment levels in 5–6 years. Concentrations of mineral nitrogen, especially NH_4-N, increased while the concentration of organic nitrogen decreased after ditch network maintenance. These changes persisted for the whole six-year period. The overall effect of these changes resulted in a slight lowering of total dissolved nitrogen concentrations. With the exception of a few sites, runoff water pH increased after ditch maintenance and remained high during the 6-year period. Concentrations of DOC decreased at all sites after ditch maintenance and was still at a low level after six years. Concentrations of base cations (Ca, Mg, K, Na) increased significantly after ditch maintenance and were still high after six years. High concentrations of Al and Fe immediately after the digging operations were observed in a few sites. Concentration of total dissolved P did not change much and tended to decrease rather than increase.

Key words: ditch maintenance, peatland, runoff quality

INTRODUCTION

Some 6% of the total phosphorus (P) load and 5% of the nitrogen (N) load to the water courses are estimated to be caused by forestry in Finland (Ympäristöministeriö 1998). The major part of this loading results from peatland drainage and site preparations in connection with forest regeneration, which make the soil susceptible to erosion (Maa- ja metsätalousministeriö 1987, Kenttämies & Saukkonen 1996).

Most of the research into the environmental effects of peatland drainage in the 1970's and 80's focused on hydrology (Heikurainen et al. 1978, Seuna 1982, Ahti 1987). The study of the effects of forestry on stream water quality started with the Nurmes project in 1978, in which the loading of headwater streams as a result of forest drainage was studied (Ahtiainen 1988, 1990, Ahtiainen & Huttunen 1995, 1999a). By continuing the monitoring of runoff water quality in the Nurmes basins until today, valuable information on the long-term effects of cuttings and first ditching has been obtained (Ahtiainen & Huttunen 1999a and b, Kenttämies & Vilhunen 1999, Alatalo 1999). Even if forest drainage has not been as extensive in Sweden as in Finland, the environmental effects of forest drainage have been studied for almost as long (Bergqvist et al. 1984, Lundin 1982, 1984, 1992, and 1996).

About 18% of the Finnish forest area consists of drained wetlands, i.e. peatlands and paludified mineral soil sites which have been drained for forestry by open ditches (Finnish Statistical... 1999). After a change in the Forest Improvement Act in 1987 (Yksityismetsätalouden säädökset 1987), the maintenance of the forest ditch networks increased considerably. In the 1990's, about 75 000 hectares of ditch networks were annually maintained, either through the cleaning of old ditches and/or by digging complementary new ditches between the old ones. According to the National Forestry Program accepted by the Finnish government in 1999, the area of ditch network maintenance should increase to 110 000 hectares annually by the year 2010 (Maa- ja metsätalousministeriö 1999). This program includes an assessment of the environmental impacts of ditch network maintenance (Hilden et al. 1999). However, the environmental effects of ditch network maintenance have not been subject to much research so far.

The first study to investigate the effects of ditch maintenance on runoff started in northern Ostrobothnia in 1983 (Ahti et al. 1995a). After a calibration period of six years, runoff and water quality were monitored for five years after ditch cleaning in two small catchments. Kortelainen et al. (1997, 1998, 1999) has compared the water quality from forested catchments dominated by peatlands with upland catchments by using long-term data from a series of catchments described by Seuna (1983). Lahermo et al. (1996) published maps on the water quality of small streams in Finland and also tried to find connections between basin characteristics and runoff water quality.

In this study, the effects of ditch maintenance on runoff water quality during six years after treatment are reported. The study is based the set of catchments described by Ahti et al. (1995b, 1999) and Joensuu et al. (1999a, 1999b). The magnitude and duration of the changes in runoff water quality are related to basin characteristics. The most important water quality parameters from the viewpoint of water protection, i.e. nitrogen (N), dissolved organic carbon (DOC), suspended solid material (SS), phosphorus (P), iron (Fe), aluminium (Al), and pH are concentrated on.

MATERIAL AND METHODS

Study areas

Runoff from 23 catchment areas was monitored in 1990–1998, 1–2 years before and 6 years after ditch network maintenance (Fig 1, Table 1). The catchments were selected in 1995 from the 37 catchments used by Ahti et al. (1995b) and Joensuu et al. (1999a) for studying the effects of sedimentation ponds on the retention of suspended solids after ditch network maintenance. The selection of the 23 catchments was based on geographic distribution and subsoil texture.

The maintenance operations were performed in 1991–1993 according to the original planning performed by the local forestry centres. In addition to the data from the calibration period, data from control catchments were used when estimating the changes in water quality.

The selected catchments varied in area between 26 and 217 ha (Table 1), with a mean of 71 ha. On average, 34 ha in each catchment were subject to ditch maintenance, corresponding to 8.5 km (2.5–14.4 km) of ditches. The catchments included on average 24 ha of upland mineral soil sites and 13 ha of peatlands which were either pristine or left outside the maintenance operation. Most of the ditch maintenance involved cleaning of old ditches; 1.8–18.4 km per catchment. On average, 3 km of complementary new ditches were dug per catchment. The mean ditch density after maintenance was 250 m ha^{-1}.

The tree stands and the site types were characterised by applying the TASO forestry planning system (Kinnunen & Ärölä 1993). The volume of tree stands averaged across all catchments was 65 $m^3 ha^{-1}$ (variation range 15–190 $m^3 ha^{-1}$). The corresponding characteristic for the peatland forest stands only was 58 $m^3 ha^{-1}$.

The soil characteristics of the ditch maintenance areas were inventoried systematically along the ditches in 1994. At a minimum of 50 sampling points per site, the depths of the ditch and the peat layer were measured, and additionally subsoil texture, peat type and peat decomposition (von Post) were subjectively determined for the different soil layers visible in the ditch profile. Soil characteristics for the bottom layer of the ditches, i.e. the part of the ditch which is most closely in contact with runoff water, are given in Table 1.

Water sampling

Runoff water sampling was started during the snowmelt period in spring and continued once a week until the freezing period in late autumn. No water samples were taken during winter. The total number of water samples was 3867 (between 108 and 244 samples per catchment). The samples were taken directly into 500 ml polyethene bottles from flowing water in the middle of the main ditch. The samples were sent to the Central Laboratory of the Finnish Forest Research Institute (FFRI), and were stored for analysis at 5 °C.

Electric conductivity and pH were determined using the standard methods of FFRI (Jarva & Tervahauta 1993). The samples were filtered and the fibre glass filters (pore size 1.2 µm) were weighed for suspended solids after drying at 60 °C (Joensuu *et al.* 1999a). Concentrations of total dissolved phosphorus, sodium, potassium, magnesium, calcium, aluminium and iron were determined from the filtrates using a plasma emission spectrophotometer (ICP/AES, ARL 3580). Total dissolved nitrogen (N_{tot}), ammonium (NH_4), and nitrate (NO_3) were determined spectrophotometrically with a Tecaton FIA-analyser. The concentration of dissolved organic matter was determined as $KMnO_4$-consumption in 1990–91 and as dissolved organic carbon (DOC) with a Shimadzu carbon analyser from 1992 onwards. For 750 samples, the determination was done by

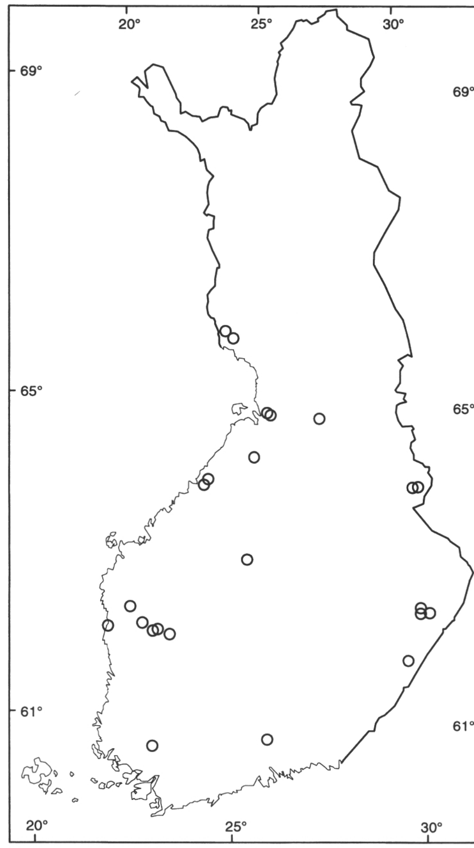

Fig. 1. Location of catchment sites

Kuva 1. Tutkimusalueiden sijainti

both methods and the values of $KMnO_4$-consumption were converted to DOC by using the following equation (Joensuu et al. 2001):

$$C_{DOC} = 0.164\ C_{KMnO4} + 3.2 \quad (r^2 = 0.978) \qquad (1)$$

The catchment characteristics and runoff water quality are described by using basic statistics: distributions, means, medians, and standard errors. The duration of the effects as well as the relationships between water quality and basin characteristics were examined using the Mann-Whitney U-test, which is suitable for skewed distributions, and correlation (Pearson) and regression (SYSTAT 1996) statistics.

Table 1. Some basin characteristics. [1]Soil texture and type at bottom of new or maintained ditches, in km of ditch. Fine = mineral soil dominated by clay and/or fine loam, medium = mineral soil dominated by coarse loam and/or silt, coarse = mineral soil dominated by sand and/or gravel.

Taulukko 1. Valuma-alueiden ominaisuuksia. [1]Kivennäismaalajiteluokkien ja turpeen osuus kunnostusojien pohjassa, km ojaa. Hieno= saven tai henon hiesun vallitsema kivennäismaa, keskikarkea = karkean hiesun tai hiedan vallitsema kivennäismaa, karkea = hiekan tai soran vallitsema kivennäismaa.

Catchment *Valuma-alue*	Location *Sijainti*	Total area *Val.al. pinta-ala* ha	Treated area *Kunn.oj. ala* ha	Fertile peatlands *Reheviä soita* %	Poor peatlands *Karuja soita* %	[1] Bottom Soil texture and type — *Pohjamaan tyyppi*: Fine *Hieno*	Medium *Keskik.*	Coarse *Karkea*	Peat *Turve*	*Total Yht.*
						km of ditch — *km ojaa*				
Pöytyä	60°42'N, 22°49'E	33.3	13.9	60.0	0.0	3.92	0.00	0.28	0.00	4.2
Karvia	62°10'N, 22°39'E	31.3	29.2	0.0	100.0	0.00	3.75	0.85	0.00	4.6
Karvia	62°11'N, 22°46'E	79.0	17.4	0.0	100.0	0.00	11.08	3.12	0.00	14.2
Kihniö	62°08'N, 23°07'E	42.9	19.5	2.0	98.0	0.00	0.00	0.00	3.97	4.0
Orimattila	60°51'N, 25°51'E	75.2	35.7	14.3	85.7	2.05	0.00	0.00	6.38	8.4
Pyhäselkä	62°28'N, 30°04'E	24.8	24.8	0.0	61.5	0.00	0.79	0.00	1.71	2.5
Pyhäselkä	62°29'N, 30°04'E	59.8	25.8	35.0	5.0	0.00	1.96	0.00	1.54	3.5
Kiihtelysvaara	62°25'N, 30°18'E	100.2	25.3	12.0	62.0	0.00	0.47	2.24	3.19	5.9
Punkaharju	61°59'N, 29°40'E	64.1	24.4	12.2	68.3	0.00	0.31	1.38	4.61	6.3
Kinnula	63°22'N, 25°12'E	217.0	22.6	22.1	17.3	1.45	0.26	0.00	4.88	6.6
Isojoki	62°11'N, 21°53'E	48.8	14.9	0.0	61.4	0.29	3.05	0.57	0.19	4.1
Kauhajoki	62°26'N, 21°59'E	87.6	51.2	0.0	77.8	0.00	0.00	7.60	1.20	8.8
Kauhajoki	62°15'N, 22°20'E	89.1	69.3	0.0	20.9	0.00	13.51	3.47	2.32	19.3
Kannus	64°03'N, 23°58'E	26.2	15.5	9.1	40.9	2.36	0.16	0.31	2.67	5.5
Kalajoki	64°07'N, 23°58'E	97.0	83.1	41.7	0.0	0.28	2.17	8.11	3.24	13.8
Kuhmo	64°01'N, 30°09'E	63.4	22.9	21.6	41.2	0.00	0.79	0.00	5.91	6.7
Kuhmo	64°01'N, 29°59'E	119.9	45.1	0.0	78.4	0.00	2.35	0.00	8.55	10.9
Vihanti	64°25'N, 25°18'E	38.0	29.8	17.0	38.3	0.14	0.00	2.44	3.93	6.5
Oulu	64°57'N, 25°46'E	147.8	33.7	36.9	2.9	0.90	0.36	1.62	5.92	8.8
Oulu	64°59'N, 25°40'E	122.6	57.7	0.0	9.8	0.00	0.55	12.63	0.83	14.0
Utajärvi	64°55'N, 27°15'E	48.6	45.7	4.0	26.0	1.44	12.38	0.58	0.00	14.4
Keminmaa	65°55'N, 24°55'E	146.0	54.6	80.0	0.0	0.00	1.25	5.00	6.25	12.5
Tornio	66°00'N, 24°17'E	30.0	23.4	94.0	0.0	0.00	2.21	0.14	4.55	6.9

RESULTS

Nitrogen

The mean annual concentration of N_{tot} during the calibration period was 0.78 mg l^{-1}. After ditch network maintenance the annual N_{tot} concentrations varied between 0.59 and 0.67 mg l^{-1}. The basin mean varied from 0.32 to 1.30 before and from 0.31 to 1.16 after the treatment. The slight decrease in N_{tot}-concentration found during the first three years (Ahti et al. 1999) was still seen in the sixth year after the maintenance (Fig. 2).

Before treatment, catchment mean concentration of NH_4–N varied between 0.001 and 0.142, and after ditch maintenance between 0.004 and 0.405 mg l^{-1}.

Mean NO_3-N concentrations were lover for the treatment sites compared to the control sites during the pre-treatment period and the difference was significant (Fig. 2). The effect of ditch maintenance on NO_3 concentrations was therefore difficult to ascertain.

Mean annual concentrations of mineral nitrogen (NO_3-N + NH_4-N) generally remained at a raised level in the treatment catchments during the whole six-year period compared to the control catchments. The catchment mean annual N_{min} concentration varied between 0.15 and 0.19 mg l^{-1} after the treatments, and between 0.05 and 0.08 mg l^{-1} in the control sites. The concentration of organic nitrogen (N_{tot}–N_{min}) decreased significantly after ditch network maintenance and remained low during the whole six-year period (Fig 2).

Phosphorus

During the pre-treatment period, catchment mean annual concentrations of dissolved total phosphorus varied between 0.027 and 0.458 mg l^{-1}. In the post-treatment period, the corresponding variation was from 0.031 to 0.143 mg l^{-1}. The distinct decrease in the maximum value was due to usually high concentrations before maintenance at one site, Ruskeesuo, and the marked decrease after treatment.

In the first year of the post-treatment period, P concentrations tended to increase in the runoff water from both treated and control sites. In the control sites this increase exceeded the corresponding increase in the treated sites (Ahti et al. 1999). During the five last years of the post-treatment period, P concentrations were lower than during the calibration period. Phosphorus concentrations in the control sites were also lover during the treatment period than in the calibration period and, consequently, concentrations from the control and treatment sites did not show any statistically significant difference. In the sixth year of the post-treatment period, P concentrations from the treatment sites were, however, lower than in the control areas and the difference was significant ($p<0.01$) (Fig. 2).

During the pre-treatment period, the monthly concentrations of total dissolved phosphorus were positively correlated with organic nitrogen and DOC concentrations (Table 2). In the post-treatment period, the P concentrations were also positively correlated with the concentrations of sodium, potassium, magnesium, aluminium and iron.

Suspended solids

Mean annual concentrations of suspended solids increased considerably after ditch maintenance. The increase was most conspicuous in the first year after maintenance, particularly in the following spring (Joensuu et al. 1999a, Ahti et al. 1999), but could still be clearly seen in the sixth year after treatment (Fig. 2).

The type of subsoil explained 62% of the variation in the concentration of suspended solids (Joensuu et al. 1999a):

$$C_{ss} = -11.2 + 19.6L_{ft} + 7.52L_{mt} + 3.82L_{ct} + 1.49L_{p} \quad (2)$$
$$(r^2 = 0.62,\ F = 9.84,\ p<0.001)$$

where C_{ss} = concentration of suspended solids, mg l^{-1}, L_{ft} = total length of the ditches dug into fine-textured subsoil within each catchment, km ($p<0.01$), L_{mt} = total length of the ditches dug into medium-textured subsoil, km ($p<0.001$), L_{ct} = total length of the ditches dug into coarse-textured subsoil, km ($p<0.05$) and L_p = total length of the ditches dug into deep peat, km.

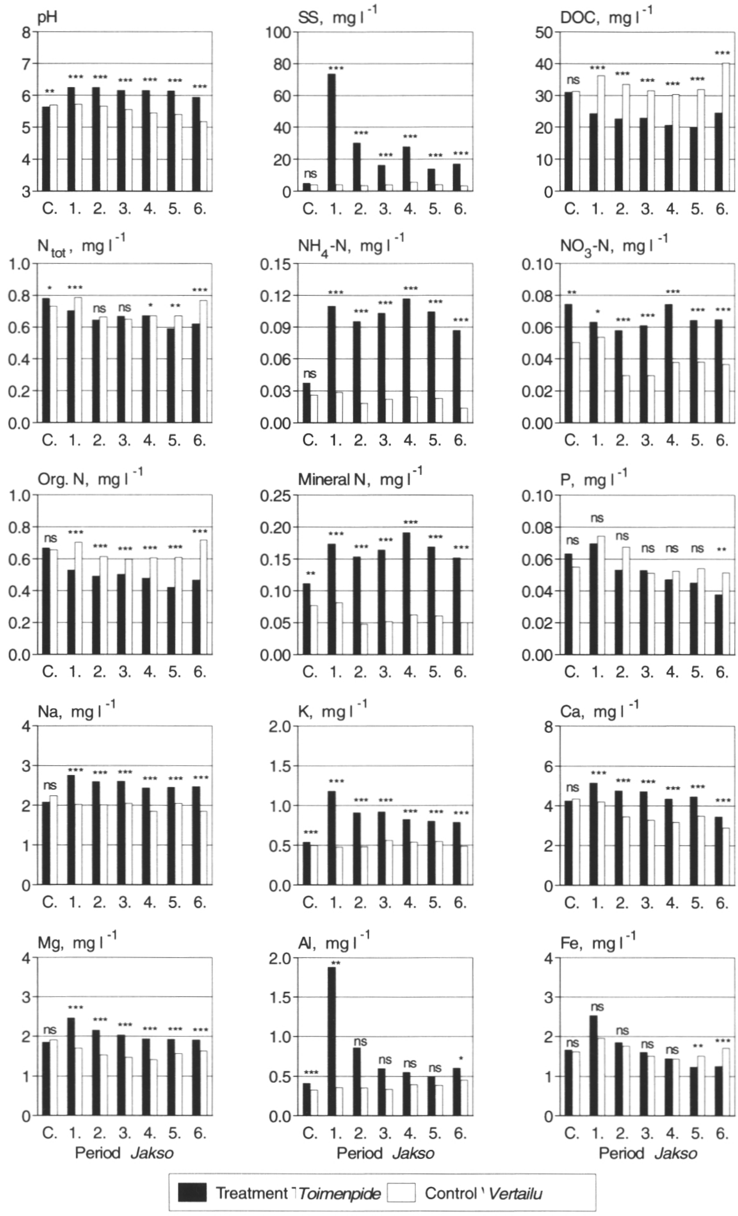

Fig. 2. Mean pH, electric conducitivity (EC) and concentrations of suspended solids (SS), DOC, N_{tot}, NH_4-N, NO_3-N, organic N, mineral N, total dissolved P, Na, K, Ca, Mg, Al and Fe in treated areas and control areas before ditch network maintenance and in six years after it. Significant differences between control and treatment (Mann-Whitney U-test): ns = nonsignificant, * = p< 0.05, ** = p < 0.01, *** = p < 0.001. C.= calibration period, 1.–6. = years after treatment.

*Kuva 2. pH:n ja sähkönjohtavuuden (EC) sekä kiintoaine- (SS), N_{tot}-, NH_4-N-, NO_3-N-, orgaanisen typen, mineraalitypen, P-, Na-, K-, Ca-, Mg-, Al- ja Fe-pitoisuuksien keskiarvot vertailualueilla ja toimenpidealueilla ennen kunnostusojitusta ja kuutena vuotena kunnostusojituksen jälkeen. Vertailu- ja toimenpidealueiden merkitsevät erot: ns = ei merkitsevä * = p<0.05, ** = p<0.01, *** = p<0.001. C. = kalibrointijakso, 1.–6. = kunnostusojituksen jälkeiset vuodet.*

DOC and pH

Pre-treatment mean annual DOC concentrations were 31.0 mg l^{-1} and 23.3 mg l^{-1} during the 6-year post-treatment period. Catchment mean values varied between 12.0 and 50.2 mg l^{-1} before ditch network maintenance and between 11.2 and 58.0 mg l^{-1} afterwards. During the calibration period, DOC concentrations from the treatment and control sites did not differ from each other. Post-treatment mean annual concentrations of DOC were lower for the treatment sites (Fig. 2) and the difference was significant ($p<0.001$).

During the pre-treatment period, DOC concentrations correlated positively with organic nitrogen, iron and phosphorus, and negatively with pH. After ditch maintenance DOC concentrations were still correlated with organic nitrogen, phosphorus and pH, but not with iron (Table 2).

Differences in pH between the treatment sites (mean 5.63) and control sites (mean 5.69) was small during the pre-treatment period (Fig. 2). Immediately after ditch maintenance, however, the mean pH value increased by 0.6 pH units. In the sixth year after ditch maintenance, pH continued to be 0.3 units higher than during the pre-

Table 2. Pearson correlation coefficients between monthly values of some water quality parameters before (a; n=225) and after (b; n=942) ditch network maintenance. SS = suspended solids, EC = electric conductivity. Statistically significant values ($p<0.05$) are given in boldface.

Taulukko 2. Eräiden vedenlaatumuuttujien kuukausikeskiarvojen väliset Pearsonin korrelaatiokertoimet ennen (a) kunnostusojitusta ja sen jälkeen (b). SS = kiintoaine, EC = sähkönjohtavuus. Merkitsevät erot (p < 0.05) lihavoidulla tekstillä.

a)	Ntot	NH_4-N	NO_3-N	Org. N	Min..N	DOC	C/N	SS	EC	pH	Na	K	Ca	Mg	Al	Fe
Ntot	1.000															
NH_4-N	**0.473**	1.000														
NO_3-N	**0.415**	0.036	1.000													
Org. N	**0.891**	**0.286**	0.017	1.000												
Min. N	**0.585**	**0.518**	**0.874**	0.154	1.000											
DOC	**0.642**	0.196	-0.181	**0.815**	-0.059	1.000										
C/N	**-0.450**	-0.177	-0.201	**-0.404**	**-0.258**	0.103	1.000									
SS	**0.445**	**0.562**	0.100	**0.341**	**0.359**	0.111	**-0.363**	1.000								
EC	**0.491**	0.147	**0.258**	**0.434**	**0.293**	**0.248**	**-0.317**	0.191	1.000							
pH	0.202	0.196	**0.315**	0.043	**0.365**	**-0.335**	**-0.495**	**0.440**	**0.373**	1.000						
Na	**0.443**	**0.379**	**0.301**	**0.293**	**0.442**	-0.018	**-0.459**	**0.493**	**0.439**	**0.685**	1.000					
K	**0.339**	0.106	**0.360**	0.212	**0.359**	-0.116	**-0.376**	0.216	0.156	**0.406**	**0.540**	1.000				
Ca	**0.491**	0.119	**0.373**	**0.387**	**0.377**	0.034	**-0.484**	**0.292**	**0.701**	**0.685**	**0.494**	**0.404**	1.000			
Mg	**0.472**	0.119	**0.353**	**0.374**	**0.360**	0.021	**-0.481**	**0.339**	**0.699**	**0.701**	**0.556**	**0.416**	**0.972**	1.000		
Al	-0.208	**-0.262**	-0.191	-0.091	**-0.291**	0.082	**0.256**	-0.157	**-0.263**	**-0.602**	**-0.395**	-0.215	**-0.459**	**-0.371**	1.000	
Fe	**0.574**	**0.649**	-0.034	**0.539**	**0.287**	**0.395**	**-0.285**	**0.510**	0.161	**0.246**	**0.350**	0.105	**0.267**	**0.261**	-0.157	1.000
P	**0.395**	0.099	-0.018	**0.464**	0.033	**0.442**	-0.110	0.136	**0.292**	-0.111	0.027	0.098	0.097	0.084	0.025	0.180

b)	Ntot	NH_4-N	NO_3-N	Org. N	Min..N	DOC	C/N	SS	EC	pH	Na	K	Ca	Mg	Al	Fe
Ntot	1.000															
NH_4-N	**0.605**	1.000														
NO_3-N	**0.423**	**0.200**	1.000													
Org. N	**0.755**	0.068	-0.037	1.000												
Min. N	**0.680**	**0.848**	**0.686**	0.033	1.000											
DOC	**0.535**	-0.040	**-0.159**	**0.832**	-0.115	1.000										
C/N	**-0.138**	-0.043	0.024	**-0.168**	-0.022	**0.140**	1.000									
SS	0.006	0.009	0.025	-0.011	0.021	-0.081	-0.047	1.000								
EC	**0.244**	0.106	**0.255**	**0.142**	**0.214**	0.012	**-0.163**	-0.074	1.000							
pH	-0.015	**0.160**	**0.182**	**-0.213**	**0.215**	**-0.481**	**-0.248**	0.002	**0.414**	1.000						
Na	**0.300**	**0.241**	**0.232**	**0.143**	**0.299**	**-0.125**	**-0.234**	0.047	**0.499**	**0.598**	1.000					
K	**0.152**	0.043	**0.247**	0.060	**0.164**	**-0.131**	**-0.178**	**0.323**	**0.239**	**0.237**	**0.479**	1.000				
Ca	**0.161**	0.085	**0.205**	0.067	**0.170**	-0.065	**-0.152**	-0.059	**0.889**	**0.473**	**0.441**	**0.225**	1.000			
Mg	**0.188**	0.033	**0.281**	0.100	**0.174**	-0.080	**-0.198**	0.043	**0.873**	**0.538**	**0.530**	**0.464**	**0.896**	1.000		
Al	0.020	-0.096	**0.128**	0.029	-0.003	-0.055	-0.082	**0.381**	-0.048	-0.019	**0.204**	**0.895**	-0.051	**0.221**	1.000	
Fe	**0.285**	**0.143**	**0.208**	**0.195**	**0.217**	0.033	**-0.126**	**0.353**	0.089	**0.183**	**0.451**	**0.891**	0.083	**0.321**	**0.890**	1.000
P	0.351	-0.042	0.029	**0.493**	-0.016	**0.353**	**-0.120**	**0.217**	**0.144**	0.017	**0.361**	**0.568**	0.107	**0.232**	**0.524**	**0.637**

treatment period (Fig. 2). Concurrent with these changes at the treated sites, the mean annual pH in the control sites decreased from 5.69 to 5.18.

Base cations

Concentrations of sodium, potassium, calcium and magnesium in runoff water were higher after ditch maintenance (Fig. 2). The differences between treatment and control sites were statistically significant ($p<0.001$) throughout the six-year post-treatment period, and the increase could still be clearly seen during the sixth year after treatment for all four base cations. The concentrations of all base cations correlated positively with each other and with the pH-values, both before and after treatment (Table 2).

After having been only slightly higher (0.54 mg l^{-1}) than in the control areas (0.49 mg l^{-1}) during the pre-treatment period, the mean annual concentration of K varied between 0.79 and 1.18 mg l^{-1} during the post-treatment period. The mean annual K concentration in the control sites during post-treatment period varied between 0.48 and 0.56 mg l^{-1}.

Iron and aluminium

The mean concentrations of Fe and Al showed elevated values after treatment especially the first year, but later the influence of ditch maintenance was less (Fig. 2). However, the median annual concentrations of Fe and Al in the treated sites did not increase after ditch maintenance. This was because the increases in Fe and especially Al concentrations were usually short-lived and occurred in only a few of the 23 sites. Such peak concentrations were particularly strong in the southernmost Pöytyä site, which was eutrophic and had a thin peat layer over a fine textured subsoil. The mean annual Al concentration of the first year after ditch maintenance at this site was 22.2 mg l^{-1} and that of Fe 15.6 mg l^{-1}, with individual samples during the digging operation exceeding 160 mg Al l^{-1} and 120 mg Fe l^{-1}. Elevated mean concentrations also occurred during the second, third and sixth year after treatment.

DISCUSSION

In earlier studies dealing with drainage of pristine peatlands, long-term changes in the concentration of suspended solids in runoff have been reported (Kenttämies 1987, Ahtiainen & Huttunen 1999a, Alatalo 1999). At a site studied by Manninen (1995, 1998, 1999), the effects of ditch maintenance could still be seen in the concentration of suspended solids 3–5 years after the digging operations.

The increased loads of phosphorus resulting from forest drainage have been connected with an increase in the load of suspended solids (Kenttämies 1980, 1981, Kenttämies & Vilhunen 1999, Ahtiainen & Huttunen 1999a and b). In our material the concentrations of total P, which does not include particulate phosphorus, were not substantially changed by ditch maintenance. Furthermore, P concentrations were only weakly correlated to subsoil texture, but were positively correlated to DOC concentrations. It can therefore be concluded that a great part of the dissolved P in our data is organic phosphorus.

The concentration of suspended solids increased conspicuously after ditch network maintenance. This change was most probably connected with a corresponding increase in the concentration of particulate P. However, as particulate P is largely unavailable for algae even in the runoff waters from agricultural soils (Ekholm 1998), it is probably much less available in forest waters which contain mineral particles originating from the unfertilised bottom surfaces of the ditches. Consequently, it might be more relevant to use total dissolved phosphorus to estimate the effects of ditch network maintenance.

Runoff waters from organic soils have been reported to contain more N than waters from mineral soils (Saukkonen & Kortelainen 1995, Kortelainen et al. 1997, Kortelainen & Saukkonen1998, Kortelainen et al. 1999). Ahtiainen & Huttunen (1999a) and Manninen (1999) both reported raised concentrations of total nitrogen after first ditching and ditch maintenance. However, in our study, there was a slight decrease in concentrations of total N, which persisted throughout the six-year observation period. In addition to the effect of different methods of chemical analysis being used between the studies, the discrepancy can be explained by natural variation (Joensuu et al. 2001).

Total N consists of organic and inorganic forms. In our data, organic N was the dominant form. However, the concentration of mineral nitrogen clearly increased after ditch maintenance while the concentrations of organic N decreased. The decrease in organic N was reflected in the clear decrease in DOC concentrations which they were strongly correlated to.

The significant increase in pH after ditch maintenance persisted throughout the six-year observation period. This change is probably related to the drop in the water table depth. After treatment some of ditch water is derived from deeper soil layers, which have higher pH and concentrations of exchangeable base cations. In the Docksmyren peatland area in Sweden, the pH of soil water was 0.5–1.0 units higher in deep peat layers than in surface peat, and correspondingly, the concentrations of the base cations were higher and the concentrations of organic N and DOC lower in deeper peat layers (Lundin 1996).

Most of the changes in runoff water quality caused by ditch network maintenance were still clearly to be seen six years after treatment. It is therefore important to continue monitoring in order to determine when the effects of ditch maintenance diminish to control levels.

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TIIVISTELMÄ

Kunnostusojituksen pitkän ajan vaikutus valumaveden ominaisuuksiin

Laajamittainen metsäojitusalueiden kunnostaminen alkoi Suomessa vuoden 1987 jälkeen. 1990-luvulla ojitusalueita kunnostettiin vuosittain keskimäärin 75 000 hehtaaria. Vuosina 2000–2010 toteutettavan Kansallisen metsäohjelman mukaan vuosittain tullaan kunnostamaan 110 000 hehtaaria ojitusalueita.

Tutkimuksessa tarkastellaan kunnostusojituksen vaikutusta valumaveden kiintoaine- ja ravinnepitoisuuksiin pitkällä aikavälillä kaivun jälkeen 23: lla eri puolilla Suomea (Kuva 1) sijaitsevilla käytännön kunnostusojitusalueilla. Havaintoaluejoukko on osa vuonna 1990 aloitettua Metsätalouden vesistöhaitat ja niiden torjunta (METVE) -projektiin liittyvää laskeutusaltaiden toimivuutta käsittelevää tutkimusalueverkkoa (Ahti et al. 1995b). Tämän tutkimuksen tarkastelujakso käsitti yhdestä kolmeen vuotta kestävän kalibrointivaiheen ja kunnostusojituksen jälkeisen kuuden vuoden veden laadun seurannan sulan maan kaudella.

Tutkimusaluepari muodostui toimenpidealueesta ja vertailualueesta, joilla tehtiin perustamisvaiheessa ojien kunnon kartoitus sekä puuston ja kasvupaikkojen inventointi. Kunnostusojituksen jälkeen tehdyssä ojakohtaisessa inventoinnissa mitattiin systemaattisella otannalla kunnostettujen ojien syvyydet sekä kartoitettiin silmävaraisesti ojaprofiilin kivennäismaa- ja turvelajit sekä mitattiin maalajien kerrospaksuudet ojaprofiilissa. Vesinäytteitä analysoitiin kaikkiaan 3867 kpl. Näytteet otettiin yleensä viikoittain ja kevättulvien aikana kaksi kertaa viikossa. Näytteenottokausi jatkui lumentuloon ja ojien jäätymiseen saakka.

Vesinäytteet suodatettiin lasikuitupaperisuodattimen läpi (huokoskoko 1,2 mm). Suodatetuista näytteistä määritettiin liuennut kokonaisfosfori, natrium, kalium, magnesium, kalsium, alumiini ja rauta ARL 3580 ICP plasma emissio spektrofotometrillä. Kokonais-, ammonium- ja nitraattityppi määritettiin spektrofotometrisesti Tecaton FIA-analysaattorilla. Veteen liuenneen orgaanisen aineksen pitoisuus määritettiin vuosina 1990–1991 kaliumpermanganaatin kulutuksena SFS 3036 menetelmällä ja vuoden 1992 alusta orgaanisen hiilen määränä (DOC) Shimazu-hiilianalysaattorilla. Kaliumpermanganaatin kulutuksena mitatut arvot muunnettiin liuenneen orgaanisen hiilen arvoiksi. Lisäksi näytteistä

määritettiin pH-arvo ja sähkönjohtavuus.

Kunnostusojituksen jälkeen kiintoaineen, ammoniumtypen ja emäskationien pitoisuudet sekä valumaveden pH-arvo kasvoivat. Orgaanisen typen ja liuenneen orgaanisen hiilen pitoisuudet sen sijaan laskivat. Totaalitypen ja totaalifosforin pitoisuudet eivät oleellisesti muuttuneet kunnostusojituksen vaikutuksesta. Vaikutukset olivat yleensä pitkäaikaisia. Vielä kuuden vuoden kuluttua kunnostusojituksesta muutokset olivat selvästi havaittavissa. Korkeita rauta- ja alumiinipitoisuuden huippuja esiintyi muutamilla alueilla kaivun aikana ja välittömästi kunnostusojituksen jälkeen.

Valumaveden ominaisuuksien seurantaa tullaan jatkamaan yhdeksällä tämän tutkimuksen alueista. Tavoitteena on näillä alueilla vähintään 10 vuoden aikasarjat.

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