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# Evapotranspiration 1961–1990 in Finland as function of meteorological and land-type factors

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Basin-wise values of mean annual total evapotranspiration for the period 1961–1990 were obtained from the water balance equation and examined using following factors: the sum of effective temperature (over the land area), the relative area of open peatlands, the amount of growing forest stock ($m^3$ $ha^{-1}$), the proportion of dense stands (i.e. the reduction in forests where evapotranspiration increases with the volume of growing stock less than usual, due to the lack of water, reduced vitality of trees and reduced evapotranspiration from the forest-floor vegetation), and lake evaporation, taken from preliminary work. The values of the variables were first obtained in 10 km × 10 km grid-squares, and then averaged over the basin areas. 96% of the total variance of the water balance evapotranspiration was explained. The mean standard error is 14.6 mm, and the maximum 30.7 mm. Evapotranspiration was determined separately for fields, open peatlands, lakes and forests. As compared with that of fields, evapotranspiration from open peatlands was 305 mm higher, and from lakes 170–300 mm higher, with an inreasing difference southwards. In Lapland evapotranspiration from forests was 35 mm higher than over fields, and in other regions 50 mm higher. The change in evapotranspiration from 1961–1975 to 1976–1990 was also studied.

## Introduction

Basin-wise values of mean annual evaportranspiration for the period 1961–1990 were calculated and explained by regression analysis by Hyvärinen *et al*. (1995). In this report, the same work is carried out more thoroughly, using a larger number of accurate variables. This is important in order to understand the consequences of land-use, both in forestry and environmental planning, and and also for hydrological modelling.

The total mean annual evapotranspiration (mm over the total area, inland water bodies included) was considered to be the sum of various contributions (and a constant term), and was explained by a corresponding regression analysis. Each contribution was the product of a certain effect and the proportion of the area where this effect was valid, multiplied by the constant of the regression analysis. The effects were:

- the thermal effect (valid over all land areas, i.e. the total area excluding inland water bodies);
- the forest stands effect (occurring in forest stands), which gives increased evaporation compared to that from low vegetation; it is assumed to be proportional to the volume of growing forest stands);
- the dense stands effect (negative), occurring in heavy stands, which have a relatively smaller increase of evapotranspiration with increasing growing stock due to the lack of water in the soil, reduced vitality of the trees, and, especially, an appreciably reduced amount of forest floor vegetation due to a lack of light. ‘Dense stands’ were defined as a function of the volume of forest growing stock and the humidity of the climate; and
- wet mire effect, due to additional evapotranspiration from water surfaces (occurring on open peatlands) and the effect of lakes.

The corresponding formulae are given in Chapter “Methods”.

The main changes in these factors and their influence on changes in evapotranspiration were also studied. For this purpose, evapotranspiration was calculated for the two periods 1961–1975 and 1976–1990, and additionally for the year 1992, using specific values of certain forest variables available for that year, while values for the other variables were those for the period 1961–1990.

## Methods

### Evapotranspiration as the sum of various contributions

Mean evapotranspiration (mm year$^{-1}$) for the total area (consisting of land and inland waters) was calculated from a regression equation as the sum of various contributions. The variables contributing to explaining evapotranspiration are first given in their exact forms. Each contributing factor is valid for a certain land-type, but is given for the total land area (including lakes and rivers). Concerning the classification of the land-types used, ‘forestry land’ consists of forests and peatlands, i.e. practically all land with natural vegetation. The terms, the sum of which gives the total evapotranspiration, are as follows:

$c_0$ = the constant term of the regression equation

The thermal contribution:

$$\mathrm{CE}_\mathrm{T} = c_1(1 - L)T, \tag{1}$$

where $c_1$ = a positive coefficient, $L$ = the proportion of land area covered by lakes and rivers and $T$ = the sum of effective temperatures. Let us denote daily mean temperatures for each date $i$ averaged over the period 1961–1990 (or any period considered), by $t_i$. The value of $t$ is then obtained by summing the positive values of $t_\mathrm{I}$ – 5 °C during the year. The values of $T$ were obtained from Solantie and Drebs (2000).

The forest stands contribution:

$$\mathrm{CE}_\mathrm{K} = c_2(1 - L)UK_\mathrm{U}, \tag{2}$$

where $c_2$ = a positive coefficient, $U$ = the proportion of land area covered by forest stands, and $K_\mathrm{U}$ = the mean volume of growing stock (m$^3$ ha$^{-1}$) in such forests.

The dense stands reduction:

$$\mathrm{CE}_\mathrm{Kt} = c_3(1 - L)DF(K_\mathrm{D} - K_0), \tag{3}$$

where $c_3$ = a negative coefficient, $D$ = the proportion of forestry land, comprising heavy and mature stands, $F$ = the proportion of forestry land in the land area; further, $K_D$ = the amount of growing stock in advanced thinning stands and mature stands, if it is large enough to cause the contribution by forest vegetation to evapotranspiration to be lower than $CE_K$ ('restricted'), due to a lack of water (and lack of light for forest floor vegetation), and $K_0$ = the threshold volume of growing stock above which the evapotranspiration is restricted; note that $K_0$ also varies spatially. In cases of $K_D < K_0$, this term is neglected. Thus, $D$ = the proportion of such forests of forestry land where $K_D > K_0$.

The wet mire contribution:

$$CE_N = c_4(1 - L)N, \qquad (4)$$

where $c_4$ = a positive coefficient, and $N$ = the proportion of land area consisting of open peatlands. This contribution is approximated as being proportional to the area of open or nearly-open peatlands (*neva* in Finnish). It accounts for the excess evapotranspiration from shallow water surfaces on peatland. Generally, water surfaces on mires are concentrated on open peatlands. Most of the area of open peatlands are fens which regularly become covered by snow melt waters. In early summer, the shallow water layer on the peat gets relatively warm, but its area contracts during the middle of summer, becoming more extensive again later on. In southern and western Finland are also found nearly-open peatlands that are Spaghnum bogs with permanent ponds.

The contribution of lakes:

$$CE_L = c_5 L e_L \qquad (5),$$

where $c_5$ = a positive coefficient, and $e_L$ = evaporation from lakes in the considered area as given by Hyvärinen *et al.* (1995). The thermal contribution is calculated for all land-types except permanent water bodies (rivers and lakes); consequently, the evapotranspiration for each land-type is the sum of $c_0$ (discussed in more detail in section "Evapotranspiration for the various land-types"), the thermal term ($c_1 \times T$), and none, one or two other terms for those contributions valid for the land-type considered.

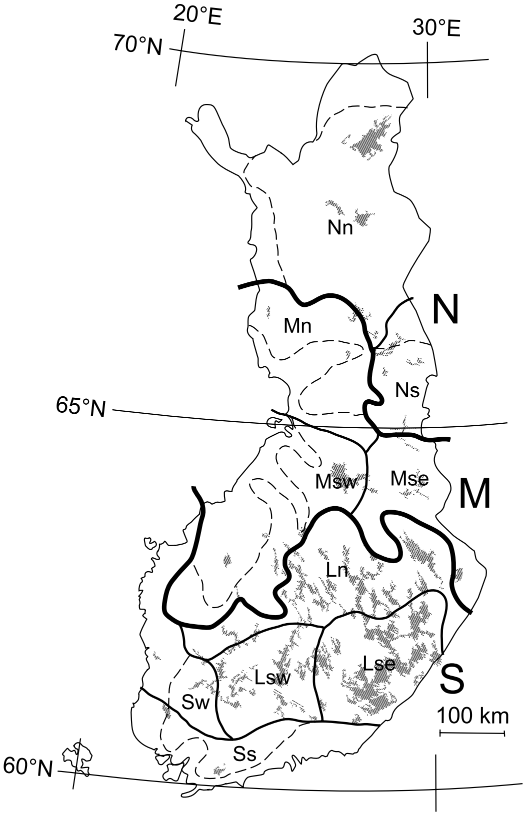

**Fig. 1**. Zones (N, M, S, thick lines) and regions consisting of basins for which evapotranspiration is obtained (Capital and small letter, thin lines. Uniform lines separate neighbouring regions while broken lines separate regions from neighbouring 'empty' areas. N = the northern boreal zone, Nn = Lapland, Ns = Kuusamo, M = the middle boreal zone, Mn = north part of eastern Bothnia, Msw = south-western part of eastern Bothnia, Mse = south-eastern part of eastern Bothnia. S = the southern boreal zone, Ln = northern Lake-Finland, Lsw = south-western Lake-Finland, Lse = south-eastern Lake-Finland, Sw = western Finland, Ss = southern Finland.

Each contribution to the total evapotranspiration in the regression analysis is subject to considerable areal variation: Referring to Fig. 1, the proportion of lakes is only high in Lake-Finland, while the proportion of open fields is only large in southern and western Finland; the proportion of open peatlands is high in the northern boreal zone but low in the southern boreal. Further, dense stands only occur in the southern boreal zone, and there is a large variation in the volume of growing forest stock between the regions.

The proportions of the various land-types and their volumes of growing stock is based on municipality forest statistics for 1992, compiled by Tomppo *et al*. (1998). The values were then found for 10 km × 10 km grid-squares, and corrected to correspond to the values for the periods 1961–1990, 1961–1975 and 1976–1990, etc., based on forest statistics (Ilvessalo 1957, Anon. 1974, 1979, 1986, 1992, 1994) for any variable $R$, denoted $R_{61–90}$, $R_{61–75}$, and $R_{76–90}$, etc., respectively.

The nomenclature of the land-types introduced into this study from the forest statistics requires detailed clarification. 'Forestry land' consists of 'productive forests' (their proportion of the total forestry land area is denoted by $m$), of 'poorly growing' forests ($w$), and of waste land ($v$), consisting mostly of wholly or nearly open peatlands, but also of rocks, forest roads etc. Forests also include, in addition to the areas of actual stands, logged and recently-planted areas. Denoting the proportion of such areas of forestry land by $m_a$, and the proportion of forests with actual stands by $m_u$, we note that

$$v + m + w = v + m_a + m_u = 1. \qquad (6)$$

Further, denoting the proportion of the total land area comprising forestry land by $F$, the proportion of the total land area comprising forests with actual stands ($U$) can be given as

$$U = Fm_u = F(1 - v - m_a). \qquad (7)$$

Dense stands form a certain part of forests, in which evapotranspiration is 'restricted', i.e. less than that usually calculated for forests as a function of the volume of growing stock. In the forest statistics, dense stands are included in a group called 'advanced thinning and mature forests'. Such forests were considered as 'dense' if the volume of growing stock there ($K_D$) exceeded a certain limit $K_0$ that depends on climatic and soil conditions.

Let us consider values for the periods 1961–1975 and 1976–1990, and for the year 1992, using subscripts 61–75, 76–90, and 92 to refer to them. On the basis of the results of the National forest inventories, we can also estimate that during the period 1961–1990 there were, on average, 47% more logged or recently-planted areas than in 1992. We thus obtain (referring to Eq. 7):

$$U_{61–90} = [1 - (v_{92} + \Delta v) - 1.47m_{a92}]F, \qquad (8)$$

where Dv = $v_{61–90} - v_{92}$, obtained from a separate map.

From the results of the forest inventories, we may approximately obtain:

$$U_{61–75} = [1 - (v_{92} + 1.9\Delta v) - 1.61m_{a92}]F, \quad (9)$$

and

$$U_{76–90} = 2U_{61–90} - U_{61–75}. \qquad (10)$$

The grid-square values of the volume of growing stock in forests with actual stands for the period 1961–1990, denoted by $K_{U61–90}$, were obtained by correcting the corresponding 1992 values:

$$K_{U61–90} = K_{U92} + \Delta K_U \qquad (11).$$

Here $\Delta K_U$ is obtained as

$$\Delta K_U = \Delta K_{m+w}/(1 - 1.47m_{a92}). \qquad (12)$$

$\Delta K_{m+w}$ = the (negative) difference in the values of the volume of growing stock in forests (productive and poorly growing) between the period 1961–1990 and in the year 1992 in a grid-square. Approximately we have

$$K_{U61–75} = K_{U61–90} + \Delta K_U/2.6 \qquad (13)$$

and

$$K_{U76–90} = K_{U61–90} - \Delta K_U/2.6. \qquad (14).$$

The changes in the volume of growing stock in forests are practically accounted for by the changes in the volume of growing stock in advanced thinning and mature forests, comprising about 1/2.6 of forests with stands. Thus, we have

$$\Delta K_{\mathrm{D}61\text{–}75} = Z_{61\text{–}75}(K_{\mathrm{D}92} + 3.6\Delta K_{\mathrm{U}} - K_0), \quad (15)$$

$$\mathrm{D}K_{\mathrm{D}76\text{–}90} = Z_{76\text{–}90}(K_{\mathrm{D}92} + 1.6\Delta K_{\mathrm{U}} - K_0) \quad (16)$$

and

$$\Delta K_{\mathrm{D}61\text{–}90} = 0.5(K_{\mathrm{D}61\text{–}75} + \Delta K_{\mathrm{D}76\text{–}90}). \quad (17)$$

Here $Z$ indicates the occurrence ($Z = 1$) or absence ($Z = 0$) of the dense stands contribution. $Z_{61\text{–}75} = 1$ in those grid squares where $K_{\mathrm{D}92} + 3.6\Delta K_{\mathrm{U}} > K_0$, and $Z_{61\text{–}75} = 0$ where $K_{\mathrm{D}92} + 3.6\Delta K_{\mathrm{U}} < K_0$ or $K_{\mathrm{D}92} + 3.6\Delta K_{\mathrm{U}} = K_0$; note that $K_0$= the threshold volume of growing stock above which the tree evapotranspiration is restricted. Further, $Z_{76\text{–}90} = 1$ where $K_{\mathrm{D}92} + 1.6\Delta K_{\mathrm{U}} > K_0$, and $Z_{76\text{–}90} = 0$ where $K_{\mathrm{D}92} + 1.6\Delta K_{\mathrm{U}} < K_0$ or $K_{\mathrm{D}92} + 1.6\Delta K_{\mathrm{U}} = K_0$.

To find the values of $K_0$, in order to estimate where and to what degree heavy and dense stands effect occurs, we begin with the fact that the potential forest evapotranspiration increases by about 1.14 mm a year and by 0.25 mm in July for an increase of 1 $\mathrm{m}^3\ \mathrm{ha}^{-1}$ in the volume of growing stock ($K$), but on condition that the water supply is unlimited, i.e. $K < K_0$ (Hyvärinen *et al.* 1995). On the other hand, let us compare two regions X and Y, both having equal precipitation in July ($P_7$), while the evapotranspiration in July, without the effect of growing stock ($E_{0,\,7}$), in region X is $\Delta E_{0,\,7}$ mm higher than in region Y. Suppose now that in the forests of both regions $K = K_0$ and that the amounts of actual evapotranspiration are equal. In this case, we conclude that, approximately, $K(\mathrm{Y}) - K(\mathrm{X}) = 4\Delta E_{0,\,7}$ $\mathrm{m}^3\ \mathrm{ha}^{-1}$. Correspondingly, if $(E_{0,\,7} - P_7)_{\mathrm{A}} - (E_{0,\,7} - P_7)_{\mathrm{B}} = 20$ mm, then $K(\mathrm{Y}) - K(\mathrm{X}) = 80$ $\mathrm{m}^3\ \mathrm{ha}^{-1}$. In the southern boreal zone, the water resources for evapotranspiration are restricted, but in the middle boreal only seldom. Thus, at the southern edge of the middle boreal zone where $K_{\mathrm{D}61\text{–}90} = 200$ $\mathrm{m}^3\ \mathrm{ha}^{-1}$, $K_{0,\,61\text{–}90} = 200$ $\mathrm{m}^3\ \mathrm{ha}^{-1}$ as well. Noting that in these areas $(E_{0,\,7} - P_7)_{61\text{–}90} = -10$ mm (Hyvärinen *et al.* 1995), we can make a rough but generally-valid estimation:

$$K_{0,\,61\text{–}90}\ (\mathrm{m}^3\ \mathrm{ha}^{-1}) = 160 - 4(E_{0,\,7} - P_7)_{61\text{–}90}\ \mathrm{mm}. \quad (18)$$

Accordingly, in the southern boreal zone where $(E_{0,\,7} - P_7)_{61\text{–}90}$ ranges from –10 mm (region Y) to 10 mm (region X), $K_{0,\,61\text{–}90}$ ranges from 200 to 120 $\mathrm{m}^3\ \mathrm{ha}^{-1}$.

To estimate the wet mire contribution, it is necessary to estimate the temporal changes of peatlands having an abundance of such surfaces. The proportion of open and nearly-open peatlands in the northern part of the northern boreal zone remained constant in time, while in the other parts of the country a major part of the peatlands was drained during the period 1952–1988, causing a considerable decrease in such mires. Since practically all the waste land in these areas consists of open (or nearly-open) peatlands, the decrease in waste lands is practically equal to the decrease in open peatlands due to draining.

Remembering that the proportion of the land area comprising open peatlands is denoted by $N$, and that the proportion of forestry land comprising waste land is denoted by $v$, we may write

$$(N_{52} - N_{61\text{–}90})/(N_{52} - N_{88}) = (v_{52} - v_{61\text{–}90})/(v_{52} - v_{88}), \quad (19)$$

from which we obtain

$$N_{61\text{–}90} = N_{52} - [(v_{52} - v_{61\text{–}90})/(v_{52} - v_{88})] (1 - N_{88}/N_{52})N_{52}. \quad (20)$$

The average value of $(v_{52} - v_{61\text{–}90})/(v_{52} - v_{88})$ was calculated for an area consisting of the four forest board districts with most drained mires (Etelä-Pohjanmaa, Keski-Pohjanmaa, Pohjois-Pohjanmaa and Kainuu); for $v_{61\text{–}90}$, annual values were approximated according to the results of the National forest inventories since the third in 1951–1953. As a result, $(v_{52} - v_{61\text{–}90})/(v_{52} - v_{88}) = 0.616$. The ratio $N_{88}/N_{52}$ was approximated in grid-squares as the proportion of undrained mires in 1988 (data provided by Kari T. Korhonen of the Forest Research Institute), and denoted by $n_{88}$. Now, also employing the values of $N_{52}$ in grid-squares, digitalized by the author from the map analyses of maps (13) and (16) in Ilvessalo (1960), we obtain the grid-values of $N$ for various periods as

$$N_{61\text{–}90} = N_{52} - 0.616(1 - n_{88})N_{52}, \quad (21)$$

$$N_{61\text{–}75} = N_{61\text{–}90} + 0.53(N_{52} - N_{61\text{–}90}), \quad (22)$$

$$N_{76\text{–}90} = N_{61\text{–}90} - 0.53(N_{52} - N_{61\text{–}90}) \quad (23)$$

and

$$N_{92} = n_{88}N_{52}. \quad (24)$$

## Special conditions in northern Lapland

The transition between the northern boreal zone (A) and tundra (C), i.e. the subarctic belt (B), runs through the three northernmost municipalities of Finland (Enontekiö, Inari and Utsjoki). For this reason, the municipality forest statistics were developed into statistics for three separate regions, A, B, and C. The division was made according to values of $L_{61\text{–}90}$ such that areas with $L_{61\text{–}90}$ > 620 °Cd belong to A, areas with $L_{61\text{–}90}$ < 540 °Cd to C and the rest to B (Solantie and Drebs 2000). The land areas of the municipalities consisted of these regions as follows (%):

| | A | B | C |
|---|---|---|---|
| Enontekiö | 10.6 | 34.7 | 54.7 |
| Utsjoki | – | 5.5 | 94.5 |
| Inari | 45.3 | 45.7 | 9.0 |

'Forestry land' comprised all land, and was divided into productive forests, poorly growing forests and waste land (with proportions (%) denoted by $m$, $w$ and $V$) so that their means within each municipality equalled the statistical values. All forests were assumed to be situated in regions A and B. Thus, forests comprise 85% of region B in Utsjoki; making the approximation that $w$(B) = 8% and $V$(B) = 7%, the rest of the waste land and poorly-growing forests in Utsjoki were assigned to the tundra (C); we thus have $w$(C) = 26% and $V$(C) = 74%. In regions A and B, waste land consists mostly of open fens. The values of $V$ in the grid-squares in regions A and B for Inari and Enontekiö were therefore approximated by the proportion of open peatlands ($N$) as produced from the map analyses of Ilvessalo (1960) (maps 13, 16); however, in those grid-squares in Inari where $N$ < 21%, $V$ was approximated by 21%. Consequently, on average in Inari $V$(A) = 21% and $V$(B) = 22%, while in Enontekiö, correspondingly, $V$(A) = $V$(B) = 20%. The forests of Inari were divided between the regions A and B so that $m$(A) = 60% and $m$(B) = 40%, and the forests of Enontekiö so that $m$(A) = 50% and $m$(B) = 20%. Poorly-growing forests make up the rest of the regions A and B; thus, in Inari $w$(A) = 19% and $w$(B) = 38%, and in Enontekiö, correspondingly, $w$(A) = 30% and $w$(B) = 60%. The rest of the poorly-growing forests and waste land were assignated to tundra. Consequently, in region C in Inari we have $w$(C) = 10% and $V$(C) = 90%, and in Enontekiö, correspondingly, $w$(C) = 12% and $V$(C) = 88%.

In each municipality, the tundra (region C) was approximated as being uniform with respect to $V$ and $w$. In regions A and B, each being considered separately, the values of $m$ were approximated as being equal in all grid-squares, while $V$ varied according to the occurrence of fens, and $w$ was determined as a residual. The volume of growing forest stock per hectare of all land in the grid-squares was calculated as the weighted means of their municipality values for the various land-types.

In northern Lapland, $\text{CE}_{\text{Kt}} = 0$, and

$$E = \text{CE}_{\text{T}} + \text{CE}_{\text{K}} + \text{CE}_{\text{N}} + \text{CE}_{\text{L}} + c_0. \quad (25)$$

For the period 1961–1990, the values of $E_{\text{T}}$ and $E_{\text{L}}$ are obtained as for the rest of Finland, but the values of $\text{CE}_{\text{N}}$ and $\text{CE}_{\text{K}}$ were taken as

$$\text{CE}_{\text{N}} = \text{CE}_{\text{N52}} \quad (26)$$

and

$$\text{CE}_{\text{K61–90}} = c_3[(1 - L/100)(m_{92}K_{\text{M92}} + w_{92}K_{\text{w92}} + (m_{92} + w_{92})\text{DK}_{\text{U61–90}}], \quad (27)$$

where $m_{92}$ = the proportion of the area of forestry land comprising productive forests in 1992, and $\Delta K_{\text{U61–90}}(\text{A}) = -4\ \text{m}^3\ \text{ha}^{-1}$, $\Delta K_{\text{U61–90}}(\text{B}) = -2\ \text{m}^3\ \text{ha}^{-1}$, and $\Delta K_{\text{U61–90}}(\text{C}) = 0\ \text{m}^3\ \text{ha}^{-1}$.

Further, in each of the areas A, B, and C the values of $\text{CE}_{\text{K61–90}}$ were also applied for the other periods considered. For northern Lapland this method was also applied in single grid-squares of the northern boreal zone outside these three municipalities in situations where $L$ < 620 °Cd.

## Evapotranspiration for the various land-types

Evapotranspiration for the various land-types was calculated as follows (with reference to Eqs. 1–5:

Forests, excluding openings:

$$E_F = c_0 + CE_T/(1 - L) + (CE_K/U + CE_{Kt}/DF)/(1 - L) = c_0 + c_1T + c_2K_U + c_3(K_D - K_0). \quad (28)$$

Cultivated fields, mires excluding open peatlands, and openings in the forests:

$$E_0 = c_0 + CE_T/(1 - L) = c_0 + c_1T \quad (29).$$

Open peatlands:

$$E_N = c_0 + CE_T/(1 - L) + c_4(CE_N/N)/(1 - L) = c_0 + c_1T + c_4, \quad (30)$$

and lakes

$$E_L = c_0 + CE_L/L = c_0 + c_5e_L. \quad (31)$$

## Results

### Main results (Tables 1 and 2)

The coefficient of multiple correlation was 98%, and 96% of the total variance of the evapotranspiration was explained. The mean error of explanation is 14.6 mm; for one basin only (basin 61.7.0, above Jaurakkajärven luusua) did the error of estimate (30.7 mm) exceed 30 mm. The coefficients were very close to those obtained in the preliminary study by Hyvärinen *et al.* (1995). All the contributions are significant at the 5% level, and all but $CE_K$ at the 1% level. $CE_T$ and $CE_L$ are the most significant and accurate variables. The most interesting addition to the results of the preliminary research is the moderate significance of the dense stands reduction. The rather weak significance of $E_K$ may be caused by the rather high correlation of $CE_K$ and $CE_T$ ($r$ = 0.69); i.e., part of $CE_K$ may be included in $CE_T$. (A simple experiment sustains this assumption. Let us replace the value of $c_2$ = 0.81 by 1.13 obtained by Hyvärinen *et al.* (1996), and the value of $c_1$ = 0.388 by 0.371 to counterbalance this effect, so that the forest stands contribution should be on average 15 mm higher and the thermal contribution 15 mm lower. As a result, the change in the explained evapotranspiration would have a mean of –1 mm and standard deviation of 3 mm, and the standard error of explanation would be only 0.2 mm higher). The highest correlation coefficient ($r$ = 0.77) was between $CE_K$ and $CE_{Kt}$, and the signs of their constants became opposite, as expected. The greatest negative correlation was noted between $CE_N$ and $CE_K$ ($r$ = –0.85), and the second greatest between $CE_N$ and $CE_T$ ($r$ = –0.70).

Towards the end of the period, the dense stands reduction increased, and exceeded the increase in the forest stands contribution, which well explains the appreciable decrease of evaporation in the southern Lake-Finland area compared to the period 1931–1960. In the southern boreal zone, growing forest stands generally achieve a volume of 200 m$^3$ ha$^{-1}$ at around the age of 50 years; at this stage, both growth and evaporation show a decrease. On the other hand, in the old forestry system prevailing till the year 1960, forests were thinned during the raising period, with the result that a value for the volume of growing forest stock of 200 m$^3$ ha$^{-1}$ was achieved at around the age of 70 years; the

**Table 1**. Statistical values of the regression analysis: coefficients of the variables in the regression equation for evapotranspiration with their standard errors, *t*-statistics and *p*-values (Eqs. 1–5).

| Term | Value | S.E. | *t*-statistic | *p*-value |
|---|---|---|---|---|
| Constant term ($c_0$) | $c_0$ = –100.0 | 31 | –3.3 | 0.002 |
| Thermal contribution ($CE_T$) | $c_1$ = 0.388 | 0.026 | 15.2 | $4 \times 10^{-18}$ |
| Forest stands contribution ($CE_K$) | $c_2$ = 0.81 | 0.40 | 2.8 | 0.007 |
| Dense stands contribution($CE_{Kt}$) | $c_3$ = –4.1 | 1.14 | 2.1 | 0.046 |
| Contribution of wet mires ($CE_N$) | $c_4$ = 305.0 | 108 | –3.6 | 0.001 |
| Contribution of lakes ($CE_L$) | $c_5$ = 1.31 | 0.09 | 12.7 | $1 \times 10^{-15}$ |

reduced rivalry with neighbouring trees resulted in more light and nutrients and less soil frost for single trees, so that growth and evapotranspiration continued to increase until this greater age. However, with the present-day higher number of single trees per hectare, forests are more productive, but have shorter periods of intensive growth for single trees. Further, the coverage of forest floor vegetation has decreased from the 1950s to 1990s by 43% and the coverage of shrubs by 53% (Vanha-Majanmaa 2000: table 6.3, p. 93); obviously the evapotranspiration from these has also decreased. Grouping the basins as seen in Fig. 1, calculating evaporation by land-types according to Eqs. 30–33, and weighing each evapotranspiration in the land-type and basin considered by the relative areas of each basin, we obtain the amounts of evaporation (mm year$^{-1}$) by land-types (Table 2)

## Spatial distribution of evapotranspiration

The evapotranspiration from open peatlands ($E_N$) having shallow and warm water surfaces is greater than from other land-types, exceeding the evaporation from open fields in all areas by about 305 mm, which is three times the standard error of $E_N$. The high evapotranspiration from open peatlands is expected, because in northern Finland, where they are mostly concentrated, they are usually covered by shallow water for a long time after the snow melt covered. The evapotranspiration from lakes ($E_L$) is the second highest. The difference between $E_N$ and $E_L$ decreases southwards from 130–140 mm in Lapland to 0 mm in southern Finland. This is in accordance with the fact that the coverage and duration of water surfaces on open peatlands decreases southwards while the open-water period for lakes increases. The speed at which winter deepens, i.e.the rate of fall of mean temperature in late autumn and early winter, decreases southwards, so that for a long period the loss of heat from the water surface of southern lakes only slightly exceeds the flux of heat up to the surface by the mixing of water. In Lapland evapotranspiration from forests is 30 mm higher than from open fields; the corresponding difference in the other regions being greater, i.e., 50 mm. This difference increases southwards due to the increase in the volume of growing forest stock, albeit this increase is partly eliminated by the effect of limited water resources.

**Table 2**. Evapotranspiration by land-types in basins of the various climatic zones and their regions.

| | Evapotranspiration from | | | | |
|---|---|---|---|---|---|
| | Lakes $E_L$ | Open peatlands $E_N$ | Forests $E_F$ | Fields $E_0$ | Land and lakes $E$ |
| Lapland | 326 | 462 | 188 | 157 | 225 |
| Kuusamo | 404 | 514 | 257 | 209 | 285 |
| Northern boreal | 340 | 471 | 200 | 166 | 236 |
| Northern part of eastern Bothnia | 423 | 524 | 255 | 219 | 288 |
| South-western part of eastern Bothnia | 486 | 587 | 335 | 282 | 353 |
| South-eastern part of eastern Bothnia | 492 | 568 | 319 | 263 | 336 |
| Middle boreal | 469 | 561 | 305 | 256 | 327 |
| Northern Lake-Finland | 555 | 620 | 374 | 315 | 385 |
| Western Finland | 608 | 668 | 419 | 363 | 413 |
| South-eastern Lake-Finland | 601 | 677 | 392 | 372 | 440 |
| South-western Lake-Finland | 609 | 670 | 421 | 365 | 437 |
| Southern Finland | 691 | 691 | 444 | 386 | 435 |
| Southern boreal | 588 | 651 | 394 | 346 | 413 |

## Contributions of various land-types to the total evapotranspiration

The contribution of the various land-types to the evapotranspiration of the total land area was calculated according to Eqs. 1–5, the results being given in Table 3.

A contribution to the total evapotranspiration is termed high with values of 31 mm or more, moderate with values of 13 to 30 mm, weak with values of 4 to 12 mm and insignificant with values of 3 mm or less. The relative area of open peatlands decreases rapidly southwards, while the relative area of lakes increases slightly. Thus, the contribution of open peatlands in Lapland and in the northern part of the middle boreal zone is high, and higher than the contribution of lakes. In the other parts of the northern and middle boreal zone both contributions are moderate. Regarding the contribution of open peatlands in the southern boreal zone, it is weak in the northern Lake-Finland area, and insignificant in the other regions of this zone, while the contribution of lakes in the regions of Lake-Finland is high; in western and southern Finland their contribution is moderate. In all areas the combined contribution of fens and lakes is from 17 to 66 mm.

The contribution from forest stands is high in all regions, except for the three northernmost ones, where it is moderate. In most regions this contribution is the largest, the exceptions being the three northernmost regions and south-eastern Lake-Finland. In spite of the occurrence of the dense stands reduction in the southern regions, the forest contribution, obtained as the sum of the forest stand contribution and the dense stands reduction, is high in the same regions where the forest stands contribution is high, with the exception of south-eastern Lake-Finland, where it is moderate.

## Application of the regression model: temporal changes in the evapotanspiration from forests and open peatlands

The contributions of forests, wet mires and forestry land as a whole to total evapotranspiration for the periods 1961–1975, 1976–1990 and for the year 1992, as calculated by the regression equation, are given in Table 4; the corresponding contributions of the two components of forest evapotranspiration are shown in Table 5.

Due to the large drainage operation carried out on the peatlands in the middle boreal zone during the period 1961–1990, the area of afforested areas and the evapotranspiration from grow-

**Table 3**. Contribution of lakes ($CE_{L61–90}$), wet mires ($CE_{N61–90}$), forest stands ($CE_{K61–90}$), dense stands ($CE_{Kt61–90}$), and forests ($CE_{F61–90}$) to evapotranspiration from basins of the various climatic zones and their regions.

| | $CE_{L61–90}$ | $CE_{N61–90}$ | $CE_{K61–90}$ | $CE_{Kt61–90}$ | $CE_{F61–90}$ |
|---|---|---|---|---|---|
| Lapland | 11 | 36 | 21 | 0 | 21 |
| Kuusamo | 20 | 21 | 30 | 0 | 30 |
| Northern boreal | 13 | 33 | 23 | 0 | 23 |
| Northern part of eastern Bothnia | 9 | 33 | 25 | 0 | 25 |
| South-western part of eastern Bothnia | 16 | 20 | 33 | 0 | 33 |
| South-eastern part of eastern Bothnia | 23 | 13 | 38 | 0 | 38 |
| Middle boreal | 16 | 22 | 32 | 0 | 32 |
| Northern Lake-Finland | 39 | 5 | 46 | –6 | 40 |
| Western Finland | 15 | 2 | 50 | –12 | 38 |
| South-eastern Lake-Finland | 64 | 2 | 54 | –41 | 13 |
| South-western Lake-Finland | 44 | 1 | 56 | –23 | 33 |
| Southern Finland | 23 | 2 | 45 | –14 | 31 |
| Southern boreal | 44 | 3 | 50 | –19 | 31 |

ing forest stands have increased. This increase of evapotranspiration has been counterbalanced by the reduction of evaporation from open peatlands. At the same time, the evapotranspiration in forests in the southern boreal zone has decreased due to the structural change of the growing forest stands, in spite of the increase in the volume of growing stock. The dense stands reduction, as extrapolated to the year 1992, is obviously exaggerated. The reasons are discussed in section "The role of soils".

## Discussion

### Critical comparison: Changes in the total evapotranspiration from 1961–1975 to 1976–1990 as derived from the water balance equation and the regression equation

When considering the changes in the total evapotranspiration from the regression equation ('calculated') between the two 15-years periods under review, corrections due to two effects should be taken into account. The change in the thermal component of evapotranspiration in the southern boreal zone is –7 mm, in the middle boreal zone –2 mm, and in the northern boreal zone –3 mm. The change in lake evaporation was approximated by the effect of the mean decrease of the open-water period between the periods, i.e., 8.5 days (based on dates published in Anon. 1981, 1993). The decrease in evaporation for this reason was estimated to be 13 mm multiplied by the proportion of lake area. Thus, the effect is 0 to –4 mm.

Let us then have a look at the 'observed' change of evapotranspiration, obtained from the water balance equation. During the period 1951–1980, 75% of the area of peatlands, i.e. 30% of the total area of the middle boreal zone, was drained. The total drop in water storage in peat due to the drainage of a mire is from 50 to 100 mm, which means 15 to 30 mm for the total area, i.e. 1–2 mm year$^{-1}$ over a period of 15 years (or 3 mm year$^{-1}$, because the ponds on mires also lost most of their water due to the drainage). The drop before 1975 was, however, approximately equal to that since 1976, so that their difference and the effect on the change in evapotranspiration were negligible.

The 'calculated' and 'observed' changes are given in Table 6. We may note that the cal-

**Table 4**. Contributions of forests (f) and wet mires (wm) to the total evapotranspiration; the time extrapolated values in the southern boreal zone for the evapotranspiration in the forests are obviously too low and are therefore bold.

| | 1961–1975 | | | 1976–1990 | | | 1992 | | |
|---|---|---|---|---|---|---|---|---|---|
| | f | wm | wm + f | f | wm | wm + f | f | wm | wm + f |
| Lapland | 18 | 36 | 54 | 24 | 36 | 60 | 24 | 36 | 60 |
| Kuusamo | 28 | 23 | 51 | 32 | 19 | 51 | 35 | 18 | 53 |
| Northern boreal | 20 | 34 | 54 | 26 | 32 | 58 | 26 | 32 | 58 |
| Northern part of eastern Bothnia | 23 | 38 | 61 | 27 | 28 | 55 | 32 | 27 | 59 |
| SW part of eastern Bothnia | 28 | 28 | 56 | 38 | 12 | 50 | 42 | 11 | 53 |
| SE part of eastern Bothnia | 33 | 17 | 50 | 43 | 9 | 52 | 44 | 8 | 52 |
| Middle boreal | 28 | 27 | 55 | 37 | 17 | 54 | 39 | 15 | 54 |
| Northern Lake-Finland | 39 | 7 | 46 | 41 | 3 | 44 | 27 | 2 | 29 |
| Western Finland | 43 | 3 | 46 | 33 | 1 | 34 | **–17** | 1 | **–16** |
| South-eastern Lake-Finland | 33 | 2 | 35 | –7 | 2 | –5 | **–43** | 1 | **–42** |
| South-western Lake-Finland | 49 | 2 | 51 | 22 | 1 | 23 | **–25** | 1 | **–24** |
| Southern Finland | 39 | 2 | 41 | 23 | 2 | 25 | **–14** | 1 | **–13** |
| Southern boreal | 39 | 4 | 43 | 23 | 2 | 25 | **–5** | 1 | **–4** |

culated change in evapotranspiration from the period 1961–1975 to the period 1976–1990 is in most regions practically the same as that observed. Of the two exceptions, for which the deviations are more than 12 mm, that for Lapland is discussed below, and that for the southern and western Finland in section "The role of soils".

In Lapland, the calculated evapotranspiration did not change from the period 1961–1975 to 1976–1990, while the observed evapotranspiration decreased by 35 mm. This discrepancy may either be due to real but unknown reasons or to the rather poor accuracy of precipitation values there.

## The role of soils

In the southern and western parts of the southern boreal zone the structural change in the forests does not seem to have had any effect on evapotranspiration; this continued to increase with the increase in the volume of growing forest stock. One possible reason is that only in these regions do glacial clay soils dominate: this has both direct and indirect consequences. Clay retains snow-melt water efficiently, so that the soil water storage on 1 June is on average about 19 mm larger than in the Lake-Finland area (Solantie 1987). During the period 1 June to 15 September, the soil water storage in the southern and southwestern areas decreases more than in Lake-Finland, so that by 15 September the storage in both regions is equal. Consequently, forests on clay soils are able to evaporate more than forests on moraine soils. As a result, the water uptake and growth of tall and dense stands only reacts significantly to drought on moraine soils. Clayey soils are also advantageous for

**Table 5**. The two additive components of the contribution of forest evapotranspiration during the periods 1961–1975 and 1976–1990, and in the year 1992. $CE_K$ = the forest stands contribution (mm) and $CE_{Kt}$ = the dense stands reduction (mm).

| | $CE_{K61–75}$ | $CE_{K76–90}$ | $CE_{K92}$ | $CE_{Kt61–75}$ | $CE_{Kt76–90}$ | $CE_{Kt92}$ |
|---|---|---|---|---|---|---|
| Northern Lake-Finland | 40 | 52 | 59 | –1 | –11 | (–32) |
| Western Finland | 44 | 56 | 64 | –1 | –23 | (–81) |
| South-eastern Lake-Finland | 48 | 60 | 69 | –15 | –67 | (–112) |
| South-western Lake-Finland | 50 | 62 | 73 | –1 | –45 | (–98) |
| Southern Finland | 39 | 51 | 60 | 0 | –28 | (–74) |
| Southern boreal | 44 | 56 | 65 | –5 | –33 | (–70) |

**Table 6**. Calculated and observed changes in evapotranspiration from the period 1961–1975 to 1976–90.

| | Calculated | Observed |
|---|---|---|
| South-eastern and south-western Lake-Finland | –45 | –49 |
| Northern Lake-Finland | –4 | –2 |
| Southern and western Finland | –20 | 25 |
| Southern boreal zone | –24 | –19 |
| SW and SE of the middle boreal | –5 | –17 |
| N of middle boreal | –9 | –8 |
| Middle boreal zone | –6 | –14 |
| Kuusamo | –4 | –6 |
| Lapland | 1 | –35 |
| Northern boreal zone | 0 | –30 |

agriculture; consequently, agricultural land comprises 30% of the area here. During the period 1961–1990, agricultural production has intensified, which means an increase in the biomass production of fields, enhancing evaporation. In accordance with this, the only basin of the middle boreal zone where evapotranspiration has increased is the Kyrönjoki basin, which is the only one where agricultural fields comprise as much as 30% and where clay soils dominate in fields. A very recent map of the areal distribution of the hydraulic conductivity of the uppermost soil layer (Hänninen *et al*. 2000) shows small values north of the clayey areas considered. Further, there is an extensive area of large values, covering south-eastern Lake-Finland and part of south-western Lake-Finland. In calculating evaporation from the total area, let us halve the value of $c_3$ for the dense stands reduction, and introduce the infiltration reduction $\mathrm{CE_I}$ as

$$\mathrm{CE_I} = 0.5(1 - L)[10 - (E_{0,\,7} - P_7)_{61\text{–}90}] \\ (\log_{10} S + 8) \qquad (32)$$

in such areas where it is negative; elsewhere $\mathrm{CE_I} = 0$. Here $E_{0,\,7}$ is equal to evapotranspirations in July, without the effect of growing stock, $P_7$ equals the precipitation in July, and $S$ = the average hydraulic conductivity of soils (m $\mathrm{s}^{-1}$) (Hänninen *et al*. 2000). The logarithm of $S$ is used instead of $S$ itself for at least three reasons. First, available water remains in the soil, even after infiltration has ceased. Secondly, trees make deeper roots in conditions where the available water lies deeper. Thirdly, the capillary rise of water must be taken into account. For the south-eastern Lake-Finland area the estimated value of $S$ is $10^{-5.3}$ (m $\mathrm{s}^{-1}$) and that of $E_{0,\,7} - P_7$ is 20 mm. With these amendments, we note that the values of $0.5\mathrm{CE_{Kt}} + \mathrm{CE_I}$(mm) for the periods 1961–1975, 1976–1990, and 1992 become –27, –54 and –76, instead of the corresponding original $\mathrm{CE_{Kt}}$(mm) values of –15, –67 and –112. In south-western Lake-Finland, where $S = 10^{-6.5}$ m $\mathrm{s}^{-1}$ and $E_{0,\,7} - P_7 = 20$ mm, the corresponding amended values of $0.5\mathrm{CE_{Kt}} + \mathrm{CE_I}$(mm) become –12, –34, and –61 mm instead of the original $\mathrm{CE_{Kt}}$(mm) values of –1, –45 and –98 mm. In both south-eastern and south-western Lake-Finland the average errors of explanation of the total evapotranspiration for the period 1961–1990 remain as they were (3 mm and 6 mm). In Western and Southern Finland, $S = 10^{-8}$ m $\mathrm{s}^{-1}$, with the exception of the Eurajoki and Kiskonki basins (9% of the area), where it is $10^{-5.5}$ m $\mathrm{s}^{-1}$. In the two latter basins, the calculated value of evapotranspiration for the period 1961–1990 was initially 8 mm higher than the ‘observed’, while for the other basins the corresponding difference was –7 mm. When the amended values are used, the ‘calculated’ values become equal to those ‘observed’ in both groups of basins. In the Southern and Western Finland area, the amended values of $0.5\mathrm{CE_{Kt}} + \mathrm{CE_I}$(mm) for the periods 1961–1975, 1976–1990, and 1992 become –2, –14, and –40, instead of the corresponding original $\mathrm{CE_{Kt}}$(mm) values of –1, –25, and –78. After these amendments, the difference in the calculated and observed changes of total evapotranspiration between the periods 1961–1975 and 1976–1990 in south-western and south-eastern Lake-Finland is 28 mm, while in southern and western Finland it is –33 mm (before the amendment, –45 mm).

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