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Areal Precipitation and Temperature in the Swedish Mountains

An Evaluation from a Hydrological Perspective

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This paper 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 Swedish mountains. All three methods estimate the areal values as a weighted mean of the observations at nearby meteorological stations. The weights are determined by:

1) a manual subjective selection of the most representative stations
3) inverse square distance weighting
4) optimal interpolation

The methods were tested in an area with complex topography and precipitation gradients. 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.

The evaluation showed that for simple runoff modelling the subjective and optimal interpolation methods performed equally well, and considerably better than inverse-distance weighting. 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 proved to be sensitive to the selection of parameter values, which pointed to possible improvements of the estimates. The optimal interpolation method seemed to be the least sensitive to changes in the meteorological network.

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 the meteorological network seldom is dense enough to fully represent the variability. As long as the time series are homogeneous, 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 selected in such a way that they adjust the simulated runoff according to the bias in the input data. However, today there is a wish to widen the range of applications for rainfall-runoff models. Correct estimates of precipitation and temperature are absolutely necessary if the models are to be used to estimate runoff in ungauged catchments, where the model parameters cannot be fixed through a calibration process, but have to be estimated from catchment characteristics (Johansson 1994a; Motovilov *et al.* 1999). Another example is climate change impact studies, which require correct estimates of internal variables like snow pack and evapotranspiration (Saelthun *et al.* 1998).

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 occassionally 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 changes in the national network, both in the number of stations and in station location, have also made it difficult to maintain homogeneous time series. Previous studies (Lindell 1993; Johansson 1994b) have indicated that the optimal interpolation method leads to more robust estimates. This paper 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.

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. The disadvantages of the subjective method are that it is time-consuming, that it requires experience and that two different persons will often come up with two different sets of weights.

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. For the subjective and inverse-distance weighting methods, precipitation was extrapolated assuming a linear increase in precipitation with elevation. This is a common method in rainfall-runoff models, and a number of investigations have shown that locally it is an acceptable approximation, at least for climatological precipitation (Daly *et al.* 1994; SNA 1995). However, it could be debated whether the approximation is valid over the large areas for which it was applied in this study, or for single storms (Creutin and Obled 1982; Blumer and Lang 1993). For the optimal interpolation method, precipitation extrapolation was based mainly on an upwind index, computed from slope in the prevailing wind directions (Häggmark *et al.* 2000). Temperature was assumed to decrease according to the wet adiabatic lapse rate (0.6°C/100 m) which as an average is considered a good approximation (SNA 1995).

As catchment areas are in the order of 1,000 km^2, they had to be divided into subunits for the areal estimates by the objective methods. Precipitation and temperature were interpolated to cells on a rectangular grid (12 × 12 km^2), and catchment estimates were determined as the weighted mean of the cells covering the catchment. The computations for each day were based on the data available for that specific day.

Subjective and Inverse Distance Weighting

A subjective selection of weights is traditionally 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, computed from the relationship between mean annual precipitation/temperature at the original station and the replacement station. In all catchments selected for this evaluation, a runoff model is running operationally. As areal estimates were then available, this ensured that the selection of weights was not influenced by any wish to prove the objective methods more accurate.

For the inverse-distance weighting method, the estimation of grid cell precipitation and temperature was based on the four stations nearest to the mid-point. The weights were set proportional to the inverse squared distances with the sum of the weights equal to unity.

The elevation correction for precipitation was set at different values above and below the timberline; 7%/100 m below and 0 above, with 800 m as the reference level. This is the approach used by the runoff model to describe the difference in the snow pack distribution above and below the timberline (Brandt and Bergström 1994), and does not imply a difference in the precipitation dependency on elevation. Looking at the total elevation range, the linear increase thus varied between sub-catchments from about 3% to 7%/100 m. Estimates by Alexandersson (SMHI personal communication), based on meteorological stations give the increase in precipitation in this region as between 4% and 9%/100 m.

Optimal Interpolation

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

$$E = \sum_{t} (P(x_i, y_i) - P'(x_i, y_i))^2 = \langle (P_i - P'_i)^2 \rangle \tag{1}$$

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

$$P'_i = \sum_{k=1}^{N} w_{ik} P(x_k, y_k) \tag{2}$$

where

$P(x_k,y_k) = P_k$ – the value at station k
w_{ik} – station weights

To find the optimal weights Eq. (1) is differentiated with respect to the weights

$$\frac{\partial E}{\partial w_{ik}} = 0 \tag{3}$$

which leads to a system of linear equations.

However, for the estimated values to be unbiased, *i.e.* for the expectation value of P'_i ($\langle P'_i \rangle$) 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 climatological background field. Furthermore, 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 smoothing the interpolated values. The final form of the system of linear equations becomes as follows

$$\sum_{k=1}^{N} \left(\mathrm{cov}(P_k - P_k^b, P_l - P_l^b) + \mathrm{cov}(O_k, O_l)\right) w_{ik} = \mathrm{cov}(P_i - P_i^b, P_l - P_l^b) \qquad (4)$$

$l = 1 \ldots\ldots N$

where

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

The solution of Eq. (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

$$\mathrm{cov}(P_k - P_k^b, P_l - P_l^b) = \sigma_k \sigma_l \rho_{kl} \qquad (5)$$

where

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

The correlation coefficient is often found to depend only on the relative location, or this can be achieved by manipulating the co-ordinate system. Homogeneous covariances can be achieved by normalising Eq. (2) by means of the standard deviations. For precipitation, the spatial variation in standard deviation follows rather well the variation in mean precipitation (Creutin and Obled 1982). In practice, this means that observations from regions with low precipitation are given a larger weight when used to estimate precipitation in areas with higher precipitation (Häggmark *et al.* 2000).

The description of the covariance field is the basis for the optimal interpolation method, and the accuracy by which it can be determined, determines the accuracy of estimated areal values. However, for operational applications 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. In this study, the covariance field for precipitation was taken from Häggmark *et al.* (2000) and for temperature from Johansson (1994b). In both cases the correlation function was assumed to depend only on horizontal distance.

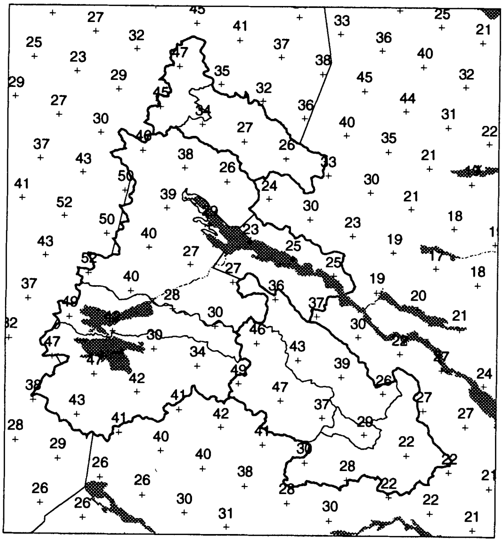

Fig. 1. Example of standard deviation values for the 12 × 12 km^2 grid used in the optimal interpolation method. The variation in standard deviation reflects the spatial variation in mean precipitation.

$$\rho \equiv 0.5\, e^{-d/L} + 0.5\left(1+2\frac{d}{L}\right) e^{-2d/L} \tag{6}$$

where

ρ – correlation
d – horizontal distance
L – scaling factor

Standard deviation for precipitation varied spatially as a function of slope in the prevailing wind direction (Fig. 1). It should be noted that this relationship was originally developed for large-scale meteorological applications, with no special consideration given to the region of this evaluation. Standard deviation for temperature was assumed to be constant.

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 (Fig. 2, Table 1). Input data came from close to 190 precipitation stations and 75 temperature stations. The mean observed annual precipitation varies from over 2,000 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 1,500 m.

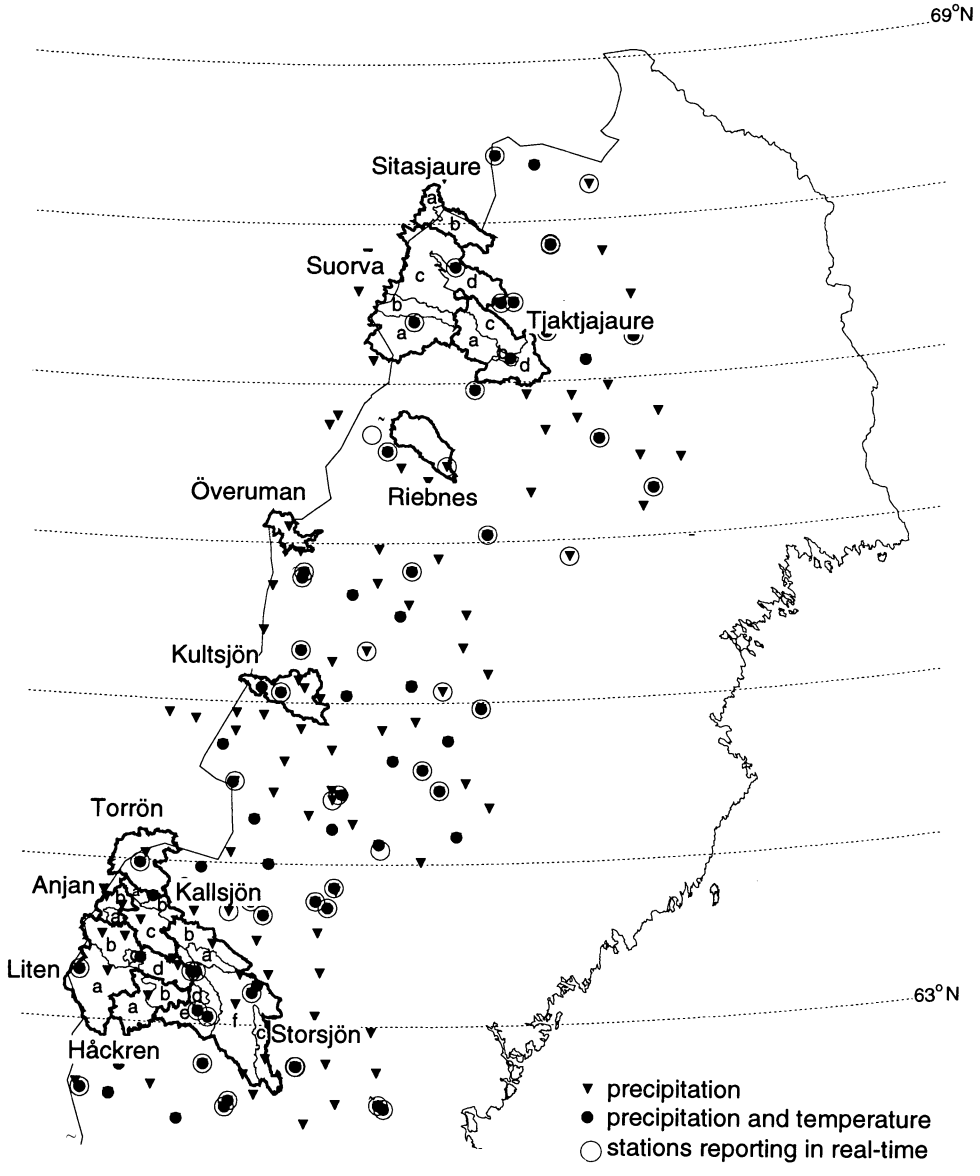

Fig. 2. Meteorological stations and test catchments for evaluation of areal estimates of precipitation and temperature. Thick lines mark main catchments with runoff stations. Sub-catchments are denoted by a, b, c etc.

Table 1 = Catchment area and mean elevation. Estimated mean annual precipitation 19770901-19970831, by the subjective method, inverse-distance weighting and optimal interpolation.

catchment	sub-catchm	area (km^2)	elevation (m.a.s.l)	forest (%)	mean annual prec (mm/year)			runoff (mm/year)
					subj	inv	opt	
Sitasjaure		978	870	0	1150	1160	800	1300
	a	319	890	0	1250	1490	1030	
	b	659	870	0	1100	1000	690	
Suorva		4691	820	4	1360	1200	880	1050
	a	1360	930	0	1420	1300	1000	
	b	554	800	0	1450	1320	970	
	c	2039	800	0	1560	1250	880	
	d	738	680	22	630	750	630	
Tjaktjajaure		2250	930	18	880	810	800	860
	a	657	1160	8	910	830	1020	
	b	106	710	17	820	820	720	
	c	689	1040	0	910	810	830	
	d	797	680	40	830	790	600	
Riebnesjaure		976	830	25	720	750	630	700
Överuman		652	790	4	1000	1070	870	1260
Kultsjön		1097	790	26	810	880	740	880
Torrön		1366	620	24	1120	1090	990	1080
Anjan		443	570	20	1160	1140	960	1100
	a	120	550	19	980	1060	900	
	b	322	580	21	1220	1170	980	
Kallsjön		1197	530	44	920	890	790	720
	a	156	620	31	1170	1110	920	
	b	247	490	56	900	850	750	
	c	793	530	43	870	860	770	
Liten		3126	700	36	860	790	710	690
	a	1563	820	21	930	840	740	
	b	821	610	49	850	780	750	
	c	33	660	46	790	760	600	
	d	709	540	56	710	700	620	
Håckren		1167	820	32	700	740	650	660
	a	730	900	25	710	740	670	
	b	436	670	44	700	740	620	
Storsjön		4782	450	54	650	650	630	410
	a	493	380	59	580	600	590	
	b	750	420	63	640	640	610	
	c	286	400	66	620	600	610	
	d	130	560	59	780	760	690	
	e	978	690	40	800	820	710	
	f	2145	370	55	580	570	600	

Estimation of Areal Precipitation for Test Basins

Sub-Catchment Precipitation

Daily values of precipitation were calculated for each sub-catchment for the period 19770901-19970831. For the test catchments the subjective and distance weighting methods generally gave considerably higher areal precipitation than the optimal interpolation method (Table 1). This was most pronounced in the high altitude sub-catchments furthest to the west, where the estimated mean annual precipitation in one case differed by as much as 80%. Exceptions were mainly sub-catchments at comparatively low altitudes in the south-eastern parts of the test region.

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

Evapotranspiration is difficult to estimate accurately, but in the test region it is a relatively small term in the water balance. Even if the accuracy is low, the error introduced into the equation will be minor. Rough estimates indicate that the lower limit should be 100-150 mm/year in the Northern and Western test basins and 250-300 mm in the Southern basins (Eriksson 1981; SNA 1995; Johansson 1999). The corresponding upper limit should be 200-250 mm and 350-400 mm respectively. These estimates allowed the determination of upper and lower limits for the ratio (Q+E)/P for the three precipitation alternatives (Table 2).

Ideally, the ratio should be equal to one, but in the estimation of areal precipitation no allowances were made for catch deficiency. The observation losses depend on station location and percentage of snow precipitation. For Swedish stations correction factors for annual precipitation are available (Eriksson 1983; Alexandersson, personal communication). Generalised to the test catchments they give correction factors between 1.15 and 1.3, with factors close to 1.15 for the southern catchments, and factors close to 1.3 for the seemingly most exposed areas, Sitasjaure and Kultsjön (Johansson 1999). Consequently, the computed ratio $(Q+E)/P$ should be in the range 1.15 to 1.3 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 1.15-1.3. Exceptions were Suorva where both values were well below 1.15 and Överuman were they were above 1.3. For the optimal interpolation even the minimum ratio values were often greater than 1.3, and it seemed that the optimal

Table 2 – The ratio of runoff plus evapotranspiration over precipitation for the period 19770901-19970831. Precipitation was estimated by three alternative methods, and an upper and lower limit for evapotranspiration was assumed.

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

interpolation method underestimated precipitation. For all methods, the ratio runoff plus evapotranspiration over precipitation varied considerably between catchments, *i.e.* no method described fully the spatial variation in precipitation as reflected by the variation in runoff.

Sensitivity to Network Changes

The sensitivity to network changes was tested by estimating the areal precipitation only from stations reporting in real-time. It meant a reduction in the number of stations by over 60% (Fig. 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. Daily values of sub-basin precipitation were estimated for the same period as with all stations, *i.e.* 19770901-19970831. 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.*

$$\frac{\sum_y |P_{y1} - P_{y2}|}{\sum_y P_{y1}} \qquad (7)$$

where

P_{y1} – sub-catchment annual precipitation (0901-0831) using all meteorological stations

P_{y2} – sub-catchment annual precipitation (0901-0831) using real-time stations only

The first criterion, the determination coefficient, had the highest values for the optimal interpolation method (Table 3). The subjective method gave a much lower agreement between daily values than the objective methods, but the other criterion, the mean difference in annual precipitation had the best value for the subjective method. As could be expected, the total amount of precipitation over a year agreed well. Overall, the optimal interpolation method seemed to be the least sensitive to changes in the meteorological network.

Table 3 – Comparison between catchment precipitation/temperature 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.

		subjective	inverse-distance	optimal
Precipitation	ρ^2	0.73	0.81	0.89
(27 sub-catchments)	mean difference (%)	5.8	14.2	6.1
Temperature	ρ^2	0.99	0.99	1.00
(8 sub-catchments)	mean difference (°C)	0.66	0.12	0.03

Estimates of Areal Temperature

As for precipitation, daily values of sub-catchment temperature were computed for the period 19770901-19970831, but as opposed to the precipitation estimates, the estimated temperatures generally differed very little for the three different methods. This was particularly true for the objective methods. This indicates that the estimated temperature is not sensitive to the selection of station weights. However, when excluding the stations not reporting in real-time, there was a clear difference between the methods. As there are much fewer temperature stations than precipitation stations and most of them report in real time, the effect of decreasing the number of temperature stations could only be investigated for 8 sub-catchments, but for these the optimal interpolation method performed best. The mean difference in annual temperature was 0.03°C between estimates based on all stations and estimates based on a reduced number of stations (Table 3). The results for the inverse-distance weighting method were not quite as good as for optimal interpolation, and they were considerably worse for the subjective weighting method, where the difference in annual temperature averaged 0.66°C (Table 3). 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.

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 previous tests, *i.e.* the coefficient of determination and the mean error in annual precipitation/temperature.

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 4). 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.

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 only slightly higher for the optimal interpolation method, and the difference in mean error was small with better values for the optimal interpolation method in 1993 and vice versa in 1994. No conclusion could be drawn on the superiority of one method to the other.

Table 4 – 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.

			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

Sensitivity Analysis

The weighting methods depend on parameters whose values may strongly affect the estimated precipitation and temperature. For the optimal interpolation method, an example of such a parameter is the covariance 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.

Precipitation – Optimal Interpolation

As described previously, the covariance function of the optimal interpolation method was divided into the correlation function and the standard deviation (Eq. (5)). Station standard deviation was determined by interpolation from the surrounding grid. The sensitivity of the standard deviation field was illustrated 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 5), particularly in the western parts.

The standard deviation field used in this investigation did not depend on the weather situation. If the normalised standard deviations for each station and year are plotted against interpolated values from the surrounding grid, the scatter plots differ considerably (Fig. 3). Considering the difference in total precipitation, it is likely that the two years were dominated by different weather systems. 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 5).

In previous investigations it was found that in the western parts of the test region

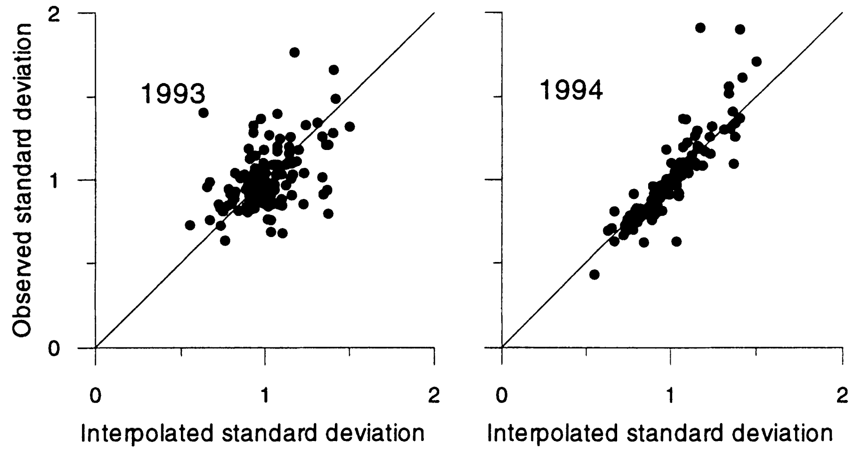

Fig. 3. Normalised observed standard deviation values for meteorological stations for 1993 and 1994 respectively, plotted against interpolated values from the surrounding grid cells.

Table 5 – 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.

			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

the correlation between stations was higher in the north-south direction then in the east-west direction (Johansson 1994b). A simple way to account for this was to multiply the east-west distance by two. Looking first at the sub-catchment precipitation, such a change in the covariance field had very little effect on the daily variation as reflected by the determination coefficient. In most Northern catchments there was however a slight difference in the annual precipitation, and the estimated values were as an average 5% 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 led to lower precipitation in, *e.g.*, Suorva. Verification against meteorological stations for the year 1993 gave no clear indication as to which correlation function was most correct, although the mean error for the western stations was lower for the alternative with doubled distance in the east-west direction (14.2% as compared to 18.1%).

Precipitation – Inverse Distance Weighting

For the inverse-distance weighting method, the linear increase in precipitation was initially 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, this led to a large increase in the estimated precipitation. For Suorva and Sitasjaure, the average increase was 40%. 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 dependency.

Sensitivity to 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 (Fig. 4).

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.

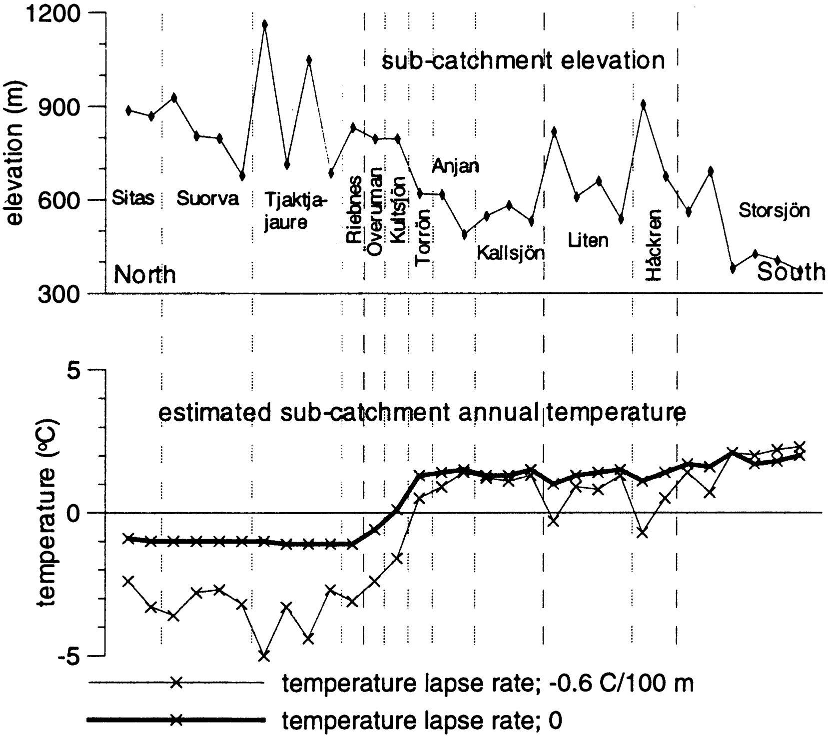

Fig. 4. Sub-catchment mean elevation (above) and mean temperature (below), with the sub-catchments ordered from North (left) to South (right). Temperature lapse rate set to 0.6°C/100 m and 0 respectively.

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. Simulations were made for the period 19770901-19970831, 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.

Verification Criteria

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

$$R^2 = 1 - \frac{\sum_t (qc(t) - qr(t))^2}{\sum_t (qr(t) - \overline{qr})^2} \qquad (8)$$

where

$qc(t)$ – simulated runoff
$qr(t)$ – recorded runoff
$\overline{qr}$ – mean recorded runoff

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 ($\overline{sferr}$)

$$\overline{sferr} = \frac{\sum_{y} |sferr(y)|}{\overline{sfvol}} \qquad (9)$$

where

$sferr(y)$ – volume error over the spring flood period (0401-0731) for each individual year
$\overline{sfvol}$ – mean spring flood runoff volume

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 6). 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 2,000 mm/year for some of the stations on the Norwegian side of the water divide. 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.

The previous water balance verification 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.

Simulations Based on Real-Time Data

Without re-calibrating the model, simulations were made using meteorological data only from stations available in real-time (Fig. 2). Generally, the degradation in the R^2 value and the volume error was greater for the inverse-distance weighting method than for the other two methods (Table 7). The optimal interpolation and subjective weighting method performed equally well.

Table 6 – Results of HBV model simulations with different estimates of areal precipitation and temperature 19770901-19970831. a) R^2-values for calibration and verification periods b) Mean springflood absolute volume error (percentage of total springflood runoff).

a) 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	

b) 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	

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. It was previously shown that if the determination coefficient for daily values was used as the criterion,

Table 7 – Results of HBV model simulations. Changes in verification criteria due to reduction of the number of stations. Average values for investigated catchments over the period 19770901-19970831. Simulations were made without recalibrating the model.

		subjective	inverse distance	opt. interpol.
precipitation	R^2	-0.04	-0.08	-0.03
(12 catchments)	volume error (%)	3.5	9.6	3.1
precipitation and temperature (3 catchments)	R^2	-0.21	-0.04	-0.03

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. This was also obvious in the model simulations (Table 7). The decrease in R^2-value for the subjective method and three investigated catchments was 0.21 as an average, as compared to a decrease of 0.09 when only precipitation data were affected.

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.* (2000). This was true in spite of the fact that the optimal interpolation method systematically underestimated total precipitation in several catchments. The inverse-distance weighting method was less reliable and can not be recommended.

None of the investigated methods described 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 replacement stations.

In the studied region much of the spatial variation of precipitation is explained by the topography. The elevation range is some 1,500 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.* (2000) 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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References

Bergström, S. (1976) Development and application of a conceptual runoff model for Scandinavian catchments, SMHI Reports Hydrology and Oceanography, No. 7, Norrköping, Sweden.

Blumer, F. P., and Lang, H. (1993) Altitudinal dependence of precipitation in the Eastern Swiss Alps. In: B. Sevruk an M. Lapin (eds.) Precipitation variability and climate change. Proc. International Symposium on Precipitation and Evaporation, Bratislava, Slovakia, Vol. 2, pp. 141-146. Department of Geography, Swiss Federal Institute of Technology, ETH Zürich, Switzerland.

Brandt, M., and Bergström, S. (1994) Integration of Field Data into Operational Snowmelt-Runoff Models, *Nordic Hydrology, Vol. 25*, pp. 101-112.

Creutin, J. D., and Obled, C. (1982) Objective Analyses and Mapping Techniques for Rainfall Fields: An Objective Comparison, *Water Resources Res., Vol. 18, (2)*, pp. 413-431.

Daley, R. (1991) *Atmospheric Data Analysis*, Cambridge University Press, ISBN 0-521-38215-7.

Daly, C., Neilson, R. P., and Phillips, D. L. (1994) A Statistical-Topographic Model for Mapping Climatological Precipitation over Mountainous Terrain, *J. Appl. Meteor., Vol. 33, (2)*, pp. 140-158.

Eriksson, B. (1981) The potential evapotranspiration in Sweden. (Den potentiella evapotranspirationen i Sverige, in Swedish.) SMHI RMK No. 28, Norrköping, Sweden.

Eriksson, B. (1983) Data on the precipitation climate of Sweden. Reference values for the period 1951-80. (Data rörande Sveriges nederbördsklimat. Normalvärden för perioden 1951-80, in Swedish.) SMHI Reports Mk 1983:28, Norrköping, Sweden.

Gandin, L. S. (1965) Objective Analysis of Meteorological Fields, Israel Program for Scientific Translations, Jerusalem, 242 pp.

Garen, D. C., Johnson, G. L., and Hanson, C. L. (1994) Mean areal precipitation for daily hydrologic modeling in mountainous regions, *Water Resources Bull., Vol. 30*, pp. 481-491.

Häggmark, L., Ivarsson, K-I., Gollvik, S., and Olofsson, P-O. (2000) Mesan, an operational mesoscale analysis system, *Tellus, Vol. 52A*, pp. 2-20.

Häggström, M., Lindström, G., Sandoval, L. A., and Vega, M.,E. (1988) Application of the HBV model to the upper Río Cauca Basin. SMHI Hydrology, No. 21, Norrköping, Sweden.

Johansson, B. (1994a) The relationship between catchment characteristics and the parameters of a conceptual runoff model – A study in the South of Sweden. Contribution to the Second International Conference of FRIEND, Oct. 1993 Braunschweig, IAHS Publication No. 221, pp. 475-482.

Johansson, B. (1994b) The use of spatially distributed input data in the HBV model. Nord. Hydr. Conf. in Tórshavn, 2-4 Aug. 1994, NHP report No. 34, pp.147-156.

Johansson, B., Edström, M., Losjö, K., and Bergström, S. (1998) Analysis and computation of snow melt. (Analys och beräkning av snösmältningsförlopp, in Swedish). SMHI Hydrology No. 75, Norrköping, Sweden.

Johansson, B. (1999) Precipitation and temperature in the HBV model. A comparison of interpolation methods. SMHI RH No. 15, Norrköping, Sweden.

Jutman, T. (1992) Production of a new runoff map for Sweden. Nordic Hydr. Conf. in Alta, 4-6 Aug. 1992. NHP report No. 30, pp. 643-651

Lindell, S. (1993) Real-time estimation of areal precipitation (Realtidsbestämning av arealnederbörd, in Swedish). SMHI Hydrology, No. 39, Norrköping, Sweden.

Lindkvist, L., Gustafsson, T., and Bogren, J. (1997) A frost assessment method for mountainous areas. In: Lindkvist, L: Investigation of local climate variability in a mountainous area. Publ. A22, Earth Sciences Centre, Göteborg University. ISSN 1400-3813.

Lindström, G. (1997) A Simple Automatic Calibration Routine for the HBV Model, *Nordic Hydrology, Vol. 28*, pp. 153-168.

Lindström, G., Johansson, B., Persson, M., Gardelin, M., and Bergström, S. (1997) Development and test of the distributed HBV-96 hydrological model, *J. Hydrol., Vol. 201*, pp. 272-288.

Matheron, G. (1971) The Theory of Regionalized Variables and Its Applications. Cahiers du Centre de Morphologie Mathematique, Ecole de Mine, Fontainebleau, France, 211 pp.

Motovilov, Y. G., Gottschalk, L., Engeland, K., and Rodhe, A. (1999) Validation of a distributed hydrological model against spatial observations, *Agricultural and Forest Meteorology, Vol. 98-99*, pp. 257-277.

Nash, J. E., and Sutcliffe, J. V. (1970) River flow forecasting through conceptual models. Part I – A discussion of principles, *J. Hydrol., Vol. 10*, pp. 282-290.

NWSRFS (1999) NWSRFS User's Manual, Release 59. National Weather Service, Hydrologic Research Laboratory, Maryland, USA.

Tabios, G. Q., and Salas, J. D. (1985) A Comparative Analysis of Techniques for Spatial Interpolation of Precipitation, *Water Resources Bull., Vol. 21, (3)*, pp. 365-380.

Thiessen, A. H. (1911) Precipitation averages for large areas, *Mon. Wea. Rev., Vol. 39*, pp. 1082-1084.

Saelthun, N. R., Aittoniemi, P., Bergström, S., Einarsson, K., Jóhannesson, T., Lindström, G., Ohlsson, P-E., Thomsen, T., Vehviläinden, B., and Aamodth, K. O. (1998) Climate change impacts on runoff and hydropower in the Nordic countries. Final report from the project "Climate Change and Energy Production". TemaNord 1998:552. Nordic Council of Ministers, Copenhagen.

SNA (1995) *Sweden's National Atlas: Climate, Lakes and Waters*, Eds: Raab, B. and Vedin, H., Bokförlaget Bra Böcker ISBN 91-7024-898-2.

Xu, C.-Y., and Vandewiele, G. L. (1992) Reliability of Calibration of a Conceptual Water Balance Model: The Humid Case. *Computational Methods in Water Resources IX. Volume 2*: Mathematical Modeling in Water Resources. Computational Mechanics Publications, Boston, MA. 773-780.

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