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A comparison of the hydrology of moorland under natural conditions, agricultural use and forestry

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Abstract Long term research has been conducted into the hydrological effects of different land usage of a wetland mire in southern Germany. Drainage for agriculture lowered the water table and reduced evaporation from about 110% of open water losses to just under the Penman short grass potential rate. The runoff regime was altered and peak flows increased. Afforestation of agricultural land increased evaporation losses to much higher levels than open water evaporation, and annual runoff was nearly halved. Forest growth reduced soil water and baseflows. Peak flows became smaller; the rate of reduction was particularly rapid in the early years of tree growth.

Une comparaison de l'hydrologie de terrains marécageux sous conditions naturelles, sous occupation agricole et sous occupation forestière

Résumé Des recherches à long terme ont été menées afin de déterminer les effets de l'occupation du sol sur un terrain humide du sud de l'Allemagne. Le drainage agricole a abaissé la nappe phréatique et réduit l'évaporation, initialement 110% des pertes sur eau libre, au taux correspondant au potentiel de Penman sous herbe coupée court. Le régime d'écoulement a été altéré et les débits de pointe ont augmenté. Le reboisement de terres agricoles a amené les pertes par évaporation à des niveaux dépassant de beaucoup l'évaporation de l'eau libre, et l'écoulement annuel a été réduit de moitié. La croissance de la forêt a réduit la teneur en eau du sol, ainsi que le débit de base. Les débits de pointe sont devenus moins importants; le taux de réduction a été particulièrement rapide durant les premières années de la croissance des arbres.

HISTORICAL BACKGROUND

The drainage and cultivation of wetlands in Europe has caused a great deal of controversy between water management bodies and nature conservation

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agencies. In addition to the loss of wetland habitats for flora and fauna, opponents of drainage schemes maintain that the water balance and climate of peat moors and their surroundings are adversely affected by these changes. The lack of data to substantiate such claims led in the early 1950s to the setting up of a number of experiments throughout Germany studying the water balance and climate of drained and undrained moor catchments. More recently the research has been widened to study how best to encourage the reversion of formerly drained and agriculturally used moor areas to their "natural" wetland state (Schuch, 1988a, 1988b).

The paper describes the experiments established in the vicinity of the Chiemsee lake in the alpine foothills of Bavaria. It was here, in the southern Chiemseemoors, that as long ago as 1892 Professor A. Baumann began observations of a cultivated high moor (Vidal, 1959). His initial studies of this Hochmoor ("high moor" or raised peat bog) led in 1895 to the foundation of the first Bavarian moor research station there, which was later absorbed into the Bavarian State Institute for Moor and Agriculture. Thus a long-standing tradition of research in this region continued when in 1954 the Institute, which was later to become the BLBP (Bayerische Landesanstalt für Bodenkultur und Pflanzenbau or Bavarian State Institute for Soil Cultivation and Plant Production) opened the moor research station near Bernau on the edge of the moor. This was to study, among other topics, the effects of agricultural use of drained high moor. Two catchments were established in 1959, providing a completely untouched area directly adjoining a cultivated site. Subsequently, as a logical extension of the original project, two more catchments in the immediate vicinity were instrumented in 1971. These had been afforested in 1962 and 1969 respectively and enabled the study of the effect of afforestation of drained and formerly agriculturally used high moors. This paper describes and compares the hydrology of these four areas.

DESCRIPTION OF THE SOUTHERN CHIEMSEEMOORS

The southern Chiemseemoors are situated 70 km southeast of Munich between a lake (the Chiemsee) to the north and the foothills of the Alps to the south (latitude 47°48'N, longitude 12°26'E). They cover an area of over 25 km^2 and rise gently from about 520 m a.m.s.l. at their northern edge up to 540 m a.m.s.l. in the southeast.

The peat layers of the moors formed in a basin of impermeable clay (Schmeidl *et al.*, 1970). The lowest peat layers formed under woodland bog conditions and contain birch and alder, often followed by fen and transition bogs; the total depth of these layers measures about 2–3 m. The overlying layer, with a thickness of 4 m, is a raised peat bog consisting of *Sphagnum* and *Eriophorum vaginatum*. During the development of the peat bog, the area was flooded extensively several times by the mountain rivers and the lake. The natural moor surface is characterized by hummocks interspersed with bog hollows and a few trees, but its appearance has in part been lost due to drainage and the cutting of peat.

The climate of the moors is determined by the nearness of the Alps.

The annual precipitation at the Bernau meteorological station averaged 1410 mm over the period 1954–1975, and most (64%) occurs during the growing season in May–October. There is precipitation on about 200 days per year, with snow from January to March, sometimes into December and April. The wettest months are June and July. The air temperature averages 7.3°C, with a mean of −2.2°C in January and 16.5°C in July. A characteristic of this area is the föhn wind from the south causing extremely low air humidity and correspondingly high evaporation rates.

THE EXPERIMENTAL SITES

The four experimental catchments discussed in this paper (Fig. 1) comprise: natural moorland or Unberührtes Moor (UM); agricultural land or Kultiviertes Moor (KM); and afforested formerly agricultural land or Aufgeforstetes Moor (FM/S to the south, and FM/N to the north). On each catchment, measurements included precipitation, discharge and water table depths.

The untouched moor area, UM, has a size of about 0.21 km^2 and its surface falls gently from south to north by 0.2%. The vegetation comprises mostly green and red *Sphagnum* in the lower lying, wetter bog hollows and *Sphagnum medii* and *Calluna vulgaris* on the higher, drier hummocks. The southern part of UM is drier and favours the growth of heathers and birch trees. On the eastern and northern edges some trees e.g. Scots pine, spruce, birch and dwarf pine are to be found. A deep ditch was dug around the catchment to prevent outside water entering the experimental site, and an inner ring ditch was cut 10–15 m from the outer ditch to collect and lead outflows to a vee notch or "Thompson" measuring weir.

The drained and agriculturally used area, KM, is about 0.32 km^2 and, since the mid 1960s, has been used exclusively as meadow. The grass is cut for hay or silage, as the ground is too soft for grazing. The surface slopes gently by about 0.2%. It was partially drained at the turn of the century and then more systematically in 1926 with ditches 100 m apart and pipe drains. The drains were 15 m apart but in the 1950s this was reduced to 6–8 m by installing additional pipe drains. Flow is recorded at a weir on the main drainage ditch which collects the surface and drainage water through a network of open ditches. A groundwater recorder was installed in the centre of the catchment mid-way between the pipe drains. Further climate instrumentation is described by Vidal (1959) and Schmeidl *et al.* (1970).

The two forested catchments (FM/S and FM/N) are each about 0.03 km^2 in area. They are on land that had been under similar agricultural usage to KM (all three catchments are on land owned by the Bavarian State). The land has pipe drains 8–10 m apart and the catchment outflows are recorded at weirs on the drainage ditches. FM/S was planted with coniferous trees in 1962 and FM/N in 1969. The trees (mainly Norway spruce) are about 800 mm apart and measured 1.5–2 m and 0.3–0.5 m in height on FM/S and FM/N respectively when the catchments were established in 1971. By January 1987 they had grown to an average height of about 12 m and 10 m. On each catchment, a groundwater recorder was sited mid-way between the pipe drains.

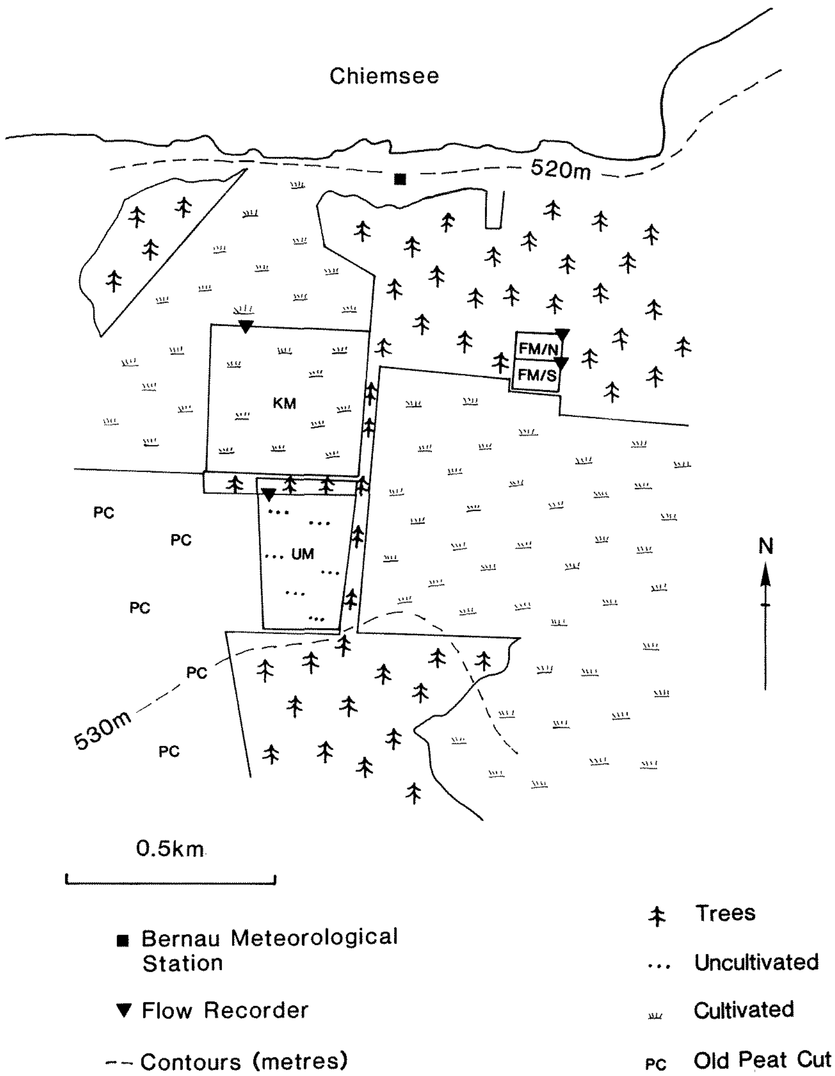

Fig. 1 Map of the Chiemseemoors experimental catchments, redrawn from topographic sheet no. 8140 of the Bavarian Ordnance Survey (8910/90).

IMPACT OF AGRICULTURE

The long term differences in flows from the untouched moorland (UM) and drained, cultivated, land (KM) have been described elsewhere (Schmeidl *et al.*, 1979; Schuch, 1972, 1973, 1976) and are only briefly reviewed here. The study of the effects of the afforestation of drained agricultural land, which has not previously been reported in detail, is the main subject of this paper. The comparisons of UM and KM indicated that evaporation losses were lower from the drained moorland due to the lower soil water content and to the absence of open water areas. In this paper, the single term "evaporation" is used to refer to both interception losses and transpiration to emphasise that they are both the result of the same physical process of evaporation. Other authors choose to use the term "evapotranspiration" to indicate the sum of both losses.

It is difficult to provide a precise water balance due to the prolonged freezing conditions in winter ensuring large quantities of snow (very difficult to record accurately with a raingauge) as well as icing of the flow measuring weirs. The recorded losses (precipitation minus discharge) over the 15-year period 1971–1985 are given in Table 1. The loss for meadowland (KM) of 465 mm $year^{-1}$ corresponds well with the estimated short grass potential evaporation (Penman) of about 500 mm (Henning & Schirmer, 1978). Losses from the wetland (UM) of 700 mm $year^{-1}$ may be compared with summer half-year (April–October) open water losses of 530 mm at Bernau (Liebscher, 1978). Comparison with other sites in Liebscher (1978) suggests the summer half-year value may be increased by about 15% to give the total annual loss. For Bernau this would be some 630 mm i.e. about 10% less than the observed wetland (UM) loss.

There has long been a debate about the magnitude of evaporation losses from wetland areas. Crundwell (1986) reviewed the literature and found conflicting results, with some studies claiming wetland plants increased evaporation losses compared with open water, and others that plants lowered losses. He concluded that evaporation losses from wetlands could be higher than from open water due to the greater surface area of the vegetation, larger aerodynamic roughness and the limited stomatal control of the plants. Some authors suggested very much higher losses from wetlands than from open water, but their sites were affected by advection and the results for UM of only a 10% difference (630 *vs* 700 mm) conform to recent findings (Linacre, 1976) of a similar rate of loss.

Peak storm flows were much higher from the drained than the undrained moorland, a finding in contrast to the results of a study at Königsmoor in north Germany (Baden & Eggelsmann, 1964). Elsewhere in Europe, conflicting results have been reported with cases where peatland drainage increased peak flows (Seuna, 1980; Nicholson *et al.*, 1989) and cases where maximum flows were reduced (Burke, 1972). The experimental sites at Chiemsee and Königsmoor both have pipe drains and ditches on a raised bog, but conditions are rather different. Chiemsee has a much wetter climate (1400 cf. 720 mm $year^{-1}$ precipitation) and deeper, less permeable peat. The untouched moor (UM) acts rather like a large bog hollow with a long

Table 1 *Average annual losses, 1971–1985*

Catchment	*Land use*	*Annual loss (mm) (precipitation – discharge)*
KM	*Grass*	*465*
UM	*Wetland*	*700*
FM/N	*"Younger" forest*	*935*
FM/S	*"Older" forest*	*980*

response time as water moves slowly across the uneven surface. Artificial drainage of KM greatly facilitated the speed of storm water flow, but the land remained wet with the water table on average only 350 mm below ground level. Thus KM is much more comparable with the pre-drained moor catchment at Königsmoor than the drained catchment where drainage lowered the water table to a depth of 600 mm, and completely eliminated surface runoff (Eggelsmann, 1990).

At both Königsmoor and Chiemsee, artificial drainage led to an increase in low flow rates, i.e. dry weather flows were higher. This is a general finding of drainage studies and reflects the greater depth of the artificial channels than the natural (undrained) stream networks (Robinson, 1990).

IMPACT OF FORESTRY

In West Germany about half of the drinking water comes from forested catchment areas (Bruenig, 1986). It is therefore important to know how this land use affects water supplies. There is also a debate in many countries concerning the impact of forests on flow regimes, particularly peak flows and dry weather discharges. The long period of records at Chiemsee allows a study of the effect of the tree growth, and the replication of "treatments" with the forests on FM/S and FM/N planted seven years apart provides a means to distinguish the effects of the tree growth from climatic variability.

Studies of forestry effects by means of *afforestation* are much rarer than those of *deforestation* due to the much longer time periods required. However, the results from afforestation are much more valuable, since deforestation leaves a non-tree area with essentially a forest soil, together with any forestry drains and an indeterminate amount of brash. There are also problems of interpretation due to the different effects of different logging methods, soil compaction, roads, tree brash, etc., as well as the need to prevent forest regrowth in the post-forest period, for example by the repeated use of herbicides. These can give rise to very different conditions between deforested areas and, say, permanent grassland. In some extreme cases deforestation has resulted in considerable erosion and loss of soil.

Alternatively, if comparisons are made between the discharge from land "with" and "without" trees, then there may be other physical factors involved; natural forest will, for example, grow preferentially on non-waterlogged areas. Where the forests are managed, the choice of areas on which to plant or remove trees may depend on physical characteristics such as ground slope and soil type.

Water balance

Early observations of the forested catchments, FM/S and FM/N, were presented by Schuch (1973, 1976) and showed lower annual yields, peak flows and baseflows from the immature (less than 10 year old) forests than from KM, particularly for FM/S. There were, however, great uncertainties posed by the other physical differences between the sites. The older forested catchment (FM/S) is more exposed than FM/N, having a non-forested southern edge, and might shelter FM/N from southerly föhn winds. Furthermore, the forested catchments are only one-tenth the size of KM and UM and no flow data were collected prior to planting. Now, with the trees over 20 years old (and more than 10 m in height) the longer records available can be used to determine the forest effect with more certainty by looking for changes over time with growth of the trees. The long-term evaporation losses for the forested catchments of 930–1000 mm year^{-1} (Table 1) are much higher than for KM or UM. This follows the general pattern of higher losses from trees than grassland (eg. Hewlett, 1982; Calder, 1990). The primary reason for the greater evaporation losses from forests is their much higher aerodynamic roughness. This leads to a much greater vertical transport of water vapour from wetted canopies during and following rainfall. Advected energy supports the high rates of evaporation of intercepted water.

In a study of flows from a grassland and a forest catchment in Britain, Calder & Newson (1979) found that forest evaporation was about 850 mm year^{-1} compared with short grass losses of about 405 mm year^{-1}, i.e. an increase of about 445 mm year^{-1}. Bosch & Hewlett (1982) reviewed the findings of catchment experiments around the world and concluded that 100% afforestation with conifers increases evaporation losses by on average about 400 mm year^{-1}. Noting the importance of climate on interception losses, Calder & Newson (1979) present a simple model of annual forest evaporation losses based on British studies, and requiring only rainfall data (to compute interception losses) and Penman short grass evaporation (to estimate transpiration losses). Interception losses are typically 30–35% of gross precipitation in high rainfall areas. Applying their model to climate data for the Chiemsee-moors yields a predicted loss from mature forest of approximately 900 mm year^{-1}.

Thus, although high, the observed losses for the forested areas at Chiemsee are not unreasonable, but it may be noted that the small size of the forest at Chiemsee may enhance its evaporation losses due to advection and edge effects. Furthermore, recent work shows the evaporation of intercepted snow from tree canopies may be much higher than that of a wet canopy (Calder, 1986).

The effect of the growth of the trees over time on discharges was investigated by direct comparison with the flows from the untouched moorland, UM. This was chosen as a "control" in preference to the cultivated moor KM, where there had been changes in the intensity of farming, and the weir was more exposed and prone to icing in winter. It also circumvented uncertainties that might have resulted if precipitation had been used as the "control" (due to problems in accurately measuring snowfall).

Table 2 shows the annual flows from the two forested catchments expressed as a proportion of the flow from UM and indicates a reduction in runoff of about 40%. In the early years, the young plantation trees had to grow through about a 1 m high mixture of long uncut grasses (*Molinia*), sedges (*Carex* sp.) and brambles (*Rubus* sp.). The annual flow ratio values of less than unity, even when the trees were small, indicate that this vegetation

Table 2 *Ratio of annual flows (per unit area) from the forested catchments FM/N and FM/S to flows from the control catchment UM; the average age of the trees in each period is shown*

Period	*FM/N Ratio*	*Age*	*FM/S Ratio*	*Age*
1971-1975	*0.72*	*4*	*0.62*	*11*
1976-1980	*0.60*	*9*	*0.56*	*16*
1981-1985	*0.57*	*14*	*0.49*	*21*
1986-1989	*0.43*	*18*	*0.41*	*25*

had a high interception loss. Other studies have found that in areas where the frequency and duration of canopy wetness are great the evaporation losses from medium height vegetation (such as heather or tall grass) may be much higher than from short grass. This is due to their greater aerodynamic roughness (e.g. Calder *et al.*, 1984). Campbell & Murray (1990) measured interception losses from 800 mm high Tussock grass (*Chionochloa rigida*) equal to 21% of precipitation. Bubenickova & Kasparek (1990) found little change in annual evaporation losses after forest was replaced by tall grass *Calamagrostis villosa*.

Thinning of the trees on FM/S and FM/N commenced in 1985. Unfortunately for the hydrological study, this work has been spread over a period of several years on each catchment, when labour was available. There has been no evidence from the annual yields of a reduction in evaporation due to the smaller interception and transpiration losses, and it may be that the decrease in the leaf area was compensated by an increase in ventilation. Calder (1990) also found that forest thinning did not affect interception losses.

Peak flows

Forests have been widely claimed to reduce flooding downstream (Lee, 1980; Wijkam & Timberlake, 1984). This may be through their increased canopy storage and by their leaf litter creating deeper, more permeable, soils. Figure 2 compares the peak instantaneous flows from UM and the forested catchments for the same storms in two time periods, to give a range of ages of the trees. To ensure that any differences between the periods were not due to differences in the magnitudes of storm events analysed, the events in the two periods were selected to contain a similar mean peak flow from UM of about 100 l s^{-1} km^{-2}, and a maximum peak of about 280 l s^{-1} km^{-2}. Between 24 and 40 storms were sampled in each period. Several important results can be seen from this graph. Firstly, there is a reduction in peak flows with increasing forest growth. The rate of reduction over time is greatest in the first 10 years, and then slows down. This was despite the trees growing from under 2 m in height when 9 years old to over 10 m at 22 years of age. Secondly, the peak flows from forested catchments are reduced proportionally much more in small storms than in larger ones. This finding results from the

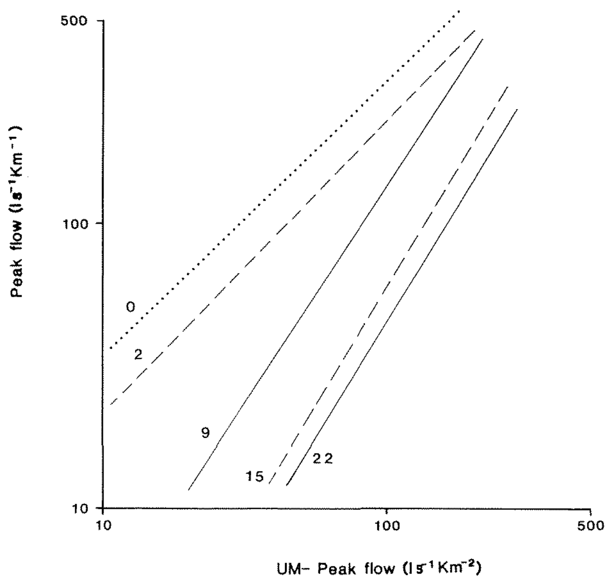

Fig. 2 Comparison of peak instantaneous discharges for different ages of forest with the untouched moorland control catchment UM. The numbers indicate the age of the trees in 1971/2 and 1984/5 on FM/N (- - -) and FM/S (——); the zero age line (· · · ·) is provided by peaks from the unplanted KM catchment.

finite interception capacity of the tree canopy, and corresponds to the same pattern noted in the comparison of flow maxima from the forested Severn and grassland Wye catchments in Britain (Robinson, 1989).

To study the form of this reduction, large storm events were selected for more detailed study of runoff time distribution (unit hydrograph) and volumes (runoff coefficient). Events with snowmelt or freezing conditions were excluded. The method used for hydrograph separation into quick storm response and delayed runoff was that used in a major review of UK floods (NERC, 1975). This involved first calculating the storm "lag" time (being the time delay between the centroid of storm rainfall and the occurrence of peak discharge). The pre-storm flow recession was extended to the time of the discharge peak, and then projected upwards to intersect the falling limb of the hydrograph at a point four times the lag after the cessation of rainfall. The "effective" rainfall of the same volume was then determined according to NERC (1975) and a unit hydrograph determined by matrix inversion.

Table 3 indicates the average peak storm flow, runoff timing and runoff coefficient for the same events selected from FM/N and FM/S in 1971–1972 and 1983–1984 corresponding to forest ages ranging from 2 to 22 years. Over this period the main change was an approximate halving of the runoff coefficient. This reduction in storm runoff amounts is the result of the larger interception losses of the tree canopy and the drier soil beneath. This difference in ground wetness is confirmed by the water levels measured in dip wells. Although there was spatial variability within each catchment as well as the practical difficulty in defining ground level, average annual depths may be compared: 200 mm for UM (but almost at the surface in parts), 350 mm in KM (mid-way between drains) and 450 mm (younger forest, FM/N) and 550 mm (older forest, FM/S). Clearly the forest helped to reduce soil water contents, with much greater drying than by drainage alone. In contrast, there was a much smaller change in hydrograph shape, with rise times only about 20% longer over this period. This may reflect the greater losses to soil water storage of early storm rainfall, but may also reflect the result of any deterioration of the old pipe drainage systems.

Table 3 *Average storm runoff characteristics and timing for different catchments and years corresponding to different ages of forest cover*

Age of trees	*Storm runoff*			*One hour unit hydrograph*		*Catchment*	*Years*
	Peak flow	*Lag time*	*Runoff coefficient*	*Time to peak*	*Peak flow*		
years	$l\ s^{-1}\ km^{-2}$	*h*	*%*	*h*	*% total*		
2	*255*	*6.1*	*50*	*4.4*	*8.9*	*FM/N*	*1971-1972*
9	*158*	*7.0*	*34*	*4.7*	*8.4*	*FM/S*	*1971-1972*
15	*227*	*6.8*	*32*	*5.6*	*9.5*	*FM/N*	*1983-1984*
22	*179*	*7.4*	*27*	*6.0*	*9.3*	*FM/S*	*1983-1984*

Baseflows

Whilst it might appear likely that higher evaporation losses from forests would reduce baseflows, it has often been argued that forests sustain low flows by encouraging infiltration into the soil due to the creation of a deep, permeable litter layer (Costin & Dooge, 1973). Support for the idea of forests reducing low flows may have also come from deforestation studies where logging compacted the soil surface and reduced infiltration and hence subsurface flows. Maitland *et al.* (1990) were unable to reach a general conclusion, and stressed the importance of local factors, including the presence of suitable storage of water in soils and upper rock layers. Calder (1986) considered the effect of forests on low flows is "poorly understood", and recommended further research. Figure 3 shows the changes in low flows against time from the two forested catchments expressed as a proportion of the flow from the much larger UM catchment. The flow parameter plotted is the daily mean discharge exceeded for 70% of the time (i.e. 255 days per year). This value was chosen in preference to the more commonly quoted 95% exceedence flow since flows from both the small forested catchments ceased for some time each year. It indicates that baseflows are reduced by forestry. Low flows were decreased by a much greater amount than annual yields as they occur mainly in the growing season, the time of highest transpiration and interception losses. Forest growth reduced recharge (cf. deeper water table depths) and summer baseflows were smaller.

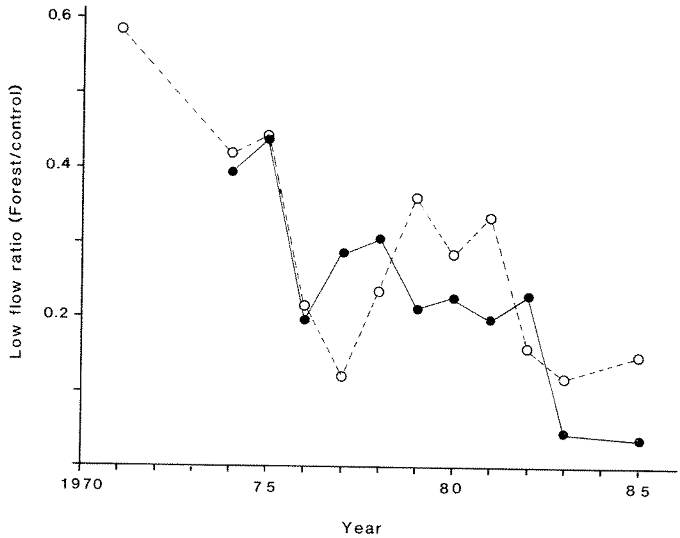

Fig. 3 Low flows (exceeded 70% of the year) from FM/N (——) and FM/S (- - -) expressed as a proportion of corresponding exceedance flow from the control catchment, UM; points are not shown for years when the 70 percentile flows from the forested catchments were zero.

CONCLUSIONS

The four experimental catchments at Chiemsee provide about 100 site-years of hydrological observations. It has been shown that land use changes comprising agricultural drainage and forestry may have a profound effect on flow regimes. Drainage of wetlands increased flows and reduced evaporation losses. Peak flows were greater and low flows were higher. The effects of drainage were, however, more than counterbalanced by those of forestry, which had the following effects:

(a) evaporation losses were increased by about 480 mm year^{-1}, and annual runoff was reduced by the order of 40%;
(b) low flows were reduced by a greater relative amount, over a 60% reduction in the 70 percentile exceedance flow;
(c) peak storm flows were attenuated, particularly for smaller events; and
(d) soil water levels were reduced and, by analogy, so was any recharge to an underlying aquifer.

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