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Report Summary

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Abstract

This report presents an evaluation of three different methods for estimation of areal precipitation and temperature, with special emphasis on their applicability for runoff modelling in the Scandinavian mountains. All three methods estimate the areal values as a weighted mean of the observations at nearby meteorological stations. The weights are determined by:

a) a manual subjective selection of the most representative stations
b) inverse square distance weighting
c) optimal interpolation

The methods were tested for a mountainous region in the north-western part of Sweden, which is an area with few meteorological stations and complex precipitation gradients. The elevation range is some 1500m, but meteorological stations are normally located at low altitudes in the valleys. For the subjective and inverse distance weighting methods, precipitation was extrapolated to higher elevations by assuming a linear increase with elevation. For the optimal interpolation method the climatological spatial variation in precipitation was described by means of the standard deviation, related to topographical features. Temperature was extrapolated using the wet adiabatic lapse rate. The evaluation included comparison of areal estimates, verification against point observations and the water balance equation and sensitivity analyses with respect to method parameters and network changes.

For operational runoff modelling in Sweden, areal precipitation and temperature have traditionally been estimated by the subjective weighting method. This evaluation showed that for routine applications this time-consuming method can be replaced by optimal interpolation. Inverse-distance weighting can not be recommended in areas with few stations and complex gradients.

The evaluation also showed that none of the methods correctly described the spatial variation in precipitation and temperature in the investigated region. They are thus not directly applicable for non-routine modelling applications where the estimation of runoff is not the sole objective. All methods also proved to be sensitive to at least some of the necessary parameters like, e.g., elevation dependency. This pointed to possible improvements of the estimates, as the parameters for the evaluation were selected without special consideration to local conditions. The optimal interpolation method seemed to be the least sensitive to changes in the meteorological network.

Key words
Areal precipitation; Hydrological modeling; Optimal interpolation

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APPENDIX

1 INTRODUCTION

Rainfall-runoff models are commonly used tools to estimate river runoff when observations are not available. Typical applications are hydrological forecasts and extension of time series. All such models need areal estimates of precipitation and temperature as input data. In regions with large gradients these estimates are often uncertain. As long as the time series are homogenous, systematic errors may be taken care of by calibrating the models against observed runoff (Xu and Vandewiele, 1992). The values of the model parameters are then set in such a way that they adjust the simulated runoff according to the bias in the input data. Today, however, there is a wish to widen the range of applications for rainfall-runoff models. One example is climate change impact studies, which require correct estimates of internal variables like snow pack and evapotranspiration (Saelthun et al, 1998). Correct estimate of precipitation and temperature are also necessary if the models are to be used in ungauged catchments, where the model parameters can not be fixed through a calibration process, but have to be estimated from catchment characteristics (Johansson, 1994a, Motovilov et al., 1999).

The areal precipitation and temperature for a catchment is normally determined as a weighted sum of the surrounding meteorological stations. In operational models, the weights have traditionally been determined by means of Thiessen polygons (Thiessen, 1911, NWSRFS 1999), through inverse-distance weighting (Jutman, 1992) or by a subjective selection of the most representative stations (Häggström et al 1988). More sophisticated methods like kriging (Matheron, 1971) and Gandin's optimal interpolation (Gandin, 1965) have been shown to more accurately describe point precipitation (Creutin and Obled, 1982, Tabios and Salas, 1985), but have only exceptionally been used for operational purposes in hydrology (Garen et al, 1994).

The mountainous region in the western parts of Sweden is an area with complex gradients in precipitation and a sparse network of meteorological stations. It makes it extremely difficult to estimate the areal precipitation accurately. Lately drastic changes in the meteorological network have also made it difficult to maintain homogenous time series. Previous studies (Lindell 1993, Johansson 1994b) have indicated that the optimal interpolation method leads to more robust estimates. This report describes a systematic evaluation, comparing the optimal interpolation method to the more traditional subjective weighting and inverse-distance weighting methods. The sensitivity to method parameters like, e.g., lapse rate has been investigated and also the sensitivity to network changes. Direct comparisons have been made of point and areal estimates for a number of catchments, as well as indirect comparisons through rainfall-runoff modelling.

2 METHODS

Most methods described in the literature are objective, i.e. there are strict rules for the selection of weights, and they can be computerised to perform automatically. The disadvantage of these methods is that they often lack routines to judge station representativity. Lack of representativity can be caused by, e.g., poor data quality, unsuitable location of the station and complex gradients leading to very different precipitation and temperature values for nearby areas. If the weights are selected subjectively, station representativity is included implicitly, especially if the selection is made based on experience and knowledge of the relevant region. Station representativity is most important in regions with few meteorological stations and complex gradients. The disadvantages of the subjective method are that it is time-consuming, that it requires experience, that two different people will come up with two different sets of weights and that it might be difficult to motivate the actual selection five years later.

In the investigated region, meteorological stations are normally located in the valleys and data have to be extrapolated to higher altitudes without any explicit information on actual elevation dependency. Locally, a number of investigations have shown that a linear increase in precipitation with elevation is an acceptable approximation, at least for climatological precipitation (Daly et al, 1992, SNA, 1995. It was thus the extrapolation method used for the subjective and inverse-distance weighting, even if the approximation may not be valid over large areas or for single storms (Creutin and Obled, 1982, Blumer and Lang, 1993). Temperature was assumed to decrease according to the wet adiabatic lapse rate, 0.6°C/100 m (SNA, 1995). For the optimal interpolation precipitation extrapolation was based mainly on an upwind index, computed from topography and prevailing wind directions (Häggmark et al, 1997).

As catchment areas are in the order of 1000 km^2, they had to be divided into sub-units for the areal estimates by the objective methods. Precipitation and temperature were interpolated to cells on a rectangular grid, and catchment estimates were determined as the weighted mean of the cells covering the catchment (see further section 2.3.2). The computations for each day were based on the data available for that specific day.

2.1 Subjective selection of weights

Traditionally, a subjective selection of station weights is used to estimate areal precipitation and temperature in operational runoff modelling applications in Sweden. The selection of weights and representative stations is based on climatological rainfall maps, station location and quality. Missing data are replaced by neighbouring stations, applying correction factors.

For the comparison of areal estimates from the objective methods, catchments where a runoff model is used operationally were selected. As areal estimates were then available, this ensured that the selection of weights was not influenced by any wish to prove one method more accurate.

2.2 Inverse-distance weighting

The estimation of grid cell precipitation was based on the four stations nearest to the mid point, and the weights were set proportional to the inverse squared distances with the sum of the weights equal to unity. This approach was also used for the runoff map of Sweden 1961-90, which was produced by means of a runoff model (Jutman, 1992).

2.3 Optimal interpolation

2.3.1 *Theoretical background*

A textbook description of optimal interpolation is found in, e.g., Daley (1991). The aim is to determine the weights so as to minimise the error in the estimated precipitation/temperature:

$$E = \sum_t (P(x_i,y_i) - P'(x_i,y_i))^2 = \langle (P_i - P_i')^2 \rangle \tag{2.1}$$

where

$P(x_i,y_i) = P_i$ = the true value at x_i,y_i

$P'(x_i,y_i) = P_i'$ = the estimated value at x_i,y_i

$$P_i' = \sum_{k=1}^{N} w_{ik} \cdot P(x_k,y_k) \tag{2.2}$$

$P(x_k,y_k) = P_k$ = the value at station k

w_{ik} = station weights

To find the optimal weights Equation 2.1 is differentiated with respect to the weights w_{ik}:

$$\frac{\partial E}{\partial w_{ik}} = 0 \tag{2.3}$$

which leads to a system of linear equations.

However, for the estimated values to be unbiased, i.e. for $\langle P_i' \rangle$ to equal $\langle P_i \rangle$, either constraints must be put on the weights, or $\langle P_i' \rangle$ must be equal to 0 (Creutin and Obled, 1982, Daley, 1991). In this application the latter was achieved by the introduction of a background field. This could, e.g., consist of climatological values or forecast values from a numerical weather prediction model, assuming that as an average over a long period, the predicted values equals the actual precipitation.

The observed station values may not be fully representative for the area where the station is located. The values are affected by the immediate surroundings of the station as well as by direct measurement errors. This is considered by introducing an observational error which has the effect of slightly smoothing the interpolated values (Figure 1). The final form of the system of linear equations becomes as follows:

$$\sum_{k=1}^{N}(\mathrm{cov}(P_k - P_k^b, P_l - P_l^b) + \mathrm{cov}(O_k, O_l)) \cdot w_{ik} = \mathrm{cov}(P_i - P_i^b, P_l - P_l^b) \qquad (2.4)$$

$l = 1 \ldots\ldots. N$

where

P^b represents the background field
O the observational error and
cov( ) the covariance
$\mathrm{cov}(O_k, O_l)$ is assumed to be 0 if $k \neq l$ for data from meteorological stations

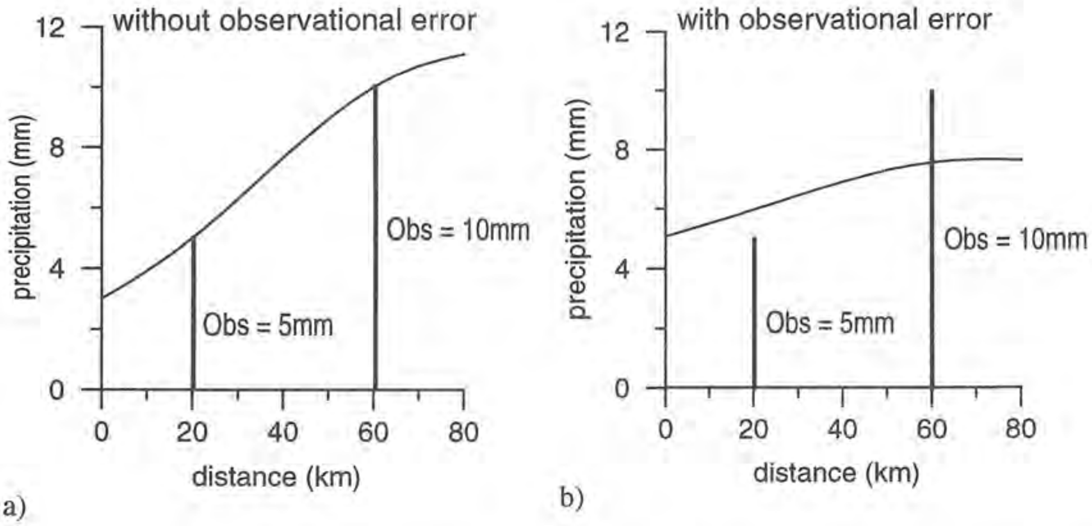


Figure 1 *Optimal interpolation along a line with two fictive precipitation stations; a) without considering the observational error, b) with observational error*

Daley (1991) argues that the weights derived from Equation 2.4 are optimal only if the covariances are correct, and normally the covariances are not known but have to be modelled or estimated. The method should then be called statistical interpolation. However, in this report the term optimal interpolation will be used.

The solution of Equation 2.4 involves inversion of matrices which must not be singular. This can be prevented if the covariances are homogeneous, *i.e.* if they depend only on the relative location of (x_i,y_i) and (x_k,y_k) and not on the absolute locations. The covariances can be written as:

$$\operatorname{cov}(P_k - P_k^b, P_l - P_l^b) = \sigma_k \cdot \sigma_l \cdot \rho_{kl} \tag{2.5}$$

where

σ_k, σ_l are standard deviations and
ρ_{ik} the correlation coefficient

The correlation coefficient is often found to depend only on the relative location, and homogenous covariances can be achieved by normalising Equation 2.2 by means of the standard deviations. For precipitation, the areal variation in standard deviation follows rather well the variation in mean precipitation (Creutin and Obled, 1982). In practice, the effect is that observations from regions with low precipitation are given a larger weight when used to estimate precipitation in climatologically higher precipitation areas (Häggmark et al, 1997).

The description of the covariance field is essential to optimal interpolation, and the accuracy by which it can be determined, determines the accuracy of the method. The correlation is normally estimated by plotting pair-wise correlation coefficients versus distances and fitting a function to the resulting swarm of values. The determination of the standard deviation field is discussed below.

2.3.2 Determination of the covariance field

In the middle of the 1990s, covariance fields for a number of meteorological variables were determined by Häggmark et al (1997) for a grid with a resolution of approximately 12x12km^2 covering Northern Europe. For precipitation the correlation between points was expressed as:

$$\rho = 0.5 \cdot e^{-\frac{d}{L}} + 0.5 \cdot (1 + 2 \cdot \frac{d}{L}) \cdot e^{-2 \cdot \frac{d}{L}}$$

ρ = correlation
d = horizontal distance
L = scaling factor

The correlation for temperature also included elevation, but in this application with a climatological background field, a correlation function with elevation did not work well. Instead the same formula was used as for precipitation, but with a different scaling factor (Johansson, 1994b).

The standard deviation was assumed to be constant for temperature. For precipitation a separate value was assigned to each grid cell, in the investigated region depending mainly on wind direction and topography, combined into an upwind index. These correlation and standard deviation values were developed for real time meteorological applications, using a numerical weather model forecast as the background field. The results in this report were mainly computed from historical data, using climatology as the background field. The standard deviations for precipitation as computed by

Häggmark (personal communication) were then based on typical wind directions, not varying in time.

For operational applications, also in hydrology, it is essential to have available a predefined covariance field, even if it is not the best possible for each individual catchment. The creation of such a field for each application is otherwise far too time-consuming. The present evaluation was therefore carried out with this covariance field developed for applications over a very large area.

3 TEST BASINS

The different methods for estimating areal precipitation and temperature were tested for catchments in the North Western parts of Sweden. The main catchments were in some cases divided into sub-catchments (Figure 2, Appendix Table A1). In all catchments operational spring flood forecasts are made of the inflow to hydropower reservoirs located at the outlet. Input data have come from close to 190 precipitation stations and 75 temperature stations. The mean annual precipitation varies from about 2000 mm/year on the Norwegian side of the water divide to around 600 mm/year in the eastern parts. The elevation range in the most northern catchments is close to 1500 m.

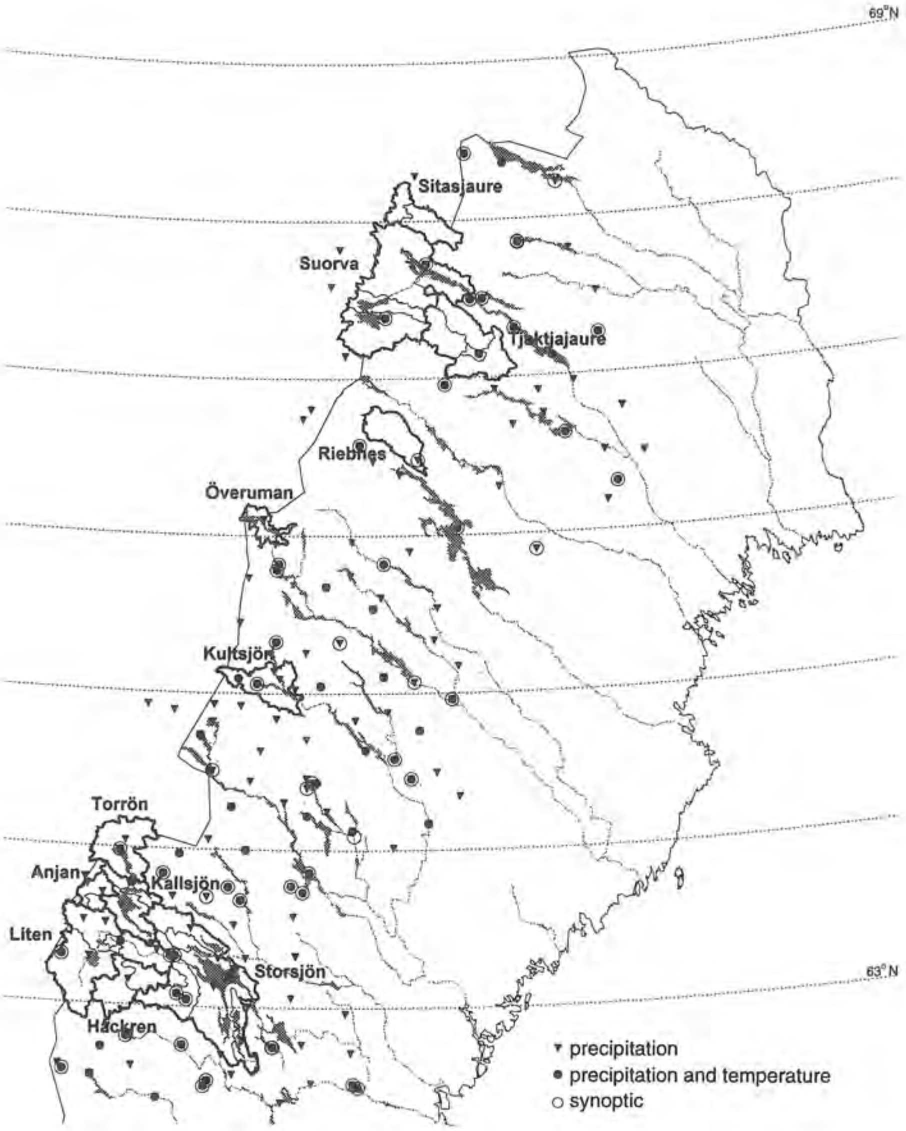


Figure 2 *Meteorological stations and test catchments for evaluation of areal estimates of precipitation and temperature. Thick lines mark main catchments with runoff stations. See also Appendix, Table A1.*

4 ESTIMATION OF AREAL PRECIPITATION AND TEMPERATURE FOR TEST BASINS

In this chapter, catchment estimates of precipitation and temperature by the three different weighting methods are compared. The accuracy of the precipitation estimates is investigated by means of the water balance equation, and the sensitivity to network changes is evaluated.

4.1 Estimation of areal precipitation

4.1.1 Sub-catchment precipitation

Daily values of precipitation were calculated for each sub-catchment for the period 1977 09 01 – 1997 08 31.

As stated above, the precipitation was assumed to increase linearly with elevation in the subjective and distance weighting methods. In studies of snow accumulation no such increase was found above the timberline (Bergström and Brandt, 1984), which could be explained by redistribution of snow in wind-exposed areas. In runoff modelling, this can be considered in a simplified manner, by assuming that no increase in precipitation occurs above the timberline (Lindström et al, 1997). As the aim was to use the data for runoff models, the same method was used when estimating areal precipitation for this evaluation, with the linear increase below the timberline (800 m.a.s.l.) set to 7 %/100 m, using 800 m as the reference level. Looking at the total elevation range, the linear increase thus varied between sub-catchments from about 3 % to 7 %. Estimates by Alexandersson (SMHI, personal communication), based on meteorological stations give the increase in precipitation in this region as between 6 % and 29 % per 100 m with sea level as the reference, i.e. between 4 % and 9 % using 800 m as the reference.

In the optimal interpolation method, the scaling factor in the correlation formula was set to 270 km. An example of the standard deviation values for part of the test region is shown in Figure 3. The values are based on the assumption that precipitation mainly occurs when wind direction is from the south-west (75 % south-west, 25 % east), and the relationship between upwind index and standard deviation were derived from precipitation data from 1994 (Häggmark, personal communication).

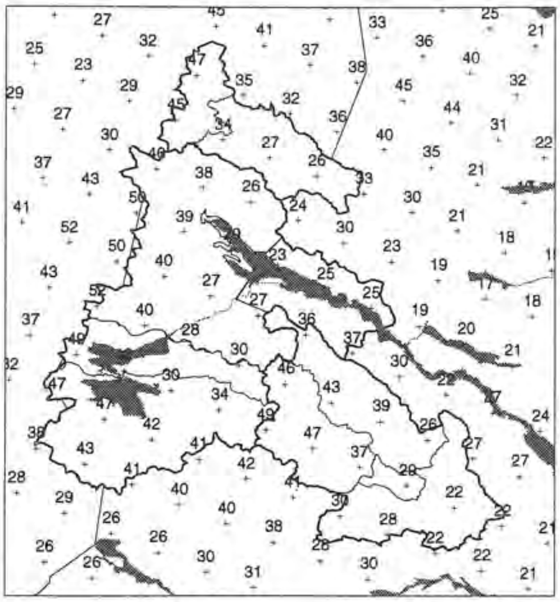


Figure 3
Example of standard deviation values for the 12x12km² grid used in the optimal interpolation method. The variation in standard deviation reflects the spatial variation in mean precipitation.

For the test catchments the subjective and inverse-distance weighting methods generally gave considerably higher areal precipitation than the optimal interpolation method (Figure 4, Appendix Table A2). This was most pronounced in the high altitude sub-catchments furthest to the west, where the estimated mean annual precipitation differed by as much as 80 % for one sub-catchment. Exceptions were mainly sub-catchments at comparatively low altitudes in the south-eastern parts of the test region.

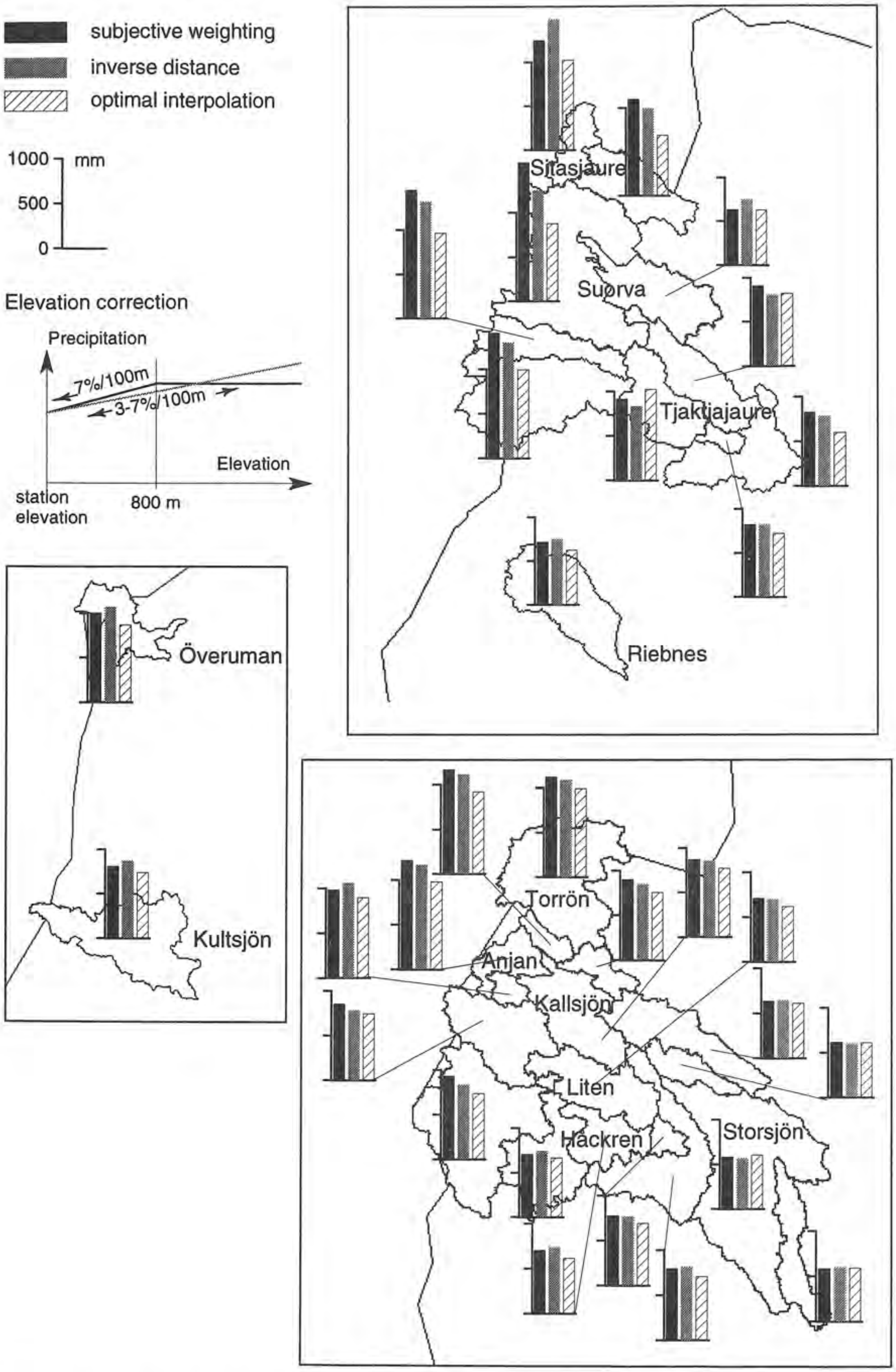


Figure 4 *Estimated mean annual sub-catchment precipitation 1977 09 01-1997 08 31.*

4.1.2 Water balance equation

One way to verify estimates of areal precipitation is through the water balance equation. Over long periods, the storage of water can be neglected and the equation takes the form:

$P = Q + E$
$P =$ precipitation
$Q =$ runoff
$E =$ evapotranspiration

Runoff can be observed, but unfortunately areal evapotranspiration is even more difficult to estimate than precipitation. Long-term mean values are often taken from the water balance equation, assuming that precipitation and runoff are known. However, the evapotranspiration in the test region is a relatively small term in the water balance. Even if the accuracy is low, the error introduced into the equation will be minor.

The upper evapotranspiration limit should be the so called potential evapotranspiration. This potential evapotranspiration has been calculated for meteorological stations in Sweden by Eriksson (1981) using the Penman equation for grassland. Presumably, the potential evaporation decreases with decreasing temperature and increasing elevation. As the meteorological stations used by Eriksson are at a low altitude as compared to the catchments, the computed values can not be used directly to estimate catchment potential evaporation. Lindström et al (1996) showed that a simplified version of the Thorntwaite equation (Thorntwaite, 1948) gave a good agreement with the values computed by Eriksson:

$E_p = K_T \cdot \mathrm{STF}(t) \cdot T$
$E_p =$ potential evaporation
$\mathrm{STF}(t) =$ monthly coefficient
$T =$ temperature

A value of 0.25 was recommended for the coefficient K_T.

The equation was thus used to estimate mean potential evapotranspiration for the test catchments assuming the land cover consisted of grassland only (Table 1). All the three weighting methods gave similar values for the temperature estimates, and thus also for the potential evapotranspiration. The values ranged from about 200 mm/year in the north-west to 400 mm/year in the south-east. Except for the most southern test basins the forest percentage is low, and in the mountainous parts there are large areas of bare rocks. It is thus likely that potential evapotranspiration for grasslands constitutes the upper limit for basin evapotranspiration. As the precipitation is high, evapotranspiration is probably only to a small extent restricted by the availability of water, and more by the ground being covered by snow in late spring and early autumn. A very rough estimate of the lower limit of basin evapotranspiration is 50% of the potential evapotranspiration.

According to the National Atlas of Sweden (SNA, 1995), the mean evapotranspiration is less than 100 mm/year in the north-western part of the test region, and approximately 300 mm/year in the south-eastern part (Table 1). Those are values estimated from the water balance equation, and in the six most westerly test basins they are actually somewhat lower than 50 % of the potential evaporation according to the Thorntwaite formula.

Catchment	Potential evaporation – Thorntwaite (mm/year)	Evapotranspiration - SNA (mm/year)
Sitasjaure	219	~100
Suorva	230	~100
Tjaktjajaure	227	~150
Riebnesjaure	239	~200
Överuman	248	~100
Kultsjön	267	~100
Torrön	322	~100
Anjan	345	~150
Kallsjön	351	~250
Liten	332	~200
Håckren	305	~250
Storsjön	416	~300

Table 1 *Mean annual potential evaporation for test catchments 1977 09 01-1997 08 31, calculated according to a simplified version of the Thorntwaite equation, and actual evaporation from the National Atlas of Sweden.*

Catchment	Mean precipitation (mm/year)			Mean runoff (mm/year)
	Subjective	Inverse-distance	optimal	
Sitasjaure	1149	1157	802	1305
Suorva	1362	1195	885	1051
Tjaktjajaure	879	809	798	856
Riebnesjaure	721	751	627	722
Överuman	1004	1070	868	1255
Kultsjön	808	877	739	881
Torrön	1119	1087	993	1080
Anjan	1158	1139	959	1096
Kallsjön	915	890	789	718
Liten	859	789	711	693
Håckren	704	738	647	663
Storsjön	650	646	633	410

Table 2 *Catchment mean annual precipitation and mean annual runoff for 1977 09 01-1997 08 31. Precipitation estimated by subjective weighting of neighbouring stations, squared inverse-distance weighting and optimal interpolation.*

The ratio (Q+E)/P was computed for the three precipitation alternatives (table 3) and with two values of evapotranspiration; the upper limit being the potential evapotranspiration from the modified Thorntwaite formula, and the lower limit being either 50 % of the potential evapotranspiration or the value from the National Atlas, whichever the lowest.

Catchment	**(Q+E) / P**					
	subjective		Inverse-distance		optimal	
	min	max	min	max	min	max
Sitasjaure	1.22	1.33	1.21	1.32	1.75	1.90
Suorva	0.85	0.94	0.96	1.07	1.30	1.45
Tjaktjajaure	1.10	1.23	1.20	1.34	1.21	1.36
Riebnesjaure	1.17	1.33	1.12	1.28	1.34	1.53
Överuman	1.35	1.50	1.27	1.40	1.56	1.73
Kultsjön	1.21	1.42	1.12	1.31	1.33	1.55
Torrön	1.05	1.25	1.09	1.29	1.19	1.41
Anjan	1.08	1.24	1.09	1.27	1.30	1.50
Kallsjön	0.98	1.17	1.00	1.20	1.13	1.35
Liten	1.00	1.19	1.09	1.30	1.21	1.44
Håckren	1.16	1.38	1.11	1.31	1.26	1.50
Storsjön	0.95	1.27	0.96	1.28	0.98	1.30
mean	**1.09**	**1.27**	**1.10**	**1.28**	**1.30**	**1.50**

Table 3 *The ratio of runoff plus evapotranspiration over precipitation for the period 19770901-19970831. Precipitation was estimated by three alternative methods, and an upper an lower limit for evapotranspiration was assumed.*

Ideally, the ratio should be equal to one, but in the estimation of areal precipitation no allowances were made for observation losses. For the period 1961-90, reference normals were computed for Swedish precipitation stations both for directly observed values and for values corrected for observation losses (Alexandersson, SMHI, personal communication). From these data a general correction factor for observation losses for each station could be estimated (Appendix Figure A1). For stations in the vicinity of the test catchments, the factors vary from around 1.1 to 1.3. A previously published report (Eriksson, 1983) recommended considerably higher correction factors; 1.2-1.5, based on information on wind exposure, percentage of solid precipitation and number of days with precipitation for the different stations. The same information was used to estimate correction factors by a formula recently recommended by the Nordic Working Group on Precipitation (Förland et al, 1996). The factors thus achieved were only slightly higher than those retrieved from Alexandersson's data, which were therefore considered as the most reliable. No information was available for the Norwegian stations used in some catchments, but the corrections were assumed to be approximately the same as for the Swedish stations. Generalised to the test catchments it led to correction factors between 1.15 and 1.20, with factors close to 1.15 for the southern catchments, and factors close to 1.2 for the seemingly most exposed areas, Sitasjaure and Kultsjön. Consequently, the computed ratio (Q+E)/P should be in the range 1.15 to 1.20 for the test catchments.

For the subjective method, as well as for the inverse-distance weighting method, the interval given by minimum and maximum values for (Q+E)/P generally included the interval 1.15-1.2. An exception was Suorva where both values were below one for the subjective weighting method, and Överuman were they were well above 1.2. For the optimal interpolation even the minimum ratio values were, with a few exceptions, greater than 1.2, and it seems that the optimal interpolation method underestimates the precipitation.

4.1.3 Conclusions

Comparing the three weighting methods, the optimal interpolation, with the covariance field applied here, gives lower areal precipitation for the test catchments than the other two. Verification by means of the water balance equation indicates that the optimal interpolation underestimates precipitation.

For all methods, the ratio runoff plus evapotranspiration over precipitation varies considerably between catchments, i.e. no method describes fully the spatial variation in precipitation as reflected by the variation in runoff.

4.2 Sensitivity to network changes - precipitation

4.2.1 Evaluation technique

The sensitivity to network changes was tested by estimating areal precipitation only from stations reporting in real-time, which meant a reduction in the number of stations by over 60 % (Figure 2). This was obviously a very drastic change, which does not normally occur in operational applications except for shorter periods. It should clearly show the ability of the different weighting methods to deal with a decrease in the number of meteorological stations.

For the objective methods, new stations weights were calculated for the real-time stations, without considering their representativity in relation to the stations they replaced. In the subjective weighting method, the missing stations were instead replaced by a near-by real-time station, applying a correction factor. This correction factor was based on the long-term mean precipitation at each station, which meant that the long-term mean sub-basin precipitation remained more or less the same. It would have been more correct to change the station weights also for the subjective method, but that required a manual effort which was not practical to carry out for all catchments.

Daily values of sub-basin precipitation were estimated for the same period as with all stations, i.e. 1977 09 01-1997 08 31. Two criteria were used to evaluate the weighting methods:

- the correlation between daily values estimated from all stations and real-time stations respectively, expressed as the determination coefficient ρ^2,
- the mean difference in estimated annual precipitation, in percentage of mean annual precipitation, i.e.

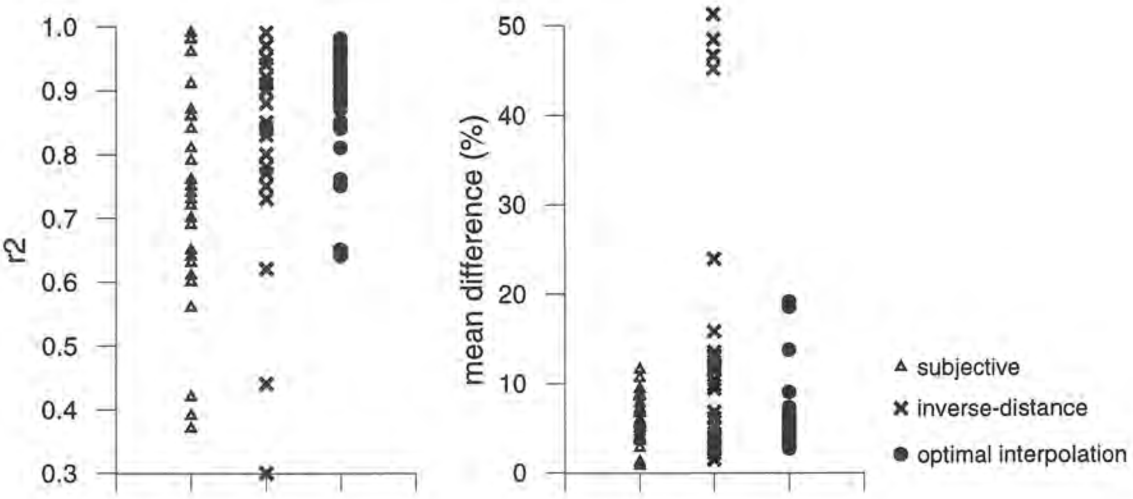
$$\frac{\sum \left| P_{y1} - P_{y2} \right|}{\sum P_{y1}}$$

where
P_{y1} = sub-catchment annual precipitation (0901-0831) using all meteorological stations
P_{y2} = sub-catchment annual precipitation using real-time stations only

For two sub-catchments only real-time stations had originally been used in the subjective weighting method, and these were excluded from the comparison.

The first criterion, the determination coefficient, has the highest values for the optimal interpolation method (Figure 5).

The subjective method gives a much lower agreement between daily values than the objective methods, but the other criterion, the mean difference in annual precipitation has the best value for the subjective method, i.e. the total amount of precipitation over a year agrees well. The criterion value is only slightly lower than for the optimal interpolation method, and the difference is caused by high values in the three western sub-catchments of Suorva. If they are excluded the optimal interpolation method performs better as an average.



	subjective	Inverse-distance	optimal
ρ^2	0.73	0.81	0.89
mean difference (%)	5.8	14.2	6.1

Figure 5 *Comparison between catchment precipitation estimates based on all available meteorological stations and estimates based only on stations reporting in real-time (1977 09 01-1997 08 31). The coefficient of determination refers to daily values, and the mean difference to the annual estimates. The diagram shows results for each individual catchment and the table mean values for all catchments.*

4.2.2 Conclusions

Overall, the optimal interpolation method seems to be the least sensitive to changes in the meteorological network. The performance of the subjective method is obviously affected by the correction factor applied for the replacing station. In this case an appropriate value could be found as both the original and replacing stations had been operating for some time, and estimates of long-term mean precipitation were available. If no such information exists, if, e.g., the replacing station was recently started, the determination of the correction factor requires more consideration, and it does also become more uncertain.

4.3 Estimates of areal temperature

4.3.1 Sub-catchment temperature

As for precipitation daily values of temperature were computed for the period 1977 09 01-1997 08 31. Comparisons were made of mean annual and monthly temperatures for the different weighting methods. It was not possible to verify the absolute values, as was the case for precipitation through the water balance.

To estimate the background field for the optimal interpolation, it was necessary to make some assumption about the elevation dependence. The lapse rate was set to 0.6°/100 m, irrespective of the weather situation just as for the other two weighting methods. The scaling factor in the correlation formula was set to 600 km. The correlation function used by Häggmark et al. (1997) included both the horizontal and vertical distance between stations and grid points. This led to some problems at high altitudes, as the correlation between low-lying stations and grid points became very low.

There were only minor differences between the mean sub-catchment temperature estimated by the different weighting methods, and no obvious systematic ones (Figure 6, Appendix Table A3).

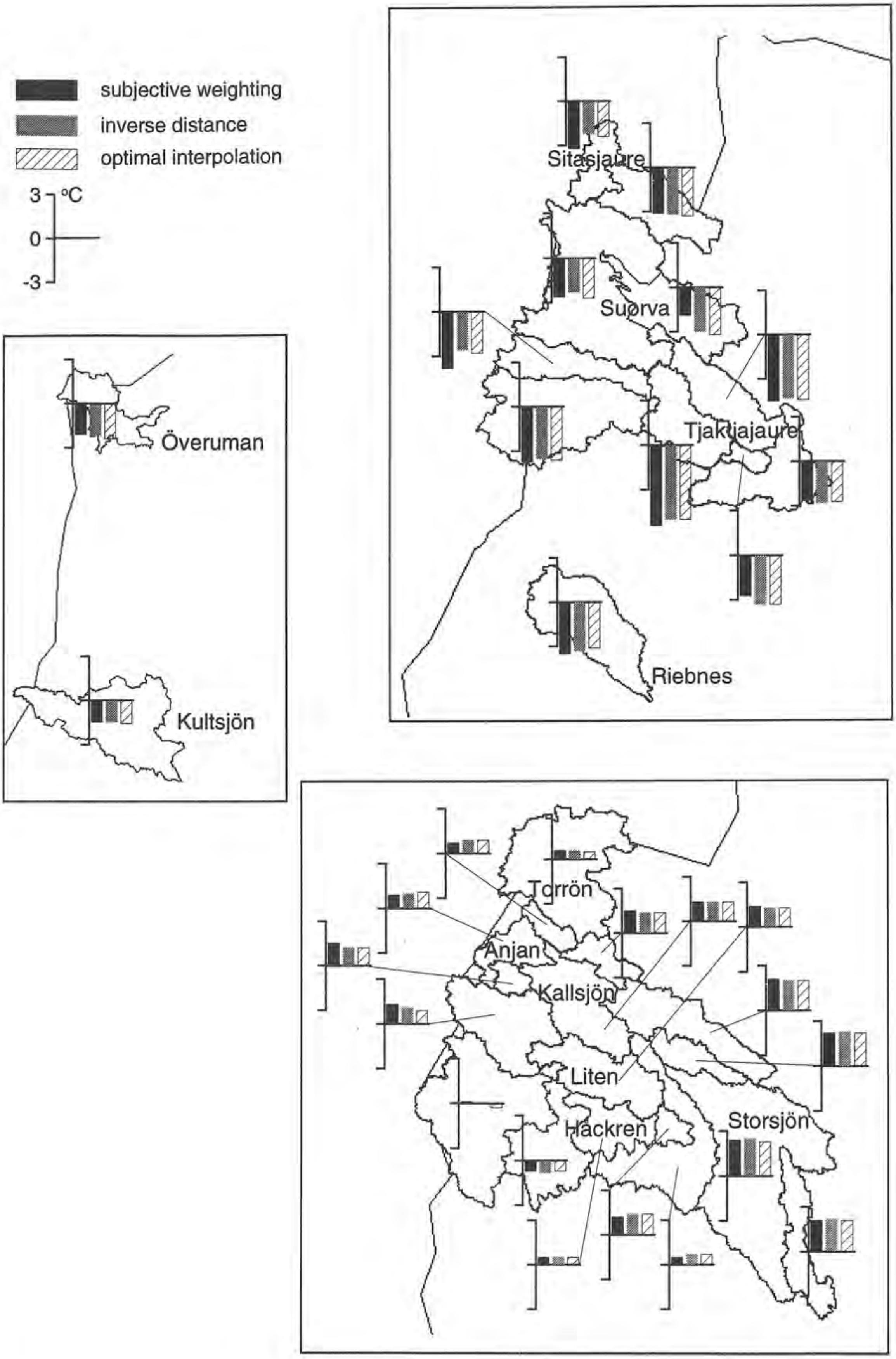


Figure 6 Estimated mean annual sub-catchment temperature 19770901-19970831.

4.4 Sensitivity to network changes - temperature

The sensitivity of the temperature estimates to changes in the meteorological network was evaluated in the same manner as for precipitation. The sub-catchment temperature computed from all available stations was compared to the temperature computed from the synoptic stations only. The correlation for daily values was computed as well as the difference in mean annual temperature. However, as there are very few temperature stations available in this region and almost all are synoptic, comparisons could only be carried out for some of the southern sub-catchments.

Areal temperature is often considered easier to estimate than areal precipitation, and from the comparison between the three interpolation methods it seems that the results are not very sensitive to the selection of weights. However, when excluding some of the stations there was a clear difference between the methods. The optimal interpolation method clearly performed best, with a mean difference in annual temperature of 0.03°C. The results for the inverse-distance weighting method were not quite as good as for optimal interpolation, while they were considerably worse for the subjective weighting method, where the difference in annual temperature averaged 0.76°C (Table 4).

In analogy with precipitation, a correction term was applied to the replacement station in the subjective weighting method. Considering the low sensitivity to the selection of station weights, erroneous values of the correction terms seem to be the most likely reason to the large differences in estimated temperature. For precipitation the correction factors were chosen well, but the results for temperature illustrate the sensitivity to such a correction term.

Sub-catchment	subjective weighting		inverse-distance		optimal interpolation	
	ρ^2 (%)	diff (°C)	ρ^2 (%)	diff (°C)	ρ^2 (%)	diff (°C)
Torrön	0.98	0.93	0.99	0.15	1.00	0.03
Äcklingen	0.98	0.96	0.98	0.21	1.00	0.04
Juveln	0.98	0.96	0.99	0.14	1.00	0.04
Storrenssjön	0.98	1.00	0.99	0.15	1.00	0.03
Anjan	0.99	0.65	0.99	0.13	1.00	0.03
Kallsjön	0.99	0.78	0.99	0.07	1.00	0.03
Storsjön	1.00	0.01	1.00	0.04	1.00	0.03

Table 4 *Comparison between catchment temperature estimates based on all available meteorological stations and estimates based only on stations reporting in real-time (1977 09 01-1997 08 31). The coefficient of determination refers to daily values, and the difference to the absolute difference in annual temperatures.*

5 VERIFICATION AGAINST POINT OBSERVATIONS

All three methods evaluated in this report are mainly intended for areal estimates. A straightforward way to assess the accuracy is however to compare point estimates at meteorological stations to actual observations. For the subjective method it was not considered feasible, but for the objective methods it was done by excluding one station at a time from the analysis, and estimating the precipitation/temperature at the station location. The calculations were made for two years, 1993 when station precipitation averaged 770 mm and 1994 when the average was 550 mm. The criteria used to evaluate the methods were the same as for the homogeneity tests in section 4, i.e. the coefficient of determination and the mean error in annual precipitation.

5.1 Precipitation

For precipitation both evaluation criteria showed better values for the optimal interpolation method, especially for the stations in the western parts were the gradients are particularly steep and the network sparse (Table 5). The results were similar for 1993 and 1994, and bearing in mind the difference in precipitation for these two years it seems safe to conclude that the optimal interpolation method more accurately estimates point precipitation. The same conclusion was drawn by Tabios and Salas (1985) in a study in a topographically more homogenous region in the Continental United States.

			ρ^2	mean error (%)
1993	All stations (128)	Inverse distance weighting	0.76	13.6
		Optimal interpolation	0.78	11.6
	Western stations (28)	Inverse distance weighting	0.70	24.9
		Optimal interpolation	0.71	18.1
1994	All stations (129)	Inverse distance weighting	0.72	15.2
		Optimal interpolation	0.74	11.0
	Western stations (29)	Inverse distance weighting	0.70	23.0
		Optimal interpolation	0.71	16.7

Table 5 *Verification of precipitation estimates against point observations. Verification was carried out by excluding one station at a time and estimate precipitation from the remaining stations. The coefficient of determination refers to daily values, and the mean absolute error to the total estimates.*

The station standard deviation values required for the optimal interpolation method were interpolated from the surrounding grid.

5.2 Temperature

With temperature the main differences over the year are explained by the seasonal variation. This leads to very high values for such a criterion as the coefficient of determination, and makes it difficult to distinguish the different interpolation methods with respect to accuracy. The coefficient of determination was slightly higher for the optimal interpolation method, and the mean error was slightly lower for the inverse-distance weighting method (Table 5). No conclusion could be drawn on the superiority of one method to the other.

			ρ^2	mean error (°C)	mean (°C) obs/com
1993	All stations (45)	Inverse distance weighting	0.95	0.45	0.56/0.59
		Optimal interpolation	0.96	0.47	0.56/0.57
	Western stations (12)	Inverse distance weighting	0.95	0.58	0.07/0.11
		Optimal interpolation	0.95	0.59	0.07/-0.04
1994	All stations (50)	Inverse distance weighting	0.97	0.51	0.22/0.25
		Optimal interpolation	0.98	0.50	0.22/0.23
	Western stations (12)	Inverse distance weighting	0.95	0.42	-0.20/-0.15
		Optimal interpolation	0.96	0.47	-0.20/-0.29

Table 6 *Verification of temperature estimates against point observations. Verification was carried out by excluding one station at a time and estimate temperature from the remaining stations. The coefficient of determination refers to daily values, and the mean absolute error to the mean temperature.*

6 SENSITIVITY ANALYSIS

The weighting methods depend on parameters whose values may strongly affect the estimated precipitation and temperature. For the optimal interpolation method, examples of such parameters are the covariance field and the background field. For the other methods precipitation elevation corrections and temperature lapse rates influence the estimates. In this section the methods' sensitivity to some of these parameters is investigated.

6.1 Precipitation - optimal interpolation

6.1.1 Sensitivity to standard deviation field

The covariance function is divided into the correlation function and the standard deviation. The sensitivity of the standard deviation field was investigated by replacing the interpolated standard deviation for the point estimates, by the actual values for each year and station. This made little difference to the coefficient of determination, but led to a large improvement in the total estimates (Table 7), particularly in the western parts.

			ρ^2	mean error (%)
1993	All stations (128)	Optimal interpolation (1)	0.78	11.6
		Optimal interpolation (2)	0.78	6.4
		Optimal interpolation (3)	0.78	10.1
	Western stations (28)	Optimal interpolation (1)	0.71	18.1
		Optimal interpolation (2)	0.72	6.0
		Optimal interpolation (3)	0.71	10.8
1994	All stations (129)	Optimal interpolation (1)	0.74	11.0
		Optimal interpolation (2)	0.74	7.6
	Western stations (29)	Optimal interpolation (1)	0.71	16.7
		Optimal interpolation (2)	0.71	8.7

Table 7 *Verification of point estimates of precipitation against observations.*
(1) Station standard deviation interpolated from surrounding grid cells.
(2) Station standard deviation computed from station observations for the actual year.
(3) Station standard deviation computed from station observations for 1994.

The standard deviation field used in this investigation does not depend on the weather situation. If the normalised standard deviations for each station and year is plotted against interpolated values from the surrounding grid, the scatter plots differ considerably (Figure 7). The explanation is probably that 1993 with its rather high precipitation was dominated by another type of weather systems coming from another direction than those of 1994. Ideally the standard deviation should vary with, e.g., wind direction or pressure distribution. This could be illustrated by estimating precipitation for 1993 using standard deviation values from 1994. The fit is not as good as with the values from 1993 (Table 7) even if it is better than with interpolated values.

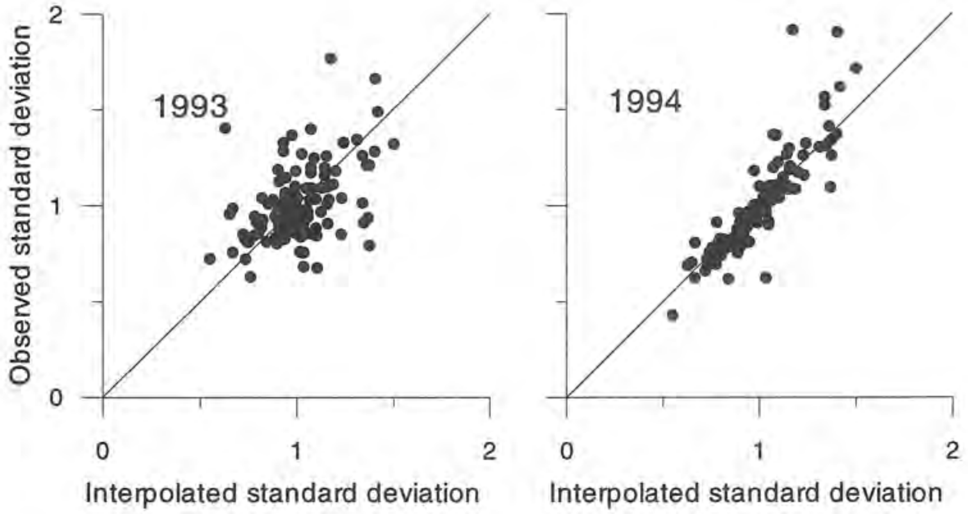


Figure 7 *Normalised observed standard deviation values for meteorological stations for 1993 and 1994 respectively, plotted against interpolated values from the surrounding grid cells.*

6.1.2 Sensitivity to correlation function

In previous investigations it was found that in the western parts of the test region the correlation between stations was higher in the north-south direction then in the east-west direction (Johansson, 1994). A simple way to account for this is to multiply the east-west distance by two. Looking first at the sub-catchment precipitation, it is clear that such a change in the covariance field has very little effect on the daily variation as reflected by the determination coefficient (Figure8). In the northern catchments there was however a notable difference in the annual precipitation, and the estimated values were generally lower for the alternative with higher correlation in the north-south direction. This could be explained by the precipitation pattern, as there are two clear maxima in precipitation; one along the water divide towards the Norwegian border, and one along the more eastern water divide between the Suorva and Tjaktjajaure catchments. Lower weights for the Norwegian stations lead to lower precipitation in, e.g., Suorva.

Verification against meteorological stations for the year 1993 gave no clear indication as to which correlation function is most correct, although the mean error for the western stations is slightly lower for the alternative with doubled distance in the east-west direction (14.2 % as compared to 18.1 %).

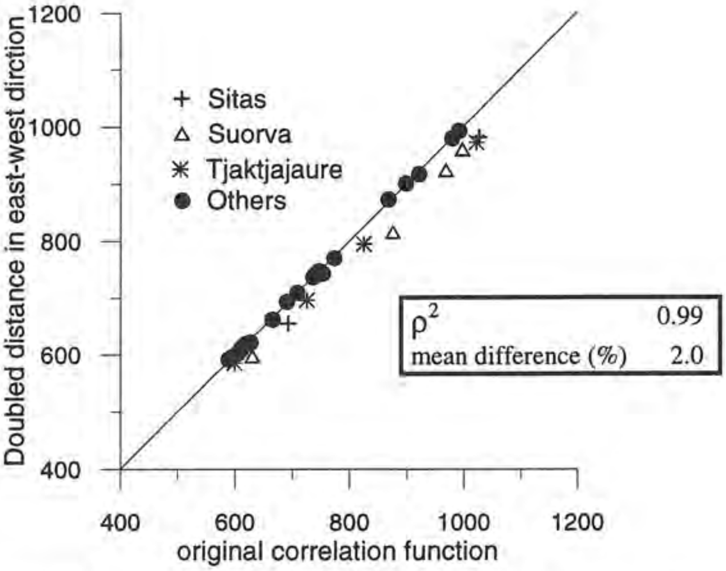


Figure 8 *Comparison between catchment precipitation estimates 1977 09 01-1997 08 31 based on different correlation functions. The coefficient of determination refers to daily values, and the mean difference to the annual estimates. The diagram shows the estimated mean annual precipitation for each sub-catchment.*

6.1.3 Sensitivity to the background field

Through the introduction of a background field, the interpolation is made on the deviation from this field, not directly on the observed values. Errors in the spatial distribution of the background field might thus lead to errors in the estimated precipitation. The climatological field used in the previous tests is an estimate of the long-term daily mean precipitation for the region. The spatial distribution is described by means of the standard deviation field, a reasonable assumption as it has been shown that the ratio mean precipitation over coefficient of variation is fairly constant (Creutin and Obled, 1982). In the test regions the background field varies from slightly above one millimetre to approximately three millimetres per day. This means that on days with large precipitation the background field has a rather small effect, but on days with low precipitation it might reinforce the climatological pattern.

An alternative background field, which still maintains the property that the long-term mean value equals the true mean, is to use daily station precipitation. For each grid cell the background field was given as a mean of the four nearest stations, once again adjusted by the standard deviation. As a sensitivity test, the sub-basin precipitation was computed using this background field. It should be seen only as a sensitivity test, as the correlation function and standard deviation field were still based on a constant background field, and would look different if a time varying field was used. The results of the test are summarised in Figure 9. There is no systematic difference, in the sense that the new background field generally leads to higher or lower precipitation, but for single basins there are differences, which in some cases are of the same order of magnitude as the ones caused by drastic changes in the station network.

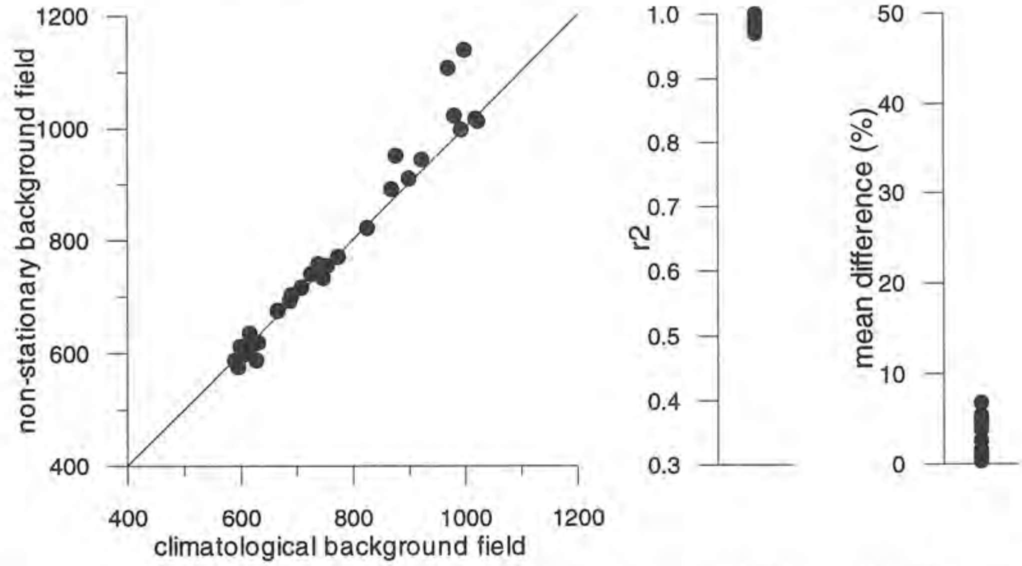


Figure 9 *Comparison between catchment precipitation estimates 1977 09 01-1997 08 31 based on different background fields. The coefficient of determination refers to daily values, and the mean difference to the annual estimates. The diagram to the left shows the estimated mean annual precipitation for each sub-catchment.*

The test shows that the selection of the background field is of importance. However, as for the correlation function, verification against point observations gave no clear preference to one alternative (Table 8), although the results were slightly better for the climatological background field.

	Climatological background field	Non-stationary Background field
ρ^2	0.73	0.70
mean error (%)	11.1	12.4

Table 8 *Verification of point estimates of precipitation against observations 1988 09 01-1997 08 31, with a climatological background field and a non-stationary background field based on the data from the 4 nearest stations. The coefficient of determination refers to daily values, and the mean error to the annual estimates.*

In real-time applications in meteorology in Sweden, the background field is taken from a numerical weather forecast. The single effect of this background field is difficult to evaluate as the input observations also are different, but comparisons for the period 1995 10 01-1997 08 31 indicate that as an average there are no systematic differences as compared to the climatological background field (Figure 10).

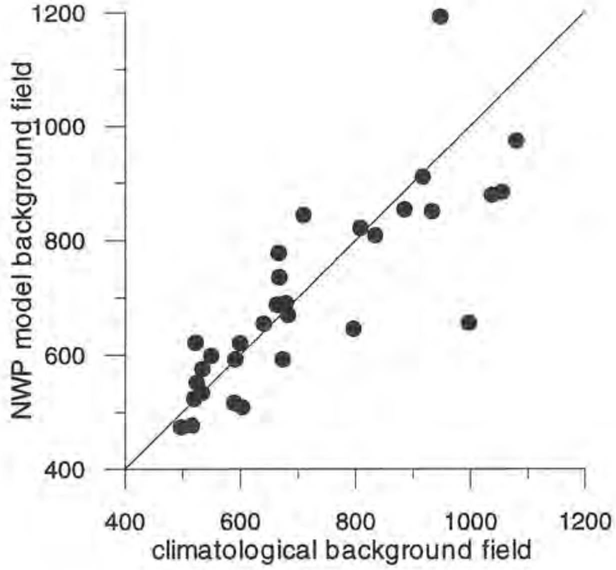


Figure 10 *Comparison between catchment precipitation estimates 1995 10 01-1997 08 31 based on a climatological background field and a numerical weather prediction model field. The diagram shows the estimated annual precipitation for each sub-catchment. The estimates are not quite comparable as input data differ to some extent.*

6.1.4 Conclusions

For rainfall-runoff modelling in areas with a considerable snow pack, the accurate estimate of total precipitation is normally of more importance than the actual timing of a precipitation event. With respect to this, the standard deviation field seems to be the most important parameter for the optimal interpolation method. The selection of correlation function and background field affects the estimated precipitation values, but not to the same extent.

6.2 Precipitation - inverse-distance weighting

6.2.1 Sensitivity to elevation correction

Initially the linear increase in precipitation was set to 7 %/100 m below the timberline, using 800 m as the reference level. In reality the value varies considerably between locations (SNA, 1995), and to test the sensitivity of the parameter it was set to 10 %/100 m, a fairly common value in Swedish applications.

Especially for the north-western catchments (Sitas and Suorva), this led to a large increase in the estimated precipitation (Figure 11), an increase of the same order of magnitude as the difference between the weighting methods. In the southern catchments the difference between station elevation and catchment mean elevation is smaller, and the estimated precipitation was consequently less affected by the change in elevation correction.

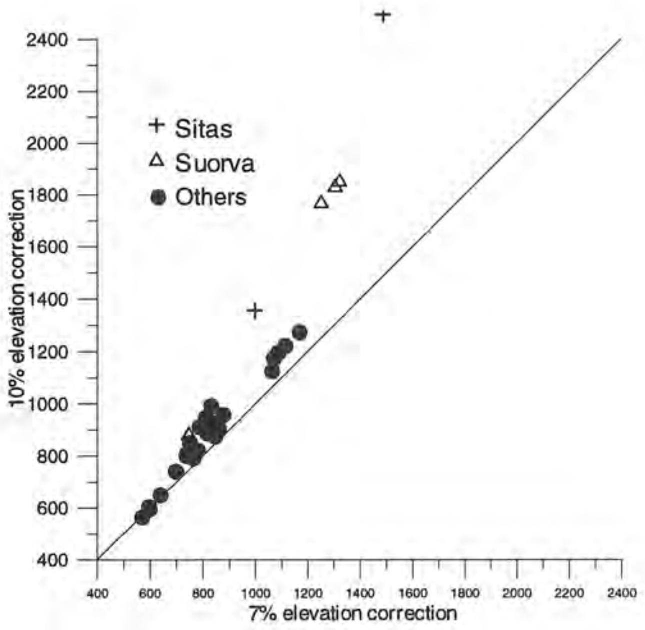


Figure 11 *Comparison between catchment precipitation estimates 1977 09 01-1997 08 31 with different elevation corrections. The diagram shows the estimated annual precipitation for each sub-catchment. The differences are largest for the sub-catchments of Sitas and Suorva Note that the axis scale is not the same as in similar diagrams (e.g. Figure 10).*

6.2.2 Sensitivity to the selection of weights

By setting the weights proportional to the inverse squared distance, the nearest stations are given very large weights. This is a notable difference to the optimal interpolation method, where the solution of the system of linear equations normally leads to weights for a large number of stations. It is possible that the inverse-distance weighting method thus becomes more sensitive to changes in the meteorological network. Therefore a test was made, setting the weights directly proportional to the inverse distance, and using the eight nearest stations instead of four. The stations were also selected within a greater radius.

With all stations available, the estimated total areal precipitation was similar to the original one (Figure 12). More surprising was that as an average there was no improvement in the results when comparing the estimates from all stations to that of the stations reporting in real-time (Table 9).

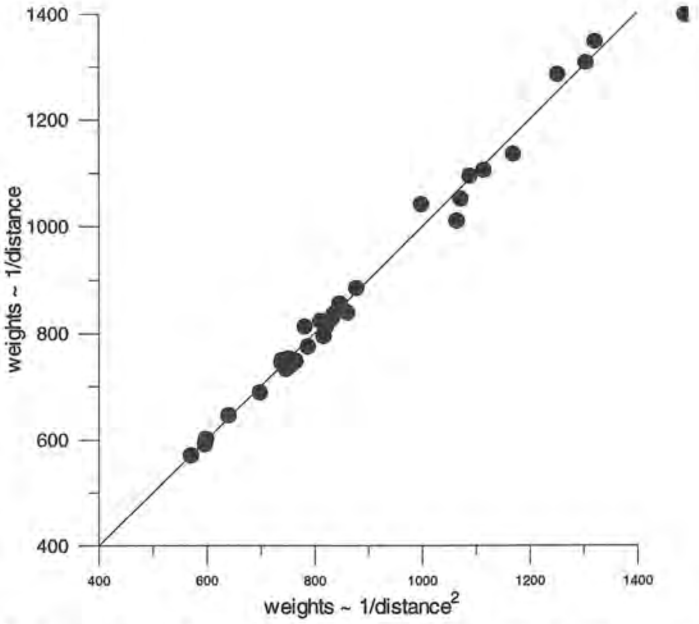


Figure 12 *Comparison between catchment precipitation estimated with weights proportional to the squared inverse distance and the plain inverse distance respectively (1977 09 01-1997 08 31). The diagram shows the estimated annual precipitation for each sub-catchment.*

	weights ~ 1/distance^2	weights ~ 1/distance
ρ^2	0.81	0.81
mean error (%)	14.2	14.2

Table 9 *Comparison between catchment precipitation estimates based on all available meteorological stations and estimates based only on stations reporting in real-time (19770901-19970831). The coefficient of determination refers to daily values, and the mean difference to the annual estimates.*

6.2.3 Conclusions

The original estimates by the inverse distance weighting method were based on the four nearest stations and the squared distances. Increasing the number of stations to eight and using plain distances should result in a more smoothed precipitation field, less sensitive to network changes. However, the effect on the estimated catchment precipitation was very small, also for estimates from a reduced number of stations.

The estimates were far more sensitive to the precipitation elevation correction. In the most northern catchments, there is a large difference between station elevation and catchment mean elevation and there an increase in elevation correction from 7 %/100 m to 10 %/100 m led to an increase in precipitation by around 40% (67% in the most extreme case).

6.3 Temperature - optimal interpolation

6.3.1 Sensitivity to the temperature lapse rate

Clearly it is not always correct to use 0.6°C/100 m as the temperature lapse rate (Lindkvist *et al.* 1997; Johansson *et al.* 1998). The effect of the lapse rate was tested by setting it to 0 in the optimal interpolation method, which in this aspect can be said to be representative for all the three methods. On an annual basis, the results showed that the difference in estimated temperature between sub-catchments to some extent can be explained by the latitude, but locally almost completely by the difference in elevation (Figure 13).

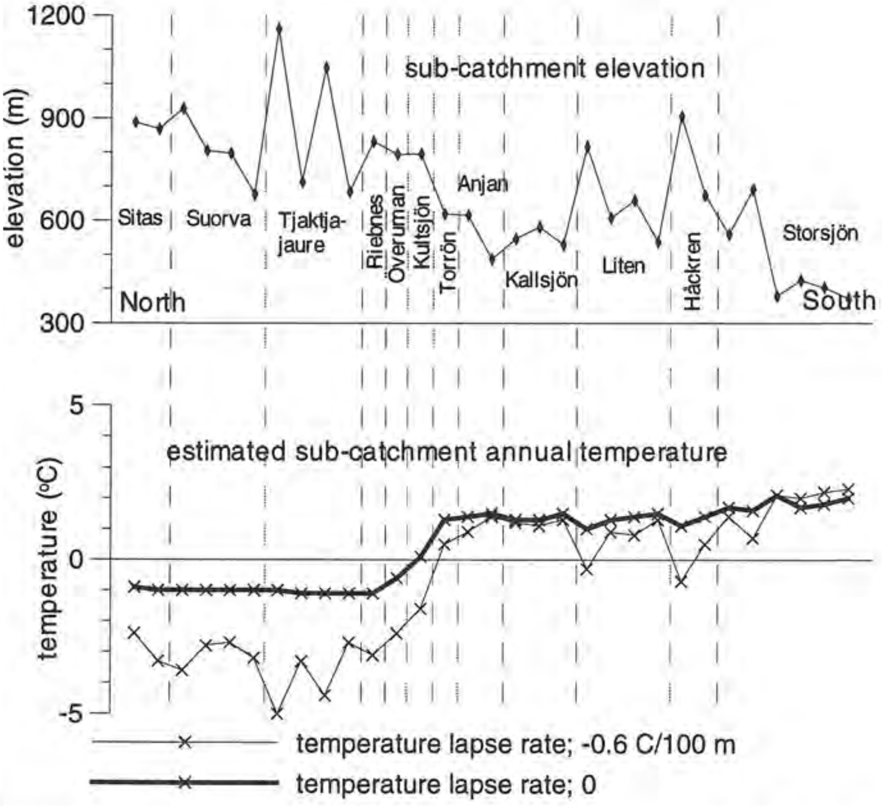


Figure 13 *Sub-catchment mean elevation (above) and mean temperature (below), with the sub-catchments ordered from North (left) to South (right). Temperature lapse rate set to 0.6°C/100 m and 0 respectively.*

7 RAINFALL-RUNOFF MODELLING

In hydrology, the estimation of areal precipitation and temperature is the first step in estimation of runoff. A common application is rainfall-runoff modelling and hydrological forecasting. One way to test the areal estimates is consequently to use them as input data to a rainfall-runoff model. It does not necessarily follow that the more accurate areal estimates produce better modelling results. As long as the parameters of the model are calibrated against observed runoff systematic over- or underestimates of precipitation and temperature can be adjusted for by the selection of model parameters. However, by comparing the results for different periods and different sets of meteorological stations, it is possible to assess the robustness of the areal estimates.

7.1 Simulations

The main tool for operational runoff modelling and forecasting in Sweden is the conceptual HBV model (Bergström, 1976, Lindström et al., 1997) which was used to test the areal estimates from subjective weighting, inverse-distance weighting and optimal interpolation. Simulations were made for the period 1977 09 01-1997 08 31, with half the period used for calibration and the other half for verification. The calibration was carried out using an automatic procedure (Lindström, 1997). Simulations were made with two data sets, one including all available meteorological stations and the other one including only those reporting in real-time.

7.1.1 Verification criteria

Two criteria were used to evaluate the model simulations. The first was the R^2 value recommended by Nash and Sutcliffe (1970):

$$R^2 = 1 - \frac{\sum_t (\mathrm{qcom}(t) - \mathrm{qrec}(t))^2}{\sum_t (\mathrm{qrec}(t) - \overline{\mathrm{qrec}})^2}$$

qcom(t) = simulated runoff
qrec(t) = observed runoff
$\overline{\mathrm{qrec}}$ = mean observed runoff

For a specific catchment this criterion agrees well with a subjective evaluation of the hydrograph, i.e. a simulation resulting in a higher R^2-value is generally considered better at a visual inspection. However, it is not always possible to judge the results from two different catchments by the R^2-value. In catchments where a great part of the runoff variance is explained by, e.g., the spring flood peak it is normally easier to get a high R^2-value. At the outlets of all the test catchments there are hydropower reservoirs. As the reservoirs are heavily regulated, simulations can not be made of the reservoir outflow. The model is therefore calibrated against reservoir inflow, and the recorded inflow is computed as the sum of the observed outflow and the change in reservoir storage. If the reservoirs are large in relation to the upstream catchment, small errors in the observed reservoir levels lead to large errors in the recorded inflow. It is smoothed out over a few days, but makes the observed hydrograph very jagged, and the resulting R^2-values low. A lower R^2-value for one catchment as compared to another does consequently not necessarily imply less accurate areal estimates of precipitation and temperature.

A simulation may result in a high R^2 without the runoff volume being simulated correctly. In the test region an important application of hydrological modelling is the forecast of the spring flood volume. It is thus essential to simulate this as accurately as possible, and as a second criterion the mean absolute error of the spring flood volume was introduced ($\overline{\mathrm{sferr}}$):

$$\overline{\mathrm{sferr}} = \frac{\sum_{y} |\mathrm{sferr}(y)|}{\overline{\mathrm{sfvol}}}$$

sferr(y) = volume error over the spring flood period (0401-0731) for each individual year

$\overline{\mathrm{sfvol}}$ = mean spring flood runoff volume

7.1.2 Simulations based on all meteorological stations

During the calibration period the model performance was similar for all three areal estimates, with one exception; the Suorva catchment and the inverse-distance weighting method (Table 10). This is a complicated catchment where the mean annual precipitation for the surrounding stations varies from some 500-600 mm for the stations within the catchment to some 2000 mm/year for some of the stations on the Norwegian side of the water divide. It is a variation not simply explained by the difference in elevation, and it is rather surprising that an automatic objective method like the optimal interpolation works as well as it does compared to the subjective weighting where special consideration can be taken when selecting the most representative stations.

R^2	subjective		inverse distance		opt. interpol.		
	cal.	ver.	cal.	ver.	cal.	ver.	cal. period
Sitasjaure	0.88	0.89	0.89	0.81	0.89	0.87	1987-97
Suorva	0.90	0.92	0.79	0.68	0.90	0.93	1977-87
Tjaktjajaure	0.86	0.80	0.85	0.82	0.87	0.85	1987-97
Riebnes	0.82	0.77	0.82	0.76	0.83	0.79	1977-87
Överuman	0.74	0.82	0.74	0.81	0.74	0.79	1987-97
Kultsjön	0.88	0.82	0.88	0.84	0.89	0.87	1977-87
Torrön	0.78	0.82	0.78	0.81	0.78	0.83	1987-97
Anjan	0.83	0.72	0.83	0.73	0.82	0.72	1977-87
Kallsjön	0.61	0.64	0.61	0.63	0.60	0.64	1987-97
Liten	0.93	0.91	0.92	0.90	0.92	0.91	1977-87
Håckren	0.88	0.89	0.87	0.89	0.88	0.89	1987-97
Storsjön	0.63	0.56	0.63	0.57	0.63	0.57	1977-87
Mean	**0.81**	**0.80**	**0.80**	**0.77**	**0.81**	**0.81**	

a)

Volume error	subjective		inverse distance		opt. interpol.		
(%)	cal.	ver.	cal.	ver.	cal.	ver.	cal. period
Sitas	5.7	3.8	4.6	12.3	5.1	6.5	1987-97
Suorva	2.9	4.9	22.7	37.4	3.5	9.3	1977-87
Tjaktjajaure	7.2	12.4	8	8.6	6.5	7.6	1987-97
Riebnes	5.3	7.4	5.8	8.4	5.1	6.4	1977-87
Överuman	4.8	5.1	4.4	12.4	5.2	7.9	1987-97
Kultsjön	4.9	6.8	7	6.1	5.9	4.1	1977-87
Torrön	4.4	4.0	4.3	4.0	3.8	3.7	1987-97
Anjan	3.0	6.6	3.2	5.8	4.4	5.9	1977-87
Kallsjön	6.9	6.1	6.3	5.2	7.3	5.4	1987-97
Liten	4.8	9.0	5.5	9.5	5.3	9.3	1977-87
Håckren	6.6	6.2	6.9	5.1	7.7	5.8	1987-97
Storsjön	5.4	6.3	5.6	6.5	6.6	8.3	1977-87
Mean	**5.2**	**6.6**	**7.0**	**10.1**	**5.5**	**6.7**	

b)

Table 10 *Results of HBV model simulations with different estimates of areal precipitation and temperature 1977 09 01-1997 08 31 (for Sitasjaure from 1978 09 01).*

a) R^2-values for calibration and verification periods

b) Mean springflood absolute volume error (percentage of total springflood runoff).

During the verification period the inverse-distance weighting method did not perform as well as the other two as an average, although it was mainly three catchments along the Norwegian border that caused the problems. Comparing the subjective weighting and the optimal interpolation, there were only two catchments where there was a clear difference between the methods. In Tjaktjajaure and Kultsjön the R^2 criterion was notably better for the optimal interpolation.

The water balance verification in section 4.1.2 showed that there were large variations in the ratio (Q+E)/P between the catchments. This was also reflected in the runoff model parameters. There was no systematic variation in the parameters that govern the runoff volume. The indication is that none of the methods describes the spatial distribution of precipitation correctly. Also the threshold temperature value that determines whether precipitation falls as snow or rain varied considerably between catchments. However, this is not only an effect of the areal temperature estimate, but also of the distribution of precipitation and temperature within the sub-catchments, which was the same for all three methods.

7.1.3 Simulations based on real-time data

Without recalibrating the model, simulations were made using meteorological data only from stations available in real-time. Geographically, this means that the exclusion of stations was random. For some catchments there was a drastic change in the number of nearby stations, for others hardly any change at all (Figure 2). The changes were most notable along the Norwegian border as all Norwegian stations were excluded. Most of the stations with temperature data report in real-time, and the effect of decreasing the number of temperature stations could only be investigated for three catchments.

As an average, the decrease in the R^2-value due to loss of precipitation data was considerably higher for the inverse-distance weighting method than for the other two methods (Table 11). However, it was still the Suorva catchment that was main reason for the difference being so high.

R^2	Subjective		inverse distance		opt. interpol.		
	cal.	Ver.	cal.	ver.	cal.	ver.	cal. period
Sitas	-0.01	-0.04	-0.18	-0.04	-0.01	-0.06	1987-97
Suorva	-0.08	-0.03	-0.46	-0.49	-0.06	-0.12	1977-87
Tjaktjajaure	0	0	-0.04	0.02	0	0	1987-97
Riebnes	-0.02	-0.02	0	-0.04	-0.01	-0.01	1977-87
Överuman	-0.02	-0.05	-0.06	-0.05	-0.04	-0.10	1987-97
Kultsjön	-0.10	-0.01	-0.04	-0.01	-0.02	0	1977-87
Torrön	-0.04	-0.11	-0.02	-0.05	-0.02	-0.05	1987-97
Anjan	-0.09	-0.09	-0.10	-0.04	-0.06	-0.04	1977-87
Kallsjön	-0.10	-0.10	-0.02	-0.02	-0.02	-0.02	1987-97
Liten	-0.04	-0.04	-0.04	-0.05	-0.03	-0.02	1977-87
Håckren	-0.01	-0.05	-0.01	-0.01	-0.03	-0.04	1987-97
Storsjön	0	-0.01	-0.01	-0.08	0	0	1977-87
Mean	**-0.04**		**-0.08**		**-0.03**		

a)

Volume error	Subjective		inverse distance		opt. interpol.		
	cal.	Ver.	cal.	ver.	cal.	ver.	cal. period
Sitas	0.1	3.3	26.3	10.8	-0.3	6.6	1987-97
Suorva	6.8	3.1	36.0	29.0	8.8	17.6	1977-87
Tjaktjajaure	0.1	1.0	11.5	4.4	1.5	-0.8	1987-97
Riebnes	-0.6	2.9	-1.2	3.9	0.4	1.6	1977-87
Överuman	1.7	5.4	12.0	12.4	4.2	7.0	1987-97
Kultsjön	12.6	0.1	8.1	5.1	4.4	4.1	1977-87
Torrön	2.5	7.3	4.1	2.6	0.9	4.0	1987-97
Anjan	6.1	3.9	19.2	9.6	3.5	2.3	1977-87
Kallsjön	1.9	6.2	1.8	0.2	-1.7	0.6	1987-97
Liten	8.2	5.5	6.3	3.7	4.2	-0.7	1977-87
Håckren	1.5	2.2	5.4	16.0	2.1	7.2	1987-97
Storsjön	-0.1	1.3	3.9	-1.1	0.2	-2.3	1977-87
Mean	**3.5**		**9.6**		**3.1**		

b)

Table 11 *Results of HBV model simulations with different estimates of areal precipitation and temperature. Changes in verification criteria due to reduction of the number of rainfall stations. Simulations were made without recalibrating the model.*

a) Change in R^2-values

b) Change in mean springflood absolute volume error (percentage points).

The results were similar for the spring flood volume error, although the bad performance for the inverse-distance weighting method was more general. For the other methods there were two catchments that stood out from the rest; Kultsjön (calibration period) for subjective weighting and Suorva (particularly the verification period) for optimal interpolation. The reason for the large increase in volume error for these catchments reflects some of the characteristics of the methods. As mentioned above, the subjective weights have been taken from the operational model set-up. With the weights comes a general precipitation correction factor, which is used to correct for known homogeneity breaks in the input data. For Kultsjön such a break occurred around 1983/84, and the precipitation correction factor was consequently set to different values before and after 1984. The homogeneity break was mainly caused by one meteorological station. When that station was excluded from the real-time simulations in the manner of this test, a large volume error occurred.

For the optimal interpolation method, the results for Suorva emphasise the importance of a correctly described standard deviation field. One of the stations within the catchment starts in 1987, and was thus not included in the calibration period. The precipitation for this station is very low, and the actual standard deviation is lower than what is reflected by the climatology of the surrounding grid. The automatic weight given to the station thus became too low, which became more pronounced in the real-time simulations when only a few stations were available in that area. In the subjective weighting method, the knowledge of the extremely low precipitation at the station could be considered in the selection of the replacement factor, something which is more complicated in an automatic weighting method.

As the test catchments are large and as winter precipitation is accumulated in the snow pack, the accuracy of the daily precipitation estimates is less important than the total precipitation over a number of days or even months. In section 4.2.2 it was shown that if the determination coefficient for daily values was used as the criterion, areal estimates by the optimal interpolation method from real-time data agreed better with estimates from all available data than estimates by inverse-distance or subjective weighting. Due to the lack of sensitivity to daily variations, such an advantage of the optimal interpolation method may not be reflected in more accurate runoff simulations.

The direct comparison of estimated temperatures indicated that the optimal interpolation method was less sensitive to changes in the station network than the other two methods, and that the differences for the subjective method were considerable. The same results were reflected by the model simulations (Table 12). The decrease in R^2-value for the subjective method and investigated catchments was 0.21 as an average, as compared to a decrease of 0.09 when only precipitation data were affected. One reason could be the general assumption that areal temperature is easier to estimate than areal precipitation, and as a consequence less effort was given to finding suitable replacement stations.

R^2	**subjective**		**inverse distance**		**opt. interpol.**		
	cal.	ver.	cal.	ver.	cal.	Ver.	cal. period
Torrön	-0.23	-0.18	-0.02	-0.04	-0.02	-0.05	1987-97
Anjan	-0.17	-0.29	-0.11	-0.05	-0.05	-0.04	1977-87
Kallsjön	-0.23	-0.14	-0.02	-0.02	-0.02	-0.02	1987-97
Mean	**-0.21**		**-0.04**		**-0.03**		

Table 12 *Results of HBV model simulations with different estimates of areal precipitation and temperature. Changes in R^2-value due to reduction of the number of rainfall and temperature stations. Simulations were made without recalibrating the model.*

7.1.4 Conclusions

The HBV simulations based on the automatic objective optimal interpolation performs at least as well as simulations based on the manual subjective weighting method. The inverse-distance weighting method is less reliable, especially in regions with complex precipitation gradients. The investigated area is one of the most difficult in Sweden for which to estimate areal precipitation and temperature. The meteorological network is sparse and the precipitation gradients complex. It is thus safe to conclude that for routine runoff modelling applications, the time-consuming subjective weighting method can be replaced by the automatic optimal interpolation method based on the covariance field developed by Häggmark et al (1997). However, the variation in the model parameters governing runoff volume and snow melt occurrence vary as randomly between catchments for the optimal interpolation method as for the subjective weighting method. This is an indication that none of the methods describes the spatial distribution of precipitation and temperature correctly.

The subjective weighting method appears to be very sensitive to changes in the availability of temperature data. The reason could be a belief that one does not need to be as careful in replacing temperature stations as in replacing precipitation stations.

8 FINAL CONCLUSIONS

The investigation has shown that for routine runoff modelling applications, the time-consuming subjective weighting method to estimate areal precipitation and temperature could be replaced by the automatic optimal interpolation method based on the covariance field developed by Häggmark et al (1997). This is true in spite of the fact that the optimal interpolation method systematically underestimates total precipitation in several catchments. The inverse-distance weighting method is less reliable and can not be recommended.

None of the investigated methods describes correctly the spatial distribution of precipitation and temperature in the investigated region. From that follows that they are not directly applicable for non-routine runoff modelling applications, e.g. accurate estimates of internal model variables, simulations without calibrating the model parameters or combination with other types of input data like remote sensing.

In operational rainfall-runoff modelling in Sweden, there has been a general belief that it is easier to estimate areal temperature than areal precipitation. The subjective method proved to be extremely sensitive to a reduction in the number of temperature stations, indicating that more consideration should be given to the selection of station weights.

In the studied region much of the spatial variation of precipitation is explained by the topography. The elevation range is some 1500 m, and the meteorological stations are almost exclusively situated in the valleys. In the subjective and inverse-distance weighting method the climatological dependency on elevation is described by an elevation correction factor which is normally set to the same default value in all catchments. In catchments with a mean elevation much higher than the station elevation, the areal estimates are extremely sensitive to the value of the correction factor; a change from 7 % to 10 % may increase the estimated areal precipitation by as much 65 %. In some regions the elevation correction factor can be related to the topography by means of digital elevation data bases (Daly et al, 1992), but the lack of precipitation data in the investigated part of Sweden makes it very difficult.

Instead of applying an elevation correction factor, the optimal interpolation method describes the climatological variation of precipitation by means of the standard deviation field. The availability of digital elevation data bases has made it possible to relate the standard deviation to topography. Häggmark et al. (1997) found a relationship between standard deviation and slope against the wind direction during precipitation. Their standard deviation field was originally developed for large scale applications permitting, e.g., no variation in prevailing wind directions. Presumably a better spatial description could be achieved by taking more consideration to local conditions. In the north-western parts of Sweden, it is known that prevailing wind directions during precipitation are from the west on the western side of the water divide, and from east to south-east on the eastern side. Such a knowledge should be fairly easy to implement in the creation of the standard deviation field. Ideally, the standard deviation field should be created daily, on the basis of actual wind directions. The comparison of station standard deviation for 1993 and 1994 shows that the pattern may vary considerably between years, depending on the dominating weather systems.

The optimal interpolation method contains a systematic approach to describe the variation in precipitation due to, e.g., topography, by means of the standard deviation field. It may be difficult to find this relationship, but if local variations in wind direction and speed are considered, it is likely that the relationship in itself is the same over large areas. It can thus be applied also in regions with a sparse network of meteorological stations. Historical data can be used to find the relationship, so one does not depend only on the existing network. Once the standard deviation field has been established the method is easy to adopt. There will never be a completely accurate description of the standard deviation field, but it seems that the optimal interpolation method has a good potential for future development.

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APPENDIX A

Catchment	Sub-catchment	Area (km^2)	Mean elevation (m.a.s.l)	Percentage of forest
Sitasjaure		**978**	**870**	**0**
	Sitasjaure övre	319	890	0
	Sitasjaure nedre	659	870	0
Suorva		**4691**	**820**	**4**
	Virihaure	1360	930	0
	Vastenjaure	554	800	0
	Akkajaure norra	2039	800	0
	Suorva	738	680	22
Tjaktjajaure		**2250**	**930**	**18**
	Litnok	657	1160	8
	Laitaure	106	710	17
	Sitojaure	689	1040	0
	Tjaktjajaure	797	680	40
Riebnesjaure		**976**	**830**	**25**
Överuman		**652**	**790**	**4**
Kultsjön		**1097**	**790**	**26**
Torrön		**1366**	**620**	**24**
Anjan		**443**	**570**	**20**
	Storrenssjön	120	550	19
	Anjan	322	580	21
Kallsjön		**1197**	**530**	**44**
	Äcklingen	156	620	31
	Juveln	247	490	56
	Kallsjön	793	530	43
Liten		**3126**	**700**	**36**
	Ånnsjön	1563	820	21
	Öster-Noren	821	610	49
	Greningen	33	660	46
	Liten	709	540	56
Håckren		**1167**	**820**	**32**
	Ottsjön	730	900	25
	Håckren	436	670	44
Storsjön		**4782**	**450**	**54**
	Näckten	493	380	59
	Näldsjön	750	420	63
	Alsensjön	286	400	66
	Sällsjön	130	560	59
	Ockesjön	978	690	40
	Storsjön	2145	370	55

Table A 1 *Data on test catchments.*

Catchment	**Sub-catchment**	**Mean precipitation (mm/year)**			**Mean runoff (mm/year)**
		Subjective	inverse-distance	optimal	
Sitasjaure		**1150**	**1160**	**800**	**1305**
	Sitasjaure övre	1250	1490	1030	
	Sitasjaure nedre	1100	1000	690	
Suorva		**1360**	**1200**	**880**	**1051**
	Virihaure	1420	1300	1000	
	Vastenjaure	1450	1320	970	
	Akkajaure norra	1560	1250	880	
	Suorva	630	750	630	
Tjaktjajaure		**880**	**810**	**800**	**856**
	Litnok	910	830	1020	
	Laitaure	820	820	720	
	Sitojaure	910	810	830	
	Tjaktjajaure	830	790	600	
Riebnesjaure		**720**	**750**	**630**	**722**
Överuman		**1000**	**1070**	**870**	**1255**
Kultsjön		**810**	**880**	**740**	**881**
Torrön		**1120**	**1090**	**990**	**1080**
Anjan		**1160**	**1140**	**960**	**1096**
	Storrenssjön	980	1060	900	
	Anjan	1220	1170	980	
Kallsjön		**920**	**890**	**790**	**718**
	Äcklingen	1170	1110	920	
	Juveln	900	850	750	
	Kallsjön	870	860	770	
Liten		**860**	**790**	**710**	**693**
	Ånnsjön	930	840	740	
	Öster-Noren	850	780	750	
	Greningen	790	760	600	
	Liten	710	700	620	
Håckren		**700**	**740**	**650**	**663**
	Ottsjön	710	740	670	
	Håckren	700	740	620	
Storsjön		**650**	**650**	**630**	**410**
	Näckten	580	600	590	
	Näldsjön	640	640	610	
	Alsensjön	620	600	610	
	Sällsjön	780	760	690	
	Ockesjön	800	820	710	
	Storsjön	580	570	600	

Table A 2 *Mean precipitation for test basins 1977 09 01-1997 08 31, estimated by different methods, using all available meteorological stations. Mean runoff for the same period. (For Sitasjaure 1978 09 01-1997 08 31.)*

Catchment	Sub-catchment	Mean temperature (^oC)		
		Subjective	inverse-distance	Optimal
Sitasjaure		**-3.1**	**-2.9**	**-3.0**
	Sitasjaure övre	-3.2	-2.2	-2.4
	Sitasjaure nedre	-3.1	-3.2	-3.3
Suorva		**-2.9**	**-2.8**	**-3.1**
	Virihaure	-3.7	-3.5	-3.6
	Vastenjaure	-3.8	-2.6	-2.8
	Akkajaure norra	-2.6	-2.3	-2.7
	Suorva	-1.9	-3.0	-3.2
Tjaktjajaure		**-4.0**	**-3.9**	**-3.9**
	Litnok	-5.4	-5.0	-5.0
	Laitaure	-2.7	-3.3	-3.3
	Sitojaure	-4.5	-4.3	-4.4
	Tjaktjajaure	-2.6	-2.8	-2.7
Riebnesjaure		**-3.5**	**-3.3**	**-3.1**
Överuman		**-2.1**	**-2.2**	**-2.4**
Kultsjön		**-1.5**	**-1.5**	**-1.6**
Torrön		**0.6**	**0.5**	**0.5**
Anjan		**1.1**	**1.0**	**1.1**
	Storrenssjön	1.5	1.2	1.2
	Anjan	0.9	1.0	1.1
Kallsjön		**1.3**	**1.3**	**1.3**
	Äcklingen	0.7	0.9	0.9
	Juveln	1.5	1.4	1.4
	Kallsjön	1.3	1.3	1.3
Liten		**0.7**	**0.5**	**0.4**
	Ånnsjön	0.1	0.0	-0.3
	Öster-Noren	1.3	1.1	0.9
	Greningen	0.8	0.9	0.8
	Liten	1.4	1.3	1.3
Håckren		**-0.2**	**-0.3**	**-0.3**
	Ottsjön	-0.7	-0.8	-0.7
	Håckren	0.5	0.5	0.5
Storsjön		**1.9**	**2.0**	**1.9**
	Näckten	2.1	2.2	2.1
	Näldsjön	2.1	2.0	2.0
	Alsensjön	2.2	2.3	2.2
	Sällsjön	1.2	1.4	1.4
	Ockesjön	0.5	0.7	0.7
	Storsjön	2.4	2.5	2.3

Table A 3 *Mean temperature for test basins 1977 09 01-1997 08 31, estimated by different methods, using all available meteorological stations. (For Sitasjaure 1978 09 01-1997 08 31.)*

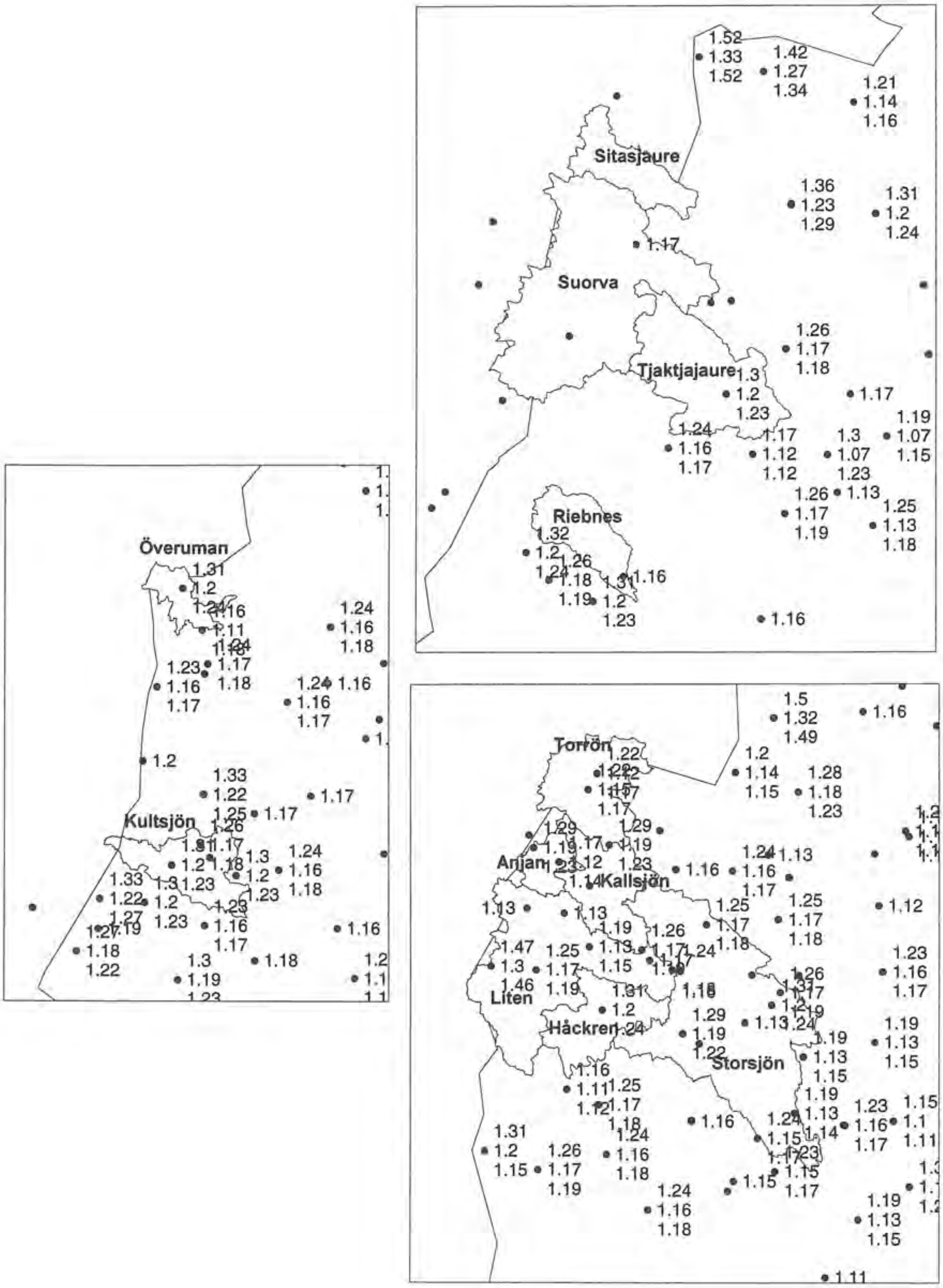

Figure A 1 *Precipitation corrections due to measurement losses. Top values according to Eriksson (1983), middle values according to Alexandersson (personal communication), bottom values according to Förland et al (1996).*

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