Natural resources and
bioeconomy
studies 25/2018

WAMBAF – Good Practices for Ditch Network Maintenance to Protect Water Quality in the Baltic Sea Region

Leena Finér, Dovilė Čiuldienė, Zane Libieté, Elve Lode,
Mika Nieminen, Edward Pierzgalski, Eva Ring, Lars Strand
and Ulf Sikström

Luke
NATURAL RESOURCES
INSTITUTE FINLAND

Natural resources and bioeconomy studies 25/2018

WAMBAF – Good Practices for Ditch Network Maintenance to Protect Water Quality in the Baltic Sea Region

Leena Finér, Dovilė Čiuldienė, Zane Lībieté, Elve Lode, Mika Nieminen, Edward Pierzgalski, Eva Ring, Lars Strand and Ulf Sikström

Natural Resources Institute Finland, Helsinki 2018

Production of this report was financed by the European Regional Development Fund.

Finér, L., Čiuldienė, D, Lībieté, Z., Lode, E., Nieminen, M., Pierzgalski, E., Ring, E., Strand, L. and Sikström, U. 2018. WAMBAF – Good Practices for Ditch Network Maintenance to Protect Water Quality in the Baltic Sea Region. Natural resources and bioeconomy studies 25/2018. Natural Resources Institute Finland, Helsinki. 35 p.

ISBN 978-952-326-575-2 (Print)
ISBN 978-952-326-576-9 (Online)
ISSN 2342-7647 (Print)
ISSN 2342-7639 (Online)
URN http://urn.fi/URN:ISBN:978-952-326-576-9

Authors: Leena Finér, Dovilė Čiuldienė, Zane Lībieté, Elve Lode, Mika Nieminen, Edward Pierzgalski, Eva Ring, Lars Strand and Ulf Sikström
Publisher: Natural Resources Institute Finland (Luke), Helsinki 2018
Year of publication: 2018
Cover photo: Photo Lars Högbom
Printing house and publishing sales: Juvenes Print, http://luke.juvenesprint.fi

Summary

Leena Finér[1], Dovilė Čiuldienė[2], Zane Lībieté[3], Elve Lode[4], Mika Nieminen[5], Edward Pierzgalski[6], Eva Ring[7], Lars Strand[8], Ulf Sikström[7]

[1]Natural Resource Institute Finland (Luke), Yliopistokatu 6, FI-80100 Joensuu, Finland, leena.finer@luke.fi
[2]Lithuanian Centre for Agriculture and Forestry (LRCAF), Liepų str. 1, LT-53101 Girionys, Kaunas distr., Lithuania, d.ciuldiene@gmail.com
[3]Latvian State Forest Research Institute (Silava), Rīgas iela 111, Salaspils, LV-2169 Latvia, zane.libiete@silava.lv
[4]Tallinn University Institute of Ecology, Uus-Sadama 5, 10120 Tallinn, Estonia, elve.lode@gmail.com,
[5]Natural Resource Institute Finland (Luke), Latokartanonkaari 9, FI-00790 Helsinki, Finland, mika.nieminen@luke.fi
[6]Forest Research Institute (IBL), Sekocin Stary ul. Braci Lesnej nr 3, 05-090 Raszyn, Poland, E.Pierzgalski@ibles.waw.pl
[7]The Forestry Research Institute of Sweden (Skogforsk), Uppsala Science Park, SE-751 83 Uppsala, Sweden, eva.ring@skogforsk.se, ulf.sikstrom@skogforsk.se,
[8]Skogsstyrelsen, Skånes distrikt, Bangårdsgatan 6, Box 6, 243 21 Höör, Sweden, lars.strand@skogssyrelsen.se

These good practices for ditch network maintenance (DNM) were prepared within the WAMBAF project (Water Management in Baltic Forests); project period from 1.3.2016 to 28.2.2019, which was initiated to tackle the problems relating to water quality after forestry operations in the Baltic Sea Region. The main aim of these good practices for DNM to protect water quality is to give background information and an overview of available water protection measures that can be used in conjunction with DNM on peatlands and paludified mineral soils to reduce the export of suspended solids (SS), nitrogen (N), phosphorus (P), and methyl mercury (MeHg) within the Baltic Sea Region. The good practices for DNM also deal with the suitability of DNM for peatlands and paludified soils by presenting tradeoffs between its benefits and detrimental impacts on water quality, as well as the planning of water protection measures to avoid or reduce transport of SS and nutrients to the receiving water bodies. In this document, we (i) describe the aims of DNM and give an overview of the existing scientific knowledge of the effects of DNM on tree growth, soil properties, hydrology and soil hydraulics, and drainage water quality, (ii) present factors for assessing the suitability of DNM, and (iii) present the principles of DNM planning and water protection for the reduction of the exports of SS, N and P to the water bodies in the Baltic Sea Region. The key messages of the different chapters are:

Aim and impacts of ditch network maintenance:

- DNM is carried out to sustain or increase forest growth.
- DNM may increase the soil bearing capability and therefore improve the trafficability of peatland forest sites.
- DNM has a minor impact on annual runoff, but it may increase peak flows.
- DNM generally increases export of suspended solids.

Assessment of the suitability of ditch network maintenance:

- When establishing the suitability of DNM:
    - Attention must be paid to the characteristics of the receiving water body and the site-specific water conditions in the DNM area such as groundwater inflow from confined aquifres and suscebtibility to flooding during the growing season.
    - The effect of first-time drainage, ditch drainage capacity and tree stand volume must be evaluated.
    - Other factors to consider: tree species composition, understory vegetation, soil characteristics and climate.

Planning ditch network maintenance and water protection:

- Water protection should be considered in the planning stage of the DNM.
- Water protection structures are constructed before any DNM.
- Avoiding erosion is the utmost importance.
- Ditch sections showing signs of erosion are left uncleaned.
- Dam structures are used to control water velocity.
- Sedimentation ponds are used to retain SS.
- Wetland buffers are effective in retaining both SS and dissolved nutrients.

Monitoring the impacts of water protection:

- Monitoring the efficiency of water protection measures is useful for promoting water protection in DNM.
- Visual inspection of all water protection structures in DNM sites is organized by the operators/field personnel and aim at good quality protection. Water quality monitoring networks are organized by administrators and are viable tools for developing water protection in DNM.

Training for ditch network maintenance:

- Education in water protection is required for work on certified forest properties.
- Continuous education and training are needed for promoting good quality DNM.

Preface

These good practices for ditch network maintenance were prepared within the WAMBAF project (Water Management in Baltic Forests), project period from 1.3.2016 to 28.2.2019, which was initiated to tackle the problems relating to water quality after forestry operations in the Baltic Sea Region. WAMBAF focuses on three main factors that significantly impact water quality: riparian forests, forest drainage and beaver activity. The main motivator for the project is to support the implementation of EU Water Framework Directive (WFD) (2000/60/EC). Within the good practices special emphasis is placed on the reduction of transport of suspended solids, nutrients and mercury to water bodies from forest areas, but also on increasing the water retention capacity in forests to mitigate the potential water shortage caused by a changing climate.

Keywords: Baltic Sea Region, ditch cleaning, forest drainage, guidelines, nutrient leaching, suspended solids, water protection

Contents

1. Introduction

Water-related infrastructures regulating water conditions in forests can serve several functions. Above all, they are used to regulate soil water conditions to enable satisfactory tree growth. Such regulation may involve lowering of the groundwater level (GWL) using drainage ditches. In periods with lower rainfall and symptoms of drought, drainage ditches equipped with technical installations can be used to raise the GWL. Water-related infrastructure in forest catchments can also be used to increase water retention capacity through restoration of old reservoirs or by the construction of new ones as well as to improve water quality in downstream water bodies through the restoration of wetlands.

In the Baltic Sea Region, the objectives of water management vary. In the northern countries (Estonia, Finland, Latvia and Sweden), drainage for sustained or increased tree growth is the primary focus, but in Poland, for example, water retention is of greater importance. However, the basic prerequisite for designing the drainage systems is to take into account both environmental and economic aspects.

We compiled existing documented knowledge, primarily from peer-reviewed scientific publications, but also from other relevant reports and national guidelines (Piirainen et al. 2017). Most of the scientific knowledge is based on Finnish studies. In addition, some methods and measures used in operational forestry in the Baltic Sea Region countries are described even though their implementation is not based on scientific studies. It should be kept in mind that since the water management knowledge presented in the good practices for DNM has been studied to varying extents – and often only as case studies – the generalization of the documented results and the presentation of firm conclusions and recommendations are not always possible.

In this document, we (i) describe the aims of DNM and give an overview of the existing knowledge of the effects of DNM on tree growth, soil properties, hydrology and soil hydraulics, and drainage water quality, (ii) present factors for assessing the suitability of DNM, and (iii) present the principles of DNM planning and water protection for reduction of the export of SS, N and P to the water bodies in the Baltic Sea Region.

We hope that these good practices for DNM may serve as an inspiration in the daily work of forest and environment managers, administrators and policy makers, and other stakeholders who are involved in developing drainage system management, but also be a basis for revision of policies and legislation regulating DNM operations in the Baltic Sea Region.

Finally, we would like to highlight that this compilation focuses on the benefits and suitability of DNM, and the methods for reducing SS, N and P transport to receiving water bodies. When implementing DNM operations in different countries, the national legislation and the forest certification systems need to be followed. Special consideration may be required for ecologically and recreationally valuable or protected areas. Moreover, other values, such as the potential influence on biological diversity, must be taken into consideration. These issues, mentioned above, are not dealt with in these good practices for DNM. Last, but not least, it must be understood that DNM must be profitable from the economic point of view either for the forest owner or, for the society as a whole, but most preferably to both of them. This issue is also shortly commented in these good practices for DNM. For the terminology used in these good practices for DNM, we refer to the earlier report prepared in the WAMBAF project (Piirainen et al. 2017).

2. Aim and impacts of ditch network maintenance

2.1. Aim of ditch network maintenance

The primary aim of DNM in already drained and established forest stands is to sustain or increase tree growth by improving the water transportation capacity of the ditch network. When reforesting drained forest sites, the aim of DNM is to facilitate the establishment and development of the new stand by lowering the GWL, which has been temporarily raised because of significant reduction in evapotranspiration. Overall, DNM should sustain or increase forest growth and the investment should be financially justifiable. However, DNM may be a harmful forestry operation from water quality and other environment protection perspectives (Joensuu et al. 2002, Nieminen et al. 2010). Thus, it is important to minimize the number of DNM operations and the negative impacts on water quality each operation.

2.2. Tree growth

Water is an important growth factor in every phase of the development for all plants (Päivanen and Hånell 2012). Extreme conditions, both drought and flood reduce plant growth and different tree species have differing tolerances to extreme soil water conditions. Among the native and commercially utilized species in the Baltic Sea Region forests, downy birch (*Betula pubescens*) is the least sensitive to waterlogging and Norway spruce (*Picea abies*) the most sensitive (Niinemets and Valladares 2006). Trees are especially sensitive to waterlogging at the end of the growing season, when the soil is still warm and microbial activity high (Kozlowski 1982, Päivänen 1984 cited in: Päivänen and Hånell 2012). In spring, waterlogging may disturb the initiation of tree growth (Huikari and Paarlahti 1967 cited in: Päivänen and Hånell 2012, Zālītis 2012).

The purpose of carrying DNM is to lower GWL (Ahti and Päivänen 1997), improve soil aeration and thus, sustain or increase tree growth (Lauhanen and Ahti 2001, Ahti 2005, Hökkä and Kojola 2001, 2003). DNM has been shown to lower GWL by 5–10 cm on drained boreal peatlands over the growing season (Ahti and Päivänen 1997, Päivänen and Sarkkola 2000). In sites with a shallow peat layer and sandy subsoil, however, the lowering of GWL may be much greater (Koivusalo et al. 2008). On the other hand, minor changes may occur in mature stands where GWL is already low before DNM. In such stands, it is the evapotranspiration of the tree stand, rather than the drainage capacity of the ditch network, that controls GWL. In these areas, where GWL is already low before DNM, the increase in tree growth may be negligible after DNM. A GWL lower than 35–40 cm from the soil surface during late growing season suggests that there may be no need for DNM, as GWL is already sufficiently low for adequate tree growth (cf. Sikström and Hökkä 2016, Zālītis 2012). Correspondingly, if the GWL is constantly above that level during the late growing season, it indicates the need for DNM (Sarkkola et al. 2012). With the exception of the depth of the GWL, the length of the waterlogging episodes influences tree growth (Vompersky et al. 1997, Toth and Gillard 1988), and the GWL and soil water conditions can be highly variable within a drained site depending on drainage intensity and site and stand properties.

Quantitative data from drained peatlands in Finland suggest that DNM increases stand growth by 0.5–1.8 m^3 ha^{-1} yr^{-1} in Scots pine stands with standing stem volumes of ca. 20–150 m^3 ha^{-1}, and the growth increase lasts for 15–20 years (Sikström and Hökkä 2016). The response is higher and lasts longer in the north than in the south. For the tree species other than Scots pine, there is very little information available. Data from Latvia, however, suggest a stable growth increase after DNM both in Scots pine and Norway spruce stands of different age classes; DNM was reported to have increased tree growth by 10–13% in middle-aged and pre-mature spruce stands (Lazdins, unpublished data). Also, data from a Swedish survey study indicated growth increase in Scots pine and Norway spruce stands after DNM, except for in stands with high stand volume (Sikström, unpublished data).

By 2011 in Estonia, DNM had been carried out on about 23% of the drained forest land. It was estimated that first-time drainage and DNM have increased volume increment by up to 2 m^3 ha^{-1} yr^1, totaling about 1 Mm^3 yr^{-1} in Estonian forests (Estonian Strategy 2011). However, the volume increment induced by first-time drainage and DNM on drained wet soils in Estonia has been reported to vary over a very large range, from 0 to 1.5 m^3 ha^{-1} yr^{-1} (tree age varying between 32 and 75 years, period 1958–1967), depending on ditch density, the age and type of the trees, and the site type (Ots 2015).

There are no data for the effects of DNM on regeneration success at the stand establishment phase and at the early development of the regeneration (Photo 1). However, in drained peatlands soil moisture conditions may be either too dry or too moist for seed germination, and the growth of established seedlings is impaired by high GWL (Saarinen et al. 2013). According to Zālītis (2006), the height growth of spruce seedlings, subjected to waterlogging in July and August, was reduced by 50% over the next two growing seasons.

Photo 1. Clear-cut forest area with the GWL close to the soil surface in eastern central Sweden (100 km north of Stockholm). The ditch cleaning and mounding with an excavator was conducted in March 2015, about a month after the harvest, and one year before the photo was taken. Photo Ulf Sikström.

DNM can be profitable in terms of return of investment and net present value, but not always (Aarnio et al. 1997, Hytönen and Aarnio 1998, Ahtikoski et al. 2008, 2012, Ots 2015). It has been found in Finland that complementary ditching, and a combination of complementary ditching and ditch cleaning, are usually more profitable than ditch cleaning alone. Good-to-medium site quality and high temperature sums generally increase the profitability of DNM (Aarnio et al. 1997, Ahtikoski et al. 2008). Low-stocked, northern located stands are examples where DNM is not always profitable even if pre-DNM drainage conditions are poor (Ahtikoski et al. 2012). The time between DNM and the next harvest following DNM is also an important factor affecting the profitability of DNM.

2.3. Soil properties

Peat soils have low bulk densities and, therefore, their bearing capacities are low so heavy forest machines can cause compaction and rutting (Uusitalo and Ala-Ilomäki 2013, Cambi et al. 2015). Wet peat has a lower bearing capacity than dry peat (Cambi et al. 2015). Lowering of GWL by DNM reduces soil water content by increasing runoff and enhancing tree growth and thus evapotranspiration, primarily in quite low-stocked stand types (see section 3.4). The improved conditions for tree growth after lowering of GWL also increase the growth of tree root systems, which significantly improves the bearing capacity of peat soils (Uusitalo and Ala-Ilomäki 2013, Uusitalo et al. 2015).

2.4. Hydrology and hydraulics

Theoretically, discharge should increase immediately after DNM as the GWL in the ditches is lowered and gravity increases water flow into ditches. Soon after DNM, a new equilibrium will be achieved between the water level in the ditches and the water level in the drained catchment (Koivusalo et al. 2008). Another factor that could increase runoff after DNM is the degeneration of the understory vegetation due to the lowering of GWL, and subsequent decrease of evapotranspiration. However, empirical studies, have generally reported only minor changes rather than clear increases in annual runoff during the first 1–2 years after DNM (e.g. Joensuu et al. 1999, Åström et al. 2002). Hansen et al. (2013) estimated an increase of up to 10 mm in runoff during the first month after DNM and, thereafter, no differences between drained and control catchments. The results of a simulation study using the hydrological FEMMA model indicated that runoff increases by 10–25% during the first year after DNM in climatic conditions, corresponding to long-term average conditions in Finland (Nieminen et al. 2017).

There are probably many reasons behind small changes in runoff after DNM, but one factor could be the changed peat properties induced by the first-time drainage. After such drainage, peat subsides and becomes more decomposed, and its hydraulic properties change. Most of the peat subsidence takes place within the first few years after the first-time drainage (Lukkala 1949 cited in: Laine et al. 2006). Peat subsidence and decomposition increase its bulk density, which is higher in drained peatlands (106–160 kg m^{-3}) than in pristine mires (Minkkinen and Laine 1998 cited in: Laine et al. 2006). Peat with high bulk density has a high water retention capacity and low hydraulic conductivity (Boelter 1964, Päivänen 1973 cited in: Laine et al. 2006). Thus, the lowering of the GWL and transportation of water into ditches is more difficult after DNM than after first-time drainage.

DNM may have minor effects on annual runoff volumes, but it may induce significant changes in runoff dynamics. For example, peak runoffs may increase after DNM and thereby increase the erosive force of water and transportation of SS (Tuukkanen et al. 2016). Many studies report increases in low flow rates after first-time drainage (Ahti 1987, Sirin et al. 1991, Johnson 1998, Prévost et al. 1999), but, to the best of our knowledge, the effect of DNM on low flow rates has not been studied.

2.5. Water quality

The effects of DNM on water quality have been studied in about 50 catchments in Finland. The results show that DNM significantly increases the transport of SS, whereas the transport of total dissolved N does not change much (Joensuu 2002, Joensuu et al. 1999, Nieminen et al. 2010). The results related to P transport are more variable, as the P transport has been measured as either remaining unchanged (Åström et al. 2002), increasing (Nieminen et al. 2010), or decreasing slightly after DNM (Joensuu et al. 2006, 2012). The impacts of DNM on SS transport are the highest 1–3 years after the operation, and thereafter the transport rates return to their initial levels in 10–20 years, except in very fine-textured soils (Finér et al. 2010, Palviainen et al. 2014, Lībieté 2015). The export of total mercury (Hg) and methyl mercury (MeHg) was studied in two DNM areas in Sweden (Hansen et al. 2013). In one of those areas, the concentrations for both total Hg and MeHg increased in the drainage water over the first few days after the digging, yielding an excess Hg export corresponding to 15% of the annual transport of this first year. In the other area, no excess Hg export could be detected. It was shown in one other study that soil disturbance can increase the risk for Hg leaching (Porvari et al. 2003, Eklöf et al. 2016).

The leaching of N and P may increase eutrophication of downstream surface waters (e.g. Smith 2013), and numerous adverse effects have been documented due to increased SS concentrations and export (e.g. Fairchild et al. 1987, Newcombe and MacDonald 1991, Henley et al. 2010). High SS concentrations in surface waters reduce light penetration, which may cause disruption of plant cells and respiratory surfaces and, therefore, decrease primary production. High SS loads may also reduce the number and diversity of salmonid populations and other fish species and aquatic invertebrates. The role of sediments in the sorption, storage, transport, and release of contaminants is also important. The leaching of Hg increases its accumulation in food webs; methylmercury (MeHg) is highly neurotoxic (Chang 1977).

Key messages of the chapter

- *DNM is carried out to sustain or increase forest growth.*
- *DNM may increase the soil bearing capability and, therefore, improve the trafficability of peatland forest sites.*
- *DNM has a minor impact on annual runoff, but it may increase peak flows.*
- *DNM generally increases export of suspended solids.*

3. Assessment of the suitability of ditch network maintenance

The aim of DNM is to sustain or improve tree growth. However, there is no convenient, robust method for visually evaluating the soil water conditions and the water transportation capacity of the ditch network in the field, and their influence on tree growth (Sikström and Hökkä 2016). This makes it difficult to judge the need for DNM easily and its optimal timing to maintain tree growth in established forest stands. On the other hand, since the deterioration of the ditches happens slowly, there is no clearly distinct optimal timing for the operation (Sikström and Hökkä 2016). Furthermore, there are several other factors to consider when establishing the suitability of DNM. These factors, and when possible guiding criteria for some of the factors, are described below, as a guide for assessing the suitability of DNM for specific sites within a drainage area. The decision-making process is summarized in the flow chart shown in Figure 1. It is important to note that DNM areas are usually heterogeneous and consist of forest stands and ditches with different water transport capacities. In assessing the suitability of DNM, both the stand properties (its evapotranspiration capacity) and the drainage area-specific factors should be considered, which makes the decision-making highly complex. For example, having a large tree stand with high evapotranspiration capacity in the downstream part of a drainage area (with, therefore, no need for DNM) and a low-stocked tree stand in the upstream part may sometimes necessitate cleaning ditches in the downstream part to enable sufficient drainage for the whole area. However, sometimes it may be reasonable to leave the ditches in the downstream area uncleaned.

3.1. Receiving water body and special water conditions

The status and pollution buffering capacity of the receiving water body both need to be taken into account when evaluating the potential impact of DNM on water quality. The information about the buffering capacity of the water body can be obtained from the regional environment authorities within the EU countries. Also, high conservation or recreational values in the DNM area or the receiving water body need to be considered in order to decide if the whole DNM area, or parts of it, should be excluded from the DNM operation.

In areas where DNM might affect the quantity or quality of the water in aquifers reserved for the drinking water supply, DNM should be avoided, or carried out paying special attention if it cannot be avoided. There are also areas, which are frequently affected by floods during the growing season. Frequent flooding suggests that DNM will not improve the drainage and such areas should be excluded from DNM. In addition, specific hydrogeological conditions, for example, confined aquifer discharge and the existence of sulfide deposits under peat layers, can limit the applicability of DNM. The regional environmental authorities can be contacted for information on the location and management recommendations of such areas. In contrast, in Latvia, 86% of forests on peat soils and 60% of forests on waterlogged or drained mineral soils are located in confined aquifer discharge areas. Discharge waters are rich in mineral nutrients and, therefore, once the horizontal water flow is activated by the drainage, forests can retain high productivity for a long time (Indriksons and Zālītis 2000, Indriksons 2010). In Finland and Sweden, the coastal areas of the northern parts of the Baltic Sea contain sulfide deposits below peat which become highly acidic when oxidized. Therefore DNM needs to be carried out while retaining these deposits under anoxic conditions (Nieminen et al. 2016a,b). In Finland, guidelines have been developed for the management of forests on sulfide rich soils (Nieminen et al. 2016a,b).

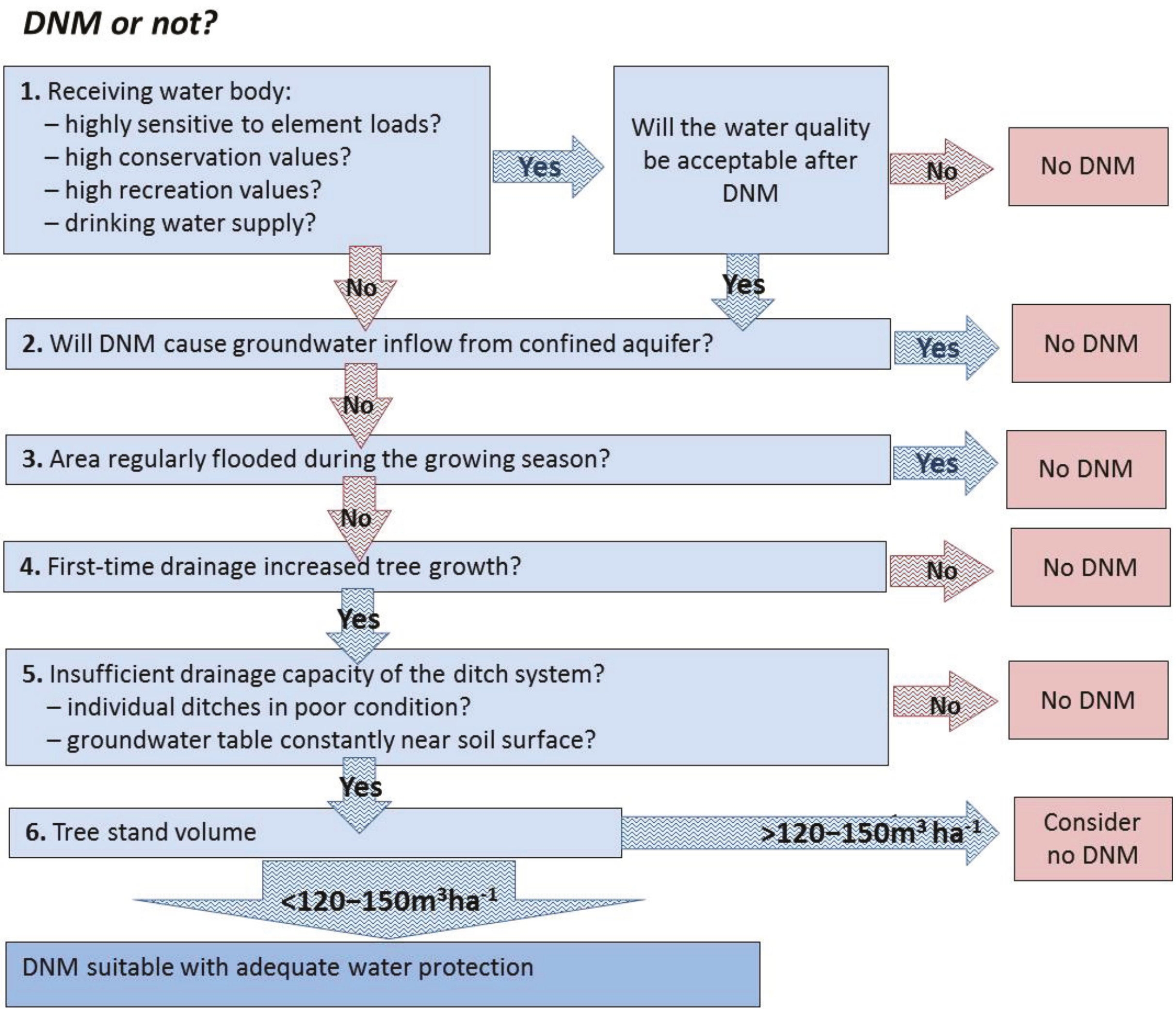

Figure 1. Prior to any decision on DNM, it is important to assess the suitability of DNM for the area in question. The decision flow chart illustrates the main factors, with some criteria given, to be considered when assessing the suitability of DNM. In Lithuania if tree stand volumes are > 250 m^3 ha^{-1} in Scots pine and Norway spruce stands no DNM should be considered (Kapustinskaite and Ruseckas 1979. For planning of water protection, see Figure 4.

3.2. Growth response of the first-time drainage

An important factor for assessing the suitability of DNM is whether first-time drainage has increased forest growth. In Finland, the annual volume growth after first-time drainage should exceed 1.5 m^3 ha^{-1}, and the tree stand should facilitate the growing of high quality timber before DNM can be considered according to the national guidelines. Usually, forest stands, which do not exceed the 1.5.m^3 ha^{-1} growth limit, provide a poor supply of one or more nutrients, or are located in harsh climatic conditions in the northern latitudes.

3.3. Drainage capacity of ditches

Although 20–40-year old ditches may still be functioning well, ditches eventually deteriorate and lose their water transportation capacity due to peat subsidence, blocking by vegetation, collapse of the walls, accumulation of harvest residues, sedimentation of eroded soils etc. (e.g. Paavilainen and Päivänen 1995) (Photo 2). Harvesting operations can also affect the functioning of ditches, particularly when forestry machinery has to cross over them. This deterioration of the ditch network may impair drainage conditions and reduce tree growth (Heikurainen 1980, Hånell 1988). Ditch deterioration and the subsequent impairment of drainage conditions and reduced tree growth are gradual processes. Thus, soil water conditions may be close to optimal for tree growth for a long time after first-time drainage. Mature forest stands may retain high productivity even if the condition of ditches is poor (Zālītis et al. 2010). However, the situation changes significantly after final felling and DNM is generally needed as one of the measures to establish the new tree stand.

Photo 2. These ditches have deteriorated in southern (left) and eastern central Sweden (right), but there is no need for DNM from a forest production point of view due to the high evapotranspiration capacity of these tree stands. Photo Ulf Sikström.

Visual inspection of the water transportation capacity of ditches was previously used as the only method for establishing the need for DNM in Finland. However, that may have overestimated the true need for DNM, particularly in mature stands, where tree stand evapotranspiration dominates the water balance of a drained area (Lauhanen et al. 1998, Laine 1986, Sarkkola et al. 2012). However, the time elapsed since the last ditching operation may potentially indicate the need for DNM. For example, the probability that DNM is needed is relatively high 25–30 years after first-time drainage and very high after 50 years (Hökkä et al. 2000, Zālītis 2006, Zālītis et al. 2010).

3.4. Forest stand and its management

As described in the previous chapters, it is well established that the forest stand strongly influences the water balance of a site and consequently, the soil water content. Partial (thinning) or total removal (clear-cutting) of the tree biomass raises the GWL (Fig. 2). The studies compiled by Sikström and Hökkä (2016) suggest that thinning generally raises GWL by up to 15 cm and clear-cutting by up to 40 cm. The magnitude of the GWL rise is dependent on (i) the pre-treatment GWL (the deeper the initial level, the greater rise), (ii) the size of the biomass removal (the greater the removal, the greater rise), and (iii) the hydraulic conductivity of the soil (the lower the conductivity, the greater the GWL rise). In the few reported studies on the effects of harvesting in sites with mineral soils, the GWL rise was generally larger than in peat soils, probably because both the initial GWL and the hydraulic conductivity of the soils were lower (see Sikström and Hökkä 2016).

Considering stand development, the need for DNM is greatest in the early phase of the rotation period, when water evapotranspiration by the tree stand still contributes little to the water balance. Later on the need for DNM may also arise after harvesting, particularly after final felling, but sometimes also after partial cuttings (commercial thinnings). At later phases, in more highly stocked stands with volumes exceeding about 150 m^3 ha^{-1}, DNM may not increase tree growth or lower the GWL, thus it may be an unnecessary operation in such forests (Sarkkola et al. 2010) (Photo 3). However, in such forest areas, cleaning of some ditches may be necessary for moving water from upstream areas. Growth responses after DNM may also be weak when GWL is deeper than 35–40 cm before DNM (Sarkkola et al. 2012). It has been suggested that fertilization may be an alternative to DNM since appropriate nutrient addition usually increases leaf area and tree growth, and subsequently evapotranspiration. This then decreases the importance of the ditch network in maintaining site drainage conditions (Heikurainen and Päivänen 1970, Ernfors et al. 2010).

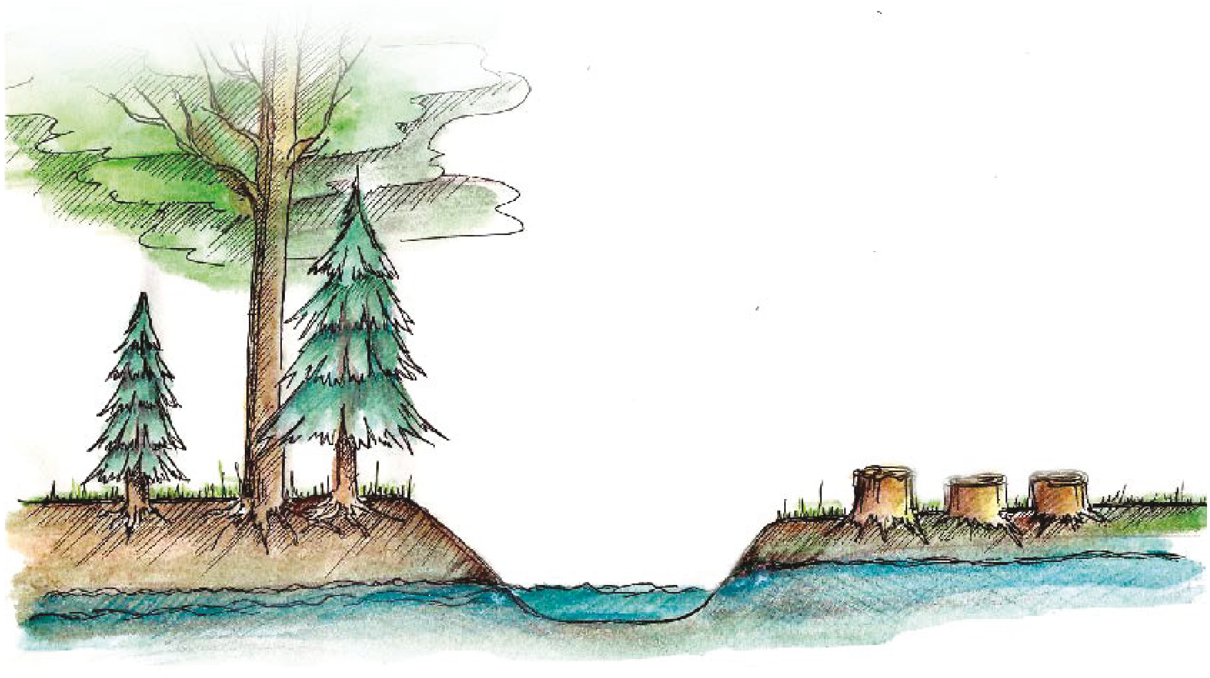

Figure 2. A schematic picture of a forest stand and a clear-cut area on a drained peatland. The ground-water table rises after clear-cutting as illustrated in the figure. Figure Ilze Paulina.

Photo 3. DNM may not increase tree growth in stands with volumes higher than 150 m^3 ha^{-1}, as for example in these Norway spruce stands in southern Sweden, because the evapotranspiration may provide adequate drainage. Photo Ulf Sikström.

3.5. Other factors to consider

Tree species and understory vegetation composition

When considering the suitability of DNM the tree species composition of the forest stands should be taken into account, as the evapotranspiration capacities of different tree species vary and they affect on the water balance of the site differently. Thus, if the stand contains a substantial proportion of a tree species with a high transpiration capacity, the need for DNM may be lower than for stands containing species with lower transpiration capacities. For example, the transpiration capacity of birch leaves is higher that of pine and spruce leaves (Pallardy 2008). In Latvia, there are examples where a birch admixture in young Norway spruce stands helped to retain biological drainage in areas with low ditch network densities and fine-textured, poorly drained soils (Lībieté, unpublished).

The composition of the understory vegetation is affected by the soil moisture conditions (e.g. Päivänen and Hånell 2012). Therefore, its composition should be considered in the suitability assessment, since increased coverage of moist tolerant species may indicate a need for DNM. On well-drained peatlands, both overstory and understory vegetation consist mainly of the same species as found in upland mineral soils (e.g. Bušs 1981), and indicate good aeration of the soil. A high abundance of moist-tolerant species, especially *Sphagnum* mosses, sedges (*Carex* sp.) and shrubs (e.g. *Ledum palustre, Betula nana*, *Vaccinium uliginosum*), may indicate high GWL, probably because of the poor condition of ditches (Päivänen and Hånell 2012).

Soil characteristics

The texture of mineral soil and the humification degree of peat soils can be used to estimate how drainable the soil is. Well-humified peat soils with high bulk density, and fine-textured mineral soils (grain size <0.063 mm) have high water-retention capacities and low hydraulic conductivities. Thus, such sites are difficult to drain efficiently, and drainage may only lower GWL close to the ditches i.e.

no more than about 5–15 m from them (e.g. Jutras and Plamondon 2005). It is noteworthy that peat bulk density increases and its hydraulic conductivity decreases with time due to drainage caused by the continuous decomposition of peat. Thus, it may become increasingly difficult to drain peat sites effectively in the future.

Climate

The need for DNM after first-time drainage seems to arise earlier in northern locations compared to southern locations because there is less biological drainage (i.e. evapotranspiration) in the north due to slower stand development. Thus, drainage is more dependent on the condition of ditches in the north than in the south, where tree stands have larger stem volumes and biological drainage may dominate over the water transportation capacity of the ditch network (cf. Sarkkola et al. 2013). In the harsh climate of the north, investments in DNM may not be financially viable (Hökkä et al. 2016).

Key messages of the chapter:

- *When establishing the suitability of DNM:*
  - *Attention must be paid to the characteristics of the receiving water body and the site-specific water conditions in the DNM area such as groundwater inflow from confined aquifers and suscebtibility to flooding during the growing season*
  - *The effect of first-time drainage, ditch drainage capacity and tree stand volume must be evaluated.*
  - *Other factors to consider: tree species composition, understory vegetation, soil characteristics and climate.*

4. Planning ditch network maintenance and water protection

Good planning is essential for successful DNM and water protection. The planning process starts by assessing the need and suitability of DNM (see Chapter 3) before it proceeds to the actual planning of DNM operations and water protection measures. Existing knowledge of local climatic and hydrological conditions, as well as the condition of ditches, soil types and depths, the characteristics of the tree stand and receiving water bodies, all facilitate the planning. Information about the timber transport routes and the existing and planned road network is also used. Existing planning tools can be used for timing the DNM operations and identifying suitable water protection measures and their location. If timber harvesting is also planned to be carried out in the area it is useful to plan them together. The removal of the trees alongside ditches, which is necessary when carrying out ditch cleaning with excavators, can be done alongside harvesting operations. That allows for the removal of logging residues deposited in the ditches as part of the ditch cleaning operation following harvesting.

4.1. Planning of water protection measures

The planning of water protection measures and characterization of the water pathways in the drainage network is an essential part of the planning of DNM. The entire stream network (including ditches) of the catchment, and especially the downstream water bodies of the sub-catchment where the DNM is to be implemented, should be taken into account when planning DNM. The DNM plan should be documented and used during the drainage operation.

The planning starts with the topographic maps of stream networks in the catchment including the drained area. Existing GIS tools, old maps and drainage plans, aerial photographs, field examination etc. can be used for the delineation of the entire forest catchment area and for the location of the existing ditches. Also, a computer soft-ware that uses LIDAR data is available for detecting ditches. Field examination of the functioning of the existing ditch network is important, both from an ecological and an economic point of view. A general principle is that the water protection structures which capture the released elements are constructed before any drainage operation is started. Special care in planning water protection should be undertaken where drainage waters are released to a highly sensitive or valuable water body. The type and the location of the water protection structures can be documented on a map of the DNM area (Fig. 3).

In principle, there are three options for managing water quality in drained sites: 1) decrease SS and nutrient release from the drainage site by controlling drainage intensity i.e. through the length of the ditches in the DNM area, the depth and width of the ditches, and ditch slope, 2) decrease SS and adhered nutrient release by controlling the velocity and erosive force of drainage water, and 3) capture the SS and nutrients released after drainage before they enter the receiving water body. Good practices for implementing these options are given in the following sections (4.2–4.4) and a flowchart illustrating the logical order of planning water protection in DNM areas is shown in Figure 4.

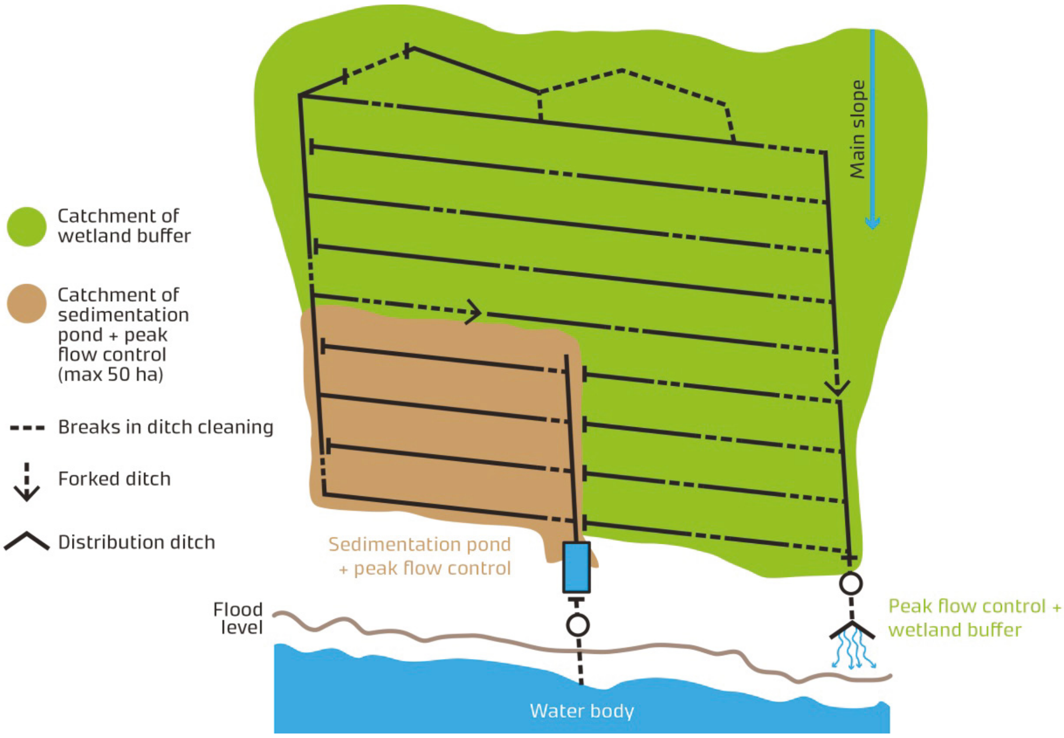

Figure 3. An example of a map showing a DNM area with water protection structures. It is important that the water protection structures are not located in the area which is frequently flooded. Source: Natural Resources Institute Finland and Metsähallitus Forestry Ltd.

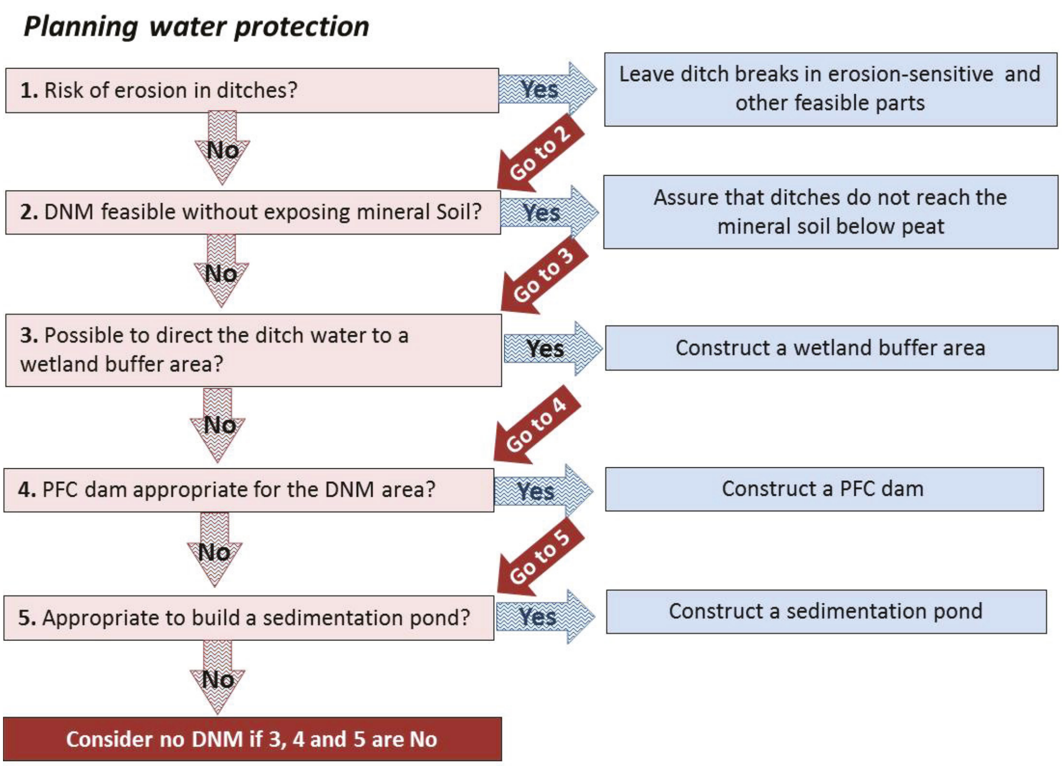

Figure 4. A flowchart illustrating the logical order of planning different water protection structures in DNM areas where DNM has been found to be suitable (see Figure 1).

4.2. Controlling drainage intensity and ditch slope

Planning of DNM starts by identifying the ditches which need to be cleaned and the supplementary ditches which need to be excavated. The ditches which have retained their drainage capacity are not treated. During this phase, ditches/stretches of ditches which show signs of erosion are identified and left as uncleaned ditch breaks (Photo 4). As the velocity and erosive force of water are greater in the collector than the feeder ditches, leaving stretches of collector ditches uncleaned – whenever it is possible without risking site drainage conditions – may be a particularly efficient means of reducing erosion in areas with a high erosion risk. According to the modeling study by Haahti et al. (2017), well-targeted breaks have the potential to decrease erosion effectively and are the only sediment control structure in the ditch network that can have a significant effect on ditch bank erosion.

For planning ditch cleaning, information on the catchment area of the ditches and the slopes on their entire length, as well as the soil type in ditch beds and banks, is needed. Soil type information needs to be acquired from a field visit since the resolution of the existing soil type maps might be inadequate. If the slope of the ditch is steeper than that recommended for the shearing strength of the soil, it will significantly increase the erosion risk. The RLGis -program can be used for identifying the erosion risk within ditches (Fig. 5) (http://www.eia.fi/).

Photo 4. A ditch in Latvia which should not have been cleaned because of the highly erodible soil causing high sediment load to downstream water bodies. Photo Zane Lībieté.

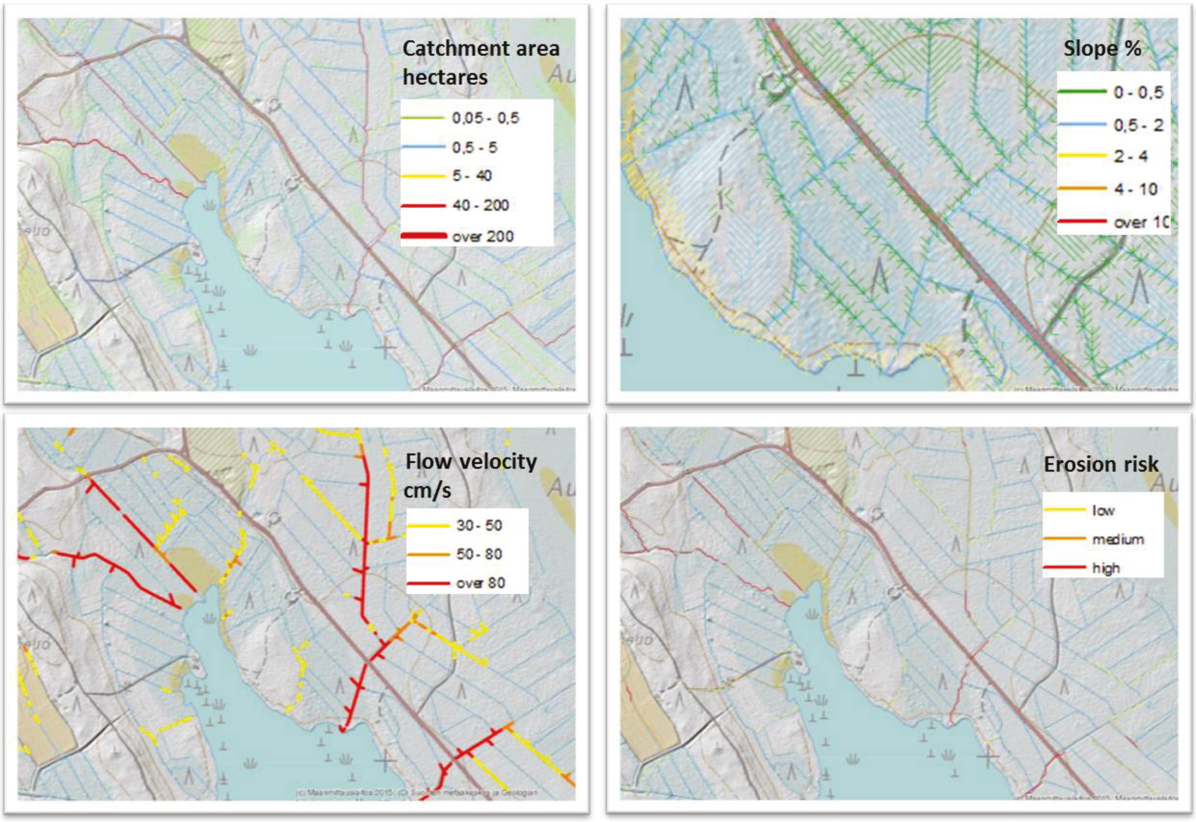

Figure 5. Visualizations of analyses of catchment areas, slopes, water flows and erosion risks of each ditch in a drainage area carried out with RLGis –program (http://www.eia.fi/). Figure Antti Leinonen.

Drainage intensity can be controlled by varying ditch length, width and depth. Usually, DNM does not change the total length of ditches in the drainage area by much, but the ditch depth and width can be controlled. The depth of the ditches should be managed in such a way that they do not enter the mineral soil underlying the peat. By keeping the ditches in peat, the export of SS can be significantly reduced (Joensuu et al. 1999, Nieminen 2003). This is especially true in DNM areas with fine-textured and medium-textured mineral soils (grain size <0.063 mm and 0.063–0.63 mm, respectively) below peat, because such soils are eroded more easily than coarse-textured mineral soils (grain size >0.63 mm).

Another potential measure to control erosion, and thus water quality, in DNM areas is to develop an excavator´s scoop so that only the bottoms of ditches are cleaned and their banks remain intact (Photo 5). This novel approach has recently received attention in Sweden, but there are no data on its impact on SS and nutrient transport. Developing methods to decrease unnecessary disturbance of the ditch profiles, while still having sufficient drainage capacity in the drainage network, should be increasingly studied, both by DNM research and operational forestry.

Photo 5. A ditch-bottom cleaning machine (called Varanen) doing ditch network maintenance in southern Sweden. To date there are no studies of its impacts on erosion and how long-lived the ditches are after cleaning. Photo Anja Lomander.

4.3. Controlling the velocity and erosive force of drainage water

Different dam structures can be implemented to reduce the velocity and erosive force of water. Peak flow control (PFC) structures with runoff regulating pipes have been shown to reduce the transport of SS and particulate nutrients in DNM areas efficiently (Marttila and Klöve 2010, Marttila et al. 2010). The correct functioning of the PFC structure is dependent on correctly dimensioned pipes (Fig. 6. Photo 6), which stop high flow rates while allowing through water at lower rates. Under optimal conditions, the whole drainage network acts as a water retention area with reduced water flow velocity and erosion risk during the peak flows. The critical point in the functioning of a PFC structure is the proper dimensioning of the base flow pipe according to local catchment and climatic conditions, such as the catchment size, average slope, and regional precipitation patterns. While a too small pipe might cause too great long-term water retention in the upstream ditch network, potentially decreasing tree vitality and growth, a pipe that is too large might have only a small effect on water flow regulation during peak flows. A sedimentation pond is usually excavated above the PFC structure to retain the sediments which are released even with a PFC structure. A combined PFC/pond structure is reasonable in the sense that, while it is generally recommended to carry out DNM only during dry periods, PFC is ineffective in retaining SS immediately after DNM when flow rates are low and SS concentrations are high (Haahti et al. 2017). To achieve the best performance of sedimentation ponds, however, low flow conditions with concurrent high SS concentrations are optimal (Joensuu et al. 1999, Haahti et al. 2017). To enhance the performance of a PFC structure, another means could be to seal the base flow pipe temporarily during times of low flows, during and after DNM (Haahti et al. 2017).

Photo 6. Outlet of a peak flow control structure with two pipes in a drained area located in central Finland. A sedimentation pond has been constructed upstream of the peak flow control structure. Photo Leena Finér.

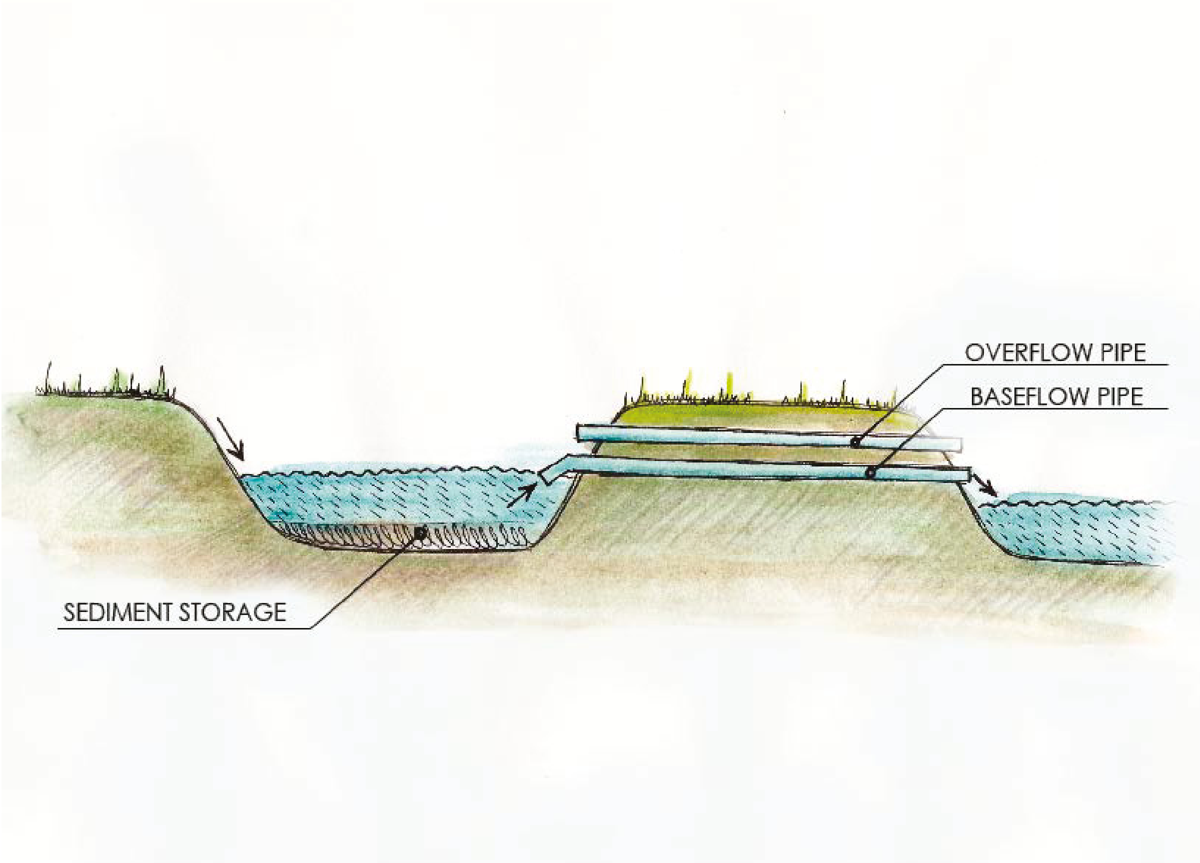

Figure 6. A schematic drawing of a peak flow control structure. Figure Ilze Paulina.

PFC structures have small effect on reducing the export of dissolved elements in drainage water. Thus, they should not be designed to be used as the only water protection structure where the loads of dissolved elements are high.

The efficiencies of dam structures without flow-through pipes, such as submerged and above-ground-level dams made of stones or soil, have received little attention (Liljaniemi et al. 2003, Hansen et al. 2013). In constructing these dams, care should be taken that the effective area for water storage above the dam is sufficiently large for effective reduction in water flow velocity and that there is sufficient storage area for the retention of SS. The modeling study by Haahti et al. (2017) indicated that dams, which effectively pond the water above them, could have the potential to reduce SS exports significantly.

4.4. Capture released sediments and nutrients

Sedimentation pits and ponds

The purpose of the sediment pits and ponds is to capture sediment and particulate nutrients released from the active forest management area before they enter the receiving water bodies. Traditionally, they are a deepened and widened section of a ditch, in which water has a wider flow cross-sectional area and a reduced flow rate (i.e. down to 0.2 m s^{-1} at least), which facilitates the deposition of suspended sediments to the bottom of the pond. In general, the sedimentation ponds are efficient for capturing particles with diameters greater than 0.05 mm, whereas smaller particles can be captured by the wetland buffers (Kasak et al. 2016). Usually, sedimentation pits are constructed in the drainage ditches within the DNM area and the larger sedimentation ponds are constructed at the outlet ditches. Operational guidelines for water quality protection in drained peatlands generally suggest sedimentation pits (1–2 m^3) as a means, to retain SS, but there is no empirical data concerning their efficiency. The modeling study by Haahti et al. (2017) indicated that sedimentation pits may sometimes even increase erosion by increasing flow velocity above them.

The use of sedimentation ponds to mitigate SS transport is complicated because their efficiency depends on their design, especially on the parameters pond volume and water retention time. Water retention time reduces as the pond is filled by sediment, thus regular removal of the deposited sediments is needed to maintain efficient sediment retention. The efficiency of a pond is poor until the amount of sediment input increases to a high level, possibly because sediments do not settle down irrespective from each other, but collectively as more or less tightly adhered flocs or composites of particles. Well-functioning sedimentation ponds reduce sediment transport by 30–40% and they are particularly effective for the coarse-textured (grain size >0.63 mm) sediments (Photo 8, Fig. 7). Very large ponds (>400 m^3) might be needed to retain >50% of the SS loading (Nieminen et al. 2018). It may be unnecessary to excavate ponds in areas where the inflowing sediment comprises either light organic particles or fine-textured (particle size < 0.063 mm) mineral soil. Ponds should only be established in areas where the pond bottom and walls do not reach erosion-sensitive mineral subsoil.

Photo 7. A sedimentation pond in eastern central Sweden (100 km north of Stockholm). The pond was constructed in February 2013, about two years before the photo was taken. Photo Ulf Sikström.

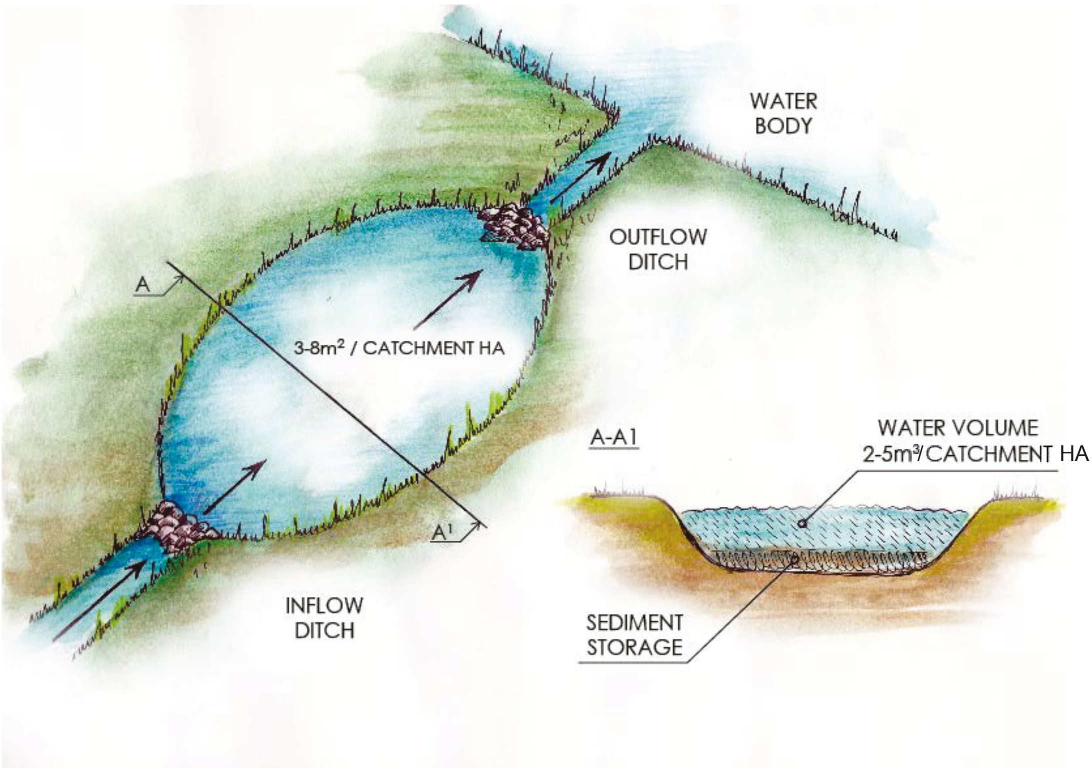

Figure 7. Schematic diagrams of a sedimentation pond. The ditch downstream of the pond is not cleaned. A–A1 indicates the position of the cross section illustrated on the right. Figure Ilze Paulina.

Wetland buffers

Natural and restored wetland buffers, also known as overland flow areas, are the most efficient of the different water protection structures at retaining SS and nutrients in drainage areas (Nieminen et al. 2015) (Photo 9, Fig. 8). Highly efficient SS retention has been reported, particularly where the SS inputs to buffer areas were large and the size of the buffer area was at least 0.5–1.0% of the size of the whole upstream catchment area (Nieminen et al. 2005). In addition, efficient retention of dissolved nutrients has been seen, especially after transient high nutrient loadings (Väänänen et al. 2008, Vikman et al. 2010).

Photo 8. Wetland buffer, also named overland flow area, in northern Finland. Photo Antti Leinonen.

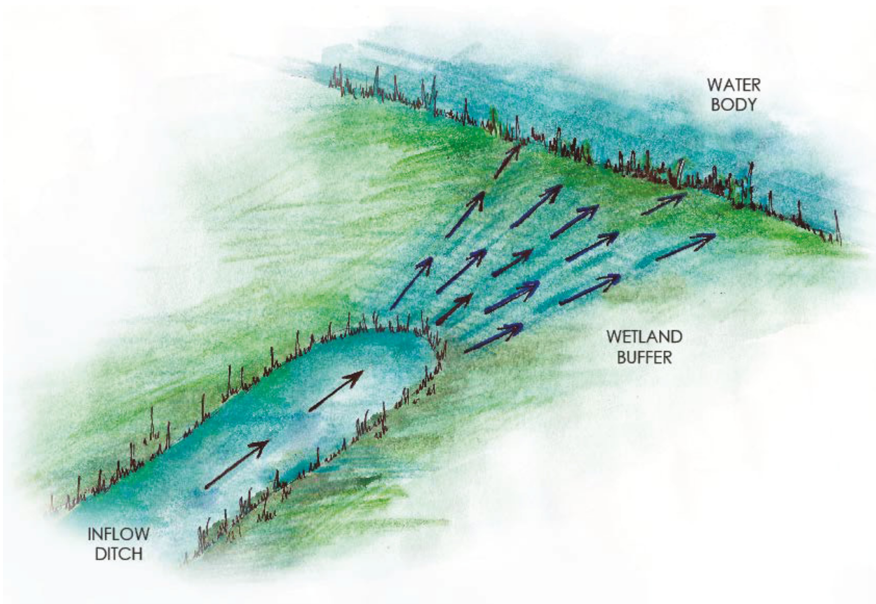

Figure 8. A schematic diagram of a wetland buffer. Figure Ilze Paulina.

Although wetland buffers have proven to be the most efficient water protection structure, their use in operational forestry is very limited. One major limitation to their use is that blocking or filling in the ditches in a designed wetland buffer area raises the GWL not only in the buffer area itself, but also in the upstream area. On sloping land, the area with a raised GWL above the buffer area may be just a few meters or tens of meters long, but in the very flat lowlands, the rewetted area may extend to several hundreds of meters from the buffer area. Thus, although the use of wetland buffers is currently recommended as the most efficient means of reducing the export of SS and nutrients in forested catchments, their use in operational forestry is restricted to areas where sloping land facilitates the construction of the buffer without severely disturbing tree growth in the upstream productive forest land. In flat areas other water protection methods should be used instead of wetland buffers. Wetland buffers should also not be established on pristine mire areas with endangered plant species as vegetation in wetland buffer areas undergoes substantial changes due to increased nutrient input from the upstream DNM area (Hynninen et al. 2011).

Key messages of the chapter:

- *Water protection should be planned in conjuction with DNM.*
- *Water protection structures are constructed before any DNM.*
- *Avoiding erosion is of the utmost importance.*
- *Ditch sections showing signs of erosion are left uncleaned.*
- *Dam structures are used to control water velocity.*
- *Sedimentation ponds are used to retain SS.*
- *Wetland buffers are effective in retaining both SS and dissolved nutrients.*

5. Monitoring the impacts of water protection

The efficiency of water protection measures in reducing the transport of SS and nutrients needs to be regularly monitored. The results should be analyzed and used to improve water protection practices and for evaluating the quality of the work.

5.1. EU Water Framework Directive

The Water Frameowrk Directive (WFD), which requires all inland and coastal water bodies to reach a minimum "good" ecological status, defines quality standards for the concentrations of elements and hazardous substances in waters (Table 1). For the implementation of the WFD, various types of condition assessments are carried out in national water bodies: assessment of the ecological status, status assessment of the Salmonid habitat, status assessment for the nitrate sensitive areas and general assessment of the status of hazardous substances (2000/60/EC). The ecological status is assessed separately for the different types of water bodies (e.g. streams or lakes, dark or light water bodies etc.). There is a principle of 'one-out all-out' to determine the actual status of the water body, meaning that, for example, the overall status would be classified as 'good', only if all the classification criteria are 'good' at minimum (Ibid). Therefore, it is important to be aware of valid legislation and the ecological importance of water bodies being connected downstream of the DNM area (Table 1).

Table 1. Limit values for the water quality parameters according to EU legislation. Notes:*AA: annual average; **MAC: maximum allowable concentration; ***LV: limit values.

Chemical parameter	Concentration	Sampling frequency per year	Directive
pH	LV ≥ 6[A,B]	Every month	Directive 78/659/EEC[C]
Suspended solids (mg l^{-1})	LV ≤ 25[A,B]		
BOD_5 (mg l^{-1} O_2)	LV ≤ 3[A]; ≤ 6[B]		
Total ammonium (mg l^{-1} NH_4)	LV ≤ 0.04[A]; ≤ 1[B]		
Nitrites (mg l^{-1} NO_2)	LV ≤ 0.01[A]; ≤ 0.03[B]		
Total phosphates (mg l^{-1} PO_4)	LV ≤ 0.2[A]; ≤ 0.4[B]		
Nitrates (mg l^{-1} NO_3)	LV < 50		Nitrates Directive 1/676/EEC[D]
Hg (µg l^{-1})	AA ≤ 0.05; MAC ≤ 0.07	3 times per year	Directive of the European Parliament and of the Council 2008/105/EC[E]

[A]Limit value of chemical parameter for salmonid waters.
[B]Limit value of chemical parameter for cyprinid waters.
[C]Council Directive 78/659/EEC of 18 July 1978 on the quality of fresh waters needing protection or improvement in order to support fish life. Official Journal of the European Communities, No L 222, p. 10. http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:31978L0659
[D]Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. Official Journal of the European Communities, No L 375, p. 8. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0676
[E]Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council. Official Journal of the European Union, p. 14. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2008.348.01.0084.01

5.2. Monitoring in practice

The monitoring of water quality can be organized in various ways. The most effective way from an environmental perspective would be to monitor all DNM areas. That would require continuous monitoring of runoff and regular sampling of runoff water for chemical analyses over a long period before and after DNM, to be able to calculate the change in element loads. In most cases, in daily work operations, that is not reasonable because of the long time required, the accurate sampling procedures and analytical methods used, and thus, the resultant high costs (Photo 10). This kind of monitoring commonly requires installations and procedures more suitable for extensive monitoring studies and research projects.

In Finland, the Ministry of Agriculture of Forestry has funded the establishment of a monitoring network consisting of 11 protected unmanaged catchments and 20 managed small forested catchments for continuous monitoring of runoff and runoff water quality. That network provides information of the element loads produced by forestry practices at national level (http://kartta.luke.fi/vesidata/). The results are used by the Ministry of Agriculture and Forestry and other stakeholders for reporting the quality of water protection and for developing water protection in forestry.

Photo 9. Discharge monitoring station at an outlet of a forest drainage area in Finland. Discharge, turbidity, pH and nitrate concentrations are monitored continuously throughout the year at the station. Photo Sauli Jaakkola.

A suggested minimum level of follow-up in daily forest operational work is a visual inspection of the quality of the constructed water protection structures according to predefined criteria. These criteria can be, for example, the volume of a sedimentation pond, the dimensions of the pipes in a PFC dam, the length of a wetland area, etc. In addition, it is important to determine whether retained sediments in constructed sedimentation ponds need emptying, to ensure the best possible retention capacity. This kind of self-monitoring could also be integrated with an external audit which may be required in certified forests.

Key messages of the chapter

- *Monitoring the efficiency of water protection measures is useful for promoting water protection in DNM.*
- *Visual inspection of all water protection structures in DNM sites is organized by the operators/field personnel and aim at good quality of water protection.*
- *Water quality monitoring networks are organized by administrators and are viable tools for developing water protection in DNM.*

6. Training for ditch network maintenance

Education and training are needed for planning and carrying out DNM and adequate water protection measures in forestry. Basic education is provided by the professional schools, colleges, universities and other organizations as a part of the education for a profession, or as supplementary education and training courses. Updating the knowledge from various sources of information and training by exercising profession are part of the everyday work. It is also important to receive feedback about the quality of work e.g. by self-monitoring to learn how the good practices have been implemented. Demonstration areas have been established in different Baltic Sea Region countries to help to visualize the good water protection practices in the field.

In Sweden, a certificate in water protection education is required for people carrying out forest operations in certified forests. The education program operational in 2017, was developed by Skogsbrukets Yrkesnämnd and was organized with several schools, companies and the Swedish Forest Agency. The target groups of the education were the personnel responsible for forest management, as well as the contractors and engineers who carry out the actual drainage work. The duration of the education was two days, consisting of a theory day and a day out in the forest. The education ended with a knowledge test, the passing of which earned the student a certificate.

The content of the education program was planned to meet the following objectives:

- How drainage affects the biomass production capacity of the soil
- How drainage affects greenhouse gas fluxes
- Planning of ditch network
- Difference between first-time drainage, ditch cleaning and remedial ditching
- Current legislation, authorization procedure and responsibilities of operators
- Information about environmental impacts of DNM
- A simple assessment to identify ecologically valuable environments in the field
- How sedimentation ponds and other water protection measures are designed
- Various types of excavators and buckets for ditching
- How to construct road tunnels that avoid creating obstacles to forest transportation
- EU Water Framework Directive
- Certification requirements concerning ditch network maintenance

In Latvia two-day courses for private forest owners are organized by the Forest Advisory Service Centre to educate them about the importance of water in the forest ecosystem, forest management impacts (including drainage) and the principles of DNM.

In Finland, different organizations arrange courses on water protection in DNM and in every second year, national water protection days are organized for forest and environment managers and administrators (https://www.metsakeskus.fi/metsatalouden-vesiensuojelupaivat-2017-oulussa).

Key messages of the chapter:

- *Education in water protection is required for work on certified forest properties.*
- *Continuous education and training are needed for good quality DNM.*

7. References

Aarnio, J., Ahti, E., Hytönen, L.A. and Lauhanen, R. 1997. Kunnostusojitus. In: Mielikäinen, K. and Riikilä, M. (eds.). Kannattava puuntuotanto. Kustannusosakeyhtiö Metsälehti. p. 102–108. (In Finnish).

Ahti, E. 1987. Water balance of drained peatlands on the basis of watertable simulation during the snowless period. Communicationes Instituti Forestalis Fenniae 141. 64 pp.

Ahti E. 2005. Kunnostusojitus. [Ditch network maintenance operation]. In: Ahti E., Kaunisto, S., Moilanen, M. and Murtovaara, I. (eds.). Suosta metsäksi, suometsien ekologisesti ja taloudellisesti kestävä käyttö. [From peat to forest, ecologically and economically sustainable use of peatland forests]. Tutkimusohjelman loppuraportti. Metsäntutkimuslaitoksen Tiedonantoja 947. (Finnish Forest Research Institute Research Papers 947). p. 114–120. (In Finnish).

Ahti, E. and Päivänen, J. 1997. Response of stand growth and water table level to maintenance of ditch networks within forest drainage areas. In: Trettin, C.C., Jurgensen, M.F., Grigal, D.F., Gale, M. and Jeglum, J. (eds.). Northern forested wetlands: ecology and management, chapter 32. CRC Press Inc., Lewis Publishers, USA. p. 449–457.

Ahtikoski, A., Kojola, S., Hökkä, H. and Penttilä, T. 2008. Ditch network maintenance in peatland forest as a private investment: short- and long-term effects on financial performance at stand level. Mires and Peat 3(3). 11 p.

Ahtikoski, A., Salminen, H., Hökkä, H., Kojola, S. and Penttilä, T. 2012. Optimizing stand management on peatlands: the case of northern Finland. Canadian Journal of Forest Research 42: 247–259.

Åström, M., Aaltonen, E.-K. and Koivusaari, J. 2002. Impact of forest ditching on nutrient loadings of a small stream – a paired catchment study in Kronoby, W. Finland. Science of the Total Environment 297: 127–140.

Boelter, D.H. 1964. Water storage characteristics of several peats in situ. Soil Science Society of America, Proceedings 28: 433-435.

Bušs, K. 1981. Forest ecology and typology. Riga, "Zinatne". 64 pp. (In Latvian).

Cambi, M., Certini, G., Neri, F. and Marchi, E. 2015. Impact of heavy traffic on forest soils: A review. Forest Ecology and Management 338: 124–138.

Chang, C.W. 1977. Neurotoxic effects of mercury – A review. Environmental Research 14(3): 329–373.

Eklöf, K., Lidskog, R. and Bishop, K. 2016. Managing Swedish forestry's impact on mercury in fish: Defining the impact and mitigation measures. Ambio 45(2): 163–174.

Ernfors, M., Sikström, U., Nilsson, M. and Klemedtsson L. 2010. Effects of wood ash fertilization on forest floor greenhouse gas emissions and tree growth in nutrient poor drained peatland forests. Science of the Total Environment 408: 4580–4590.

Estonian Strategy. 2011. Kuivendussüsteemide majandamise strateegia (Management Strategy of Drainage Systems). Riigimetsa Majandamise Keskus (State Forest Management Centre), Otsus (Decision) nr 1–32/44, Tallinn, 16 pp. (In Estonian).

Fairchild, J. F., Boyle, T., English, W. R. and Rabeni, C. 1987. Effects of sediment and contaminated sediment on structural and functional components of experimental stream ecosystems. Water, Air, and Soil Pollution 36: 271–293.

Finér, L., Mattsson, T., Joensuu, S., Koivusalo, H., Laurén, A., Makkonen, T., Nieminen, M., Tattari, S. et al. 2010. A method for calculating nitrogen, phosphorus and sediment load from forested catchments. Suomen ympäristö 10/2010. 33 pp. (In Finnish).

Haahti, K., Nieminen, M., Finér, L., Marttila, H., Kokkonen, T., Leinonen, A. and Koivusalo, H. 2017. Model-based evaluation of sediment control in a drained peatland forest after ditch network maintenance. Canadian Journal of Forest Research. 48: 130–140.

Hånell B. 1988. Post-drainage forest productivity of peatlands in Sweden. Canadian Journal of Forest Research 18(11): 1443–1456.

Hansen, K., Kronnäs, V., Zetterberg, T., Zetterberg, M., Moldan, F., Pettersson, P. and Munthe, J. 2013. DiVa - dikesrensningens effekter på vattenföring, vattenkemi och bottenfauna i skogsekosystem. IVL Svenska Miljöinstitutet AB, Report B2072. 108 pp. Stockholm (In Swedish with English abstract).
Heikurainen, L. 1980. Kuivatuksen tila ja puusto 20 vuotta vanhoilla ojitusalueilla. (Drainage condition and tree stand on peatlands drained 20 years ago) Acta Forestalia Fennica 167: 1–37. (In Finnish with English summary).
Heikurainen, L. and Päivänen, J. 1970. The effect of thinning, clearcutting, and fertilization on the hydrology of peatland drained for forestry. Acta Forestalia Fennica 104: 1–23.
Henley, W. F., Patterson, M. A., Neves R. J. and Dennis Lemly, A. 2010. Effects of sedimentation and turbidity on lotic food webs: A concise review for natural resource managers. Reviews in Fisheries Science 8:2: 125–139.
Hökkä, H., Alenius, V. and Salminen, H. 2000. Kunnostusojitustarpeen ennustaminen ojitusalueilla. (Predicting the need for ditch network maintenance in drained peatland sites in Finland) Suo - Mires and Peat 51(1): 1–10.
Hökkä, H. and Kojola, S. 2001. Kunnostusojituksen kasvureaktioon vaikuttavat tekijät. [Factors affecting growth response due to ditch network maintenance operation]. In: Hiltunen, I. and Kaunisto, S. (eds.). Suometsien kasvatuksen ja käytön teemapäivät. (Management and utilization of peatland forests) Metsäntutkimuslaitoksen tiedonantoja - The Finnish Forest Research Institute, Research Papers 832, p. 30–36. (In Finnish).
Hökkä, H. and Kojola, S. 2003. Suometsien kunnostusojitus – kasvureaktion tutkiminen ja kuvaus. [Ditch network maintenance in peatland forests – growth response and it's description]. In: Jortikka, S., Varmola, M. and Tapaninen, S. (eds.). Soilla ja kankailla – metsien hoitoa ja kasvatusta Pohjois-Suomessa. (On peatlands and uplands – forest management in northern Finland) Metsäntutkimuslaitoksen tiedonantoja - The Finnish Forest Research Institute, Research Papers 903, p. 13–20. (In Finnish).
Hökka, H., Salminen, H., Ahtikoski, A., Kojola, S., Launiainen, S. and Lehtonen, M. 2016. Long-term impact of ditch network maintenance on timber production, profitability and environmental loads at regional level in Finland: a simulation study. Forestry: An International Journal of Forest Research 90(2): 234–246.
Huikari, O. and Paarlahti, K. 1967. Results of field experiments on the ecology of pine, spruce, and birch. Communicationes Instituti Forestalis Fenniae 64(1). 135 pp.
Hynninen, A., Hamberg, L., Nousiainen, H., Korpela, L. and Nieminen, M. 2011. Vegetation composition dynamics in peatlands used as buffer areas in forested catchments in southern and central Finland. Plant Ecology 212: 1803–1818.
Hytönen, L.A. and Aarnio, J. 1998. Kunnostusojituksen erilliskannattavuus muutamilla karuhkoilla rämeillä. (Profitability of ditch-network maintenance on some oligotrophic pine mires) Suo 49(3): 87–99.
Indriksons, A. and Zālītis, P. 2000. The impact of hydrotechnical drainage on cycle of some biogenous elements in forest. Baltic Forestry 6(1): 18–24.
Indriksons, A. 2010. Cycle of biogenous elements in drained forests. Resume of the PhD thesis, Jelgava. 64 pp.
Johnson, R. 1998. The forest cycle and low river flows: a review of UK and international studies. Forest Ecology and Management 109: 1–7.
Joensuu, S., Ahti, E. and Vuollekoski, M. 1999. The effects of peatland forest ditch maintenance on suspended solids in runoff. Boreal Environment Research 4: 343–355.
Joensuu, S., Ahti, E. and Vuollekoski, M. 2002. Effects of ditch network maintenance on the chemistry of run-off water from peatland forests. Scandinavian Journal of Forest Research 17: 238–247.
Joensuu, S., Vuollekoski, M. and Karosto. K. 2006. Long-term water quality impacts of ditch network maintenance. In: Kenttämies, K. and Mattsson, T. (eds.) Metsätalouden vesistökuormitus. MESUVE-projektin loppuraportti. Suomen ympäristö 816: 83–90. (In Finnish).

Joensuu, S., Ahti, E. and Vuollekoski, M. 2012. Effects of ditch network maintenance on the chemistry of run-off water from peatland forests. Scandinavian Journal of Forest Research 17: 238–247.
Jutras, S. and Plamondon, A.P. 2005. Water table rise after harvesting in a treed fen previously drained for forestry. Suo 56(3): 95–100.
Kapustinskaite T. and Ruseckas J. 1979. The economical and bioeconomical results of forest draining. Ministry of Agriculture of Lithuanian SSR. 91 p.
Kasak, K., Piirimäe, K. and Vahtrus, S. 2016. Veekaitsemeetmed põllumajanduses: käsiraamat tootjale (Water protection measures in agriculture: handbook for producers). AS ecoprint, Tartu. 148 pp.
Koivusalo, H., Ahti, E., Laurén, A., Kokkonen, T., Karvonen, T., Nevalainen, R. and Finér, L. 2008. Impacts of ditch cleaning on hydrological processes in a drained peatland forest. Hydrology and Earth System Sciences 12(5): 1211–1227.
Kozlowski, T.T. 1982. Water supply and tree growth. Part II Flooding. Review article. Forestry abstracts 43(3): 145–161.
Laine J. 1986. Kuivatustekniikan, kuivatussyvyyden ja puuston kasvun välisiä vuorosuhteita 25 vuotta vanhoilla ojitusalueilla. (Interrelationships among ditching technique, ditching depth, and tree stand growth in 25 years old forest drainage areas) Tutkimussopimushankkeen 'Metsäojitettujen soiden ekologia' loppuraportti. Helsinki. 24 p. (In Finnish).
Laine, J., Laiho, R., Minkkinen, K. and Vasander, H. 2006. Forestry and Boreal Peatlands. In: R.K. Wieder and D.H. Vitt (eds). Ecological Studies 188: 331–357.
Lauhanen R. and Ahti E. 2001. Effects of maintaining ditch networks on the development of Scots pine stands. Suo 52(1): 29–38.
Lauhanen, R., Piiroinen, M.-L., Penttilä, T. and Kolehmainen, E. 1998. Kunnostusojitustarpeen arviointi Pohjois-Suomessa. [Evaluation of the need for ditch network maintenance in northern Finland]. Suo 49(3): 101–112. (In Finnish with English summary).
Lībieté, Z. 2015. The impact of forest management on environment and biodiversity. Final report on results of research project. Salaspils. 194 pp. (In Latvian).
Liljaniemi, P., Vuori, K-M., Tossavainen, T., Kotanen, J., Haapanen, M., Lepistö, A. and Kenttämies, K. 2003. Effectiveness of constructed overland flow areas in decreasing diffuse pollution from forest drainages. Environmental Management 32(5): 602–613.
Lukkala, O.J. 1949. Soiden turvekerronksen painuminen ojituksen vaikutuksetest (Referat: Über die Setzung des Moortorfes als Folge der Entwässerung). Communicationes Instituti Forestalis Fenniae 37. 67 pp.
Marttila, H., and Kløve, B. 2010. Managing runoff, water quality and erosion in peatland forestry by peak runoff control. Ecological engineering 36(7): 900–911.
Marttila, H., Vuori, K-M., Hökkä, H., Jämsen, L. and Kløve, B. 2010. Framework for designing and applying peak runoff control structures for peatland forestry conditions. Forest Ecology and Management 260(8): 1262–1273.
Minkkinen, K. and Laine, J. 1998. Effects of forest drainage on the peat bulk density of pine peatlands in Finland. Canadian Journal of Forest Research 28: 178–186.
Newcombe, C. P. and MacDonald, D. D. 1991. Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management 11: 72–82.
Nieminen, M. 2003. Effects of clear-cutting and site preparation on water quality from a drained Scots pine mire in southern Finland. Boreal Environment Research 8: 53–59.
Nieminen, M., Ahti, E., Nousiainen, H., Joensuu, S. and Vuollekoski, M. 2005. Capacity of riparian buffer zones to reduce sediment concentrations in discharge from peatlands drained for forestry. Silva Fennica 39(3): 331–339.
Nieminen, M., Ahti, E., Koivusalo, H., Mattsson, T., Sarkkola, S. and Laurén, A. 2010. Export of suspended solids and dissolved elements from peatland areas after ditch network maintenance in south-central Finland. Silva Fennica 44: 39–49.
Nieminen, M., Kaila, A., Koskinen, M., Sarkkola, S., Fritze, H., Tuittila, E-S., Nousiainen, H., Koivusalo, H., Laurén, A., Ilvesniemi, H. et al. 2015. Natural and restored wetland buffers in reducing sediment and nutrient export from forested catchment: Finnish experiences. In: Vymazal, J. (ed.)

The role of natural and constructed wetlands in nutrient cycling and retention on the landscape. p. 57–72. Springer, Switzerland.
Nieminen, T.M., Hökkä, H., Ihalainen, A. and Finér. L. 2016a. Metsänhoito happamilla sulfaattimailla. Luonnonvara- ja biotalouden tutkimus 12/2016. Luonnonvarakeskus, Helsinki. 42 p. (In Finnish). http://jukuri.luke.fi/handle/10024/532317.
Nieminen, T.M., Hökkä, H., Ihalainen, A. and Finér. L. 2016b. Skogsvård på sura sulfajordar. Forskning i naturresurser och bioekonomi. 13/2016. Naturresursinstitutet, Luke, Helsingfors. 40 p. (In Swedish). http://urn.fi/URN:ISBN:978-952-326-202-7
Nieminen, M., Palviainen, M., Sarkkola, S., Laurén. A., Marttila, H. and Finér, L. 2017. A synthesis of the impacts of ditch network maintenance on the quantity and quality of runoff from drained boreal peatland forests. Ambio. Doi 10.1007/s13280-017-0966-y.
Nieminen, M., Piirainen, S., Sikström, U., Löfgren, S., Marttila, H., Sarkkola, S., Laurén, A. and Finér, L. 2018. Ditch network maintenance in peat-dominated boreal forests: Review and analysis of water quality management options. Ambio. Doi.org/10.1007_s13280-018-1047-6.
Niinemets, Ü. and Valladares, F. 2006. Tolerance to shade, drought, and waterlogging of temperate northern hemisphere trees and shrubs. Ecological Monographs 76(4):521–547.
Ots, J. 2015. The Effect of Forest Drainage on Stands Growth: a Review Based on Journal Forestry Studies. Estonian University of Life Sciences, Bachelor work, Tartu. 33 pp. (Manuscript in Estonian).
Paavilainen, E. and Päivänen, J. 1995. Peatland forestry: Ecology and principles. Springer Verlag. 248 p.
Päivänen, J. 1973. Hydraulic conductivity and water retention in peat soils. Acta Forestalia Fennica 129. 70 pp.
Päivänen, J. 1984. The effect of runoff regulation on tree growth on a forest drainage area. Proceedings of the 7th International Peat Congress, Dublin, Ireland, Vol. 3: 476–488.
Päivanen, J. and Sarkkola, S. 2000. The effect of thinning and ditch network maintenance on the water table level in a Scots pine stand on peat soil. Suo 51(3): 131–138.
Päivanen, J. and Hånell, B. 2012. Peatland ecology and forestry – a Sound approach. Univ. of Helsinki, Dept. of Forest Sciences & Swedish Univ. of Agricultural Sciences, Dept. of Forest Ecology and Management, Publications 3. 267 pp.
Pallardy, S.G. 2008. Physiology of woody plants. 3rd ed. Academic Press.
Palviainen, M., Finér, L., Laurén, A., Launiainen, S., Piirainen, S., Mattsson, T. and Starr, M. 2014. Nitrogen, phosphorus, carbon and suspendid solids loads from forest clear-cutting and site preparation: Long-term paired catchment studies from Eastern Finland. Ambio 43(2): 218–233.
Piirainen, S., Finér, L., Andersson, E., Armolaitis, K., Belova, O., Čiuldiené, D., Futter, M., Gil, W., Glazko, Z., Hiltunen, T., Högbom, L., Janek, M., Joensuu, S., Jägrud, L., Libieté, Z., Lode, E., Löfgren, S., Pierzgalski, E., Sikström, U., Zarins, J. and Thorell, D. 2017. Forest drainage and water protection in the Baltic Sea Region countries – current knowledge, methods and needs for development. https://www.skogsstyrelsen.se/en/wambaf/drainage/ Forest drainage_short_document 2017.pdf
Porvari P. 2003. Sources and fate of mercury in aquatic ecosystems. Academic dissertation. University of Helsinki.
Prévost, M., Plamondon, A.P. and Belleau, P. 1999. Effects of drainage of a forested peatland on water quality and quantity. Journal of Hydrology 214: 130–143.
Sarkkola, S., Hökkä, H., Koivusalo, H., Nieminen, M., Ahti, E., Päivänen, J. and Laine, J. 2010. Role of tree stand evapotranspiration in maintaining satisfactory drainage conditions in drained peatlands. Canadian Journal of Forest Research 40: 1485–1496.
Sarkkola, S., Hökkä, H., Ahti, E., Nieminen, M. and Koivusalo, H. 2012. Depth of water table prior to ditch network maintenance is a key factor for tree growth response. Scandinavian Journal of Forest Research 27. 10 pp. doi:10.1080/02827581.2012.689004
Sarkkola, S., Nieminen, M., Koivusalo. H., Laurén, A., Ahti, E., Launiainen. S., Nikinmaa, E., Marttila, H., Laine, J. and Hökkä, H. 2013. Domination of growing-season evapotranspiration over runoff

makes ditch network maintenance in mature peatland forests questionable. Mires and Peat 11(2): 1–11.

Saarinen, M., Alenius, V. and Laiho, R. 2013. Kosteusolosuhteiden vaikutus siementen itämiseen ja taimien varhaiskehitykseen turvemaan metsänuudistusalan muokkauspinnoilla. (Summary: Effect of soil moisture conditions on seed germination and early seedling development in prepared microsites in peatland forest regeneration areas. Mires and Peat 64(2–3): 51–75.

Sikström, U. and Hökkä, H. 2016. Interactions between soil water conditions and forest stands in boreal forests with implications for ditch network maintenance. Silva Fennica 50 no. 1 article id 1416. 25 p. https://doi.org/10.14214/sf.1416

Sirin, A., Vompersky, S. and Nazarov, N. 1991. Influence of forest drainage on runoff: Main concepts and examples from central part of the USSR European Territory. Ambio 20: 334–339.

Smith, V.H. 2013. Eutrophication of Freshwater and Coastal Marine Ecosystems. A Global Problem. Environmental Science and Pollution Research 10(2): 126–139.

Toth, J. and Gillard, D. 1988. Experimental design and evaluation of a peatland drainage system for forestry by optimization of synthetic hydrographs. Canadian Journal of Forest Research 18: 353–373.

Tuukkanen, T., Stenberg, L., Marttila, H., Finér, L., Piirainen, S., Koivusalo, H. and Kløve, B. 2016. Erosion mechanisms and sediment sources in a peatland forest after ditch cleaning. Earth Surface Processes and Landforms 41: 1299–1311.

Uusitalo J. and Ala-Ilomäki J. 2013. The significance of above-ground biomass, moisture content, and mechanical properties of peat layer on the bearing capacity of ditched pine bogs. Silva Fennica 47(3) article 993. http://dx.doi.org/10.14214/sf.993.

Uusitalo, J., Salomäki, M. and Ala-Ilomäki, J. 2015. Variation of the factors affecting soil bearing capacity of ditched pine bogs in Southern Finland. Scandinavian Journal of Forest Research 30(5): 429–439.

Väänänen, R., Nieminen, M., Vuollekoski, M., Nousiainen, H., Sallantaus, T., Tuittila, E.-S. and Ilvesniemi, H. 2008. Retention of phosphorus in peatland buffer zones at six forested catchments in southern Finland. Silva Fennica 42(2): 211–231.

Vikman, A., Sarkkola, S., Koivusalo, H., Sallantaus, S., Laine, J., Silvan, S., Nousiainen, H. and Nieminen, M. 2010. Nitrogen retention by peatland buffer areas at six forested catchments in southern and central Finland. Hydrobiologia 641: 171–183.

Vompersky, S. and Sirin, A. 1997. Hydrology of drained forested wetlands. In: Trettin, C.C., Jurgensen, M.F., Grigal, D.F., Gale, M.R. and Jeglum, J.K. (eds.). Nothern forested wetlands. Ecology and management. CRC Press, Lewis Publishers. p. 189–211.

Zālītis, P. 2006. Preconditions of forest management. Riga, et cetera. 217 pp. (in Latvian).

Zālītis, P. 2012. Forest and water. Salaspils, Silava, 356 pp. (in Latvian).

Zālītis, P., Zālītis, T. and Lībiete-Zālīte, Z. 2010. Changes in stand productivity related to the deformation of drainage ditches. Mežzinātne 22(55): 103–115.

luke.fi

Natural Resources Institute Finland
Latokartanonkaari 9
FI-00790 Helsinki, Finland
tel. +358 29 532 6000