THE EFFECT OF PEAT LAND DRAINAGE AND AFFORESTATION ON RUNOFF DYNAMICS:

Consequences on Floods in the Glomma River

E. BEHEIM
Norwegian Water Resources and Energy Directorate,
Statens Park, N-3301 Tonsberg, Norway

KEYWORDS / ABSTRACT: Peat land / drainage / forestation / runoff dynamics

Drainage of peat land results in drier soil cover and reduced evaporation. This, in turn, generates higher annual runoff. However, the main hydrological effect of mire drainage is related to changes in the pathways of water through the soil, not to the change in water balance. Mire drainage can contribute both to increase and reduce runoff peaks. Changes in runoff can occur both as a direct and an indirect effect. The direct effect depends on peat hydraulic properties, mire type, the hydrological situation and drainage intensity. Where the afforestation is successful a denser forest cover will indirectly lead to reduced storm runoff as evapotranspiration will increase. The snowmelt runoff will also fall due to decreased snow melting rates and less snow accumulation. Where the peat has low hydraulic conductivity, which is often the case with fens, the drainage will result in a relatively high ground water table, low water storage capacity and rapid runoff. On mires with a high fibre content, low density and degree of humification, the conductivity and storage capacity can be relatively higher and drainage will result in increased water storage and reduced flood peaks. As time passes after drainage, the peat hydraulic properties will become saturated due to compaction by subsidence and increased decomposition, which in turn causes the runoff to increase again.

The impacts of ditching depend on the type of mire in question. On fens with a supply of water from upland fields, ditching may increase runoff from the whole watershed by bypassing the runoff from an upland area faster than the fen would have done in its natural state. Ditching of bogs causes changes in runoff dynamics only from the peat land itself. During small rainfall events on unsaturated mires, a major part of rainfall is stored and the runoff is delayed. With heavy rainfall on saturated peat, drainage here can lead to faster runoff. Runoff peaks from snowmelt are higher on drained areas if the outlet before ditching was unable to carry the melted water and if the ditches are not blocked with snow and ice. Forest stands have a dampening effect on snowmelt runoff. The snow accumulation may be reduced by 30 % in forest stands compared to clearings. Snowmelt in dense forest stands is about 2 mm/degree day. In clearings, the snowmelt is in the range 3

J. Krecek and M. Haigh (eds.),
Environmental Role of Wetlands in Headwaters, 59–75.

to 6 mm/degree day, mainly due to increased albedo. In the Glomma watershed, drainage of forest area has probably not contributed to higher runoff rates and increased flood peaks, as only a smaller portion of the watershed has been drained and because the forest growth has increased due to the drainage effect. In smaller watersheds with a high proportion of drained peat lands, especially fens, the flood peaks are likely to have increased.

1. Introduction

HYDRA was a research programme on floods initiated by the Norwegian Water Resources and Energy Directorate (NVE) The programme was initiated after a large flood in the south-eastern part of Norway in 1995 in the watersheds of the rivers Glomma and Gudbrandsdals- lågen. The flood was created by rapid snowmelt in a high altitude area combined with a 50-70 mm rainfall in the lowlands. During the flood several villages and more than 14000 ha of agricultural land were inundated, resulting in considerable damage. The extraordinary magnitude of the flood, both in volume and peak level, triggered a discussion of whether the severity of the flood was caused in part by man-made changes in land use. The working hypothesis was that the sum of all human impacts as relates to land use, hydropower development, river regulation, flood embankments works, etc., may indeed have increased the risk of floods.

The main objective of the HYDRA project was to support knowledge on effects of watershed management practices on floods, and to develop methods to reduce flood risk. The effect of drainage of peat land was considered to have contributed considerably to the flood peak in 1995. In many Norwegian watersheds, large areas of peat land have been drained for agricultural production and forestry. Therefore, drainage might have had some effects on run-off patterns.

The aim of this study is to evaluate the effect of peat land drainage on flood peaks. Existing literature on the effect of drainage is reviewed. Some calculations are presented on the effects of drains and soil moisture storage on runoff generation. Finally, a conclusion is made on the effects of drainage based on the information on the area drained and on the results of this review.

2. Peat land drainage in Norway

Drainage has been carried out to improve the growing conditions for peat land. Ditching increases temperature, content of oxygen and biological activity. In Norway, cultivation of peat lands began in the 17th century. Drainage continued on a large scale with government support until the 1970s when subsidies were discontinued and drainage reduced. Altogether about 200,000 ha have been drained for agriculture, 400,000 ha for forestry, and approximately 27,000 ha for peat production. In some regions such as in Sørlandet, the southernmost part of Norway, peat land today occupy as much as 25 % of the agricultural land.

In forest stands the open ditch network has been dug quite irregularly. Usually, the distance between the ditches has been 20-50 m. The agricultural drains have been more densely placed at 0.8 m depth and with 7-8 m intervals. The forestry drains have not been maintained to the same extent as the agricultural drains. In total, the proportion of drained area is only 20 % of the peat land area, making up about 3 million ha, which is considerably less than in the other Nordic countries.

Region	**Forest area (ha)**	**Drained area (ha)**			
	1997	**1920**	**1950**	**1980**	**1997**
Østfold	936,000	1,234	48,902	117,828	131,123
Hedmark	11,593,000	21,123	352,820	803,190	892,064
Oppland	5465000	4,778	128,874	279,118	293,322
		Drained area (% of forest area)			
Østfold	936,000	0.1	5.2	12.6	14.0
Hedmark	11,593,000	0.2	3.0	6.9	7.7
Oppland	5465000	0.1	2.4	5.1	5.4

Table1. The total mire area drained for forestry in southeast Norway in 1920-1997.

In the flood sensitive watersheds of Glomma and Gudbransdalslågen, the main reason for drainage of mires is to increase forest production. Drainage of forest land was particularly intensive in the 1950s and 1960s, when 5,000 ha was drained annually. In the period 1960 – 1985, 8-9 % of the forest area of Østfold County and 3-4 % of the forest area of Hedmark and Oppland Counties was drained. The affected area is larger than the 892,064 ha ditched, because ditching of fens might affect hydrology of the area surrounding a fen.

The statistics for forest and agricultural drainage in the regions covering the flood sensitive watersheds is given in Table 1. The percentage drained compared to the total forested area is largest in Østfold County. In most districts drainage has decreased steadily from the late 1960s. Today, mire drainage is generally not allowed and only a small portion is drained for agriculture, peat production, sport facilities and other kinds of urban development.

3. Introduction to Hydrological Characteristics of Peat and Peat land

3.1. DEFINITIONS AND CHARACTERISTICS OF NORWEGIAN PEAT LAND

Peat land is one type of a larger group of wetlands. Marshes, coastal flood plains and swamps have a mineral substrate and do not accumulate peat, whereas peat lands form in moist areas where the rate of production of organic material exceeds the rate of degradation which in turn results in organic peat deposits. Mires are usually used as a synonym for peat lands which are made up of a layer of peat exceeding 30-40 cm. Mires are classified based on hydrological characteristics as fens, which receive water from rainfall and from the surrounding area, or as bogs, where the rainfall is the only source of water input.

In Fenno-Scandia mires formed after the last Ice Age l0,000 years ago and reached their present appearance about 1000 BC. They were formed directly on mineral soils, from wet forests or from filling of lakes. Due to the varying climatic conditions in different parts of Norway, there is an exceptionally large variety of mires. Along the west coast, extensive rainfall results in very wet conditions, which sustain the development of peat on relatively steep slopes and the formation of blanket bogs which are not present elsewhere in Fenno-Scandia. The most common type of mire is fen (Aapa mires), which is found throughout the country. In the North, the ice formation and melting of these fens has resulted in large hummocks and in mires called Palsa mires. In parts of Norway with milder climate, the fens have grown, resulting in ombotrophy and the formation of raised bogs. Bogs are most abundant in the south-eastern part of Norway and in the Trøndelag region. Direct age measurements have not been made in Norway, but growth rate has been estimated at 0.2-0.4 mm/year [18]. Based on Finnish estimates the mires have grown to 60-70 % of their maximum size, which might be used as an estimate for the size of the Norwegian mires. The average depth of catotelm being observed in mire inventories is 2 m.

3.2 HYDRAULIC PROPERTIES OF PEAT

Mires consist of two different layers of organic material. The living and rapidly decaying plant layer (acrotelm) overlies a compact brown layer of partly decomposed peat (catotelm). The transition from one layer to the other is rapid. The depth of acrotelm is usually around 0.3-0.5 m. The soil properties governing flow are very different in these two types of layers. The hydraulic conductivity of the upper layer is about 0.1 m/s [7], [16]. The underlying layer has a considerably lower conductivity. The hydraulic conductivity increases with increasing fibre content and decreases with increasing humification and density [4]. The unsaturated hydraulic conductivity decreases rapidly with moisture content. This decrease is less for peat with an even pore size distribution. Well humified fen peat might have a higher unsaturated conductivity than bog peat [12]. The specific storage (S) of the upper layer is 0.8-1.0 and for the lower layer 0.13-0.26 [19], but these values are not well documented. A large variation in the peat properties is due to plant composition, degree of humification, stratification of the peat and compaction. A consistent difference between the hydraulic conductivities in the horizontal and vertical directions has not been observed [13].

Some properties of peat change following drainage [14]. Subsidence is a well-documented phenomenon. The primary subsidence of peat is caused by loss due to compaction of pores as the water table is lowered. Peat might be further compressed after drainage by wheel traffic from forestry and agricultural machines [14], which might be particularly high in case of low peat shear strength [19]. The secondary subsidence is caused by loss of carbon as CH4 and CO2, and due to leaching of carbon in runoff waters. An annual settling rate of 1.2-4 cm/year has been observed in Norway on cultivated peat soils.

3.3 HYDROLOGICAL FEATURES OF BOREAL PEAT LANDS

Some general conclusions can be made about the hydrology of pristine mires. Mires form in regions where the annual evapotranspiration (ET) is lower than the precipitation (P). The soils are relatively wet during periods when P exceeds ET because subsurface lateral and vertical water movement rates are variously limited by combinations of flat or low-lying terrain and low soil conductivity [14]. Poorly drained wetland soils are usually saturated near the surface during winter and early spring. The low gradient and near-saturated state make it likely that extensive saturationexcess overland flow will be produced [7]. Due to very little storage for rainwater, stream flow from peat bogs is poorly regulated. The old popular idea that mires act as sponges mopping up heavy rain is far from the truth if not entirely mythical [8]. The first rain after a long dry period may be effectively absorbed, but once the acrotelm is recharged the ability to retain further water is greatly limited.

Storm runoff response is controlled by the layering of the peat into two hydrologically different layers. It has been shown in many studies that runoff from mires depends on ground water level in the peat [13]. In response to rainfall, the water table may rise until it intersects the surface and the much higher permeability, and allows rapid runoff. If the ground water table lies in the transition between acrotelm and catotelm, as often is the case, rainfall results in rapid runoff response due to the very high conductivity of the uppermost layer. Due to low seepage rates from the catotelm, the base flow production from peat-covered catchments is very poor [7]. It has been observed that during dry periods in summer and winter the runoff might cease completely [3], [7], [15], [32]. The outflow from types of mires formed in valley depression, such as some fens, occurs in much the same way as for a lake i.e. controlled by the outlet configuration and the water level in the peat land. High runoff peaks during wet conditions and no flow during dry summer conditions are typical of these wetlands. It follows from the discussion above that virgin mires are characterised by a small portion of base flow and a rapid runoff response to rainfall.

Most hydrological studies of mires have been done on raised bogs where it has been shown that runoff depends on the interrelationship of ET and rainfall [14]. During the summer there may be periods of several days without rain, during which the water table falls from day to day. The plant roots extract water from both saturated and unsaturated zones and water is re-distributed at night to restore equilibrium above the water table [13]. Observations in the UK [13] show that the transpiration compared to potential evapotranspiration is very low in the early part of the summer but picks up in late June and peaks in July found that transpiration was between 50-60% of the potential evapotranspiration during the summer months and postulated that the ratio would rise to 80 % in September and remain at 100 % over the winter, as interception losses and evapotranspiration take over from transpiration. Total runoff is usually low with relatively low peaks during the growing season when ET maintains high soil moisture storage. During the dormant season when ET is low and soils remain saturated, heavy rainfall results in high peaks [14].

It should be noted that the hydrology of mires is site specific as it is depends on factors such as the surface inclination and the geological setting where the peat land has been formed. Due to the influence from the upland area, the hydrological characteristics of fens are site specific and not as well known as those of bogs, which receive water input from rain alone. In the event of a large surrounding catchment draining to a fen, it is reasonable to assume that the base flow is sustained throughout the summer and the runoff is even higher than that from bogs [14]. On the other hand, if the surrounding up1and portion is small, the base flow might cease during summer as the water from the upland will have 'evapotranspirated' in the wetland. It has been suggested that the evaporation from fens is greater than from bogs, which results in a smaller annual runoff from fens [27].

4. Review of hydrological consequences of peat land

4.1 WATER BALANCE ON DRAINED AND UN-DRAINED MIRES

Several authors report an increase in low flows following drainage [15], [31], [32]. This is due to the decrease in evapotranspiration rates due to drier topsoil caused by the lowering of the water table after drainage. In natural conditions, evaporation has been found in some studies to be higher for fens than for bogs [17]. Eyzennan`s results [12] indicate that the soil cover will be drier for fens than for bogs after drainage and therefore the decrease in evaporation might be higher for bogs.

For drained bogs the general decrease in ET is almost 100 % in midsummer and is naturally less with developed tree stands [32]. Perhaps the most important reason for the increase in base flow observed in many studies [32] is due to the fact that the soil water storage capacity is increased and the release of water from this storage maintains a high runoff throughout the summer. The increased discharge of artesian groundwater may in some cases increase summer and winter low-water runoff. An estimate of summer low-water increase is given as 50% by Sirin et al. [32] depending on the level of alteration in the drainage area.

Most research points out that drainage does not have a significant effect on the annual runoff coefficient. The annual water balance from mires tends to be similar to the overall regional water balance. Sallantaus [30] found that the annual runoff from Finnish peat mires is equivalent to the annual runoff in Finland, which means that on average 46 % of the 660 mm of rainfall runs off. The proportion of rain that generated runoff during previously reported annual runoff coefficients from drained areas was: 47 [6], 50 [30] and 69 [26]. These coefficients are in the same range as values previously observed from un-drained areas: 16 [26], 36 [34], 50-62 [7], 60 [10], 73 [26], 79 [6] and 84 [30]. The variation in runoff-coefficients is partly due to problems in measuring the water balance from mires [7], [27]. The loss of precipitation through interception is difficult to quantify because of a rather variable vegetation cover and the density of near-ground vegetation [13]. Despite small changes to the water balance, drainage changes water pathways [7] and effects individual storm peaks [19].

4.2 CONSEQUENCES OF DRAINAGE ON PEAK FLOWS

Previous studies of the effect of drainage on peak flow have provided mixed results [7], [29]. In a majority of cases a decrease [7], [23], [15] in peak flows have been reported after drainage, but an increase in floods has also been noted [9], [20], [31], [26]. The divergent effects on flows are partly due to the fact that drainage has both reducing and increasing effects on peak flows. Soil water storage may increase temporarily due to drainage and thus store part of the rainfall, whereas the channel network and the higher hydraulic gradients result in a quicker runoff [32], [19]. When additional factors affecting runoff are included, such as interception, rainfall intensity and surface morphometry, the assessment of drainage impacts becomes even more complicated [32].

During the non-frost season the main factor determining the peak on drained areas is whether overland flow in the acrotelm will occur or not. If the infiltration and storage capacities are not exceeded, the rainfall will only result in a rise in the catotelm groundwater level and the runoff will be small compared to undrained cases, where the runoff usually occurs in the acrotelm [19]. If the groundwater level rises close to the surface on drained areas, the runoff will increase. On most drained forest areas the catotelm storage will quickly be filled up and result in rapid overland flow if rain continues to fall. In ditched forest areas, the moisture deficit in the peat was rapidly satisfied, and the runoff peak was not markedly reduced by increased infiltration, at least not for heavy rainfalls [19], [31], [32]. A fivefold increase in peak runoff was observed on a Russian mire after ditching [32]. An increase of 131 % in summer peak runoff and 31 % during snowmelt peak runoff was noted after drainage in Finland with 60 cm drain depth, 40 m spacing and 40 % drained area [31]. However, 10-20 years after forest growth the drainage impacts were reduced. The spring maximum peak was 13 % smaller on the ditched area. The summer maximum was only 19 % larger on a ditched than on an unditched mire. The decreasing peak flows were related to much lower flood peaks in that period, to increased interception in the forestry canopy and to impairment of the ditches. A reduction in spring runoff after drainage when the canopy had developed has been noted by Heikurainen et al. [15].

The effect of the location of the drained area within the river basin on peak flows and timing of the peak has got some attention in the literature. Sirin et al. [32] have observed that peak runoff increases most when the drained area is situated in the upper part of the watershed. Sirin et al. [32] also showed with modelling that an even distribution of the drained area results in the lowest peaks, and that the highest peaks are observed when the drained area is close to the outlet of the drainage area, which is often the case when fens are drained. Seuna [31] observed that the peak occurred 1.5 days earlier on drained areas compared to un-drained catchments, which was related to drainage itself and clear-cutting.

Very little attention has been paid to the effect of drainage on runoff from upland areas surrounding fen mires [5]. This is unfortunate as fens in particular are suitable for drainage and forestry due to the higher nutrient status. On wetlands the upland water is partly intercepted and evaporated. After drainage the upland water is conveyed in artificial channels. Therefore, drainage evidently increases runoff from the upland portion of catchments. The effect on the flood peak is probably small as the runoff from mires is also quite rapid due to the high conductivity.

The hydrology of boreal mires is dominated by impacts of snow pack and frozen soil, which results in low runoff in the winter and high runoff during the spring snowmelt [14]. It has been assumed that the impact of forest drainage on snowmelt runoff is more complex than on summer runoff [32], although there are very few published results on snowmelt runoff from mires. Results from modelling [32] and observations [33] indicate that the effect of drainage on snowmelt runoff is small and only minor alterations in snowmelt hydrographs have been observed after drainage. Seuna [31] noted a somewhat minor increase in spring time compared to summer flood peaks in a ten-year period after drainage.

4.3 THE EFFECT OF AFFORESTATION ON RUNOFF

Much of the research on the hydrological effects of drainage has not included the effects of forestry and tree development despite the fact that peat land drainage is usually done to increase forest production. The experimental methods used have not managed to separate the hydrological effects imposed by ditching and the effect of tree development [14]. It is well known that the vegetation cover has a strong influence on the water balance [14]and that forests have widely been claimed to reduce flooding downstream [29]. The presence of forest cover is associated with reduced annual water yield. This has been demonstrated repeatedly by comparisons of similar forested and non-forested catchments and by noting the effects of deforestation, reforestation and afforestation [22]. According to Anderson et al. [1], previous results show that afforestation of conifers increases water yield of the vegetation by 140-390 mm in climates with less than 1000 mm rainfall.

Developing tree stands decrease runoff by altering snowmelt conditions and increasing interception and evapotranspiration. The development of canopy increases the surface area from where water can evaporate more rapidly. Rainfall quantity, duration and intensity, as well as the state of the crop, all play a part in determining the amount of interception. Robinson et al. [29] observed a halving of the runoff coefficient when the tree plants had grown from 2 to 22 years. Seuna [31], too, observed a decreasing trend in runoff as trees developed. The effect of forest on peak runoff from rainfall will depend on the soil moisture content. On mires with little seepage, increased evapotranspiration will result in increased soil water storage and reduce peak flows. During wet soil conditions, when precipitation exceeds evapotranspiration, the effects of forest in retarding peak flows is minimal, as the canopy storage only takes up about 2 mm of precipitation [22].

Several studies show that forests reduce runoff peaks from snowmelt [25]. Observations show less accumulation of snow in forest than in clearings, which has been related, in most cases, to the evaporation of intercepted snow [24]or to wind redistribution of intercepted snow [35]. A maximum loss of 3.3 mm/24 h has been found from two winter measurements in Sweden [24]. Some resent results in Sweden and Norway show that the interception of snow and the consequent loss in water yield can be up to 30 %.

The snowmelting rates used in snowmelt calculations from forested areas is smaller than from open fields. Generally, 2 mm/degree day has been reported from forests. The melt rate from open fields is higher and more variable than from forests. In early melting the rate is about 3 mm/degree and increases towards 5-6 mm/degree in the late snowmelt, mainly due to decreasing albedo. This indicates that in the late snowmelt 40 mm less water will run off from forests during a day of l0 degree Celsius. Indeed, timber harvesting in areas with substantial snow cover has been seen to increase snowmelt runoff [24]. Because the snowmelt from forested areas is smaller in magnitude and volume than from clear fields, it is logical to assume that afforestation of wetlands will result in smaller peak flows and smaller runoff volumes following snowmelt when the tree stand has developed.

4.4 THE EFFECT OF DITCH DEGRADATION

Over time the ditch depth on mires is reduced due to erosion, siltation, peat subsidence, freezing-thawing and vegetation. The reduction in depth occurs most rapidly during the first few years after ditching. The deeper the ditches are dug, the more rapid is the loss in ditch depth due to peat subsidence. The growth of Sphagnum and Carex in the ditches may decrease the ditch depth by 25 % after 5 years. Eventually, without any maintenance of ditches, the hydrological situation will return to its natural state. Observations in northern Finland show a decrease in ditch depth from 70-80 cm to 30-40 cm in 30 years [21]. Information is not available on how this affects runoff.

5. Effect of drainage on runoff: analysis of governing factors

Previous studies on drained and un-drained areas show converging results on the effects of ditching on peak flows. This is due to the fact that drainage has both a decreasing effect on peak flow due to increased soil water storage, and an increasing effect due to the large channel network and higher hydraulic gradients [32], [14]. The increased soil moisture storage capacity allows part of the rain to be temporarily stored in the soil which decreases flood peaks. On the other hand, when the moisture storage is filled up, continued rain results in rapid runoff as the increased channel network allows rapid overland and groundwater flow, thus enhancing floods. It is therefore important to evaluate the possible moisture storage in the peat caused by drainage.

When assessing the hydrological system of drained mires, there are three conditions that have to be fulfilled before large peak flows can be produced during or after rainfalls. These are:

- Soil and canopy water storage filled up.
- Rapid runoff from strips to ditches.
- Efficient channels to convey the increased overland flow.

When the canopy water storage is filled up, excess water will be infiltrated into the peat. When the field capacity has been reached, excess precipitation results in an immediate increase in groundwater level. The immediate increase in ground water level can be derived from effective porosity and rainfall. An increase in groundwater depth results in an increase in runoff as the hydraulic gradient is increased. In most cases it is reasonable to assume that the drainage network is able to carry the excess water away rapidly. It is also reasonable to assume that condition 3 does not usually control runoff. Where the ditches lack maintenance, the carrying capacity may have been reduced due to a decrease in channel depth by peat subsidence and increased channel roughness due to vegetation, erosion and siltation. Conditions 1 and 2 are probably the most restrictive factors for rapid runoff generation. Next we will estimate the effect of conditions 1 and 2, calculate the moisture storage available after drainage, and estimate the effect of drains on peak flows.

5.1 THE EFFECT OF SOIL MOISTURE STORAGE IN ATTENUATING PEAK FLOWS

Drainage of peat lands lowers the groundwater levels and increases the depth of the unsaturated zone. This may have a significant effect on runoff as the increased moisture storage allows rainfall to be temporarily stored in the peat [14]. The soil water storage after drainage will be evaluated in this chapter.

The depth of the unsaturated zone after drainage is dependent on the hydraulic conductivity of the peat, drainage intensity and drain depth. Where evapotranspiration from acrotelm is less than the moisture transport from the saturated catotelm, the soil moisture stays close to field capacity. The maximum rate of moisture transport depends on the depth of the groundwater table. Eyzerman [12] has shown with the Darcy moisture transport equation that 50 cm and 70 cm ground water depths for high-moor and low-moor, respectively maintain a 3-4 mm/ day moisture transport, i.e., if ET is below 3-4 mm/d the soil stays at field capacity. This is in agreement with field observations [28], when he observed that when the distance to ground water level remains below 60 cm the soil moisture content follows the theoretical matrix suction corresponding to the distance of the ground water table. The general drainage norm in Norway has been that the depth to the groundwater surface should be 30 cm [6]. Usually forest ditches have been 50-80 cm deep at 15 - 30 m distance apart. On agricultural land a ditch depth of 80 cm at 7-8 m intervals has been used in south-eastern Norway. Based on the relatively shallow drainage it is reasonable to assume that in the case of forest drainage the peat stays at field capacity, at least for groundwater fed fens, receiving a constant seepage of water from the upland.

Some approximate calculations have been made on the capacity of the soil moisture storage after drainage when the peat is at field capacity. This is done based on observations by Paivanen [6] on moisture in forestry drained Finnish peat soils. The results of these calculations indicate that the initial soil moisture storage is usually filled up by rainfall below 10mm, indicating very little moisture storage on forestry drained mires. In most cases, severe floods in the non-frost season occur due to periods of large rainfall. On such occasions moisture storage does not have a large effect on floods. According to Sirin et al. [32] peat soil storage also has little effect due to the hydro-metrological conditions prevailing during flood periods. This agrees with studies in Finland on forestry drained peat lands, where it has been observed that soil moisture storage has an attenuating effect on small rainfall events only and not on large events (Seuna 1981). Open drainage is well known to have little effect in lowering the water table of the adjoining peat land (Boelter 1972 in [13]). However, in some very special situations where the drain intensity is very high, the drains are deep and the soils relatively permeable as e.g., on some cutover peat lands, the increased soil moisture storage will attenuate the peak runoff considerably as observed in studies by Kløve [19].

5.2 THE EFFECT OF DRAINS IN GENERATING PEAK FLOWS FROM MIRES

On natural mires the water table is lowered in the summer time after periods of drought and low flow. When the water table rises in acrotelm, increased storm flow is generated due to high conductivity. At high water levels the storage coefficient is rather close to unity, which means that very large storms only cause a small rise in groundwater levels. Due to the high conductivity of the acrotelm, the transmissivity of the catotelm need not be accounted for.

Forested mires are, in their hydraulic behaviour, either similar to natural non-forested mires or similar to heavily drained cultivated peat land, depending of whether the groundwater table lies in the acrotelm or in the catotelm. The water table is generally in the catotelm during low flows. If the ditches are deep enough, recharge will not fill up the catotelm storage, the groundwater will fluctuate in the catotelm of low hydraulic conductivity, and the runoff will be similar to the runoff from cultivated and heavily drained peat lands. If the ditches are shallow, which is usually the case, the recharge will eventually fill the catotelm storage, the groundwater will rise into the acrotelm and increased recharge will be generated in the acrotelm as in natural mires. Because of the dual property of the forestry drained areas, soil properties similar to natural as well as heavily drained conditions needs to be used in a runoff calculation.

Peak flows from the different scenarios have been calculated, showing that drainage can either reduce or increase peak runoff. The main factor controlling whether the runoff increases or decreases is the location of the groundwater table before recharge occurs. If the mires are drained only to shallow depth, as is usually the case with forested mires, runoff will be generated within the acrotelm and drainage will increase the runoff peaks by almost one order of magnitude, from a peak runoff being about 10% of the daily rain intensity to a runoff peak corresponding almost to the daily mean rain intensity assuming that channel network is able to carry the storm water. The increase in peak flow is due to increased hydraulic gradients imposed by drainage. The results ([7], [18], [19]) show that runoff peaks from natural mires, about 7-20% of the daily mean rain intensity, tend to be larger than peaks from deeply plough-drained sites, the runoff peaks from the scenarios being about 7 % of the rainfall intensity. If the channels are deep enough, the groundwater table will fluctuate in the catotelm, where the hydraulic conductivity is low, so when the groundwater level controls the runoff, the peak discharge rates will always be smaller on deeply forestry drained areas than on natural mires. It should be noted that on some cultivated peat sites, the soil surface is lowered, compacted and the storage reduced. Here the groundwater level may reach the soil surface and initiate surface runoff which greatly increases peak flows.

6. Evaluation of the effects of plough drainage of peat land on flood peaks from Norwegian watersheds

Based on a review of the literature and theoretical calculations, it seems as if peat land drainage for forestry can both increase and reduce flood peaks. The effect obtained depends upon geological structure, geography, climate and ditching practices. The most important conclusions drawn from this study are:

- Ditching increases the un-saturated zone and therefore allows more rain to be temporarily stored. However, as this storage is rapidly filled, more runoff will be generated due to steeper gradients after drainage. This dual effect results in a reduction of small peak flows and an increase of intermediate peaks.

- Increased tree growth increases evaporation. Evaporation of intercepted snow results in less snow accumulation in forests than in clearings. The reduction in snow volume may be up to 30 %.
- The tree stands reduce snowmelt rates from 3-6 mm/degree-day to approximately 2 mm/ degree-day resulting in a smaller runoff peak after afforestation.
- Ditching of fens will probably increase the peak flow from the upland area. Most mires that have been drained in Norway are fens with a considerable portion of upland area. This implies that a considerably larger area than just the mires is affected by drainage. After ditching the runoff will increase if prior to ditching the runoff peak rates from upland were, at least partly, controlled by a poor carrying capacity of surface flow through the natural wetland. The importance of this effect is probably not significant as the hydraulic conductivity in acrotelm is large and the runoff also in a natural state flushy.
- The increase in intermediate peaks may result in changes of channel morphology so that channels become deeper, the flow resistance lower and the largest peaks become larger.

In the Glomma basin, the proportion of drained mires in large watersheds is generally less than 10 %. It is known that the drains function for not more than approximately 30 years. It is reasonable to conclude that the drained area is smaller than that given in table 1 and that the area of drained mires will be reduced in the future. Assuming a drained area returns to natural condition after 30 years, the drained area is well on its way to a natural state, as most of the drainage was carried out more than 30 years ago.

7. References

1. Anderson, A. R., Pyatt, D. G and J.P. Stannard (1990) The effects of clear felling on a sitka spruce stand on the water balance of a peaty gley soil at Kershope Foi'est, Cumbria. *Forestry*, 63: 51-70.
2. Arheimer, B., Andersson, L. and A. Lepisto (1996) Variation of nitrogen in forest streams – influences on flow, seasonality and catchment characteristics. *J. of Hydrology*, 179: 281-304.
3. Bay, R.R (1969) Runoff from small peat land watershed. *J. of Hydrology*, 9: 90-102.
4. Boelter, D. H. (1969) Physical properties of peats as related to degree of decomposition. *Soil Sci. Amer. Proc*. 33: 606-609.

5. Branfireun, B. A., Heyes, A. and N.T. Roulet (1996) The hydrology and methylmercury dynamics of a Precambrian Shield headwater peat land. *Water Resour. Res.*, 32: 1785-1794.
6. Burke, W (1975) Aspects of the hydrology of blanket peat. In: *Hydrology of marshridden areas* .UNESCO / IAHS, 171-182.
7. Burt, T .B., Heathwaite, A. L. and J.L. Labadz (1990) Runoff production in peat covered catchments. In: M. G. Andersson and T.P. Burt (eds), *Process studies in hillslope hydrology*, John Wiley, pp. 463-499.
8. Clymo, R. S. (1987) The ecology of peatlands. *Sci. Prog., Oxf.* 71: 593-614.
9. Conway, V. M. and A. Millar (1960) The hydrology of some small peat covered catchments in the Northern Pennies. *J. Institute of Water Engineers*, 14: 415-424.
10. Devito, K. J. and P.J. Dillon (1993) The influence of hydrologic conditions and peat oxia on the phosphorus and nitrogen dynamics of a conifer swamp. *Water Resources Research*, 29: 2675-2685.
11. Dunn, S. M. and R. Mackay (1996) Modelling the hydrological impacts of open ditch drainage. *J. of Hydrology*, 179: 37-66.
12. Eyzerman, N. I. (1993). Physical properties and drainage standards of forest soils. *Eurasian Soil Science*, 25: 104-110.
13. Gillman, K. (1994) *Hydrology and Wetland Conservation*. Institute of Hydrology, Wallingford, UK. Wiley, 101 p.
14. Gregory, J. D. (1988) Hydrologic impacts of forest water management. In: D. D. Hook et al.(eds), *The Ecology and Management of Wetlands*, Timber Pess, pp. 137-147.
15. Heikurainen, L., Kenttamies, K. and J. Laine (1978) The Environmental effects of peat drainage. *Suo*, 29: 49-58.
16. Hobbs, N. B. (1986) Mire morphology and the properties and behaviour of some British and foreign peats. *Quarterly Journal of Engineering Geology*, 19: 7-80.
17. Ingram, H. A. P. (1987) Ecohydrology of Scottish peatlands. *Transac. Royal Society of Edinburgh: Earth Sciences*, 78: 287-296.
18. Johansen, A. (1996) The extent and use of peatlands in Norway, In: Eino Lappalainen (ed.), *Global peat resources*, International Peat Society,pp .113-117.
19. Kløve, B. (1997) *Environmental impact of peat mining, development of storm water treatment methods*. PhD thesis, Lund University, 159 p.
20. Krug, A. (1993) Drainage history and land use pattern of a Swedish river system- their importance for understanding nitrogen and phosphorus load. *Hydrobiologia*, 251: 285-296.
21. Lauhanen, R., Piironen, M.L., Penttila, T. and E. Kolehmainen (1988) Evaluation of the need for ditch network maintenance in northern Finland. *Mires and Peat*, 49: 101-112 (In Finnish with English abstract and summary).
22. Lee, R. (1980) *Forest hydrology*. Columbia Univ. Press.
23. Lundin, L. (1988) Impacts of drainage for forestry on runoff and water quality. In: *Hydrology of wetlands in temperate and cold climates*, Vol.1, The Academy of Finland, 197-205.

24. Lundberg, A. (1996) *Interception evaporation, processes and measurement techniques* PhD Thesis, Luleå Univ. of Tech., Div. of Water Res. Eng. , 196pp.
25. Ohta, T., Hashimoto, T. and H. Ishibashi (1993) Energy budget comparison of snowmelt rates in a deciduous forest and an open site. *Annals of Glaciology*, 18: 53-59.
26. Panu, U. S. (1988) Environmental assessment of peatland development operations in Newfoundland. In: *Hydrology of wetlands in temperate and cold climates*, Vol.1, The Academy of Finland, 291-300.
27. Price, J. S. and D.A. Maloney (1994) Hydrology of a patterned bog-fen complex in south-eastern Labrador, Canada. *Nordic Hydrologym* 25: 313-330.
28. Paivanen, J. and E. Paavilainen (1996) Forestry on peatlands. In: Vesander, H. (ed.), *Peatlands in Finland*, Finnish Peatlands Society, 72-83.
29. Robinson, M., Gannon, B. and M. Schuch (1991) A comparison of the hydrology of moorland under natural conditions, agricultural use and forestry. *Hydrological Sciences*, 36: 565-517.
30. Sallantaus, T. (1994) Response of leaching from mire ecosystems to changing climate. In: M. Kanninen and P. Heikinheimo (eds), *The Finnish research program on climate change, second progress report*. The Academy of Finland, Publication 1/94, 298-303.
31. Seuna, P. (1981) Long-term influence on forestry drainage on the hydrology on an open bog in Finland. *National Boards of Waters*, Finland, 43: 3-14.
32. Sirin, A., S. Vompersky and N. Nazarov (1991) Influence of forest drainage on runoff: Main concepts and examples from central part of the USSR European territory. *Ambio*, 20: 334-339.
33. Starr, M. R. and J. Paivanen (1981) The influence of peatland forest drainage on runoff peak flows. *Suo*, 32: 79-84.
34. Verry, E. S. and D.R. Timmons (1982) Waterborne nutrient flow through an upland-peatland watershed in Minnesota (Ecology), 63: 1456-1467.
35. Wheeler, K. (1987) Interception and redistribution of snow in a subalpine forest on a storm-by- storm basis. In: *Proc. 55th Western Snow Conference*, Vancouver, B. C., pp. 78-87.