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Impacts of forest drainage on flow regime

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Abstract

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High floods in watercourses are of great interest, because of the potential hazards they pose to people and low-lying land near rivers. In many parts of the world, inundations are common and in northwest Europe there are high discharges almost every year, occasionally with serious consequences. In Sweden, such a major flood occurred in 1985, causing a dam-burst. Land use in the area was mainly forestry, and fairly extensive clear-felling and drainage were believed to have amplified high discharges following heavy rain. This led to investigation of the hydrological consequences of these forestry activities. Drainage was carried out both as new drainage of virgin peatlands, and as drainage of moist and wet mineral soils, i.e. remedial drainage of clear-felled areas. The investigations were made on small catchments and utilised the calibration period and control basin technique, using linear regression relations. Peatland drainage resulted in reduced high discharges, while drainage of clear-felled areas resulted in increased high discharges, as compared to forested conditions. However, drainage of clear-felled areas partly led to reduced peak flows. A high groundwater level was an important prerequisite for increased discharges. When results from small catchments were applied to larger rivers, the effects of forest drainage were small, i.e. increases were less than 10%.

Key words: Clear-felling, groundwater level, inundation, peatland, regression, remedial drainage, runoff, till.

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Introduction

Drainage experience and origins of the study

Drainage extent

In NW Europe, forest drainage has been practised for the past century. Initially, activity was low, but during the Depression years of the 1930s, drainage became extensive, and in Sweden about 56 000 ha were drained in 1933 alone. By 1940, the total drained area in Sweden was about 1 Mha. Drainage activity was low during a ten-year period which included the Second World War, but this was followed by a 35-year period of increased forest drainage. In 1984, the extent of drainage reached a peak, almost 70 000 ha being drained in that year. This has partly contributed to the highly productive forests of today.

During a three-year period (1984–86) drainage activity was comparatively high. After 1986, however, there was a rapid decline in drainage, partly caused by a changed view of forest wetlands. In 1990, new wetland drainage amounted only to about 7400 ha (the preliminary extent for 1992 is 5000 ha), in addition to a further 11 000 ha, concerning drainage of clear-felled peat and mineral soil areas, denoted 'remedial drainage'. In Sweden, 1.5 Mha have so far been drained for forestry (Hånell, 1990).

Wetland hydrology

Wetlands and drainage have attracted considerable interest during the past decade. The traditional response to forest wetlands, fens and bogs, has been to drain them. However, attitudes have changed, and the ecological value of wetlands has increasingly been recognised (Maltby, 1986; Finlayson & Larsson, 1990; Löfroth, 1991). This has mainly concerned wetlands as a diverse habitat, but hydrological values have also been considered, and the role of wetlands as graded reservoirs has been widely discussed.

The traditional hydrological concept of forest wetlands is the popular 'sponge' concept, as described by von Humbolt (Salmgren, 1978). This is interpreted as the storage of water when in excess, and its release during dry periods, thereby maintaining a consistently low water flow. The storage function is also supposed to mitigate high discharges. This view has gradually changed in favour of a modern, more complex interpretation of the hydrological function of forest wetlands (Baden & Eggelsmann, 1968; Bay, 1969; Mustonen & Seuna, 1971; Johansson, 1974; Heikurainen, 1976; Boelter & Verry, 1979).

A comparison between peatlands and sponges actually reveals similarities, especially where high water contents are concerned. Peatlands often contain over 90% by volume of water (Heikurainen, 1973). However, only small amounts of water stored in the peat are released to streamflow, if there is no input of water to the peatland. During the growing season, the main output of water from peatlands is by evapotranspiration. With no input, the outflow of water to streams soon ceases (Bay, 1969; Vidal, 1968; McDonald, 1973; Boelter & Verry, 1979). An important conclusion concerning the influence of peatlands on runoff is that peatlands do not maintain consistently low flows.

When considering the total effect of peatlands on hydrology in the environment, the topography and composition of the catchment are important. Peatlands surrounded by extensive mineral soil uplands mainly constitute transition zones. An input of water will result in an almost equal output. Conversely, catchments dominated by peatlands with a flat topography, have a runoff hydrology similar to lakes, and thus at least temporarily reduce high discharge outflows (Vidal, 1968; Boelter & Verry, 1979). Calculations for catchments in flat topography, in which peatlands make up 20% of the area and which also are part of a main drainage system, show a reduction of high flows by about 75% (Verry, 1988).

However, groundwater levels are often high in peatlands, resulting in considerable discharges when water input is high, i.e. precipitation and snowmelt. When inputs no longer occur and evapotranspiration is high, outputs of water rapidly decline, in consequence of peat characteristics such as high water retention and low hydraulic conductivity.

A fundamental consideration in relation to runoff is the fact that streamflow generation is a function of rainfall, land type and land use. Important catchment characteristics as regards runoff are slope, morphology, soil type, groundwater conditions, catchment area and drainage system. When peatlands make up a large part of the catchment, peatland characteristics may also influence the total catchment hydrology, depending on such circumstances as:

- the location of the peatland within the catchment,
- topography,
- peat type and peat thickness,
- vegetation cover,
- flow pathways and drainage network design,
- water content of the peat during periods of water input.

Peatland drainage

Forest drainage is intended to make forest production possible, to facilitate forest regeneration during the thicket stage, and to improve forest growth. Soil types of interest for drainage are those with high groundwater levels.

There are two main causes of a high groundwater level in a forest ecosystem. The one consists of purely natural high water levels, influenced by climate, topography and soils. These conditions have developed wet soils, often leading to peatland formation. Drainage of such sites is considered to be new drainage of virgin wetlands. The other cause of high water levels is the removal of the vegetation cover, in forestry often by clear-felling. This elevates the groundwater level, mainly in consequence of reduced evapotranspiration (Fig. 1; Lundin, 1979; Päivänen, 1982). To mitigate the effects of this

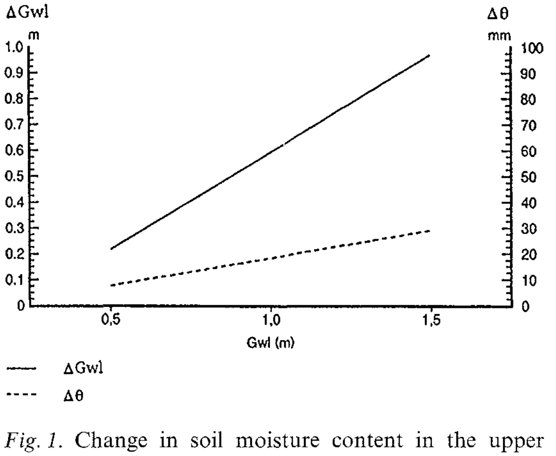

Fig. 1. Change in soil moisture content in the upper 0.55 m soil layer ($\Delta\theta$) and change in groundwater level (ΔGwl), as compared to the groundwater level at the forested site (Gwl), after clear-felling at the Masby catchment, 1973–1977.

Table 1. *Water deficit to saturation (mm) in the upper 0.5 m soil layer in drained and undrained conditions on peatlands and on clear-felled areas on mineral (till) soils. Calculations based on data on soil water and groundwater conditions in mineral and peat soils (Lundin, 1982; Lundin unpubl.)*

	Undrained	Drained
Peatland	30	100
Mineral soil	20	80

temporarily high water level, remedial drainage is carried out, to create suitable conditions for forest regeneration.

Drainage is intended to reduce waterlogging and to lower the water table to at least 0.4–0.5 m below the ground surface in periods with high levels during the growing season (Holmen, 1980). Lowering of the groundwater level provides an unsaturated soil moisture zone, extending to 0.5–1.0 m depth, where added water will be stored, retained and slowly released to maintain a low discharge. The size of this storage deficiency may be compared to ordinary, large precipitation events (Table 1). In summer, stored water largely returns to the atmosphere by evapotranspiration.

However, the presence of a drainage system shortens the water pathways through the soil from infiltration to recharge, and facilitates streamflow. These conditions act in the opposite direction to increased storage capacity, and are likely to shorten response time and increase runoff.

Hydraulic conductivity also exerts an important influence on water flow through the soil. In peat, conductivity is low (Persson, 1980), whereas higher conductivities are found in mineral soils (such as tills) which dominate the forest soils of the Nordic countries (Lind & Lundin, 1990). These differences in hydraulic conductivity between peat and mineral soils probably lead to a varying effect of drainage on runoff.

Drainage effects on hydrology

The above conditions of increased potential storage and shortened flowpaths have led to different opinions concerning the effects of forest drainage on runoff. Investigations of the hydrological effects of forest drainage have mainly shown only small changes in annual runoff

(Ayre, 1977); often, high discharges were reduced and low discharges increased (Braekke, 1970; Tamm, Holmen, Popovic & Wiklander, 1974; Heikurainen, Kenttämies & Laine, 1978). Increases in average annual runoff of 12 to 43% have been noted (Braekke, 1970; Seuna, 1974, 1988; Mustonen, 1975; Lundin, 1984; Bergquist, Lundin & Andersson, 1984). However, lower annual runoff has also been observed (Vidal, 1960; Multamäki, 1962; Starr & Päivänen, 1981; Lundin, 1988). The geophysiographical circumstances of the drainage area, and the hydrological conditions before high flow periods, exert a strong influence on the effects of drainage on runoff.

However, the investigations cited above are not comparable, for two main reasons. First, the length of the period of study. Short periods, 1–5 years, have often been involved, beginning immediately after the excavation of the drains. In other investigations, the study period began when several years had elapsed since drainage. In yet other investigations, the study period has extended over decades.

The second reason concerns the vegetation cover, the actual forest stand, of the area being drained. There is, of course, a large difference between the effects of drainage on a treeless mire, compared with those when a productive forest area is drained. The effects of mire drainage generally are increased runoff, due to facilitated runoff, while the effects associated with a tree stand are decreased runoff, due to increased water storage in the unsaturated zone, and evapotranspiration (Braekke, 1970). Evapotranspiration from a tree stand comprises as much as 60–70% of precipitation, causing a considerable decrease in runoff. The most drastic effect of such decreases will occur at low discharges, when water flow may even cease. However, investigations on low flows reveal, almost without exception, increased low discharges (Vidal, 1960; Heikurainen et al., 1978; Seuna, 1980, 1988; Laine, 1982; Lundin, 1984; Bergquist et al., 1984; Nicholson, Robertson & Robinson, 1989). These results mainly relate to drainage of treeless mires; in such cases, the facilitated runoff from the mineral soil uplands maintains the low flow. On sites with growing forests, the opposite effect on runoff probably would occur, i.e. decreased low flows, and even the cessation of flow.

Divergent prerequisites have also led to different results being obtained in respect of high discharges. When high flows are considered, the geophysiography of a catchment exerts a particularly strong influence. However, extreme natural weather conditions are probably the main cause of high peak discharges. Under such conditions, both high moisture content and high groundwater levels exist. Further input of water by precipitation or snowmelt causes extreme runoff.

When virgin, treeless peatlands are drained, the first events to occur are an increase in the storage capacity of the soil and the facilitation of water pathways. During the first, short dewatering period, runoff increases, and on the further input of water by precipitation, peak flows increase by as much as 100–200% (Laine, 1982; Lundin, 1984). This period lasts, however, only a few months, up to a half-year, after which new hydrological conditions develop, including a lowered groundwater level. During the following 10–30 year period, before a mature forest becomes established, there is a more or less treeless situation. Discharge peaks during this period change only insignificantly (Laine, 1982).

In Sweden today, drainage of treeless peatlands is undertaken on a limited scale, whereas remedial drainage after clear-felling is of greater interest. In the latter case, felling is likely to dominate the hydrological effects: clear-felling was found to increase annual runoff by up to 100% (Grip, 1982; Rosén, 1984; Brandt, Bergström & Gardelin, 1988; Seuna, 1988).

Peak discharges were found to increase after clear-felling (Seuna, 1988), proportionately more during rainfall, when the groundwater level was low, than when compared to events with the water-table close to the ground surface (Grip, 1987). Effects of drainage on peak flows on such clear-felled areas have received little attention. However, there are probably similarities between wet clear-felled areas, and naturally waterlogged soils, such as treeless peatlands. Preliminary results concerning remedial drainage of wet mineral soils show increased peak discharges, as compared both with the forested and the clear-felled state (Lundin, 1992*b*).

Various opinions have been advanced regarding the hydrological consequences of drainage. One such view asserts that drainage causes a more rapid hydrograph lapse, and shortens the duration of high flow, involving both an earlier and increased peak and a reduced base flow (Conway & Millar, 1960; Howe, Slamaker & Harding, 1967; Mustonen & Seuna, 1971; Ahti, 1980; Nicholson et al., 1989). Another view maintains that the peak is lowered, but that the duration of peak flow is extended (Multamäki, 1962; Heikurainen, 1976, 1980). Some opinions combine the above two views, claiming mainly increased base flow, as well as increased high peak flows (Seuna, 1974, 1980, 1988).

Burke (1963), on the other hand, observed decreased peak flows together with higher base flow. This concept seems to agree with recent research in Sweden, where both increased and decreased peak discharges were found (Lundin, 1984; Bergquist et al., 1984). In these cases, the size of the discharge peaks seems to reflect the variation in the results. Smaller rainfall amounts would be stored in the unsaturated soil layer, while considerable water inputs, exceeding soil storage capacity, would result in increased discharge. However, when very large quantities of water are added, as especially during the spring snowmelt, the runoff response is independent of the presence or absence of drainage (Starr & Päivänen, 1981). This has also been observed in several investigations. Peak discharges during snowmelt exceeded by 31% those expected in the undrained state, while increases during summer peaks reached 130% (Seuna, 1978). Other investigations showed a 10% decrease in spring peaks, but a 35% increase in summer peaks (Seuna, 1982). These findings were also supported by the results of Nicholson et al. (1989).

The divergent results obtained may also be affected by the ratio of peatland to catchment area. A compilation of investigations indicates that at least 50% of the catchment area would have to be peatland and more than 25% of the peatland would need to be drained to achieve an increased peak flow (Verry, 1988). In other studies, no change in spring discharge maxima occurred, but summer maxima increased by 25% (Seuna, 1988).

Materials and methods

Research approach

Flooding attracts considerable interest, and in particular the influence of clear-felling and drainage of forest land. In view of the divergent results obtained for peak flows after forest drainage, further elucidation of the response to drainage is required. The causal hydrological conditions predisposing to severe flooding are not yet clarified. The particular characteristics of one catchment give rise to results that are inapplicable to another catchment, the characteristics of which differ.

New investigations were therefore undertaken, based on field studies. Regression analysis was applied, both to earlier field data, and to new studies related directly to the present investigation, which comprises field measurements in catchments drained for forestry, including periods in the clear-felled state. Notwithstanding several earlier investigations, there are too few sufficiently extreme flood events for it to be possible to draw definite conclusions about changes caused by clear-felling and drainage, and about relationships with other hydrological conditions, in particular pre-event groundwater levels. Field measurements lasting three to five years only (the most common duration), include few very high discharges. Therefore, further field measurements were made, and, for comparison, results were utilised from other investigations which involved forest drainage.

While varying effects of drainage have been found at different peak flows within the same catchment, initial hydrological features, such as storage capacity and pre-event groundwater levels, were expected to influence the response. With only small storage capacities, i.e. high groundwater levels, the potential for high peak discharges should be considerable. Thus groundwater levels before the start of a flood event were used to separate the events.

Field research areas

One peatland catchment and two mineral soil catchments were investigated. The peatland area was mainly a treeless virgin mire; the mineral soil areas mainly consisted of moist (groundwater level (gwl) <1 m below ground surface) and wet (gwl close to ground surface) soils, initially bearing productive forest, later clear-felled and drained.

Results from the investigated areas were compared to those of other studies. One of these, D (Fig. 2), had first been studied with respect to

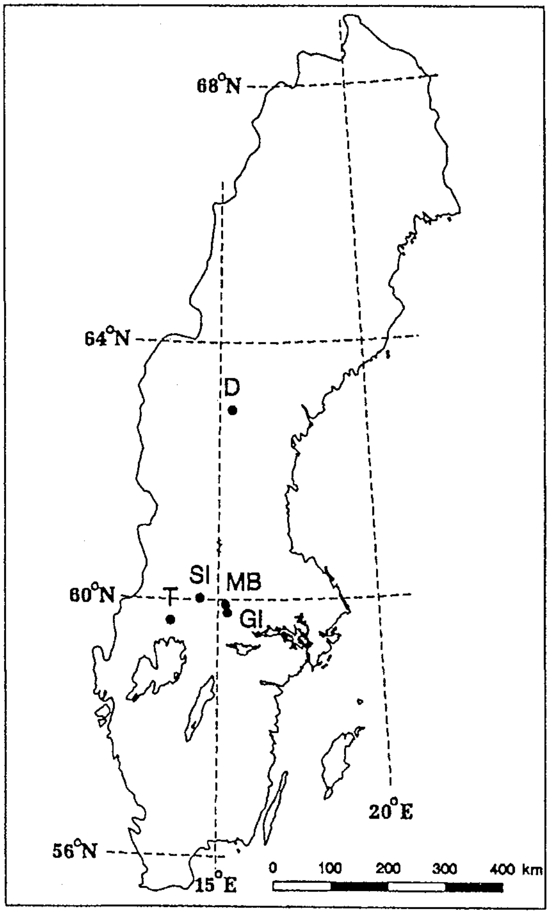

Fig. 2. Geographical location of the investigated catchments. SI: Siksjöbäcken, MB: Masbyn, GI: Gillermossen, D: Docksmyren and T: Torvbråten.

forest drainage, but was later utilised for peat fuel production (Lundin, 1984, 1992*a*). Further investigations were carried out on a bog catchment in west Sweden, the peatland Torvbråten (Lundin & Bergquist, 1990), denoted T in Fig. 2.

The Siksjöbäcken basin

The two small catchments, Letjärn (LE) and Hamptjärn (HA), constituted sub-basins of the Siksjöbäcken (SI) basin, situated in central Sweden (the Bergslagen region – 60°01′N; 14°25′E; Bergquist et al., 1984). The HA catchment constituted the control and the LE catchment the treatment catchment, where drainage was carried out (Tables 2 and 3, Fig. 3).

The calibration period extended over the years 1979–1980, drainage being carried out in spring 1981. The dewatering period, during which the groundwater level was lowered, was set to 1981 and the drained period to 1982–1985. A later period, 1991–1992, was also monitored within this project.

Table 2. *Catchment characteristics of the investigation areas Hamptjärn (HA) and Letjärn (LE)*

	HA	LE
Catchment area, km^2	1.10	1.40
Peatland area, km^2	0.31	0.34
Drained area, km^2	0	0.20
Altitude, m	300–400	325–400
Annual runoff 1980, mm	539	397

Table 3. *Climate, hydrology, peat, soil and vegetation at the catchments HA and LE (Bergquist et al., 1984)*

Precipitation, mm	936
Evapotranspiration, mm	412
Runoff, mm	524
Snow period	10 Nov.–20 April
Snow water content, mm	150
Peat cover thickness, m	2–3
Peatland type	Small sedge fens
Mineral soil surroundings	Till
Forest stand on the peatland	Pine
Forest production	<1 m^3 ha^{-1} year^{-1}

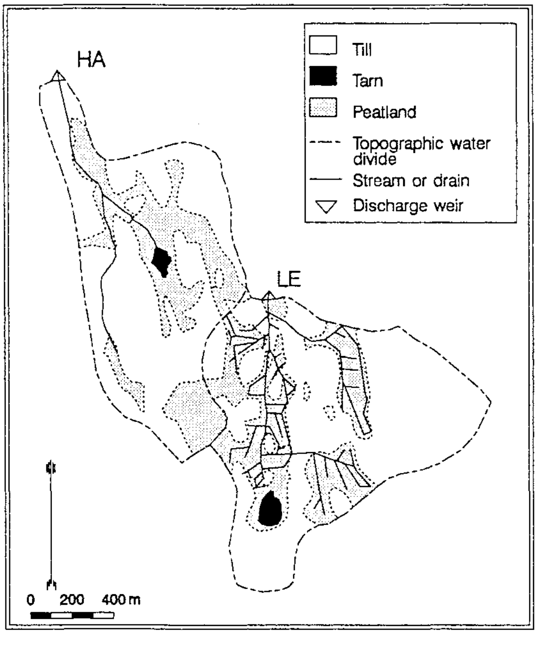

Fig. 3. The Siksjöbäcken basin with catchments Hamptjärn (HA) control, and Letjärn (LE) treatment area.

The Masbyn and Gillermossen catchments

Two small catchments on mineral soils (till), were also studied. Both were situated in central Sweden (59°55′N; 15°15′E), about 50 km east of the Siksjöbäcken basin, with the Masby (MB) catchment about 10 km north of the Gillermossen (GI) catchment (Fig. 2). The climate of the area is humid and comparatively cold, mainly owing to its elevation (340 m above sea-level). The growing season extends from 25 April to 20 October (Table 4).

The MB catchment, area 0.186 km^2, was a moist mineral soil area (Fig. 4). A few small peatlands, constituting small sedge fens (total area <1 ha), existed, but in addition to this about half of the area had a thick (0.1–0.3 m) organic layer covering a sandy-silty till. Runoff and groundwater were measured during an initial forested period of four years (1972–1975).

Table 4. *Climate and hydrology of the MB catchment (Lundin, 1982)*

Precipitation, mm	860
Evapotranspiration, mm	430
Runoff, mm	430
Mean annual temp, °C	+4
Annual degree-days	1100

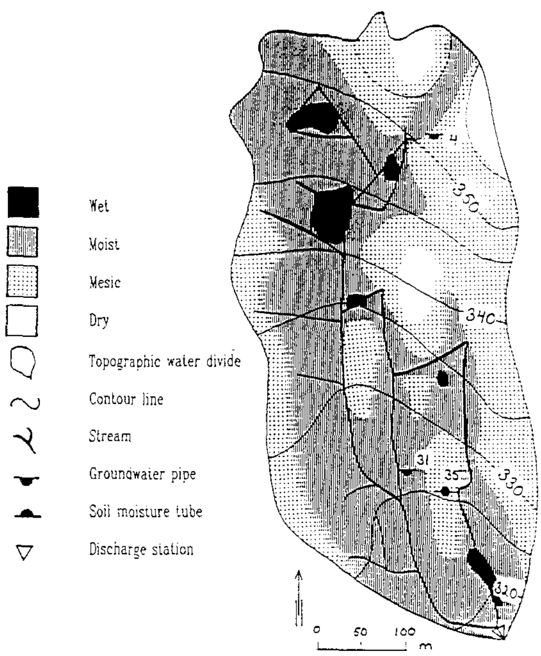

Fig. 4. The Masbyn catchment (MB), with soil moisture types, drainage network and location of the hydrological stations.

In 1976, 50% of the area was clear-felled, and in 1981 remedial drainage of more than 50% of the area was carried out. The length of the drain system was about 2 km. During the following eleven-year period, the effects of drainage of the clear-felled area, including the effects of clear-felling, were studied.

During the first 10-year period after felling, the area could be considered treeless, since only small plants had developed. In 1989, these plants had grown into a young forest, with 800–2 400 stems ha^{-1} and a stand volume of 1–4 m^3 ha^{-1} and a tree height of ca. 2.2 m. Three other stands covered the remaining 50% of the catchment, aged 16, 22 and 56 years, respectively. The stand volume varied between 46 and 149 m^3 ha^{-1}.

The GI catchment included both two small tree-covered peatlands (2.5 ha) and surrounding mineral soil areas, making up a 0.15 km^2 catchment (Fig. 5). On the peatlands the stand volume was 114 m^3 ha^{-1}, consisting of 60% pine and 20% spruce. The stand on mineral soil had a volume of ca. 300 m^3 ha^{-1}.

The calibration period extended over the years 1987–1988. In the late autumn of 1988, about 70% of the mineral soil area of the GI catchment

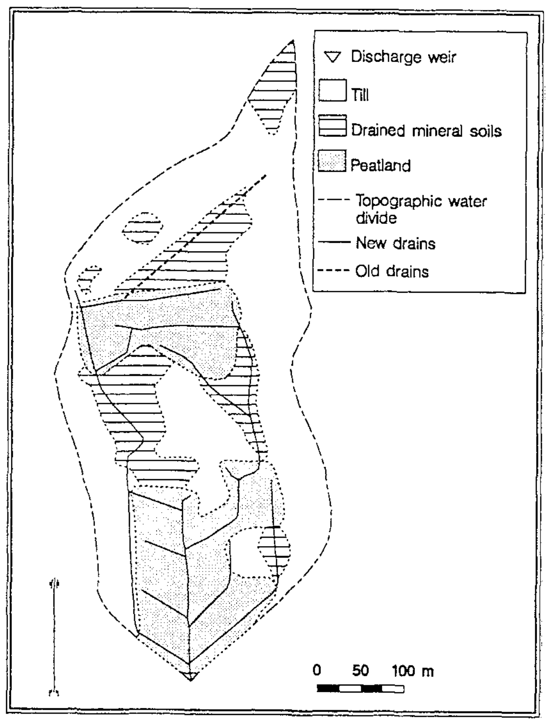

Fig. 5. The Gillermossen catchment (GI), with soil types and drainage network.

Table 5. *Catchment comparisons and treatments performed*

Control catchment	Treated catchment	Measure	Year
Hamptjärn, HA	Letjärn, LE	Drained	1981
Buskbäcken area, BB	Masby area, MB	Clear-felled	1976
		Drained	1981
Masby area, MB	Gillermossen, GI	Clear-felled	1988
		Drained	1990

was clear-felled, and during 1989 the catchment was in a treeless, but not drained, state. In 1989, the stand on one of the peatlands (1.5 ha) was thinned. In the winter of 1989/90, about two-thirds of the total catchment, i.e. the clear-felled area and the peatlands, was drained, and the drainage period of 1990–1992 was studied.

The MB catchment was compared to the adjacent catchment, Buskbäcken (BB), area 1.83 km^2. This catchment is a national field research area monitored by the Swedish Meteorological and Hydrological Institute (SMHI). Both of these catchments had been monitored during a long period (1970–1992), and the treatments at MB were carried out in 1976 and 1981. At the end of the study period, treatment effects had stabilised. This provided an opportunity to use the MB catchment as the control for the GI catchment, despite the fact that the MB catchment had earlier been both clear-felled and drained (Table 5).

Measurements and calculation methods

Field measurements were made of precipitation, groundwater levels and runoff. Precipitation was measured at intervals of one or two weeks, and transformed to daily precipitation by correlation with nearby (ca. 15 km distant) SMHI stations. Groundwater levels were measured in open tubes, both by chart recorders and by weekly manual measurements. Discharges were measured at V-notch weirs by chart recording gauges. During winter and spring, frozen groundwater in the tubes and ice at the discharge stations caused problems. However, during such cold periods, moderate to low discharges occurred.

Groundwater levels, primarily in the lagg, were measured, to investigate the influence of pre-flood levels on the hydrograph response at flood. Attempts were made to separate different high-flow events with respect to the pre-event groundwater levels.

The method used to calculate the effect of both clear-felling and drainage was based on the calibration- period and control-basin technique. Two similar, adjacent catchments, with considerable peatland or wet soil-type areas, were first studied during a calibration period before treatment. During this period, it was important that high discharges occurred which could be used in later comparisons. Regression relationships were established between daily discharges at the two catchments during the calibration period, which had a duration of about two years. Following this, forestry measures were carried out in one of the catchments, leaving the other untouched as control.

Regression relationships were then used with discharges from the control catchment, to estimate discharges for the modified catchment, assuming no treatment. These control values were then compared with the measured values after forestry operations had been carried out. Differences between the observed discharges after treatment, and the estimated discharges assuming no treatment, were considered to represent the effect of the treatment.

Accurate measurements within days were also made directly on the recording charts, to discover whether there were changes in peak sizes on an hourly scale, and to investigate changes in the time of occurrence of flood start and timing of the peak.

Statistical calculations were performed using the "Statistical Analysis System" (SAS Inst. Inc., 1985, 1987). Significance in the observed effects was analysed by use of the t-test for means and by the F-test for regression equations (Yevjevich, 1972).

Results

Effects of drainage on runoff and peak discharges

The normal annual runoff pattern of the investigated catchments exhibited both spring high flows and discharge peaks in the autumn. A few large precipitation events during summer caused high peak flows also during this generally low flow period. However, during the period directly associated with this investigation, winter temperatures for the two years 1991 and 1992 were comparatively warm, causing only minor problems with ice. Only a few peak flows occurred during the period. The summer of 1992 was the driest during the entire period of the drainage investigations.

Letjärn catchment, LE

During the calibration period, only four runoff peaks exceeded 100 l s^{-1} km^{-2}, one of which was almost 200 l s^{-1} km^{-2} (spring 1980). During 1981, there were two peak discharges >100 l s^{-1} km^{-2}, one of them the spring flow. During the ensuing four-year period, there were five peak discharges of ca. 100 l s^{-1} km^{-2}, four of which were spring flows. Two peak flows which reached ca. 200 l s^{-1} km^{-2} occurred in 1985. In 1991–92 there was one peak discharge of ca. 200 l s^{-1} km^{-2}, the only one suitable for the study of extreme floods. However, no comparable flow occurred during the calibration period. This resulted in the concentration of research efforts to peak flows at lower discharges, i.e. ca. 100 l s^{-1} km^{-2}.

Annual runoff

A regression relationship was established from daily discharges at the treatment catchment LE and the control HA during the calibration period 1979–81. Use of all daily discharges resulted in the following equation (q, l s^{-1} km^{-2}):

$$qLEc = 0.616 \cdot qHA + 2.1$$

$$(n = 399;\ r^2 = 0.696;\ SE = 0.80)$$

where q is specific discharge; c is calculated values; n is the number of daily discharges; r^2 is the coefficient of determination and SE is the standard error of estimate. The estimated variation explained 80% of the observed variation.

The measured annual discharges at the two catchments during the calibration period showed a 5.8 l s^{-1} km^{-2} higher specific discharge at the control HA compared to the catchment LE. During the first year after drainage, a period in which the main lowering of the groundwater level took place, qHA was only 4.0 l s^{-1} km^{-2} higher than qLE, indicating an increased discharge from the drained area LE. When qLE, the corresponding untreated discharge from LE, was calculated, the mean discharge was 0.7 l s^{-1} km^{-2} lower than the measured discharge at LE after drainage, i.e. an increase of 5% in the mean discharge after drainage. After the initial period following drainage, new hydrological conditions, with a lowered groundwater level, were established during the years 1982–1985. The mean annual specific discharge during this period at the drained catchment was 15.3 l s^{-1} km^{-2}, which was 1.5 l s^{-1} km^{-2} (11%), higher than the expected discharge without drainage. The change was significant at the 99.9% level.

A third period was studied 10 years after drainage, comprising 20 months in 1991–92 (Fig. 6). During this period, the mean specific discharge from the drained area was 0.4 l s^{-1} km^{-2} (4%) lower than expected for the undrained state (not statistically significant — NS).

High discharge

It was noted from the regression calculations (all daily observations before drainage) that high discharges after drainage also increased, by an average of 38%. However, when regression relationships including both high and low discharge values are used, calculated values approach the mean more closely. In consequence, calculated high flows are reduced. This could be seen when the equation was applied to the calibration period, and resulted in estimated peak discharges which reached only 60% of the measured values. On the supposition that this underestimate applied also to the period after drainage, a new estimate was made to reach 100% instead of only 60%. This would serve to change the total effect of drainage on peak discharges, from the increase first presented, to a decrease by 18%.

To address directly the issue of floods and to improve accuracy, regression relationships were established for the calibration period, using only runoff peak periods. The limited number of floods that occurred before drainage mostly resulted in fairly similar regressions, with high correlations (Table 6). A combination of all relevant daily discharges resulted in a single equation, which was used for estimating undrained

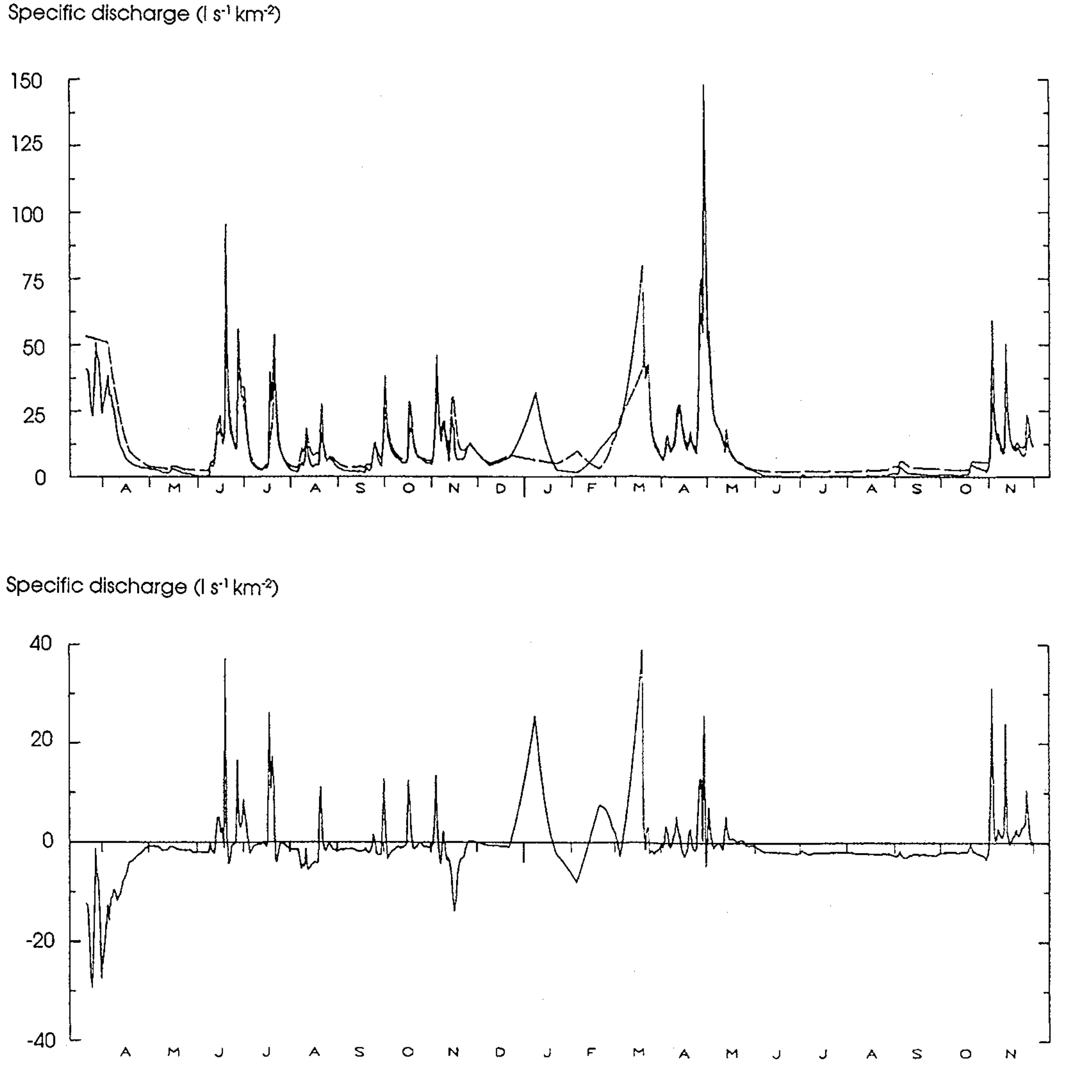

Fig. 6. Measured drained (solid line) and calculated undrained (broken line) daily discharge coefficients at the LE catchment during March 1991 to November 1992 (above). Differences between measured and calculated discharges (below).

Table 6. *Linear regression equations,* $qLEc = a + b \cdot qHAm$, *between daily specific discharge,* q *l* s^{-1} km^{-2}, *during peak flow periods of the calibration period 1979–1980. Spring peaks excluded because of differences in the time of snowmelt, caused by different aspect. c — calculated values; m — measured values;* r^2 *— coefficient of determination; n — number of daily discharges; * significant at 95% level; *** significant at 99.9% level*

Period	a	b	r^2	*n*
9–15 Aug. 1979	−5.72	1.057	0.932***	7
25 Aug.–2 Sept. 1979	−6.91	1.342	0.882***	9
22–25 Nov. 1979	2.61	0.795	0.942*	4
20–28 June 1980	11.16	1.147	0.852***	9
16–24 Oct. 1980	−9.57	0.970	0.929***	9
Combined	−1.99	1.051	0.797***	38

peak discharges after drainage at the LE catchment.

The specific discharges during the five floods from which the combined regression was constructed, were tested for homogeneity by means of a double mass plot of accumulated discharges, with qLE against qHA. No discontinuity was seen in the plot, and the regression relationship was well adjusted to the data set, the regression coefficient being 1.05 and r^2 0.993. The F-test showed significance at the 99.9% level. The means of the discharges were 37 l s^{-1} km^{-2} at HA and 36.9 l s^{-1} km^{-2} at LE. Corresponding SEs were 4.6 and 5.4, respectively.

During the first year after drainage (1981), only one high peak flow reached ca. 140 l s^{-1} km^{-2} at the drained catchment. The estimated undrained peak discharge was almost identical, showing no change in consequence of drainage. During the following four-year period (1982–1985), there were eight comparatively high peak flows, with a mean daily maximum specific discharge of 103 l s^{-1} km^{-2}. A comparison with estimated undrained conditions showed a decrease in peak discharge of 15 l s^{-1} km^{-2}, i.e. by 14%. Only during one discharge peak of 84 l s^{-1} km^{-2} was there an increase (8%). This was a relatively low peak, absolutely not an extreme flow.

During the 1991-92 period, ten years after drainage, two peak flow events occurred, of which one was the second highest measured discharge during the whole study period. The fairly moderate runoff peak in March 1992 was 6.6 l s^{-1} km^{-2} higher then the estimated undrained discharge of 73 l s^{-1} km^{-2}.

At the end of April 1992, the second highest discharge (148 l s^{-1} km^{-2}) occurred. This should be compared to an estimated undrained specific discharge of 203 l s^{-1} km^{-2}. Snowmelt had passed earlier, this flood peak being caused by heavy rain; 41 mm of rain fell during the previous three days, and a further 44 mm in one day just after snowmelt. Thus the soils were almost totally waterlogged before the 44 mm rainfall. Nevertheless, there was a comprehensive decrease in daily peak discharge, by 55 l s^{-1} km^{-2} (27%), and a total volume of 58 mm left the area during the eleven days of flood. This was 27 mm less than the volume calculated for the undrained state (Fig. 7).

Water volume, time shift and groundwater levels in floods

In the concept of flooding, not only the daily highest discharge is of interest, but also the total volume during the flood period. There was an average decrease in total water volume, of 0.9 mm day^{-1} for the ten flood periods after drainage. This was 18% lower than the expected volume without drainage.

Detailed changes within days, including the time of occurrence of flood start and of peak discharge, exhibited no change in the start of peak flow events. Neither could any change in discharge size before the start of the floods be distinguished. The very highest peak discharges of the ten events decreased by 11% (NS), and the time of occurrence of the peak was also unchanged, for the most part. However, in a few events, the peak may possibly have been earlier by 1–2 hours, than was the case in the undrained state. Before treatment, simultaneous peaks predominated on both control and treatment catchments.

Influences from pre-event groundwater levels were difficult to discern at high discharges, when the groundwater level was in the uppermost 0.1 m of the soil; variations within this layer were not perceptible. Only when smaller runoff peaks were included, could variation in drainage impact with groundwater levels be observed, there being larger decreases in peak discharges with deeper pre-event groundwater levels. When the water table was in the uppermost 0.1 m, the decrease in peak discharge was about 15%; but with the level in the layer at a depth of 0.1–0.2 m, the average decrease was 24%.

Masby catchment, MB

The MB catchment was studied during a 20-year period, which included several different forest operations. Of these, clear-felling in 1976 and remedial drainage in 1981 were considered in this investigation. Both annual average runoff and peak flows were studied. Effects of forestry measures were studied in relation to the forested state, and drainage was compared with both forested and clear-felled conditions.

Annual runoff

Runoff varied both between years and between the two catchments BB (control) and MB (treat-

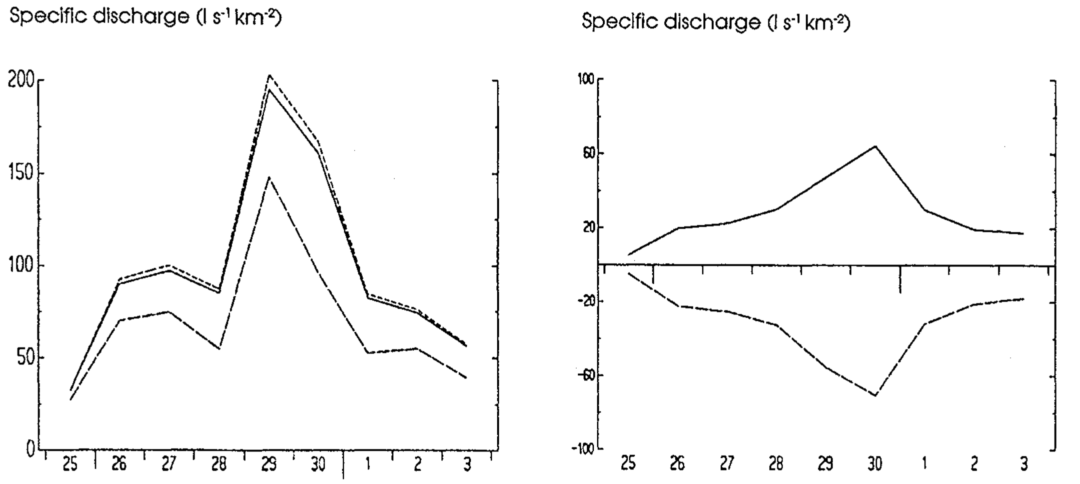

Fig. 7. The flood of 25/4–3/5 1992. Discharge coefficients at HA –, LE – – and calculated undrained at LE - - - (left). At right, the difference in daily discharges between measured values HA–LE (solid line) and measured discharges at LE–calculated discharges (broken line).

ment). Average runoffs from the control BB, during the period with MB forested, were 414 mm; 443 mm during the period with MB solely clear-felled; 472 mm during the first 4-year period after drainage, and 342 mm during the second 7-year period, 5–11 years after drainage. During the period when both catchments were forested, runoff also differed between the catchments. Average runoff from MB was 367 mm, which was lower by 47 mm than that from BB.

The regression between all daily specific discharges at the two catchments during the forested calibration period, 1972–1975, resulted in the equation:

$$qMBc = 0.87 \cdot qBB - 0.15$$

$$(n = 1410;\ r^2 = 0.883;\ SE = 0.46)$$

Insertion of the daily discharges of the impact periods during the period 1976–1981, when the catchment MB was clear-felled but not drained, resulted in an increase in mean annual runoff of 1.5 l s^{-1} km^{-2}, i.e. by 12% (Fig. 8).

Following remedial drainage, the specific discharge during the first four-year period was 6.4 l s^{-1} km^{-2}, 50% higher than that calculated for MB estimated as forested (Fig. 8). When the mean discharge after drainage was compared with the clear-felled state, an increase of 4.7 l s^{-1} km^{-2}, i.e. by 33%, was estimated.

As regards the 1986–92 period (five to eleven years after drainage), there were changes in the forest vegetation. The age of the stand increased from six to thirteen years; in 1989, the stand volume was ca. 3 m^3 ha^{-1}, as compared to ca. 0.2 m^3 ha^{-1} in 1984. During the period in question, the specific discharge at MB was 5.0 l s^{-1} km^{-2}, i.e. 54% higher than that calculated for the forested state (Fig. 8), and 3.8 l s^{-1} km^{-2} (36%) higher than that calculated for the clear-felled state. All changes were significant at the 99.9% level.

High discharge

To target the high peak discharges, a regression relationship was established, considering five peak flow periods in the calibration period. It resulted in the equation:

$$qMBc = 0.92 \cdot qBB - 5.2$$

$$(n = 63;\ r^2 = 0.960;\ SE = 4.72)$$

When this equation was applied to the period after clear-felling, the calculated average peak discharge under forested conditions would have been 156 l s^{-1} km^{-2}, which gave an increased highest peak discharge coefficient after clear-felling, of 40 l s^{-1} km^{-2} (26% greater; Table 7).

Calculated changes caused by drainage only, i.e. from the undrained, clear-felled state to drainage of the clear-felled areas, showed smaller increases in peak discharges, as com-

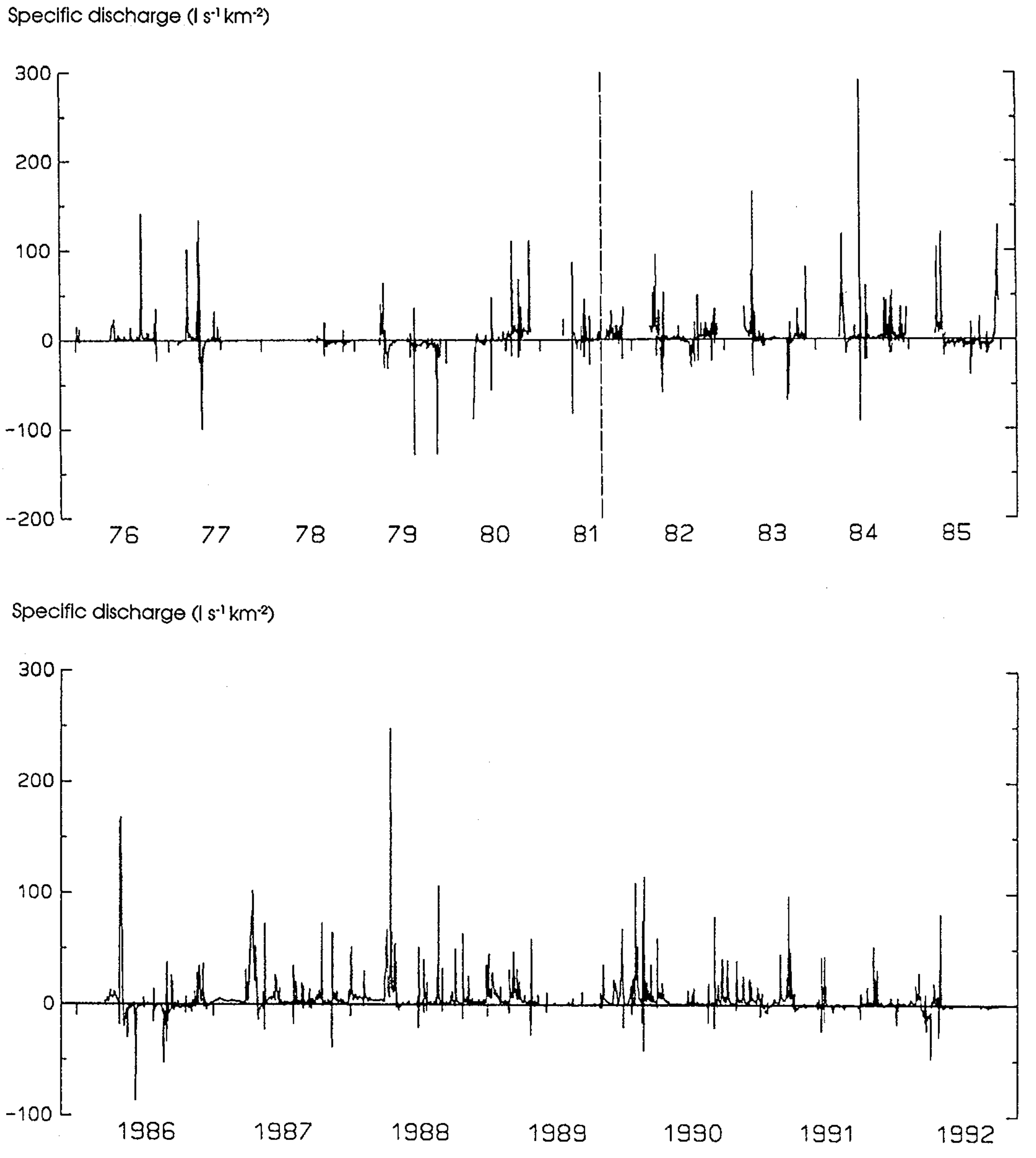

Fig. 8. Differences between measured daily discharges and estimated discharges as if forested at catchment MB during the clear-felled period 1977–81 and the period after drainage, 1982–92.

pared to changes caused by clear-felling (Table 7). The increased change from the first period after drainage to the second may have been caused, for instance, by diverging hydrological conditions or by changes in conditions at the control.

Water volume, time shift and groundwater levels in floods

The total runoff, calculated during a hypothetical flood period of five days, increased after clear-felling by 7 mm (25%). After drainage, the change in runoff averaged 12 mm (63%), as compared to the clear-felled state, and 14 mm (81%), when compared to the forested state. Evidently, these changes did not show total agreement, which most probably was caused by different ranges of the flow peaks during the periods investigated. In 1977–81, the average five-day flood was 27 mm, but was only ca. 17 mm in the periods after 1981.

During the second period after drainage, the

Table 7. *Calculated changes in daily peak discharges after clear-felling only, and after drainage of the clear-felled area, as compared with the forested and clear-felled states at the MB catchment*

State and period	Peak specific discharge, $l\ s^{-1}\ km^{-2}$			
	Calculated as forested	Measured	Change $l\ s^{-1}\ km^{-2}$	%
Clear-felled	156	196	+40	26
Clear-felled and drained, 1982–85	105	205	+100	95
1988–92	91	184	+93	102
	Calculated as clear-felled	Measured	Change $l\ s^{-1}\ km^{-2}$	%
Clear-felled and drained, 1982–85	115	192	+77	67
1986–92	97	180	+83	86

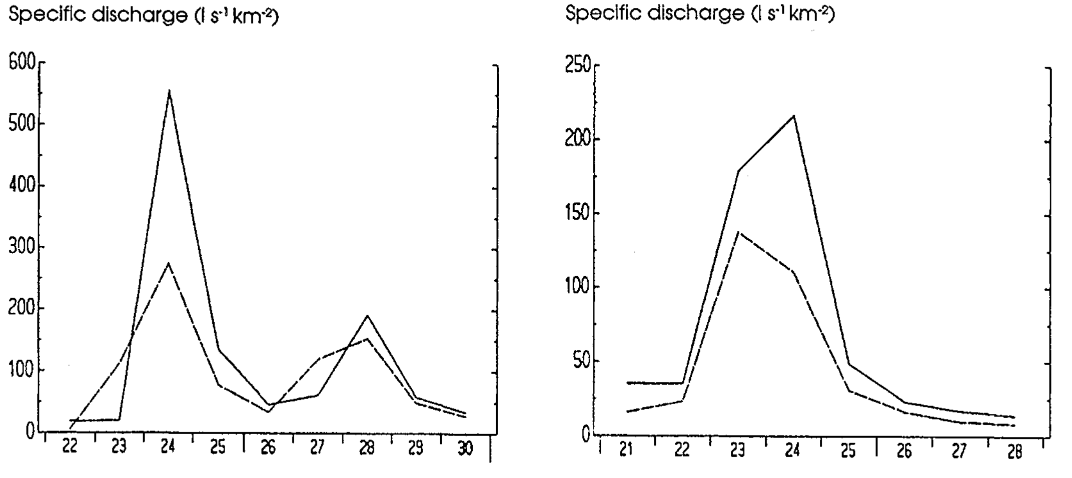

Fig. 9. Discharges at two floods at the MB catchment. June 1984 (left) and August 1988 (right). MB measured — solid line; MB calculated as forested - - broken line.

corresponding values were 10 mm (56%), and 12 mm (74%), respectively. A declining impact on peak volumes may be discernible, possibly caused by a developing tree stand. This effect could not be seen in the peak discharges.

The time shift was studied on a daily basis, but no change in the start of flood periods or in the time of peak discharges could be detected at a time resolution of two-hour intervals.

Groundwater levels prior to peak flows, pre-event discharge and precipitation, all influenced the size of peak discharges. High groundwater levels, within 0.1–0.2 m of the ground surface, coincided with high pre-runoff peak sizes, about 50 $l\ s^{-1}\ km^{-2}$. Under these conditions, both moderate (10–15 mm) and high (>30 mm) precipitation increased peak discharges by 56 $l\ s^{-1}\ km^{-2}$ (37%) after clear-felling. This increase was larger than the change by 40 $l\ s^{-1}\ km^{-2}$, obtained when peaks with lower pre-flood groundwater levels were also included.

Examination of the influence of pre-flood groundwater levels, after both clear-felling and drainage, showed that, when the groundwater level was 0.2 m below the ground surface (corresponding to pre-peak discharges lower than 20 $l\ s^{-1}\ km^{-2}$), no very high discharge actually occurred. At very high discharges (ca. 200 $l\ s^{-1}\ km^{-2}$), the groundwater levels in moist and wet soil types were found in the uppermost 0.1 m of the soil, and the water table in most of the catchment was no deeper than 0.2 m below the surface.

Gillermossen catchment, GI

The third comparison performed concerned the GI catchment. This was compared with catchment MB (above). These two catchments were chosen, in spite of the forestry measures carried out in the MB catchment, because of their proximity and their similarity in terms of size, soil type and aspect. The MB catchment had earlier been subjected to both clear-felling and drainage, but during the period of comparison with GI, no forestry operations were carried out within it. The period studied covered the years 1987-1992; drainage operations on catchment MB were carried out in 1981, which implies that fairly stable conditions prevailed during the period investigated.

Annual runoff

Runoff from catchment GI varied between the years investigated, being lower during the two years in the forested state. Annual means were 11 and 14 l s^{-1} km^{-2}, and seven peak discharges attained larger values than 100 l s^{-1} km^{-2}, including some high daily specific discharges which reached 150–170 l s^{-1} km^{-2}. After clear-felling during 1989, the annual specific discharge was 15.5 l s^{-1} km^{-2}, four daily peak discharges reaching 100–110 l s^{-1} km^{-2}. This year was, in fact, comparatively dry. After remedial drainage during the winter of 1989/90, runoff increased. Discharges in both 1990 and 1991 were 21 l s^{-1} km^{-2}, with ten peak discharges larger than 100 l s^{-1} km^{-2}, including three higher than 300 l s^{-1} km^{-2}. In April 1992, the very highest peak of that year was observed, which reached 230 l s^{-1} km^{-2}.

Regression relationships were established between GI and MB for the forested period and for the period after clear-felling. Equations established were:

Forested:

$$qGIc = 0.532 \cdot qMB + 3.5$$

$$(n = 699;\ r^2 = 0.729;\ SE = 0.60)$$

Clear-felled:

$$qGIc = 1.095 \cdot qMB + 5.0$$

$$(n = 365;\ r^2 = 0.791;\ SE = 0.85)$$

Average changes in runoff caused by forestry operations, i.e. clear-felling and drainage, were calculated. After clear-felling, the annual increase was 218 mm (80%), and after remedial drainage an increase of 306 mm (100%), was observed as an average for almost three years, as compared to the forested state. A comparison with the clear-felled state showed an increase of 50 mm (9%) (Table 8). All changes were significant at the 99.9% level.

Table 8. *Mean annual runoff from catchment GI during the periods of investigation. Measured and calculated values (mm) are compared with changes (mm) caused by forestry operations*

State and period	Runoff				
	Measured	Calculated as forested, and change		Calculated as clear-felled, and change	
Forested 1987–1988	416	—	—	—	—
Clear-felled 1989	489	271	+218	—	—
Clear-felled + drained 1990–1992	614	307	+307	564	+50

High discharge

The regressions between GI and MB, established using all daily discharges during the investigated periods, estimated an increase of 59 l s^{-1} km^{-2} (116%) in the highest peak specific discharge after clear-felling. The calculated increase in the five highest peak discharges after both clear-felling and drainage was, on the average, 133 l s^{-1} km^{-2} (177%), when compared to the forested state, and 66 l s^{-1} km^{-2} (46%), when compared to the clear-felled but undrained state.

To improve the accuracy of estimated changes in peak flows after clear-felling and drainage, five peak flow periods during forested conditions were used to obtain a good regression relationship between high specific discharges at the two catchments. This resulted in the equation:

$$qGIc = 0.737 \cdot qMB + 6$$

$$(n = 39;\ r^2 = 0.897;\ SE = 6.61)$$

This relationship was used to calculate specific discharges at GI ($qGIc$), as estimates for the forested state during periods after forestry operations, i.e. clear-felling and drainage.

In 1989, during which GI was clear-felled, another regression was established, based on five peak flows in this period. This resulted in the equation:

$$qGIc = 1.578 \cdot qMB + 30$$

$$(n = 45;\ r^2 = 0.729;\ SE = 6.13)$$

This relationship was used to calculate discharges, assuming the catchment to have been clear-felled only during the period after both clear-felling and drainage. Calculated and observed values were compared.

To estimate the influence of treatment on the hydrological response under extreme conditions, a specific discharge under forested conditions of 200 l s^{-1} km^{-2} (qMB) was inserted into the equations. This resulted in a discharge at GI of 153 l s^{-1} km^{-2}, as compared to the calculated discharge for the clear-felled period of 346 l s^{-1} km^{-2}, i.e. extreme discharge increased by 193 l s^{-1} km^{-2} (126%).

A relationship was also established during the period after drainage, to make possible the estimation of average change after both clear-felling and drainage. This was based on 10 peak flows and resulted in the equation:

$$qGIc = 1.284 \cdot qMB + 20$$

$$(n = 97;\ r^2 = 0.642;\ SE = 5.82)$$

Calculation of the corresponding extreme discharge coefficient (qMB = 200 l s^{-1} km^{-2}) gave the result 277 l s^{-1} km^{-2}, indicating an increase in extreme discharge, as compared to the forested state, of 124 l s^{-1} km^{-2} (81%). As compared to the clear-felled state, there was instead a decrease of 69 l s^{-1} km^{-2} (20%).

Observed peak flow periods

A comparison was made between the investigated periods with respect to the observed highest peak flows. In the forested period (1987–88), five peak flows occurred, with a mean daily peak discharge of 140 l s^{-1} km^{-2}. During this period, qMB exceeded qGI by 35 l s^{-1} km^{-2} at the highest daily discharge.

During the period in which GI was clear-felled (1989), there were smaller peak flows than in the previous period, as a result of fairly dry weather. The average high discharge was 104 l s^{-1} km^{-2}. The calculated discharge for the forested state for this period was only 58 l s^{-1} km^{-2}, indicating that clear-felling resulted in an increase of 46 l s^{-1} km^{-2} (80%; Fig. 10).

For catchment GI, in both the clear-felled and the drained state (1990–92), nine peak flow periods occurred, with an average daily peak discharge of 13 mm, i.e. an increase of 6 mm (87%) as compared to the forested state. Comparison with the clear-felled but undrained state showed a decreased peak discharge of 5 mm (31%). During the period 1990–92, three very high discharges occurred, reaching specific discharges of 195–271 l s^{-1} km^{-2}. During these events, the daily peak discharge exceeded the calculated forested discharge coefficient by 88–197 l s^{-1} km^{-2}, i.e. 0.8–2.6 times. Corresponding changes, in comparisons with the clear-felled state, showed peaks decreased by 51–56 l s^{-1} km^{-2} (20%; Fig. 11). There was one exception, a peak on 29 April 1992, which exhibited a comprehensive increase of 121 l s^{-1} km^{-2} (81%). However, this peak was moderate, with an estimated undrained discharge of 150 l s^{-1} km^{-2}.

Instantaneous peak discharges, on a time-scale within days, were also investigated in this comparison of GI and MB. During the forested period, eight peak discharges were studied. During the clear-felled period and the drained period, six and sixteen peaks, respectively, were studied. In addition to peak discharge, the size of the discharge before the start of the peak period and the timing of this event were studied. In the forested state, discharge at GI before the peak flow period was, on average, 85% of that at MB, and peak discharge was 58% of that at MB. After clear-felling, discharge before the start of peak flow increased 3.3 times (significant at 95% level), and peak discharge increased 1.3 times (significant at 99% level), as compared to the forested state.

With the GI catchment both clear-felled and drained, the discharge at the start of peak flow increased twofold (significant at 99% level) as compared to the forested state, but decreased by 30% (NS) as compared with the undrained, clear-felled state. Instantaneous peak discharges increased 1.3 times (significant at 99% level) by comparison with the forested state, but were unchanged as compared to the clear-felled state.

The timing of the start of hydrograph rise and the time of occurrence of peak discharge were determined on an hourly basis. After clear-felling, no change was observed; after drainage, the change was also small or indistinguishable.

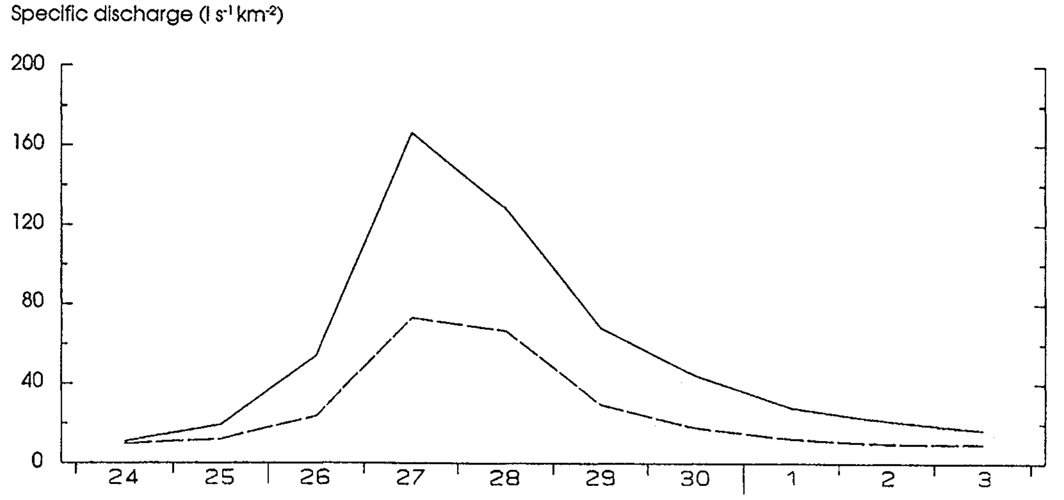

Fig. 10. The measured discharge peak after clear-felling 24 April–3 May 1989 — (solid line) compared with the calculated peak in the forested state - - (broken line).

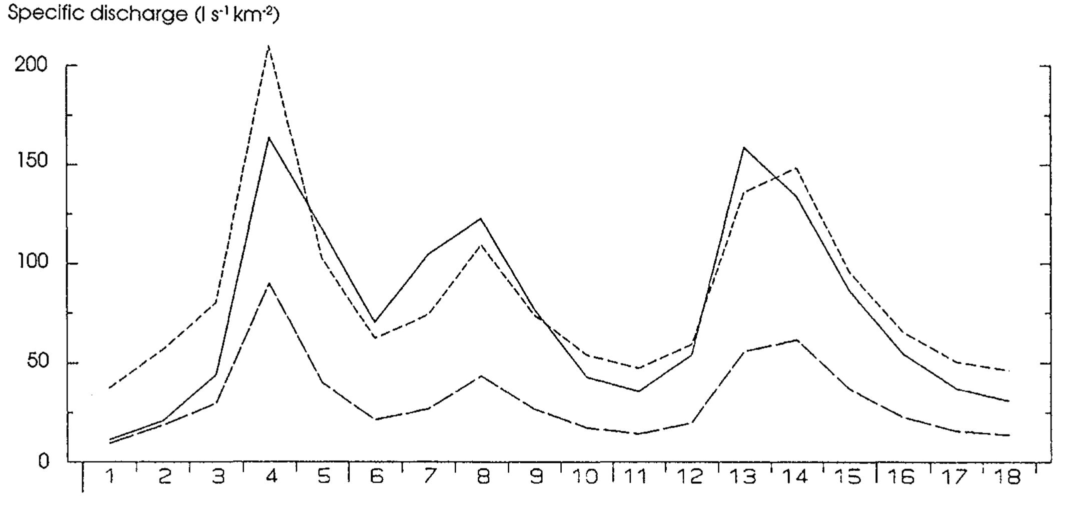

Fig. 11. The measured daily discharges — (solid line) during the high flow period in November 1991 after GI was both clear-felled and drained, compared with discharges calculated for the forested state (broken line, long dashes — —) and for the clear-felled state (broken line, short dashes - -).

Such change as could be distinguished was an advance of the peak discharge by 1–2 hours. Owing to limitations of chart resolution, this was, however, uncertain.

Water volume and groundwater levels in floods

Total runoff during peak flow periods, which often ranged over 5–10 days, averaged 19 mm for a five-day period under forested conditions at GI. At MB, runoff was larger by 3.5 mm. After clear-felling, measured runoff was 21 mm per five-day period, i.e. an increase of 11 mm (94%). After drainage, runoff was 29 mm, an increase of 14 mm (97%), as compared to estimates for the forested state. These values indicate that an increase of 3 mm was caused by drainage of the clear-felled area. However, when the two periods during which GI was in the clear-felled state before and after drainage were compared, the result was a decrease of 10 mm (26%) in runoff after drainage.

In relation to pre-peak groundwater levels and discharges, changes in instantaneous peak

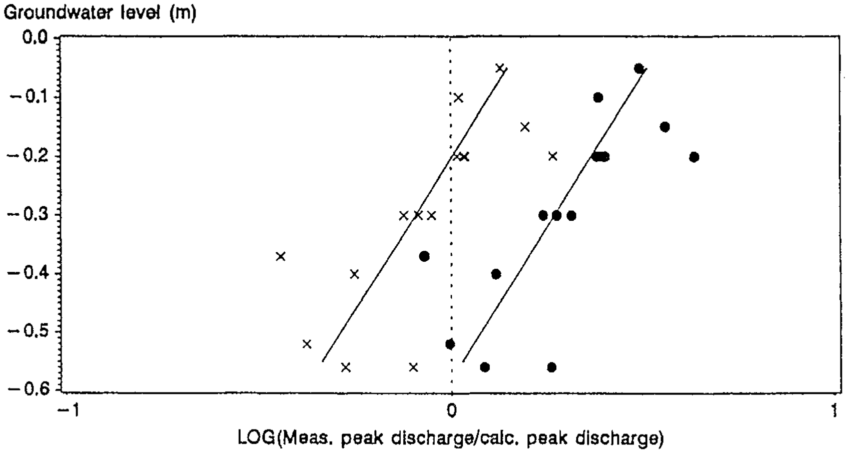

Fig. 12. Change of instantaneous peak discharges at different pre-peak groundwater levels. The ratio between measured peak discharge after clear-felling and drainage, compared with the discharge in the forested state (o) and with the clear-felled, undrained state (x). Clear-felled, drained period, 1990–92; clear-felled only, 1989; forested period, 1987–88.

discharges, after both clear-felling and drainage, showed increased peaks at almost all groundwater levels; larger increases were observed at higher groundwater levels. Drainage of a clear-felled area increased peak discharges when the groundwater level in moist and wet soil types was within 0.2 m of the surface. However, when the groundwater level was lower, decreases were observed (Fig. 12). This groundwater level corresponds to specific discharges between 20–30 l s^{-1} km^{-2}.

Discussion and conclusions

Forestry operations, such as clear-felling and drainage, influenced flood runoff and high peak discharges. Annual runoff increased after clear-felling by 12% and 80%. These results coincided with earlier findings (Grip, 1982; Rosén, 1984; Seuna, 1988). Peak discharges also increased, with the largest increase at the highest discharges, contrasting with results presented by Grip (1987).

Clear-felling elevates the groundwater level, and on moist and wet soil types, the high water level causes a deterioration of conditions for forest regeneration. Conditions approximate those on treeless peatlands. To achieve a state suitable for tree growth, drainage is necessary, to lower the water table. In this respect, clear-felled sites on mineral soil resemble peatlands. However, hydraulic conductivity is important when considering discharge. The hydraulic characteristics of mineral and peat soils differ. In forest mineral soil (often till), conductivity decreases with depth, which implies not only considerable groundwater flow in the upper soil layers, but also a reasonably high flow in the uppermost metre of the soil. In peatlands, on the other hand, the topmost layers (0.1–0.2 m) have high conductivities, but beneath this layer, conductivities are very low. Beneath the peat, in the underlying mineral soil, conductivity may again increase. This is of interest if ditches are excavated to this depth, since the mineral soil uplands can then provide a stable base flow.

At least where treeless peatlands are concerned, drainage often increases annual runoff and low discharges. Productive tree stands decrease runoff, in accordance with the effects of clear-felling, since evapotranspiration may amount to 60–70% of precipitation (Braekke, 1970).

In this investigation, peatland drainage increased annual runoff by 10%. However, during a two-year period, 10 years after drainage, runoff decreased. It is possible that an increased vegetation cover changed the situation, but it is more probable that the special hydrological circumstances during the later period were responsible. Runoff conditions during high flow periods dominate the influence of treatment on annual runoff (Lundin, 1984; Bergquist et al., 1984). In these investigations, decreased high discharges were observed. However, the effects of peatland drainage on high discharges have varied. Following drainage of a bog in west Sweden (T, Fig. 2; Lundin & Bergquist, 1990), the mean highest peak discharges decreased by 25%, even though a few unchanged peaks were found for 1% of the highest discharges (>400 l s^{-1} km^{-2}). Peaks after drainage were not higher than the corresponding peaks in the undrained state (Lundin, unpubl.).

On a large sedge fen (D, Fig. 2) in the central part of north Sweden, forest drainage mostly caused a decrease in high discharges. Notwithstanding this, occasional high discharges increased, by 1.7 times. After this peatland had been drained for peat extraction, high discharges remained lower than might have been expected for the undrained state. On one occasion only was an increased peak discharge observed. This was twice the expected undrained peak (Lundin, 1992).

The hydrological consequences of drainage of wet mineral soils – often as remedial drainage – have been investigated to a limited extent. Such drainage is often carried out after clear-felling; in future, its extent will probably decrease, as a result of efforts to arrange fellings in such a way as to avoid the need for drainage.

Drainage of mineral soil increased discharge by 50% and 80%, as compared with the forested state, and by 9% and 36% as compared with the clear-felled but undrained state. Effects on peak flows showed high discharges that increased by ca. 100% after clear-felling, and by 70–200% after drainage. However, the transition from the clear-felled, undrained state to the drained state showed no change; even decreased high discharges were observed. In part, varying hydrological circumstances between periods could explain the discrepancies, and groundwater levels affected the impact. For instance, this could be seen in the differences obtained when estimates for periods after drainage were compared with those for forested and clear-felled periods. At the GI catchment, the low runoff in 1989 provided a regression equation that gave an estimated daily peak flow after drainage of 7.7 mm. This was fairly high, and the estimated flow calculated from the equation between forested and drained conditions resulted in a more probable value for daily runoff, of 2.9 mm day^{-1}.

Increases in peak discharge were found only when the groundwater level was in the uppermost 0.2 m the soil. Peak flow then increased by 1.8 times at most. Following remedial drainage, the results also indicated a possible decrease in peak discharges after drainage and clear-felling, as compared with the forested state, when groundwater levels were lower than 0.6 m below the ground surface. For the most part, small peak discharges occurred at such groundwater levels. In the forested state, these could be caused by runoff from small, wet areas, where drainage had lowered the usually high groundwater level to a greater extent than could be achieved by the evapotranspiration of the tree stand. Runoff generation from such areas was transformed into storage in the drained soil.

Clear-felling and drainage have been considered to accelerate runoff, but no change in the time lapse was actually observed in the the materials considered here. The fact that the catchments were quite small possibly contributed to the absence of a time shift.

Peak discharge periods commonly extended over 5–10 days. During this period, the total water volume would be important as regards hazardous water flows. Calculation of the increased water volume during a peak flow period resulted in an increase after drainage, as compared to the forested state, of 2–3 mm day^{-1} (80–100%). After drainage of clear-felled areas, the changes were small.

In small streams from catchments containing considerable clear-felled and drained areas, this increase might give rise to problems, but these would mainly be local in nature. In larger rivers, very high discharges could be hazardous. However, land-use in large river basins is more diverse than that in small basins. The three rivers Öre älv, Hedströmmen and Alsterälven contain 60–70% forest land, 30–40% of this being young forests or clear-felled areas; ca. 10% of the forest land has been drained. When the changed water volume at high discharges is applied to these rivers, the resulting increased volume would be less than 1 mm day^{-1}. This should be compared with the highest daily runoffs in these rivers, viz. ca. 10 mm day^{-1}. Evidently, the influence of clear-felling and drainage associated with prevailing forestry activities cannot be regarded as conducive to hazardously high discharges. The area of forested land in Sweden is in fact increasing. Extreme weather conditions, involving high precipitation, are most likely to be decisive in causing extremely high flows in larger watercourses.

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