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Estimation of Extreme Precipitation in Norway

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Probable Maximum Precipitation (*PMP*) is an important parameter for estimation of Probable Maximum Flood. This paper describes results of *PMP* estimation by different methods, both meteorological and statistical. A survey of the highest recorded rainfall values in Norway is also presented.

Introduction

The traditional approach on flood estimation for dam design in Norway has been the use of empirical formulaes, based on enveloping curves. Regional estimates of flood values were calculated from specific flow and catchment parameters, but in recent years it became evident that the empirical formulaes gave non-consistent flood estimates (Sælthun and Andersen 1986). Accordingly, new regulations for dam design were made effective from 1 January 1981 (NVE 1986).

In the new regulations the *design inflow flood* (which is defined to have a return period $T \approx 1{,}000$ years) sets the standards for normal spillway operation, while the *Probable Maximum Flood* (*PMF*) sets the standards for dam safety (Sælthun and Andersen 1986). The design flood is usually determined by frequency analysis, while the *PMF* is calculated on the basis of probable maximum precipitation and snowmelt estimates. At the Norwegian Water Resources and Energy Administration (NVE) the use of rainfall estimates for calculation of *PMF* and design flood are based on an adaption of the Swedish HBV-model for rainfall/runoff (Bergström 1976).

This paper deals with the approach used by the Norwegian Meteorological Institute (DNMI) to provide the necessary meteorological information for flood-modelling. The main emphasis is on the estimation of an upper limit to the precipitation potential – *i.e.* the »Probable Maximum Precipitation«.

Probable Maximum Precipitation (PMP)

PMP is conceptually defined as »theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year« (Hansen *et al.* 1982). There are two principally different approaches of estimating the magnitude of *PMP* – either statistical or meteorological.

The meteorological (or »traditional«) approach consists essentially of moisture maximization and transposition of observed storms. Such storm transposition involves adjustment for elevation, moisture-inflow barriers and distance from the moisture source. These adjustments are founded on hypothetical storm models.

The statistical methods are based on estimation of values with very low probability, and are based on comprehensive series of observed rainfall values. Most of the statistical methods are rather easy to perform, but they are generally not considered as reliable as those obtained by the »traditional« approach (WMO 1986).

According to WMO (*op.cit.*) the current knowledge of storm mechanisms and their precipitation-producing efficiency is still not enough to permit precise evaluation of limiting values of extreme precipitation. *PMP* estimates, therefore must still be considered as approximations. Procedures for determining *PMP* – whether meteorological or statistical are admittedly inexcact and the results are estimates. Different, but equally valid approaches may yield slightly different estimates of *PMP*. There is no objective way of assessing the accuracy of the magnitude of *PMP* estimates derived by any known procedure. Since alternate decisions are possible at some steps in the *PMP* procedures, lower and upper limits to *PMP* can be estimated. In practice these limits are not determined, and only one set of values, or »best estimates« is usually derived.

One way to assess these uncertainties is to estimate *PMP* by different methods. This is done for some basins in Norway, and the methods and results are presented below. But it is very important to compare the estimated values with recorded values of heavy rainfall.

Table 1 – Greatest observed point rainfalls in Norway 1895-1988

Duration	Depth (mm)	Duration	Depth (mm)
1 min	4.3	6 hours	105.0
5 min	17.9	14 hours	142.2
10 min	31.5	1 day	229.6
30 min	60.0	2 days	378.9
60 min	64.9	3 days	402.4
90 min	100.0	10 days	594.0

Heavy Rainfalls in Norway

The first regular rainfall measurements in Norway dates back to about 1850, but until 1895 the network of stations was rather sparse. At most of the about 800 stations operating today, precipitation is measured just once a day (at 08 a.m.). However, the observers are instructed to report amount and duration of heavy rainfalls during the day. From 1967 rainfall in the summer season is recorded by automatic tipping bucket gauges at some stations, preferably in urban areas. Today this network comprises about 50 stations.

The maximum recorded precipitation values from both manual and automatic stations are outlined in Table 1. For durations up to 6 hours, the highest intensities are recorded in southeastern and southernmost parts of Norway – while most of the extreme values for durations exceeding 6 hours are recorded in Western Norway; in a zone 20-40 km east of the coastline. This area also is a maximum zone for average annual rainfall (*AAR*) in Norway, with values exceeding 3,000 mm/year at some stations.

The highest recorded 1-day amount was measured 26 November 1940 at Indre Matre in this maximum zone. (Actually the gauge was overtopped at this occasion, and consequently the real 1-day maximum value is somewhat higher than the official 229.6 mm). In this event strong southwesterly winds forced humid air towards the mountains in Western Norway, and the isohyetal pattern in Fig. 1 illustrates the resulting heavy orographic precipitation enhancement. The coastal islands (as Utsira and Ytre Solund) got about 15 mm, while stations in the maximum zone (as Indre Matre and Hovlandsdal) got more than 200 mm. East of the mountain range (as at Geilo) there was almost no precipitation at all in this event. The diagrams at the left hand side of Fig. 1 show that both the coastal and leeward stations had small precipitation amounts even before and after the 26 November – whereas Indre Matre recorded 379 mm in two days, 402 mm in three days and 487 mm in four days in the period 24-27 November 1940.

In the maximum zone for *AAR* along the coast from southeastern Norway and

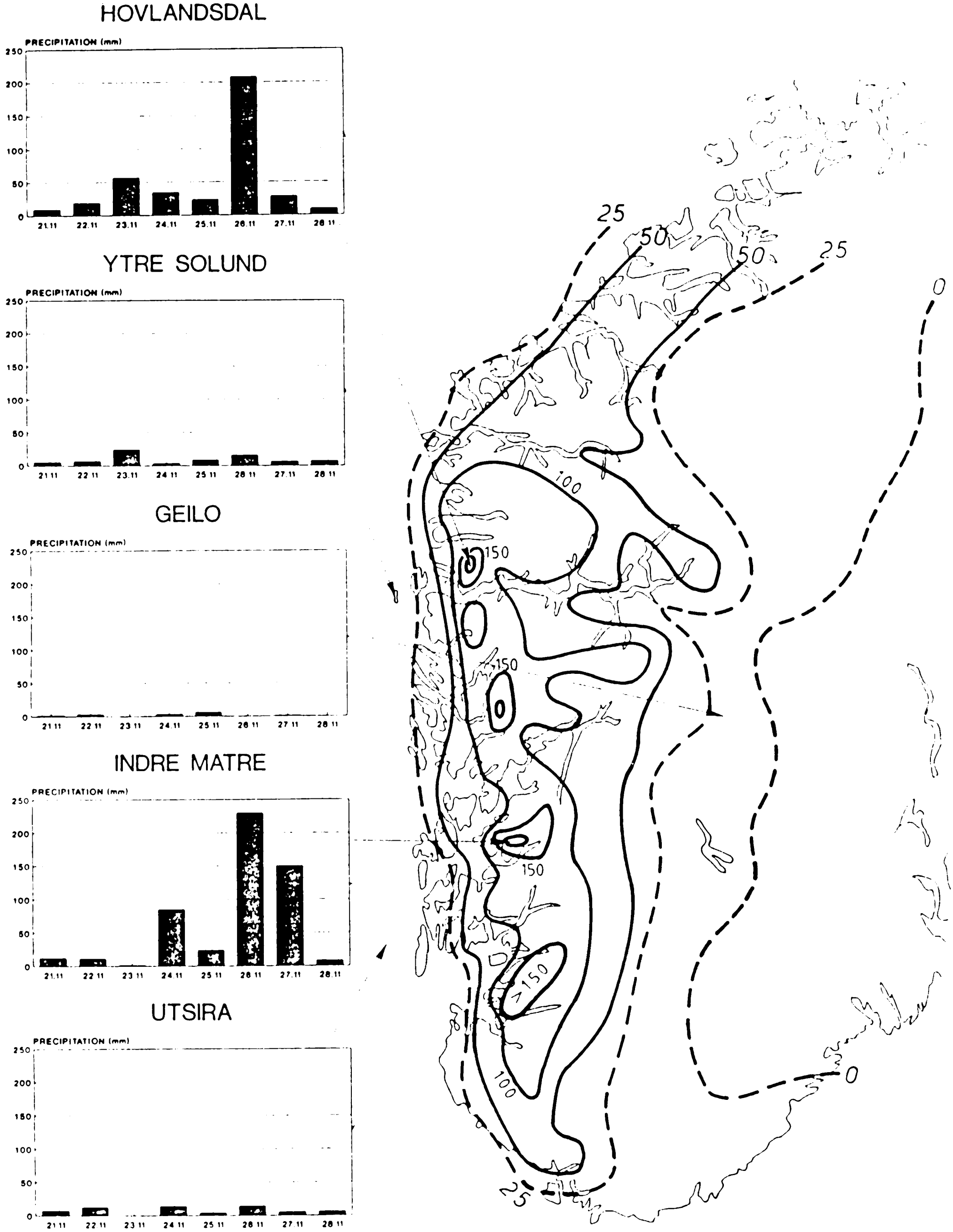

Fig. 1. 1-day precipitation (mm) in Western Norway, 26 November, 1940. Diagrams to the left illustrate daily rainfall amounts at 5 stations for the period 21-28 November, 1940.

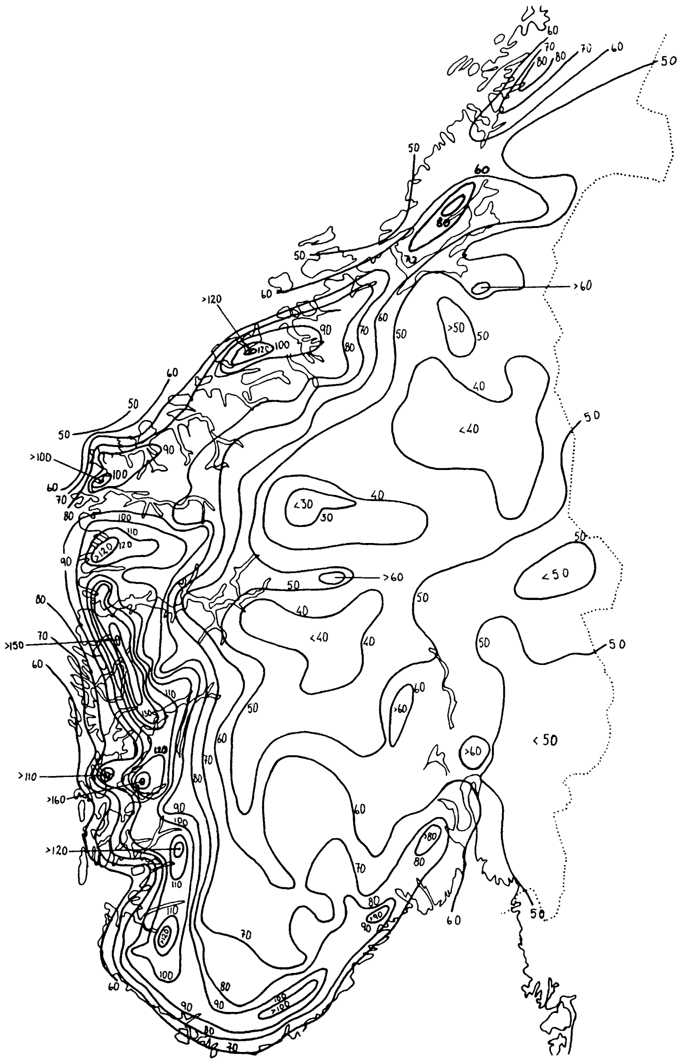

Fig. 2. Estimated 24-hour rainfall values (mm) with 5-year return period.

up to Lofoten (about 69 deg N), daily rainfall values exceeding 150 mm are not uncommon. In southeastern and eastern parts of Norway – together with areas north of 69° N, daily values above 100 mm are very rare. An interesting exception is Foldal (cf. Fig. 5), where more than 100 mm rain fell during 1.5 hours (daily total 126 mm) 28 May 1935. Thus this station got almost a third of its *AAR* during a few hours.

The distribution of estimated 24-hour precipitation with a return period of 5 years (*M5*) for Sourthern Norway is shown in Fig. 2. The map is based on Gumbel estimates from daily values for 366 stations, and covers the period 1895-1985. The daily (08-08) values are adjusted from fixed 1-day values to arbitrary 24-hour values by applying the factor 1.13 as recommended by WMO (1974, 1986). As for *AAR* there are strong regional gradients and large geographical variations in the *M*5-value. The *M*5-value varies from below 25 mm at Skjåk in the central parts, to more than 150 mm at some stations in Western Norway.

Due to the rugged terrain, the real isohyetal pattern probably is more complicated than shown in Figs. 1 and 2. As there are few rainfall stations in the mountain areas, it is very difficult to perform a detailed analysis of Depth-Area-Duration precipitation in Norway. The highly orographic influence also makes it difficult to »transpose« a precipitation pattern from one area to another, and to get sufficient data to apply the procedures of *PMP* estimation used in U.S.A. (NOAA 1988).

For estimation of extreme rainfalls in Norway, we therefore chose to primarily use statistical methods, based on measured point precipitation. After thorough evaluations it was concluded that a modified version of the statistical »Growth Factor Method« developed in Great Britain (NERC 1975; ICE 1981) seemed to give reasonable precipitation estimates even for Norwegian conditions.

Estimation of Extreme Precipitation by the »Growth-Factor-Method«

By the »Growth-Factor Method« a precipitation value *MT* with a return period *T* (years) may be approximated as a function of the value with a return period 5 years, *M*5

$$MT \sim M5\; e^{c\,[\ln(T-0.5)-1.5]} \qquad (1)$$

where the factor *c* is a function of the *M*5-value. For Norwegian 24-hour rainfall values, ($M5 \in \langle 25,200 \rangle$) the factor *c* may be approximated by

$$c \approx 0.3584 - 0.0473\,\ln(M5) \qquad (2)$$

The ratio *MT*/*M*5 is called the »growth factor«, and the growth factors for Scotland and N. Ireland (from NERC *op.cit.*) are reproduced in Fig. 3. The »estimated maximum« curve is assumed to represent the *PMP*-value, and is drawn as an envelope to maximum observed values for various durations based on a large dataset.

PMP values for Great Britain were also estimated by calculating the ratio between rainfall and precipitable water in representative air columns for major storms. All storms were then re-examined, and the observed rainfalls were maximized by the appropriate maximum storm efficiency ratio. According to NERC (1975), it was concluded that »there was broad agreement between the estimated maxima for different regions for 24 hours, and the corresponding estimated maxima from a consideration of the envelope of the growth curves«.

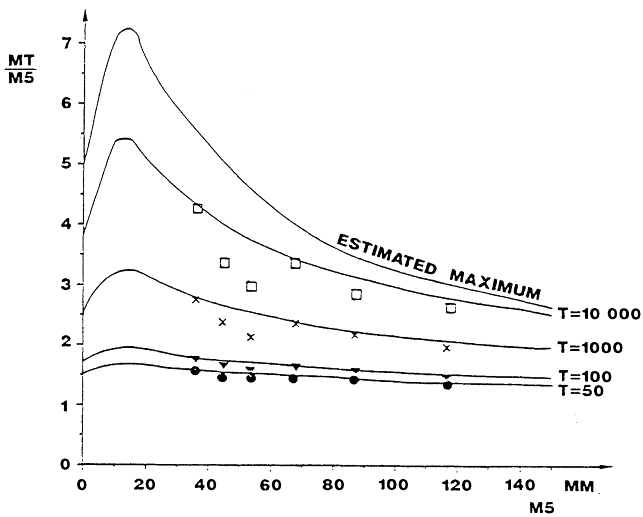

Fig. 3. Growth-Factors *MT*/*M*5 as a function of the *M*5-value. Solid curves are ratios from Scotland/Northern Ireland (NERC 1975), whereas the point values are corresponding Norwegian values for return periods (*T*) of 50 (●), 100 (▼), 1,000 (x) and 10,000 (□) years.

Frequency analyses of extreme Norwegian rainfall values were in good agreement with similar analyses for Scotland and N. Ireland (Førland 1987). This is not surprising as the precipitation regimes are quite the same in this part of Northern Europe. For further evaluation, estimates by Eqs. (1) and (2) based on daily values for 50 stations in the period 1895-1985, were compared to estimates based on the Gumbel distribution. For *M*100 the two methods gave quite similar results (Fig. 4a), whereas for *M*1000 the growth factor method for most stations gave estimates 0-30 mm (0-20%) higher than the Gumbel estimates (Fig. 4b). Considering the large uncertainties in estimates for such long return periods, and that other frequency distributions gave higher estimates than Gumbel, the *M*1000 estimates from the growth factor seemed to be reasonable.

In the standard procedures for estimation of extreme precipitation in Norway, seasonal *MT*-values are interpolated from maps showing the ratio between seasonal and yearly *M*5-values. Values for other durations than 24 hours are estimated by nomograms for *MT* (*n* hours)/*MT* (24 hours) as a function of *AAR*. Thus, when the *M*5 value is known, most of the necessary precipitation information for flood-modelling can be provided. Point values of *M*5 may be obtained from Fig. 2, or by maps of AAR and the ratio *M*5/*AAR*, where *AAR* is the average annual precipitation for the standard normal period 1931-1960.

While the real pattern of *M*5(24h) probably is more complicated than shown in Fig. 2, the isohyetal pattern of *AAR* is rather well known. The isolines for *M*5/*AAR*

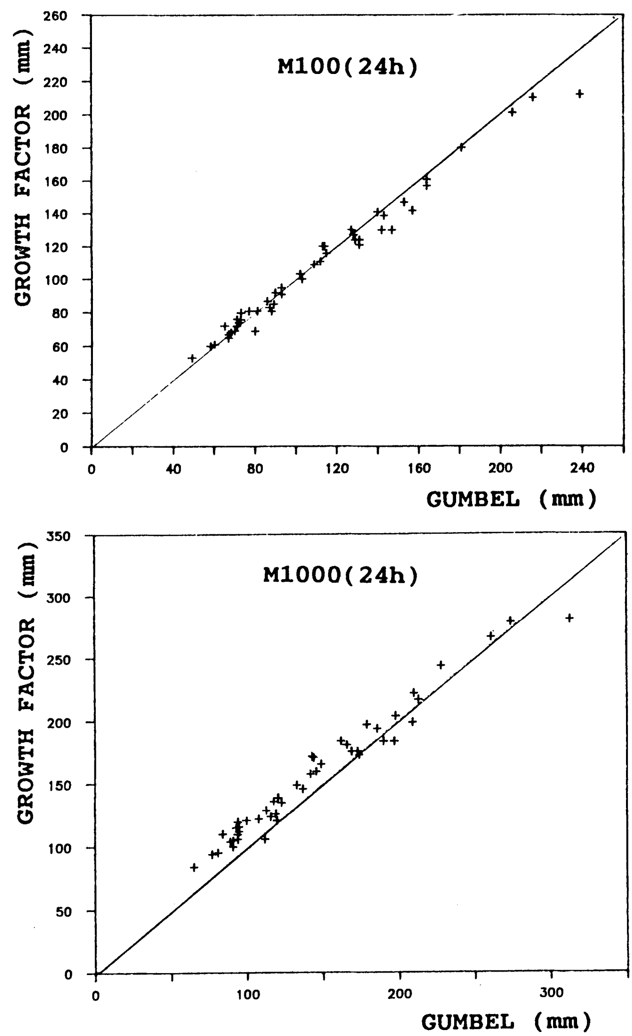

Fig. 4. Scatter diagram for »Growth-Factor« and Gumbel estimates for 24-hour rainfall with return periods: a) 100 years and b) 1,000 years.

show a much smoother pattern than the *M*5 map, – the strong gradients on the western coast almost vanish (Førland 1987). For most parts of Western Norway the *M*5(24h) value is 4-5 per cent of the normal annual rainfall, whereas in inland areas of Eastern Norway it is up to 10 per cent of *AAR*. This is in rather good accordance with the results from Great Britain (NERC *op.cit.*), where *M*5(24h)/*AAR* varies from about 4 per cent at the western coast of Scotland to about 8 per cent in eastern parts of England.

To get area values, the growth factor method is used in two different ways in

Norway. One approach, *M*I-I is to estimate *MT* and *PMP* values for a »representative point« in the basin, *i.e.* a fictive point with the same average annual precipitation as the basin average. For areas up to about 5,000 km^2, area values are then deduced by applying the british Area Reduction Factors for the appropriate durations and area sizes (NERC *op.cit.*).

An alternate method, *MI*-II is to calculate daily area rainfall values for the basin, by using weighted daily measurements from representative precipitation stations inside and close to the basin. The growth-factor method is then applied to this new set of daily area rainfall, and no area reduction is needed. For areas with representative precipitation stations, the estimates can easily be performed for specific seasons, specific durations etc.

Hershfield's Method

The statistical method of D. M. Hershfield (1965) has internationally been widely used. According to this method *PMP* is estimated as

$$PMP \sim \bar{P} + Km\ Sp \qquad (3)$$

where $\bar{P}$ is the mean value and *Sp* is the standard deviation of yearly maximum precipitation values (5 min – 24 hours) for a station. *Km* is a factor that depends on rainfall duration and varies inverse proportionally with the size of $\bar{P}$ (WMO 1986). For 24-hour rainfall, $\bar{P}$=50 mm corresponds to *Km*-value 17.5 whereas $\bar{P}$=100 mm corresponds to *Km*=15.0. Adjustments for outliers, sample size and conversion to arbitrary 24-hour values are built into the method.

The method estimates point values of *PMP* and consequently reduction factors must be applied to get area values of *PMP*. Area reduction curves and depth-duration curves preferably are based on data from the region where *PMP* values are to be estimated. According to WMO (*op.cit.*), Hershfield's method generally tends to give *lower PMP*-values than purely meteorological methods.

To use Hershfield's method for a basin, one needs long data series for a station having values of $\bar{P}$ and *Sp* typical for the basin. Due to orographic effects, it is impossible to find such »typical« stations in the mountain basins in Norway. Therefore a modified version is used in Norway. $\bar{P}$ and *Sp* in Eq. (3) are based on series of yearly maximum 1-day area precipitation for the basins, and thus no area reduction is applied.

Physical-Dynamic Estimation of PMP

This method is described in two WMO-reports (1973, 1986) and is based on maximization of the water content that theoretically can be released from the atmosphere. Given fundamental basin data, the first step is to search for events with large precipitation amounts in the basin. In this report we have aimed at estimation of 24-hour *PMP* values.

At most stations in Norway, precipitation is measured just once a day (at 06 or 07 GMT). For these stations, the highest observed precipitation for arbitrary 24-hour periods were deduced from 1- and 2-day amounts, by using the time distribution from automatic stations with continuous registrations or from synoptic stations with 2 or 4 measurements a day.

For each episode a 24-hour mean dewpoint temperature $TD1$ was found in the basin's inflow area for the 24-hour period with largest precipitation amounts. The monthly maximum observed dewpoints $TD2$ were taken from a data period of about 30 years. To avoid non-representative maximum dewpoints from fair-weather situations, we demanded a mean total cloud cover of 6-8 octas and 1 day precipitation exceeding 1 mm. All dewpoints were reduced to mean sea level.

$TD1$ and $TD2$ were converted to precipitable water $W1$ and $W2$ in a saturated pseudoadiabatic atmosphere between the ground and 300hPa. The observed 24-hour rainfall values $R24$ were multiplied by the ratio $W2/W1$ giving a 24-hour rainfall value Rm maximized for moisture only. This procedure was carried out for basins in three regions in Norway.

In addition wind maximization was carried out for basins with strong orographic effects. A 24-hour mean wind $V1$ was estimated in each episode based on the 4 main synoptic hours. Similarly monthly maximum 24-hour mean winds $V2$ for the same wind directions were calculated from 30 years of data. According to WMO (1986) an estimate of 24-hour *PMP* was achieved by multiplying Rm by the ratio $V2/V1$ giving a rainfall value Rmv maximized for both moisture and wind.

$$Rmv \equiv Rm \frac{V2}{V1} \equiv R24 \frac{W2}{W1} \frac{V2}{V1} \tag{4}$$

No transposition or smoothing was used when estimating *PMP* values. An exception was made for basin B2 in Eastern Norway where the rainfall pattern of one heavy episode in a neighbouring basin was transposed into B2. Transposition involves displacement of heavy rainfall events observed outside a specific region into that region adjusting for differences in area sizes and elevation. Because of the complicated orographic precipitation patterns in Norway, it is very dubious to transpose rainfall events.

24-hour PMP Estimates for some Basins in Norway

The physical-dynamic method and two statistical methods were used to estimate 24-hour *PMP* values for basins in 3 regions in Norway: A) Trøndelag, B) Vestlandet and C) Østlandet. The locations of the basins are shown in Fig. 5, and some key data concerning area size and precipitation conditions are presented in Table 2.

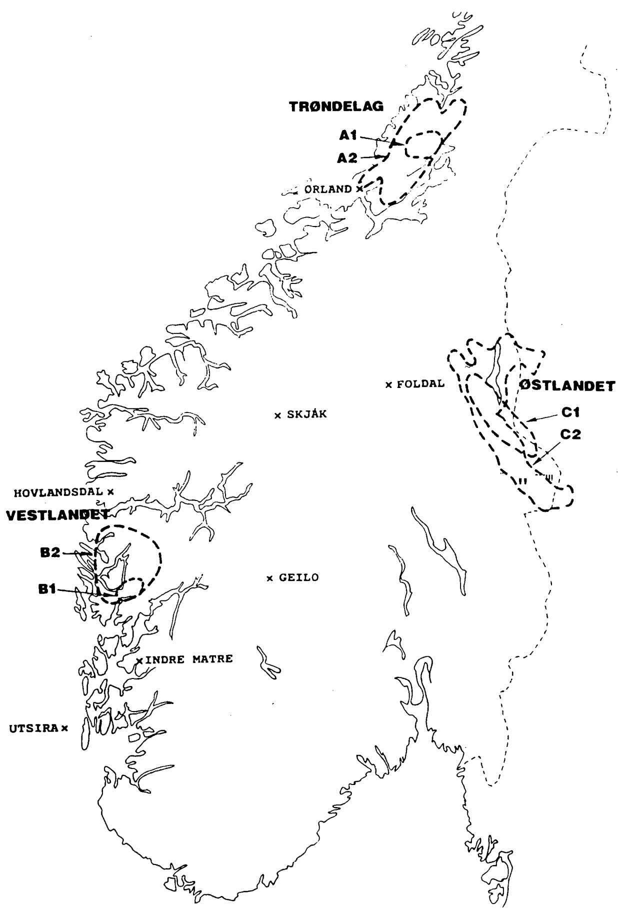

Fig. 5. Basins (A,B,C) where *PMP* is estimated. Locations mentioned in the text are also indicated.

Table 2 – Area size and precipitation for six basins in Norway

Region	Basin	Area (km^2)	*AAR* (mm/yr)	*R* 1d (mm)	*R* 2d (mm)	*R*24 (mm)
Trøndelag	A1	500	1,650	118	206	156
	A2	3,800	1,450	74	148	112
Vestlandet	B1	250	3,000	159	234	167
	B2	3,500	2,800	133	202	139
Østlandet	C1	2,000	640	70	99	76
	C2	5,250	680	50	90	70

AAR Average annual rainfall (1931-1960)

R 1d, *R* 2d, *R*24 Highest observed area rainfall during 1 day, 2 days and 24 hours

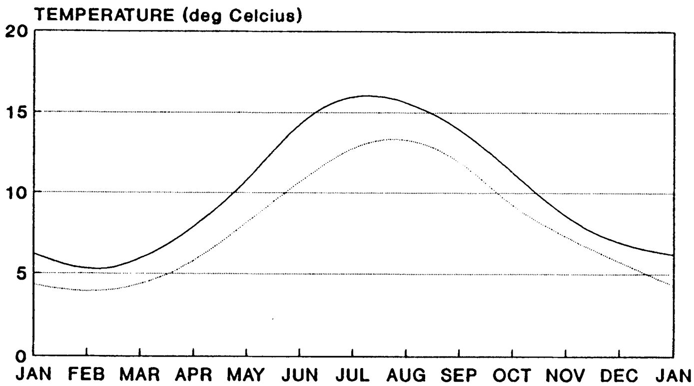

Fig. 6. Maximum 1-day dewpoints at sea level (1,000 hPa) for basin A1 (solid curve). Mean monthly sea temperature (dashed curve) for a lighthouse 60 km southwest of the basin is also indicated.

A) Trøndelag

PMP was estimated for two basins at the Fosen peninsula in Trøndelag; the minor basin Al (500 km^2) with an annual area rainfall of 1,650 mm and the major basin A2 (3,800 km^2) with *AAR* = 1,450 mm/yr (cf. Table 2).

Episodes of heavy precipitation from early 1920'ies until 1988 were investigated for the basins. Area rainfall values were calculated by Thiessen's polygon method. The highest observed 1 and 2-day values for both basins are presented in Table 2. The highest 24-hour rainfall values *R*24 were estimated to 156 mm for basin Al (October 1947) and 112 mm for basin A2 (same event).

Maximum area-dewpoints for basin A1 were deduced from the curve shown in Fig. 6. The figure also shows that for the period August-April, the maximum dewpoint estimates are 1-2°C higher than the mean sea temperature. A coarse wind maximization was based on data from the exposed site Ørland situated far southwest in basin A2. The specific wind data and other maximization data used for basin A1 are presented in Table 3. The table shows that for all the selected events with heavy rainfall, the wind direction was in the on-shore sector 230-270°, and the mean daily wind speed between 12 and 18 m/s. The highest *V*2-values (22 m/s) for this sector at Ørland occurs in December.

Maximization for moisture and wind yielded 254 mm as 24-hour *PMP* in basin A1 due to *R*24 of 156 mm multiplied by the moisture factor *W*2/*W*1 of 1.37 and windfactor *V*2/*V*/1 of 1.19.

The same maximization procedure lead to 176 mm as 24-hour *PMP* for basin A2 due to *R*24 of 112 mm, *W*2/*W*1 of 1.32 and *V*2/*V*1 of 1.31.

Hershfield's method gave area *PMP* estimates of 285 mm for basin A1 and 217 mm for basin A2 (Table 5).

Table 3 – Maximized 24-hour area rainfall for basin A1 in Trøndelag.

Date	*R*24 mm	*TD*1 °C	*TD*2 °C	*W*1 mm	*W*2 mm	*W*2/*W*1	*R*m mm	*V*1 dgm/s	*V*2 m/s	*V*2/*V*1	*Rmv* mm
21.10.47	156	7.2	10.5	14.3	19.6	1.37	214	2,416	19	1.19	254
26.11.83	130	2.8	7.3	9.6	14.5	1.51	196	2,517	21	1.24	243
29.09.32	109	8.6	12.6	16.5	24.8	1.50	164	2,513	17	1.31	214
07.10.71	97	8.8	12.0	16.7	23.6	1.41	137	2,414	19	1.36	186
09.01.81	78	1.2	6.5	8.1	13.7	1.69	132	2,714	19	1.36	179
04.12.62	86	5.1	6.9	12.7	13.9	1.09	94	2,512	22	1.83	173
28.01.32	114	5.0	6.0	12.6	13.6	1.08	123	2,514	19	1.36	167
31.10.83	85	4.9	9.5	12.4	17.8	1.44	122	2,514	19	1.36	166
01.03.75	66	0.8	5.2	8.2	12.8	1.56	103	2,712	19	1.58	163
18.09.78	73	6.9	13.5	13.8	26.6	1.93	141	2,616	17	1.06	149
25.03.53	124	5.7	6.4	13.3	13.7	1.03	127	2,518	19	1.06	135
09.01.57	89	5.0	6.5	12.6	13.7	1.09	97	2,315	19	1.27	123
20.09.66	67	8.4	13.4	16.3	26.3	1.61	108	2,515	17	1.13	122
04.12.81	81	5.6	6.9	13.2	13.9	1.05	85	2,617	22	1.29	110
26.03.82	74	5.1	6.4	12.7	13.7	1.08	80	2,516	19	1.19	95

*R*24 Highest observed 24-h area rainfall
*TD*1, *TD*2 Actual and maximum dewpoints reduced to mean sea level (1,000 hPa)
W1, W2 Precipitable water corresponding to *TD*1 and *TD*2
*V*1, *V*2 Actual and maximum 24h wind speed (for *V*1 the first two digits indicate representative wind direction in deca-degrees)
Rm, Rmv Estimated 24-h rainfall after maximization for moisture and wind speed respectively

By the *MI*-I method, the *M*5 values for a »representative point« in basin A1 is 85 and in basin A2 70 mm, and accordingly (cf. Fig. 3) the point *PMP* values are 305 and 280 mm respectively. The area reduction factors were *ARF* (24h, 500 km^2) = 0.91 and *ARF* (24h, 3,800 km^2) = 0.86. Thus the area *PMP* value is 278 mm for basin A1 and 241 mm for basin A2.

Based on daily area precipitation the *MI*-II method indicated *PMP* values of 277 mm for basin A1 and 247 mm for basin A2.

B) Vestlandet

PMP was estimated for two basins at Vestlandet; the minor basin B1 (250 km^2) with an annual area rainfall of 3,000 mm and the major basin B2 (3,500 km^2) with *AAR* = 2,800 mm/yr (cf. Table 2).

Episodes of 1-day rainfall exceeding 100 mm were maximized and area rainfall was calculated as for the Trøndelag basins. Based on data since 1940, the observed 24-hour peak values *R*24 were estimated to be 167 mm for basin B1 (August 1984) and 139 mm for basin B2 (same event).

Maximum area dewpoint and dewpoints for each episode were calculated for both basins. The highest rainfall estimates were found for the episode 26-28 September 1963, where the area $R24$ was 141 mm. The observed dewpoint was 7.2° C, while the maximum dewpoint for this time of the year was estimated to 15.5° C. This implies a moisture factor $W2/W1$ of 2.18, and accordingly $PMP \sim$ 308 mm. A crude wind maximization was done for this episode, based on wind data from a lighthouse west of the basins. A wind factor of 1.25 was found, – giving a »final« 24-hour *PMP* of 385 mm.

The maximization for basin B2 ended up with 261 mm as 24-hour *PMP* due to a $R24$ of 121 mm and a moisture factor of 2.16 based on the same rainfall episode as for basin B1. Using the same windfactor as for B1, the »final« *PMP* became 326 mm.

The *MI*-I method gave point *PMP* values of 360 and 354 mm for the two basins. By using appropriate *ARF* values, the area *PMP* values were estimated to 331 mm for basin B1 and 304 mm for basin B2.

C) Østlandet

24-hour *PMP* values were estimated for two basins around the river Trysilelva – basin C1 (2,000 km^2) with an annual area rainfall of 640 mm, and basin C2 (5,250 km^2) with AAR = 680 mm/yr (cf. Table 2).

Observed heavy precipitation episodes for the period 1949-1987 were examined and area rainfall values estimated. $R24$ peak values were calculated to 76 mm for basin C1 (September 1956) and 70 mm for basin C2 (same event).

The highest maximized values for basin C1 were obtained for the episode 6-8 September 1985, when the area rainfall $R24$ was 74 mm. The observed area dewpoint was 5.3° C, while the maximum dewpoint at this time of the year was estimated to 17.0° C. This corresponds to a moisture factor $W2/W1$ = 3.16, and accordingly a *PMP* of 234 mm.

For basin C2 the 24-hour *PMP* was estimated to 164 mm, due to a $R24$ of 70 mm, and a moisture factor of 2.34. These values were found for an episode in September 1956. Transposition of the precipitation pattern of September 7 1985 into basin B2 lead to an increased *PMP* value of 202 mm based on an $R24$ of 65 mm and a moisture factor of 3.11.

By the *M*I-I method the point *PMP* values were estimated to 234 and 235 mm for the two basins. The *ARF* values were 0.87 and 0.85, leading to area *PMP* estimates of 204 mm for basin C1 and 200 mm for basin C2.

The estimated 24-hour *PMP* values by the various methods are summarized in Table 5, and the table also includes point estimates ($\approx$ 10 km^2) for one location in each of the basins A1, B1 and C1. (The growth-factor methods *M*I-I and *M*I-II are identical for point estimates). Table 5 shows that the differences between the estimates by the two growth-factor methods are less than 10 per cent for all basins.

Table 4 – Mean, maximum and minimum values of some maximization ratios.

Basin	No.	(*R*24)/(*R* 1d)	*W*2/*W*1 Mean	Max	Min
A1	20	1.157	1.37	1.93	1.03
A2	"	"	1.40	1.89	1.03
B1	32	1.148	1.59	2.18	1.00
B2	"	"	1.52	2.16	1.10
C1	21	1.126	2.18	3.16	1.00
C2	"	"	2.01	3.11	1.07

No. Number of heavy rainfall episodes studied in each region
(*R*24)/(*R*1 d) Ratio between 24h and 1-day precipitation
*W*2/*W*1 Ratio between maximum (*W*2) and actual (*W*1) amount of precipitable water

Table 5 – 24-hour *PMP* estimates by different methods.

Basin	Area (km²)	Estimated 24-hour *PMP* values (mm) *TM*-I	*TM*-II	*HER*	*MI*-I	*MI*-II	Max obs	Max *MI*-II
A0	10	–	–	398	329	(329)	184	0.56
A1	500	214	254^A	285	278	277	156	0.56
A2	3800	148	176^A	217	241	247	112	0.45
B0	10	340	385^A	448	384	(384)	207	0.54
B1	250	308	385^A	352	331	341	167	0.49
B2	3500	261	326^A	297	304	324	139	0.43
C0	10	399	–	229	222	(222)	117	0.53
C1	2000	234	–	181	204	199	76	0.38
C2	5250	164	202^B	151	202	184	70	0.38

TM-I »Traditional method« with moisture maximization only
TM-II »Traditional method« including A) wind maximization or B) transposition
HER Hershfield's method based on daily area rainfall
MI-I Modified growth factor method: Point estimate and area reduction
MI-II Growth factor method applied on daily area rainfall values
Max obs Highest observed area rainfall (mainly based on the period 1957-1988)
Max/*MI*-II Ratio between highest observed value and *PMP* estimated by the *MI*-II method

This indicates that the schematic area-reduction factors from Britain (NERC 1975) used in the *MI*-I method are quite reasonable also for rainfall conditions in Norway.

The estimates by the modified Hershfield method are higher than the *MI*-II estimates for small basins – smaller for the basins larger than 1,000 km². The main reason for this is that the standard deviation *Sp* in Eq. (3) decreases when the maximum value $\bar{P}$ is based on area rainfall from increasing number of stations.

The »traditional method« (*TM*-I, *TM*-II) yields larger values than the statistical methods for the basins at Vestlandet and Østlandet, and lower for the Trøndelag basins. For four of the basins the *TM*-II estimates are within ± 10 per cent of the *MI*-II estimate. The largest difference occurs for the point estimate for basin C0. It seems quite unreasonable that this location should have a higher 24-hour *PMP* value than the orographic parts of Vestlandet, and 399 mm in this region is almost four times as high as the highest observed value. For basin A2 in Trøndelag the *TM*-II value is about 30 per cent lower than the *MI*-II estimate. Compared to observed values in this region a 24-hour *PMP* value of 176 mm for basin A2 seems too low. For this area transposition from neighbouring areas should be performed to check the estimated value.

Both the mean and maximum values of the moisture maximization ratio *W2/W1* (Table 4) were lowest for the Trøndelag basins and highest for the inland basins at Østlandet. The maximum ratio for any of the selected events was about 2 in both Trøndelag and Vestlandet, whereas it at Østlandet exceeded 3 in some cases (*i.e.* the maximized value is 3 times as high as the observed value). It is also interesting to note that the minimum values in all basins are equal to or slightly above 1.0, indicating that the precipitable water in some events were quite close to the estimated maximum values.

It is important to note that both the 1-day Hershfield, *M*I-I and *MI*-II estimates above are multiplied by a factor of 1.13 to give 24-hour estimates. This is done according to WMO (1986) who recommends that the *PMP* values yielded by statistical procedures should be multiplied by 1.13 if data for single fixed time intervals are used in compiling annual series. Table 4 shows that for the heavy rainfall episodes in the Norwegian basins, the mean value of this ratio is 1.16 in Trøndelag, 1.15 at Vestlandet and 1.13 at Østlandet - *i.e.* quite close to the factor recommended by WMO.

Comparison of Estimated and Observed Values

The highest observed values for the basins are presented in Table 5. This survey is not complete, as area rainfall is not calculated on a regular basis. Compared to the *MI*-II method, the highest observed point values are about 55 per cent of the *PMP* value, whereas the highest observed area values in basin C1 and C2 are below 40 per cent of the *PMP* value.

An investigation of the highest observed 1-day point values for Norway (Førland and Kristoffersen 1988) showed that the highest ratios between observed point values and the growth factor *PMP* were about 70 per cent. The ratio exceeded 60 per cent at 11 stations, and 50 per cent at 37 stations. Most of the stations with ratios above 50 per cent were situated in the orographic influenced areas in Western Norway.

For the US west of the Continental Divide (an area about 7 times as large as Norway) Riedel and Schreiner (1980) found 8 locations where the observed 24-

hour point value exceeded 70 per cent of the *PMP* value, and 23 locations where the ratio was higher than 60 per cent. The highest ratio in this region was 86 per cent, and as in Norway most of the locations with high ratios were situated in areas with orographic precipitation. Thus both the order of magnitude and the geographic situation of the locations with high ratios are in good agreement with the results from U.S.A.

Riedel and Schreiner (*op.cit.*) also studied the ratios of 24-hour *PMP* to 100 year rainfall (*M*100) for point estimates. For the US west of the Continental Divide this ratio is about 2.0 in areas with orographic influences (*e.g.* Sierra slopes), and up to 4-5 at locations where heavy rainfalls are infrequent because of sheltering or long distance from moisture sources. By the growth-factor method these ratios in Norway varies from about 2.0 in western orographic influenced areas, to 3-4 in the driest areas in sheltered valleys in central Norway. Considering that the highest ratios in the US are found in areas significantly more sheltered than any Norwegian valley, it seems as if even the ratios *PMP*/*M*100 are in good accordance with the results from U.S.A.

Discussion

As stated above it is not possible today to make a precise evaluation of the upper limits of extreme precipitation. The problems are especially serious in areas with large orographic influences and low station density, as in the mountain areas in Norway.

The *PMP* estimates by the »traditional method« (*TM*-II in Table 5) are not necessarily final *PMP* values, as some simplifications are made in the calculations, and no smoothing (based on estimates for different area sizes, durations, geographic locations etc.) has been carried out. But for most basins the *TM*-II value probably is quite close to the final »traditional method estimate«. The main stage not performed in detail in Norway is transposition. As a dominating part of the heavy rainfalls in large parts of Norway is caused by orographic influences (cf. Fig. 1), it seems dubious to reduce heavy rainfall patterns for orographic influences, transpose the small remaining non-orographic pattern to the actual basin, and then scale it up to appropriate orography. In addition the »traditional method« has some weaknesses for Norwegian weather conditions, *e.g.*:

- How realistic is it to assume that the surface dewpoint temperature does give a representative estimate of the precipitable water in the atmosphere. (For instance the highest moisture maximization factors *W*2/*W*1 for Østlandet were found for weather situations with cold air in the surface layer, and warmer air aloft. Thus the *W*1 value based on dewpoint *TD*1 probably is too low, and accordingly the maximization factor too high). Preferably the estimates of pre-

cipitable water based on surface dewpoints should be compared to values from uper-air-soundings, satellite images etc. for some selected events.
- To ensure that the maximum dewpoints are representative, they should be based on comprehensive data series, and be constricted to specific trajectory sectors and heavy rainfall episodes.
- The moisture maximization factor *W*2/*W*1 assumes that the rainfall rate varies linearly with the »precipitable water«. In orographic areas the »seeder-feeder« process plays an important role for the rainfall enhancement, and the effect of this process is not necessarily just dependent on the *W*2/*W*1 ratio.

The statistical methods are simple to perform, but probably oversimplifies the nature! For the growth-factor method, there are some doubts concerning some assumptions, *e.g.*:

- Are the growth factors based on independent data, if not, what are the consequences of this dependency on the growth factors.
- Should the *ARF* values be the same for all return periods and for all kinds of precipitation (showers, frontal or orographic rainfall)
- Is it consistent with the *PMP* concept that the enveloping growth factors assumed to represent *PMP* can be assigned to definite return periods (~ 30,000 years). The *PMP* value should by definition have an indefinite return period.

The good agreement between the *MI*-I and *MI*-II estimates, may indicate that the area reduction factor used in the *MI*-I method is quite representative. However it is not obvious that the NERC growth factors for point estimates without reservations may be used for area estimates as in the *MI*-II method. This will be further evaluated in future investigations.

Conclusions

According to WMO (1986) different but equally valid approaches may yield slightly different estimates of *PMP*. For some basins in Norway Table 5 demonstrates that the different methods yield more than »slightly different« estimates. All existing methods for estimation of *PMP* are connected to rather large uncertainties, and the estimates must be considered as approximations. By using different methods it may be possible to assess the uncertainties in the *PMP* estimates.

For Norwegian conditions a modified version of the British growth-factor method is preferred. Although the maximizing procedure differs from those usually accepted (WMO 1986), the uncertainties in estimating *PMP* in Norway are so great that this method may be regarded as least as valid as any other. In addition it is quite easy to perform and may be used for both areas with representative rainfall stations (*MI*-II) and for areas without rainfall observations (*MI*-I). In the last case the rather wellknown *AAR* pattern is one of the input parameters. For areas with uncertain *AAR* values average annual runoff may be used to assess the *AAR* value.

The *MI*-I and *MI*-II methods yield values for various return periods, various area sizes, various durations, specified seasons, and also ensures regional consistency as well as internal consistency between *M*5, *M*100, *M*1000 etc. and the *PMP* value.

For critical hydrologic regulations, the *PMP* value should be estimated by more than one method, and preferably by both statistical and meteorological methods.

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