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An Operational Grid Method for Estimation of the Areal Water Equivalent of Snow

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Abstract

Measurements along snow courses have been used in Finland to estimate the areal water equivalents of snow (AWE) since the 1930s. Today the network consists of about 170 snow courses with 50 to 80 measuring points.

The procedure of AWE estimation has now been computerized. The country is covered with a grid having a square size of 10 x 10 km. The total number of grid points is 3 858. Each point has given weights in relation to one or several of the 108 drainage basins, for which the AWEs are routinely estimated.

An adjustment factor (AF) was calculated for each grid point and for each snow course. This factor takes into account the local topography, the proximity to the sea coast and the frequency distribution of wind directions, all of which affect the distribution of snowfall.

The water equivalent at a grid point is estimated by using 1 to 4 of the nearest snow courses. The weight of each snow course is inversely proportional to its distance from the grid point. The AF ratios of snow courses and grid point are used to correct the unrepresentativity of snow course locations.

Daily precipitation and temperature are used to correct deviations between the actual observation dates and the fixed dates, which are the 1st and 16th of the month.

1. *Introduction*

The snow cover is of great importance to water resources in Finland. Nearly half of Finland's annual water resources are derived from the snow cover; this proportion is, naturally, greater in the north and smaller in the south. Each spring, the melting of snow causes a noteworthy event in Finnish water systems, i.e. the spring flood; the maximum water level is usually measured in spring. Knowledge of the water storage contained in the snow cover plays an important practical role in estimating water resources in spring and summer, e.g. hydro power and groundwater resources. The water equivalent of snow is also important in estimating the snow loads on roofs and forests.

The areal snow water equivalent has been a central topic of research in Finland. To mention only some of the most important works, *Kuittinen* (1988) has studied the determination of areal snow water equivalent using satellite images. The snowmelt simulation and the snow accumulation simulation for the watershed models were studied by *Vehviläinen* (1992). The snow accumulation and snowmelt were also studied by *Kuusisto* (1984). *Ollila* (1974, 1984) has studied the effect of elevation on the areal snow cover in Lapland and in eastern Finland.

This study was done in order to develop practical methods for estimating the point values of the monitoring network of snow cover yielding the areal water equivalent values. Users have expressed particular interest in the areal water equivalent values.

The areal water equivalent of snow is calculated twice a month during the winter period. The areal water equivalent values are now available to users as soon as they have been calculated. The values are published, e.g. in the monthly hydrological reports and the hydrological yearbooks, and they are fed into the hydrological database.

Over the years, the number of basins observed has ranged from 100 to 250. Today the areal water equivalent of snow cover is calculated systematically for 108 different drainage basins, which cover about 70 per cent of the area of Finland. The drainage basins range in area from 90 to 61 275 km^2, the proportion of lakes being from 0.0 to 29.6 per cent.

The estimates of the areal water equivalent of snow were calculated manually until 1990, when the procedure was computerized. The method of calculating the estimate of the areal water equivalent of snow presented in this paper was developed specifically for the Finnish conditions, but it is also suitable for other areas similar in terrain and climate to those of Finland.

The computerized procedure makes use of the following databases compiled by the Geographical Information System (GIS):

1) the digitized divides of the drainage basins
2) the digital terrain model with a grid size of 50 x 50 m
3) land use and forest stock data.

2. *Snow course measurements*

Since the 1930's, measurements along snow courses have been used in Finland to estimate the areal water equivalent of snow. Today the network of the snow courses consists of about 170 snow courses (Fig. 1). They have been located in the terrain so that they represent the terrain types of the region as well as possible.

Local observers measure the snow courses twice a month during winter months, on the first day and the sixteenth day of the month. This is usually the case, but sometimes the observer, being unable to go the snow course on the fixed day, has made the measurement on some other day. Daily precipitation and temperature data are then used to correct deviations between the actual observation dates and these fixed dates. The length of the snow course is 2 to 4 kilometres, extending through the different common terrain types (open areas, forest clearings, groves dominated respectively by pine, spruce and birch, and wetlands). Measurements of the water equivalent of snow are performed by measuring of the snow depth and the snow density along the snow course. The snow depth is measured at intervals of 50 metres, and for every 8 depth measurement series, one density measurement is made at different terrain types. The snow density is determined using Finnish snow scales having a cylinder with a cross-section area of 100 cm.

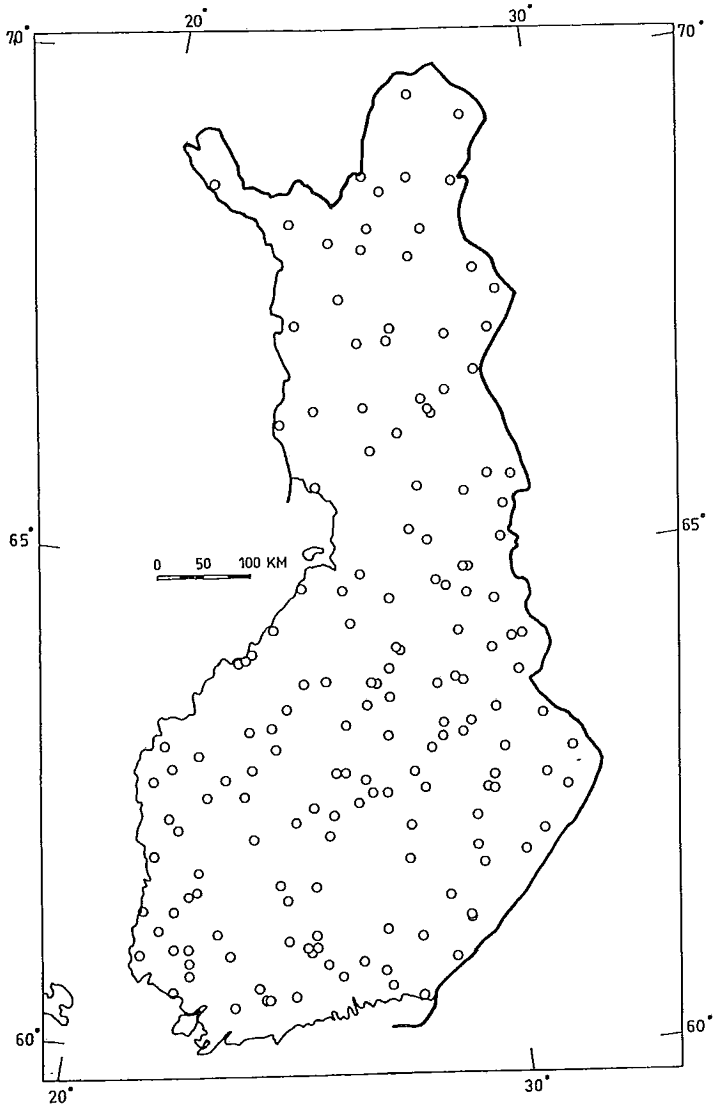

Fig. 1. The network of the snow courses.

The mean snow depth, snow density and water equivalent of the snow course measurement are calculated for the different terrain types of the snow course. The average water equivalent of snow of the region is calculated as a weighted average of these measurements, the weights being based on the distributions of different terrain types in the region. The percentages of the terrain types are obtained from the GIS databases on land use and forest stock data.

3. *Methods for calculation of the areal equivalent of snow*

Calculation of the areal water equivalent of snow is one component of the operational monitoring done twice a month during the winter periods (from 1 October to 31 May) in Finland. Until 1990 the areal water equivalent of snow was calculated manually from the beginning to the end. The mean water equivalents of the region calculated from the snow course measurements were written on a map and then the isographs of the water equivalent of snow cover were drawn subjectively. The approximate areal values were determined from the map, as in the isohyetal method. The topography, the proximity to the sea coast and the effects of lakes in the drainage basin could be taken into account by approximations. All this work was the responsibility of one person but because of the long experience of the person applying it, the method could be considered satisfying. The subjectivity of the method and its poor suitability for computerization were two serious drawbacks prompting the development of a method suited to for the Finnish conditions.

Because measurements of the snow course could not always be repeated at the same site, which was desirable, a decision was made to use the network of grid points for calculating the areal water equivalent. The country is covered with a network of grid points 10 x 10 km in size (Fig. 2). The origo of the network is located at (27°E, 60°N). The total number of grid points is 3858. The method is based on the water equivalents of snow course measurements, calculated for grid points. Accordingly, it does not matter if the locations of the snow courses differ from one year to another.

The computerized method first selects the snow courses closest to each grid point, one from each quarter, for computation of the water equivalent. The water equivalents obtained from these snow course measurements are then amended by using correction coefficients reflecting topographic factors. If the distance between the grid point and the closest snow course in one quarter is over 100 km, the water equivalent of such a snow course is excluded from the calculation. If, on the other hand, the closest snow courses are over 100 km distant in all four quarters of the grid point, the nearest snow course will be used in calculation. The final water equivalent of the grid point is the mean of these water equivalents, weighted by the reciprocals of the distances between the grid point and the points of measurement. When a water equivalent has been obtained for each grid point, the areal water equivalent can be calculated as the weighted mean of the water equivalents of all the grid points in the drainage basin. The grid points belonging to each drainage basin and their weights are determined in advance (Table 1).

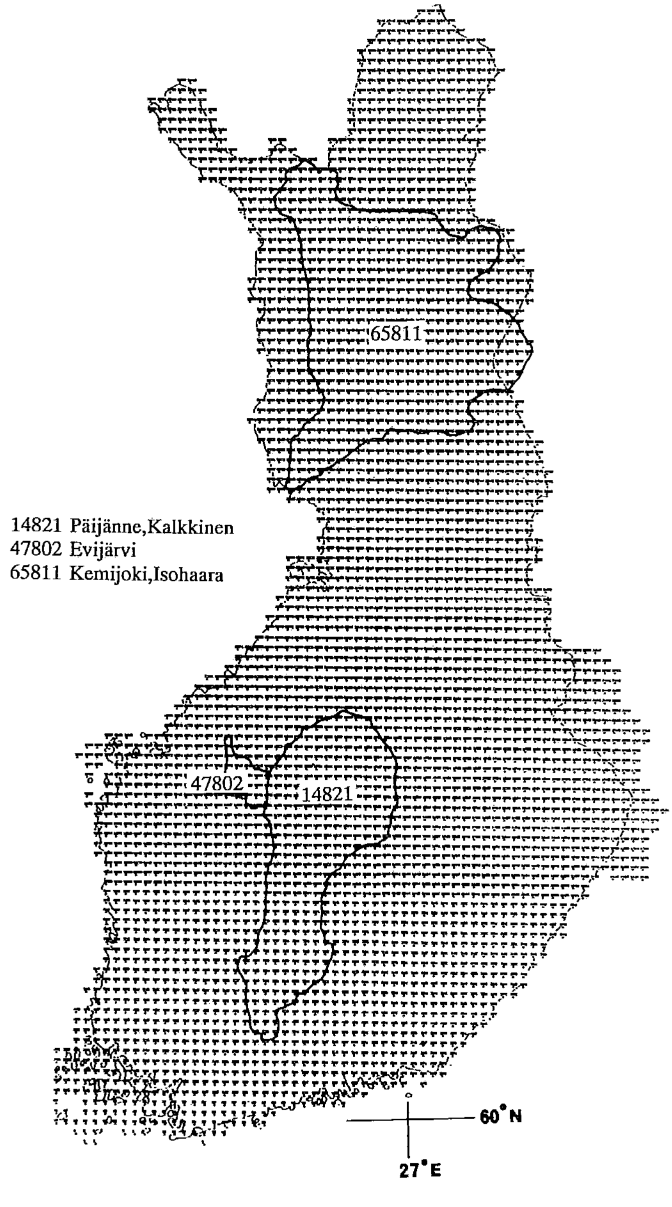

Fig. 2. The network of the grid points and the divides of some drainage basins.

The water equivalent of snow is calculated today for 108 drainage basins. The divides of drainage basins were digitized and fed into the computer memory by using the databases of GIS (Fig. 3).

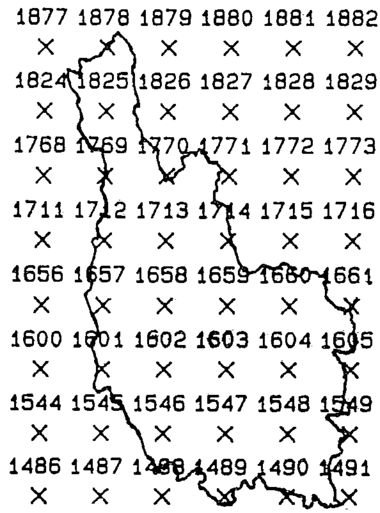

Fig. 3. An example on a digitized drainage basin. The divides of Lake Evijärvi drainage basin and the numbered grid points.

For comparison, areal water equivalents were also obtained by calculating the simple arithmetic means of the water equivalents based on snow course measurements within each drainage basin.

The computer adaptation has been developed to interpolate the water equivalents for the days between the snow course measurements. The areal water equivalents can thus be computed by the grid method and by the arithmetic means method for each day of the winter period.

Table 1. The weights of the grid points of the drainage basin of Lake Evijärvi.

Drainage basin of Lake Evijärvi (47802)					
Grid point	**Weight**	**Grid point**	**Weight**	**Grid point**	**Weight**
1488	0.1	1603	0.0	1714	0.5
1489	1.5	1604	0.0	1769	0.6
1490	0.5	1605	0.5	1770	0.8
1491	0.2	1657	0.6	1771	0.3
1546	0.9	1658	1.0	1824	0.1
1547	0.9	1659	1.0	1825	0.9
1548	0.9	1660	0.9	1877	0.1
1549	0.4	1661	0.3	1878	0.4
1601	0.5	1712	0.6		
1602	1.0	1713	1.0		

4. *Local factors affecting the distribution of snowfall*

The precipitation may change considerably over short distances, owing to local factors, of which the most important ones in Finland are orography, lakes and the sea. The southern half of Finland mostly lies 0 to 200 m above sea level. In the northern half of Finland, the terrain rises from the sea in the southwest towards the east and north, where the regions around the main divide lie mostly 300 to 500 m above the sea level; single fells, however, amount to 200 to 600 m higher, some of them exceeding the height of 1000 m. Although Finland is relatively flat and low-lying compared with many Central European countries, unevenness of terrain still contributes significantly to variations in precipitation. Finland is bounded by the Gulf of Finland in the south, the Baltic Sea in the southwest and the Gulf of Bothnia in the west, all of which affect the amount of precipitation in the coastal zone. Some 9 % of the area in Finland is covered by lakes, a fact that also has to be taken into account when calculating areal snow water equivalents.

Solantie (1975) studied the factors affecting the areal distribution of the precipitation during the winter period: the orographic slope effect and the orographic coastal effect. The results of Solantie's research were applied in this study when calculating the slope effect and the coastal effect for the grid points and for the snow courses.

In order to calculate the slope effect, the heights (h in Eq. (1) to (8)) from the mean sea level for each of the grid points and the distribution of precipitation at different winds are needed. The elevation from the mean sea level is obtained from the databases of GIS, from the digital terrain model. The distribution of the wind directions is obtained as described by *Korhonen* (1942).

The impact of the slope effect on precipitation mainly depends on the steepness of the slope and on the wind velocity at the altitude of rain formation. This can be taken into account by calculating the rise of the slope towards the grid point from the different wind directions on the basis of the elevations of the adjacent grid points (*Solantie* 1975).

The slope effect K for each grid point (i,j) is calculated as a weighted average of its eight components, determined by using the elevations of the neighbouring grid points. For winds from the south, the component is

$$Ks(i,j) = \frac{0.5[h(i,j) - h(i,j-1)]}{1} + \frac{0.25[h(i,j) - h(i+1,j-1)]}{\sqrt{2}} + \frac{0.25[h(i,j) - h(i-1,j-1)]}{\sqrt{2}} \qquad (1)$$

where $h(i,j)$ is the height of the grid point (i,j). The values of i increase from west to east, and those of j from south to north,. with one increase per 10 km. Thus the indexes of neighbouring grid points differ from each other by 1. The components for the other seven wind directions are obtained similarly:

$$Kn(i,j) = \frac{0.5[h(i,j) - h(i,j+1)]}{1} + \frac{0.25[h(i,j) - h(i-1,j+1)]}{\sqrt{2}} + \frac{0.25[h(i,j) - h(i+1,j+1)]}{\sqrt{2}} \quad (2)$$

$$Ke(i,j) = \frac{0.5[h(i,j) - h(i+1,j)]}{1} + \frac{0.25[h(i,j) - h(i+1,j+1)]}{\sqrt{2}} + \frac{0.25[h(i,j) - h(i+1,j-1)]}{\sqrt{2}} \quad (3)$$

$$Kw(i,j) = \frac{0.5[h(i,j) - h(i-1,j)]}{1} + \frac{0.25[h(i,j) - h(i-1,j-1)]}{\sqrt{2}} + \frac{0.25[h(i,j) - h(i-1,j+1)]}{\sqrt{2}} \quad (4)$$

$$Ksw(i,j) = \frac{0.5[h(i,j) - h(i-1,j-1)]}{\sqrt{2}} + \frac{0.25[h(i,j) - h(i,j-1)]}{1} + \frac{0.25[h(i,j) - h(i-1,j)]}{1} \quad (5)$$

$$Kne(i,j) = \frac{0.5[h(i,j) - h(i+1,j+1)]}{\sqrt{2}} + \frac{0.25[h(i,j) - h(i,j+1)]}{1} + \frac{0.25[h(i,j) - h(i+1,j)]}{1} \quad (6)$$

$$Kse(i,j) = \frac{0.5[h(i,j) - h(i+1,j+1)]}{\sqrt{2}} + \frac{0.25[h(i,j) - h(i+1,j)]}{1} + \frac{0.25[h(i,j) - h(i,j-1)]}{1} \quad (7)$$

$$Knw(i,j) = \frac{0.5[h(i,j) - h(i-1,j+1)]}{\sqrt{2}} + \frac{0.25[h(i,j) - h(i-1,j)]}{1} + \frac{0.25[h(i,j) - h(i,j+1)]}{1} \quad (8)$$

The weights used in calculating the slope effect are the frequencies of wind directions obtained by *Korhonen* (1942) for the different sectors:

$$K(i,j) = 0.08\,Kn(i,j) + 0.15\,Ke(i,j) + 0.20\,Ks(i,j) + 0.07\,Kw(i,j)$$

$$+ 0.11\,Kne(i,j) + 0.19\,Kse(i,j) + 0.15\,Ksw(i,j) + 0.05\,Knw(i,j) \qquad (9)$$

E.g., the frequency of winds from the north is 0.08. The values are averages for the country, calculated for the period October-April.

The coastal effect S can be defined as the average percentual increase in precipitation in the coastal zone. It occurs when the wind comes from the sea and is strongest for winds perpendicular to the coast. The regional effect is amplified, if the coast is exposed to sea winds from several directions, i.e. close to the sites where the coastline makes large turns. The effect is strongest in a belt 10 to 30 km inland from the coast. It can be considered negligible at about 50 km from the coast towards the inland (Fig. 4).

For quantitative estimates of the coastal effect, it is essential to know the frequencies of winds blowing from the sea. Considering only the winds forming an angle of at least 45^o with the coastline, the frequencies are as follows: south 0.37, southwest 0.285, west 0.17, northwest 0.125 and north 0.16.

The coastal effect S for any grid point (i,j) is now obtained according to the following equation:

$$S(i,j) = r(e)*s(d) \qquad (10)$$

where

$r(e)$ is the frequency of winds coming from the sea (in a sector of 90^o), depending on the direction of the coastline (e)

$s(d)$ is the average increase in precipitation during onland winds, depending on the distance of the grid point from the coastline (d). From the coastline to 20 km, $s(d)$ increases linearly from 0 to 40 %, and then decreases to 0 at 40 km from the coast. For distances d >40 km, $s(d) = 0$ (Fig. 5).

Within the corner areas behind of convex coastlines, precipitation is affected by the coastal effects on both sides of the corner, the overlapping sector being equal to the turning angle of the coastline. Correspondingly, there are sectors without any coastal effect behind concave corners of the coastline.

The adjustment factor, designated as Kp, is derived for each grid point (i,j) by summing up the coastal effect and the slope effect:

$$Kp(i,j) = K(i,j) + S(i,j) \qquad (11)$$

Kp ranges from 0.3 to 2.37.

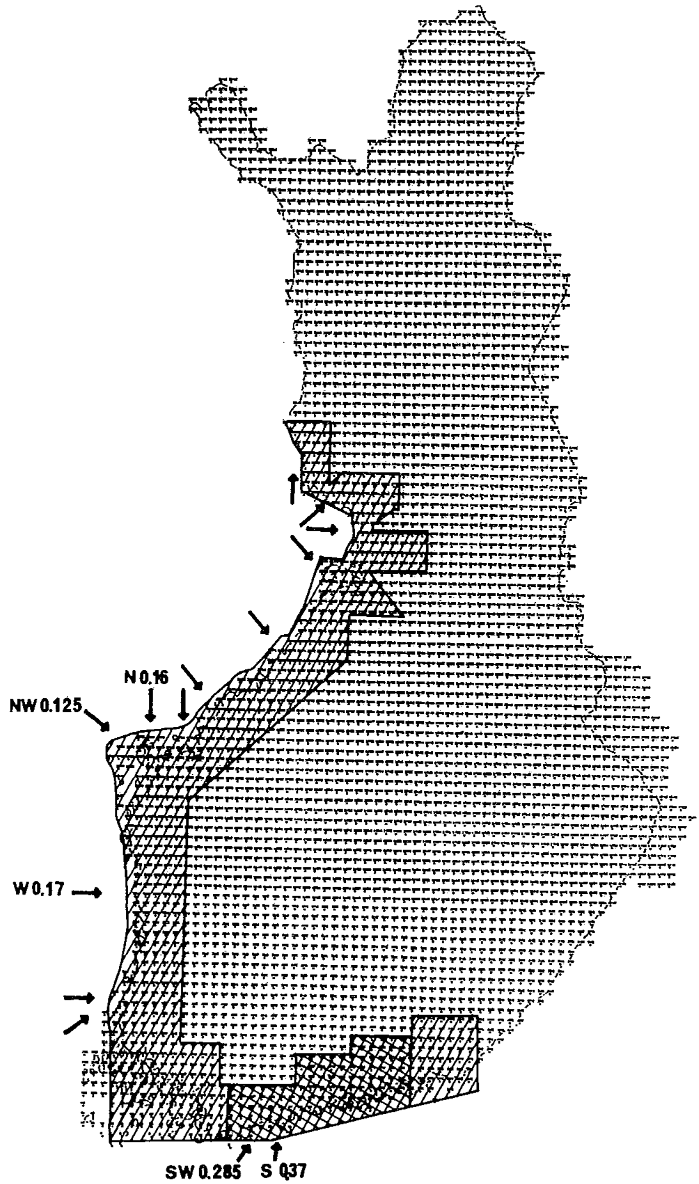

Fig. 4. The orographic coastal effect with the frequencies of coastal wind directions affecting the coastal zone.

Once the adjustment factor *Kp* has been calculated for each grid point, the adjustment factor *Kpm*, describing the orographic slope and coastal effect of the snow course, can be calculated for each snow course according to the following equation:

$$Kpm = \frac{\frac{K1}{d1}+\frac{K2}{d2}+\frac{K3}{d3}+\frac{K4}{d4}}{\frac{1}{d1}+\frac{1}{d2}+\frac{1}{d3}+\frac{1}{d4}} \tag{12}$$

where

$K1, K2, K3$ and $K4$ are the adjustment factors of the four nearest grid points

$d1, d2, d3$ and $d4$ are the distances from the snow course to the four nearest grid points, which are in the different quarters.

Kpm ranges from 0.839 to 1.162.

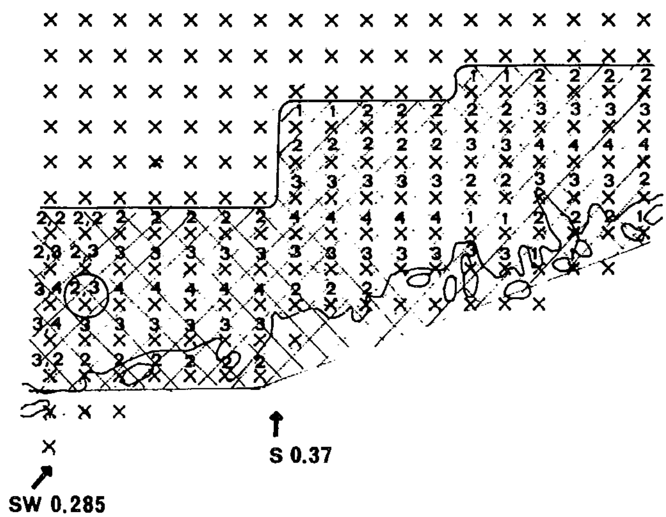

Fig. 5. A detail of the coastal zone, with point values of the average increase in precipitation (10 %). On the circled grid point, for example, the increase in precipitation is 20 % during southwesterly winds and 30 % during southerly winds.

5. *Snow water equivalent for the grid points*

For each grid point, one to four water equivalents of snow are calculated on the basis of the water equivalent values of the snow courses located in the different quarters. These water equivalent values are corrected with the rates of the adjustment factors of the grid point and the snow courses.

The equations are the following:

$$WEH1 = \frac{Kp}{Kp\,(Ma)} * WEMa \tag{13}$$

$$WEH2 = \frac{Kp}{Kp\ (Mb)} * WEMb \tag{14}$$

$$WEH3 = \frac{Kp}{Kp\ (Mc)} * WEMc \tag{15}$$

$$WEH4 = \frac{Kp}{Kp\ (Md)} * WEMd \tag{16}$$

where

WEMa, *WEMb*, *WEMc* and *WEMd* are the mean water equivalents of the four nearest snow course measurements for each grid point (four water equivalents are not always available for each grid point).

Kp is the adjustment factor of the grid point in question

Kp(*Ma*), *Kp*(*Mb*), *Kp*(*Mc*) and *Kp*(*Md*) describe the adjustment factors of the snow courses.

*WEH*1, *WEH*2, *WEH*3 and *WEH*4 are the four corrected water equivalents of snow for the grid point.

The final snow water equivalent of the grid point is the weighted average of the four water equivalents calculated for the grid point:

$$W = \frac{\frac{WEH1}{dT1} + \frac{WEH2}{dT2} + \frac{WEH3}{dT3} + \frac{WEH4}{dT4}}{\frac{1}{dT1} + \frac{1}{dT2} + \frac{1}{dT3} + \frac{1}{dT4}} \tag{17}$$

where

*dT*1, *dT*2, *dT*3 and *dT*4 are the distances of the grid point to the four nearest snow courses.

6. *Estimation of the areal water equivalent of snow*

Finally, estimation of the areal water equivalent of snow is calculated according to the equation

$$WEM = \frac{\sum_{m=1}^{n} p_m W_m}{\sum_{m=1}^{n} p_m} \tag{18}$$

where

W	is the snow water equivalent of the grid point (mm)
P	is the weight for the grid point ranging from 0.0 to1.0
WEM	is the areal snow water equivalent (mm)
n	is the number of the grid points inside the drainage basin.

The weights P depend on the location of the grid points in relation to the borders of the drainage basin and in relation to the lakes in the drainage basin. Grid points clearly within the drainage basin are allocated the weight 1.0 and those in the middle of a lake the weight 0.0. Grid points close to the borders of the drainage basin or close to the shores of a lake receive weights of 0.1 to 0.9 (Table 1).

7. *Conclusions*

The purpose of this study was to develop a suitable computerized method for routine estimation of areal water equivalents of snow in Finland. The method presented takes into account the effects of topography on precipitation. In addition, the annual water equivalents obtained by this method are comparable irrespective of changes in the locations of snow courses. The method is facile, time-saving and inexpensive. Furthermore, the method is easily computerized. The slope and coastal effects for the grid points are calculated in advance and are considered constant; these factors do not change and thus they have to be calculated only once. A map presenting the water equivalents of snow at the various grid points offers the users the possibility of calculating areal values for any drainage basins of interest. Since all stages of the method are computerized, subjectivity will not affect the results, and the areal water equivalents can be calculated by any operator. Water equivalents calculated from snow course measurements is all that is needed. If a snow course is changed or a new one established, appropriate recalculations of the coastal and slope effects are naturally required. The effects are calculated by computer.

The areal water equivalents of snow for the winters 1990/91, 1991/92 and 1992/93 were estimated by both the manual isohyet method and the grid point method presented in this paper, as well as by calculating the arithmetic means of the water equivalents of the snow courses in each of the 108 drainage basins.

All the calculations were based on the same snow course measurements. The manually derived areal water equivalents for operational use were computed by an experienced operator, and these figures can be regarded as the "true values". The grid point method and the manual method both account for the same factors affecting the areal values, and the areal values obtained by these two methods should accordingly correspond to each other.

The grid point and manual isohyet methods both account for topographic effects whereas the arithmetic means method does not. Areal water equivalents computed by the grid point method deviate from the "true values" by 0 to 20 mm. The arithmetic means, however, sometimes deviate considerably from the areal water equivalents obtained by either of the two other methods (Fig. 6). The deviation depends on the size of the drainage basin and the effect of topography on snowfall. The size of the drainage basin may be so small that there can be only one snow course or the snow courses may lie entirely outside the drainage basin.

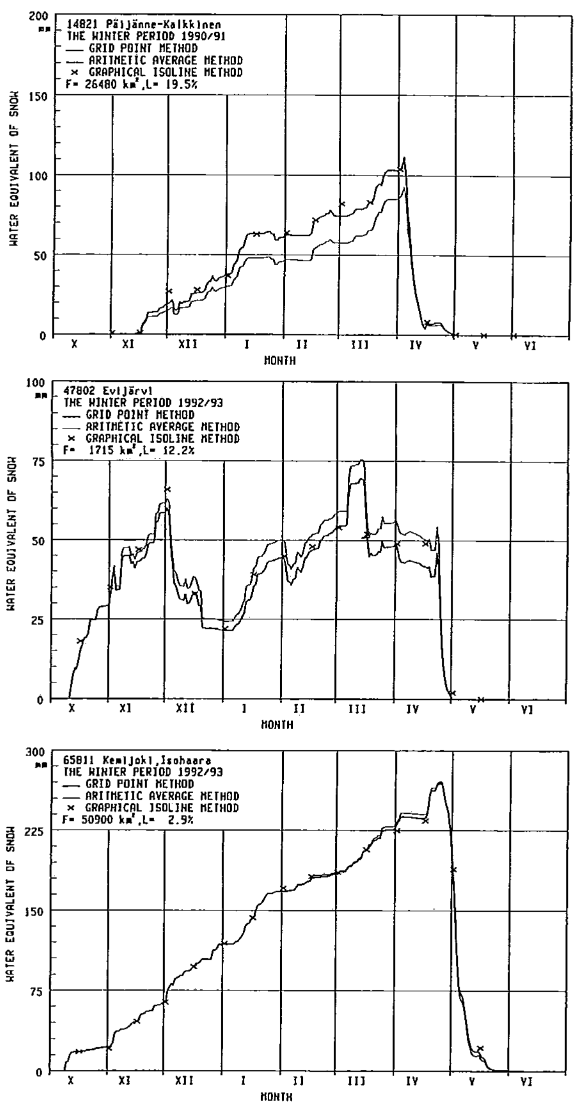

Fig. 6. The comparison curves of the areal water equivalent of snow computed by the three different methods for some drainage basins: Päijänne, Kalkkinen, Lake Evijärvi and Kemijoki Isohaara.

The correlation between the water equivalents of snow estimated by the manual isohyet method and the grid point method was calculated for each of the 108 drainage basins for the winters 1990/91, 1991/92 and 1992/93. The correlation coefficient ranged 0.91-1.00.

The estimates of the areal water equivalents of snow provided by the grid point method appear to be good. Since the winter 1993/94, only the grid point method is in regular use to estimate the areal water equivalents in Finland.

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