



Rainfall Floods and Weather Patterns

Lars Andreas Roald

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Abstract: The link between intensive rainfall, floods and weather is examined. The study is a contribution to the EBL-project: MKU 1: Klimaprediktabilitet på skala fra 0 til 100 år

Key words: Daily rainfall, floods, weather indices, storm trajectories, climate change

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Preface

NVE-Hydrology Department and the Norwegian Meteorological Institute have examined past variability of temperature, precipitation and runoff in Norway, and have developed scenarios for future runoff and other water balance elements in Norway in a series of projects commissioned by the Norwegian Electricity Industry Association (EBL). The current report is one of several project reports of the project MKU-1: "Klimaprediktabilitet på skala fra 0 til 100 år - Konsekvenser for snømagasin tilsig, flom, tørke og energiproduksjon." The current study examines the link between rainfall floods and weather patterns. The climate scenarios indicate some changes in the large scale circulation over Europe which will affect the flood regime of Norway.



Oslo, November 2008

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Summary

The distribution of rainfall and floods in Norway is strongly dependent on the direction of moving frontal systems because of the Norwegian topography. This is linked to the large scale atmospheric circulation. The two global climate models used in the studies of changes in streamflow in Norway produce different dominant airflow directions over Norway. The projected changes in precipitation and streamflow differ therefore regionally considerably. The projections of future rainfall intensities are also highly uncertain, partly because of the coarse scale of the models so far used. A better understanding of the processes underlying large flood events in the past is important for making better projections of floods in the future.

Around 1000 heavy precipitation events have been identified between 1895 and 2004 based on daily precipitation data observed by the Norwegian Meteorological Institute (met.no). The precipitation events are caused by different meteorological weather types. The study have examined the weather types causing the large precipitation events in different parts of Norway based on large scale circulation indices such as Grosswetterlagen or the Lamb-Jenkinson daily indices. The dominant weather types causing rainfall floods differ from region to region in Norway. The rainfall events have been compared to daily streamflow data from the national hydrological network operated by NVE. Around 300 rainfall flood events have been identified and form the basis for the results in this report.

The largest precipitation events occur in the late autumn or early winter in basins along the west coast at a time when part of the precipitation falls as snow. This results in many cases in only moderate floods even if the daily precipitation is high. The highest rainfall events occur in the second part of the summer and autumn in inland basins. The climate scenarios indicate a raise in the temperature, which will result in higher transition level of the precipitation from snow to rain. This will result in more intensive winter rainfall floods in the parts of Norway where the rainfall is highest.

Most precipitation events are caused by extratropical storms from the Atlantic. Several of the most severe events are caused by transport of warm and moist air from sub-tropical or tropical parts of the North Atlantic. This air mass merges usually with extratropical storms. The core of these lows can contain remnants of tropical cyclones, and several large rainfall events have been caused by such systems recently. The occurrence of tropical storms affecting Norway have been examined based on reanalysed storm trajectories from 1851 to 2007.

1 Introduction

Norway is located on the western side of the Scandinavian Peninsula, and is exposed to weather systems from the Atlantic Ocean and Norwegian Sea along the west coast. Mountain ranges in parallel with the coast forces the moist maritime air masses upwards causing heavy rainfall on the western side of the water divide. The lee side of the water divide falls within a rain shadow. The eastern part of southern Norway is exposed to weather systems from in a sector from southwest to east. Tveito and Roald (2005) have shown the strong dependency of the precipitation distribution on the atmospheric circulation for South Norway.

Floods in Norway are caused by snowmelt and/or rainfall. The magnitude of a flood is strongly dependent on initial conditions in the upstream basin. Many intensive rainfall events have not caused severe flooding because of unfavourable initial conditions. Large snowmelt floods are usually caused by a combination of melting and rainfall, and snowmelt alone can cause large floods in inner Finnmark. The snowmelt floods are dependent both on the size of the snow pack, which have accumulated through the winter, and the melting conditions during the flood. These floods cannot be linked to specific weather types, as they depend on the shifting weather conditions throughout much of the winter months.

Rainfall floods is either caused by long duration rainfall, linked to a persistent weather pattern which may last for weeks or even months as in the autumn 2000 or by locally high intensive rainfall events. The latter is caused by local convective storms, which often is of too small scale to be indicated by the large scale circulation pattern. There is nevertheless a strong connection between the weather type and the occurrence of high rainfall and rainfall floods, which differs regionally over Norway. The link between rainfall floods and circulation types is explored in this report. The study utilises observed daily rainfall series as well as observed historical floods. The weather patterns are based on daily indices describing the synoptic situation over Central and North Europe.

The current study discusses the connection based on historical information. One important issue given the projected climate change is whether the flood regime in Norway will change towards more damaging floods. The climate scenarios are based on quite coarse spatial resolution both in the global and the regional models. The scale of these models is too coarse to describe local convective rainstorms, which can pose the greatest hazards to human lives in the steep Norwegian terrain. An improved understanding of the link between the large scale weather types and the occurrence of floods will help making better projections of changes in the flood regime in the future.

The link between weather types and extremes has been explored by many authors. Lamb (1982) has linked climate to natural disasters and historical events world wide, and has described historical storms in the North Sea since 1588 (Lamb, 1991). Pfister (1999) has described climate variability in Central Europe over 500 years and has linked climatic extremes and floods to the circulation type. Glaser (2001) has a similar description of climate variability over the last 1000 years with focus on Germany. ZAMG has published a list of extreme events and disasters from 1111 to 2003 (www.zamg.ac.at) in Austria. Fagan (2000a,b) links climate to historical events. Jonsdottir and Uvo (2006) have studied

the long term variability in Icelandic hydrological data series in relation to the atmospheric circulation.

2 Time series data

2.1 Rainfall data

The Norwegian Meteorological Institute (met.no) was organised in Dec. 1866. Daily rainfall observations were made at a few stations since 1867. A countrywide net was established in 1895 to serve the infant hydropower industry with data necessary for planning the coming utilisation of Norway's large potential for electricity production. The Hydrology Department was organised at the same time, taking over the operation of the national hydrometric network.

Daily rainfall data at selected stations have been published annually since 1895-1976 in the series: "Nedbøriakttagelser i Norge" by met.no. The observations were made at 8 hrs every morning. The data was noted on the date most of the precipitation fell e.g. the day before the actual rain fell until 1915. The practice was then changed to note the value on the same day as the observation was made. The stations were gradually equipped with screens, reducing the wind loss, and thus creating a break in the homogeneity of the data series.

Daily rainfall data are available on digital form from 1957. Older series have been digitized by NVE for approx. 70 stations with long term records for the period from 1895 or later to 1956. The precipitation type e.g. rain, hail, sleet or snow was also coded together with the amount of precipitation.

2.2 Flood data

The knowledge of past floods in Norway extends back to the 1340's for some extreme events, but more detailed overview in some of the larger rivers goes back to the end of the 17th Century. The flood level is known at a few sites for large floods from 1675 and has been transferred into a number of flood stones as shown in Figure 2.1.

The water level at Minne at the outlet of Lake Mjøsa was observed once a day systematically 1824-1827. The observations were taken up again at a number of sites from 1846 to examine the feasibility of developing canals for shipping to inland towns near some of the main lakes in East Norway. The current meter was introduced in Norway in the late 1850's. Rating curves were established at several stations later in the 19th Century based on simultaneous measurements of stage and discharge. The discharge is estimated using rating curves and observed water levels.

The stability of the hydraulic control is important for the quality of the flood data. Where the control is shifting, usually because of sedimentation or erosion in the controlling section, new rating curves are established from the time after the shift. Discharge measurements are often missing at the highest floods. The discharge of these floods is

estimated from the extrapolated part of the rating curve which introduces extra uncertainty in the flood values.



Figure 2.1 Flood monuments at Elverum (left), Losna (centre) and Fagernes (right). The large difference between 1789 and 1860 is probably caused by downstream damming in 1789 caused by landslides.

The Hydrology Department was organised in 1895, simultaneously with the extension of the network of precipitation stations. Daily water levels were published in the annual series: “Vannstander i Norge” 1895-1977. The entire set of daily water levels were digitised in the late 1960’s and form the core of the Norwegian national hydrological database Hydra II operated by the Hydrology Department of NVE (Taksdal, 1999). The stations were gradually equipped with chart recorders, making it feasible to extract data with high time resolution. These charts have been digitised since 1984/85 to obtain peak flow data in addition to the once a day values. Charts prior to 1984/85 will now be digitised to obtain longer peak flow series. The chart recorders have now been replaced with digital recorders which provide the forecaster real time data from a substantial part of the station network.

NVE is now setting up a database with information of past floods, which will continuously be updated as new floods occur. The database is organised around the concept “Flood event”. A flood event is characterised by its location, date and the underlying processes causing the flood. The database does not include all minor floods, but only events which are above certain thresholds or has caused substantial damage. The database will include more than the maximum flood in a year if there are several large floods within a year compared to the entire record. It is possible to divide a long duration or geographically widespread event into sub-events. The severity of a flood event is classified into four classes: “Flood”, “Large flood”, “Severe flood” and “Extreme flood”. Since the database includes floods prior to the instrumental period, this classification has to rely on partly subjective criteria. The database has information of the initial conditions prior to the flood as well as information of the causes of the main event. The database comprises also information about references to the sources of the information and flood damage, and is linked to a Photo database. The main used access to the data base will be based on maps.

A total of some 700 historical flood events have been identified and loaded to the database from the 1340's to 2006. Figure 2.2 show the number of flood events per 5-year time slices from 1896 to 2005, the period analysed in this study. The total number and the number of severe events are both shown in the Figure. Note the large surplus of flood events in the 1930's and since 1996. Figure 2.3 show the number of events where snowmelt was an important if not the only cause of the flood, and the number of rainfall events. Snowmelt floods are present in almost every year, but the flood magnitude is often too low to qualify for a flood even of the lowest severity class. One event covers usually large areas, and independent events will therefore be few. Rainfall floods are more local, and independent events will therefore be more frequent as seen from the Figure. The time slices with most frequent rainfall floods are 1936 to 1940 and 2001 to 2005. The more severe of these rainfall floods occurred actually all through the 1930's and from 1987 to 2006 both generally warm periods.

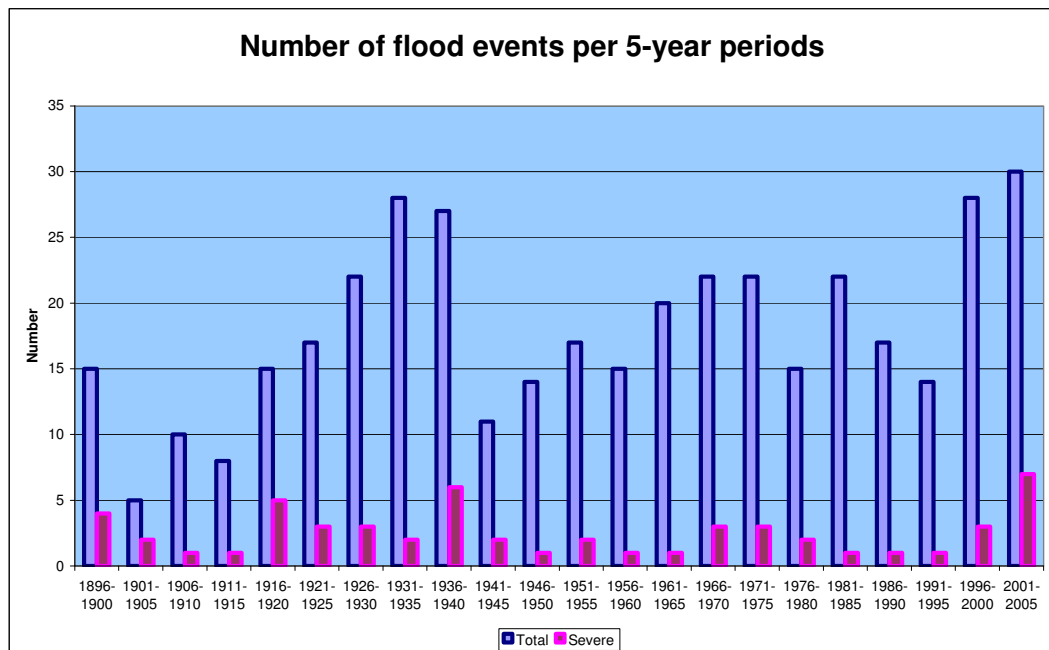


Figure 2.2 Number of flood events per 5-year period 1996-2005. The figure shows both the total number (blue columns) and the number of severe events (red columns).

The duration of a rainfall induced flood peak varies is strongly dependent on the basin size and properties as well as the duration and variability of the rainfall event. A useful measure to compare flood magnitude in different basins is the specific discharge e.g. the discharge divided by the basin area. The magnitude is still dependent on the basin area as well as on other basin properties such as the percentage of impervious surfaces, the occurrence of lakes and the steepness of the terrain. Table 2.1 gives typical specific flood magnitudes for a number of basins of different size and properties.

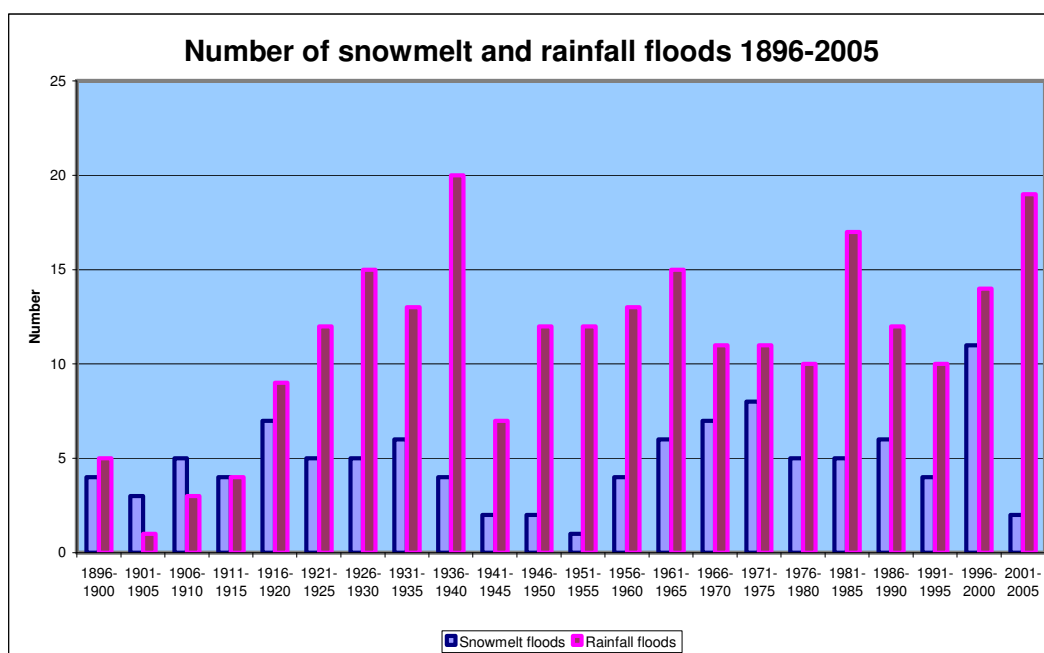


Figure 2.3 Number of snowmelt (blue) and rainfall (red) floods per 5-year time slices 1896-2005.

Table 2.1 Typical specific flood values in some Norwegian basins.

River	Station	Basin area (km ²)	Flood magnitude (l/s km ²)
Glomma	Sarpsfoss	41500	<100
Drammenselv	Døvikfoss	16020	133
Skien selv	Norsjø	10203	259
Numedalslågen	Labru	4245	302
Gaula	Haga bru	3000	1000
Coastal basins	West Norway	100-300	2500-3000
Sandvikselva	Bjørnegårdssvingen	193	525
Akerselva	Gryta	7,63	769
Tovdalselv	Tveitdalen	0,41	3372

The large basins have usually many large lakes which attenuates a flood. A flood will usually affect only a part of the larger basins which explains why the typical flood magnitudes are low. The 3000 km² Gaula basin has no upstream lakes or reservoirs which reduces the flood. The small Tveitdalen basin is near the south coast. This basin is rural, but has very high specific floods because of the size.

The highest specific discharge observed in Norway was observed in Oslo in 1975 during a short duration rainstorm, as shown in Figure 2.4. The specific discharge at the peak was 10020 l/s km². The basin area was only 0,099 km² with 97 % impervious surfaces. Figure 2.5 show the specific discharge of the Vestli semi-urban basin of 0,384 km² with 30% impervious surfaces. The amount of impervious surfaces is less in this basin.

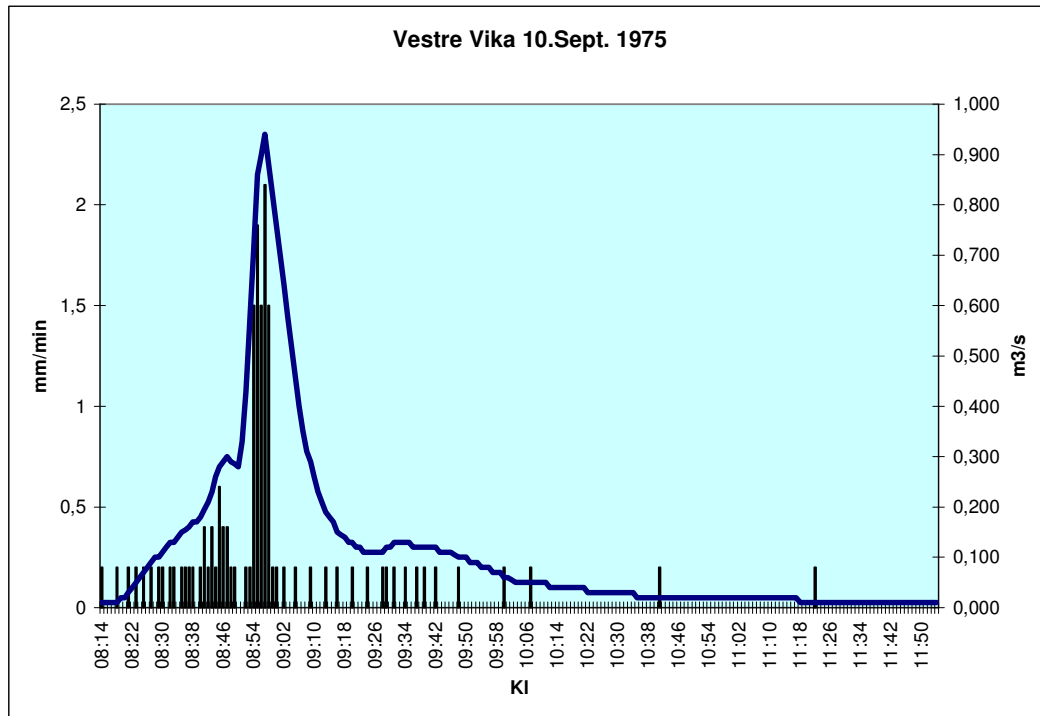


Figure 2.4 Observed discharge and precipitation in the Vestre Vika basin in Oslo during a rainstorm in 1975. The observed specific discharge of 10020 l/s km² is the highest observed in Norway.

These examples show the importance of observing floods and rainfall with high time resolution to observe the flood peak in smaller and medium sized basins. The shift from observing floods once a day more frequently causes a break in the homogeneity of the long term flood series. This is a particular problem in basins less than 100 km² and even worse in urbanised basins. Figure 2.6 show the dependency on the logging interval for the two urban flood events in Oslo shown in Figure 2.4 and 2.5. Figure 2.6 show that hourly monitoring is sufficient in this example at Vestli, where as even a five minute logging interval could lose 20 % of the peak value at the extremely urbanised Vestre Vika basin.

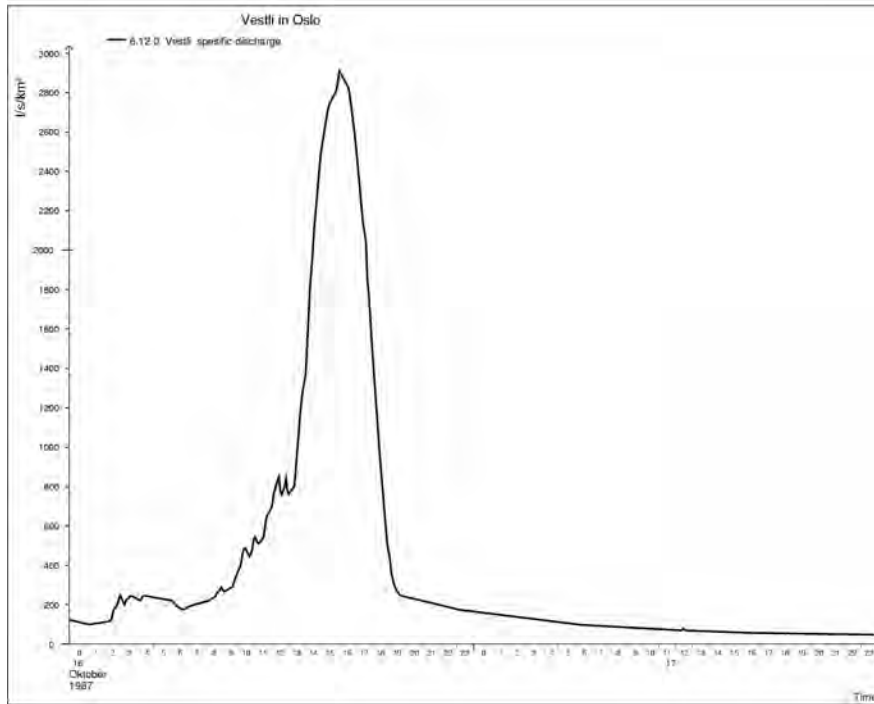


Figure 2.5 Observed discharge during the rainfall flood in October 1987 at the semi-urban Vestli basin in Oslo.

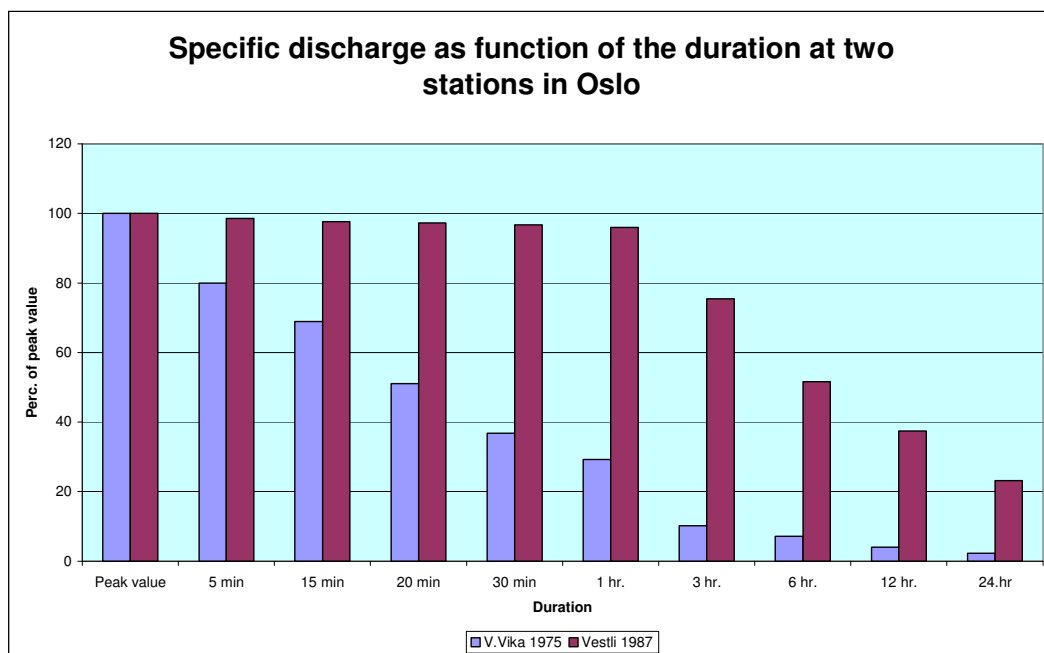


Figure 2.6 The magnitude of the specific flood during two events in Oslo as a function of the duration.

3 Rainfall and flood regions

The Norwegian land area has been divided Norway into 6 temperature regions, and 13 precipitation regions based on similarities between stations in long time series of annual and seasonal values (Hanssen-Bauer and Nordli, 1998; Hanssen-Bauer and Førland, 1994, 1998), see Figure 3.1. The Norwegian land area has been divided into 13 runoff regions based on similar methods (Førland et al. 2000). The regionalisation has been based on data from rivers not affected by regulations, since the seasonality of the streamflow changes in regulated rivers. The dataset was supplemented with naturalised series from regulated basis to obtain a better regional coverage of Norway, see Figure 3.2.

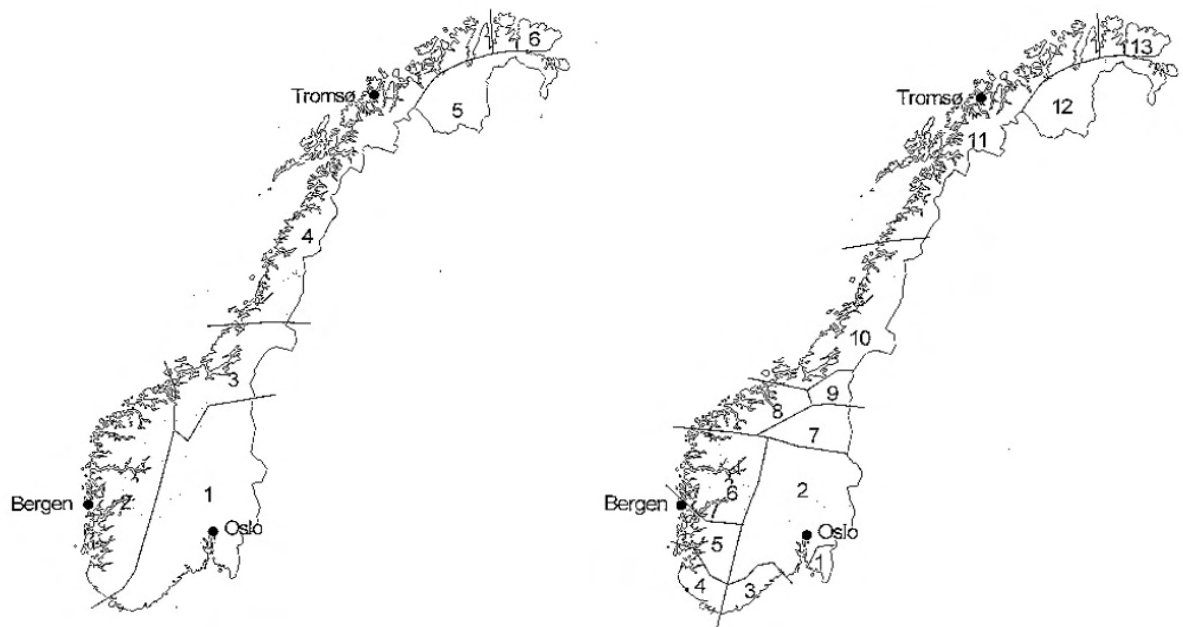


Figure 3.1 The Norwegian mainland is divided into 6 temperature regions (left) and 13 precipitation regions (right)

The seasonal distribution of streamflow can be used to divide the Norwegian mainland into regions with a similar seasonal variation based on monthly or seasonal mean values, as shown in Figure 3.2. The seasonal pattern is controlled by accumulation and melting of the annual snowpack in addition to the forcing by rainfall in the warm season. The start and the end of the snow season are controlled by the temperature and are dependent of the altitude of each basin. The regions based on the seasonality of streamflow will therefore differ from regions constructed from rainfall data only.

The flood generating processes are more dependent on the basin properties than the average seasonal distribution in each region. Depending on the topography the occurrence of lakes, bogs and other landscape elements can attenuate floods, whereas high percentage of impervious surfaces can magnify the floods compared to floods in other basins. Hydropower regulation will usually lead to reduced flood magnitudes. It is therefore less useful to divide the Norwegian mainland into flood regions based on geographical criteria. It is better to classify the basins into non-coherent groups based on catchments properties and/or the statistical properties of each basin.

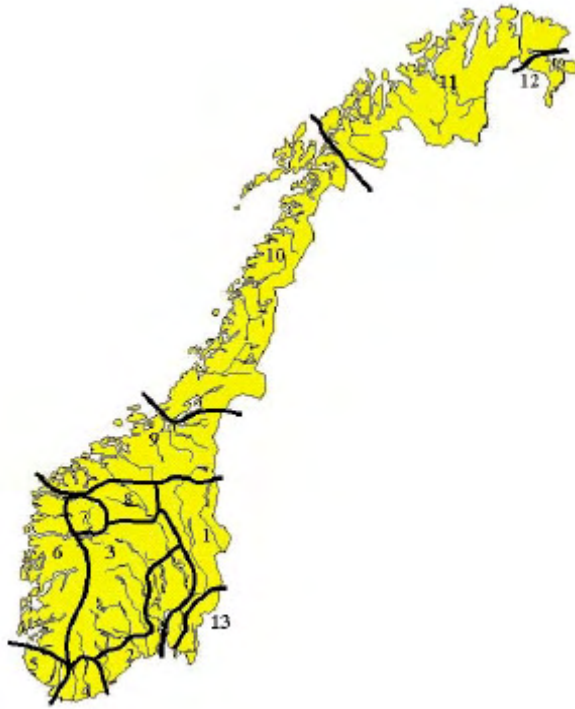


Figure 3.2 The Norwegian mainland is divided into 13 regions with similar temporal pattern of the streamflow.

This study utilises nevertheless a subdivision of Norway of Norway into districts based on county boundaries or administrative sub-regions.

4 Circulation indices

4.1 General

Weather types or circulation types have traditionally been based on classification of daily weather maps, such as Lamb indices, the German Grosswetterlagen and others. The daily distribution of highs and lows were classified into one of a number of typical weather patterns focussed on specific geographical areas. The Lamb indices are thus focussed on the British Isles, whereas the Grosswetterlagen is focussed on Central Europe. Numerical methods can now perform the classification for the Lamb indices as well as the Grosswetterlagen based on pressure fields. The focus of the classification can then be moved to other areas e.g. Norway and can result in a more relevant classification for Norwegian conditions. Another circulation index of relevance for Norway is the North Atlantic Oscillation Index (NAO) which is based on pressure gradients.

4.2 North Atlantic Oscillation Index (NAO)

The North Atlantic Oscillation Index is based on the pressure difference between the Azores high and the Icelandic low. Figure 4.1 shows the winter index. Positive values in the index indicate strong transport of mild and humid air across the Atlantic and is associated with winter floods.

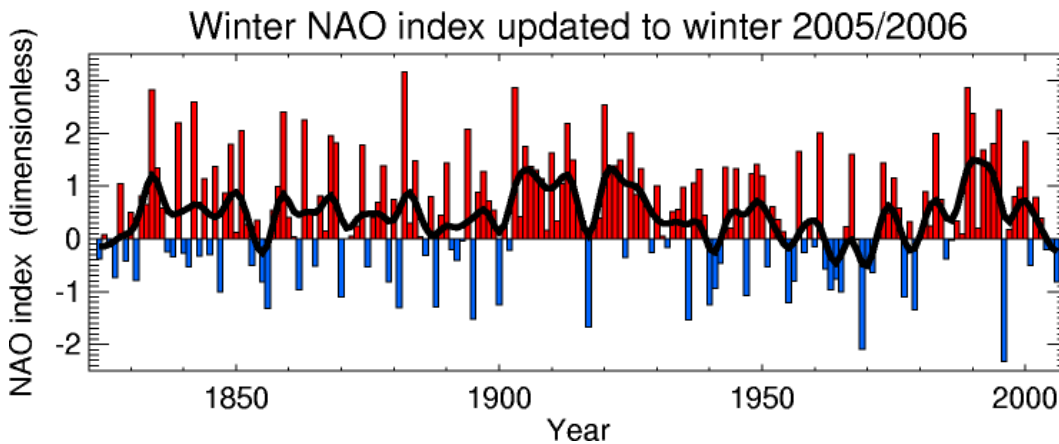


Figure 4.1 The North Atlantic Oscillation index for the winter months 1822-2005/6. (Source: CRU).

4.3 Grosswetterlagen (GRW)

F. Baur and co-workers of the former “Forschungsinstitut für langfristige Witterungsvorhersage” in Bad Homburg in Germany developed the “Kalender des Grosswetterlagens Europas” 1881-1939 in the early 1940’s. The calendar was extended by F. Baur 1946-1948. Hess and Brezovsky reworked the calendar which was re-published as “Katalog der Grosswetterlagen Europas”. The current version of the catalogue has been edited by Gerstengarbe and Werner (2005).

The classification is based on the location of the high pressure and low pressure areas controlling the dominant winds and fronts from the northeast Atlantic over Europe. A central concept is circulation types “Zirkulationsformen”. The classification scheme differs between three main types. The zonal circulation type dominates when there is a warm sub-tropical high pressure area over the North Atlantic with deep lows in the sub-polar areas, with strong westerlies with frontal systems moving eastward. The mixed circulation type is characterised by a mixture of zonal and meridional trajectories of the movement of the air masses. The meridional circulation type is characterised by stationary blocking highs between 50 and 65° N latitude. All troughs with axis orientated north-south belong to this type. Each circulation type is divided into sub-classes, depending on how far north the system is situated, as well as in a cyclonic or anti-cyclonic sub-class. The classification is summarised in Table 4.1. Figure 4.2 shows example weather maps with typical flood generating storm trajectories in different parts of Norway.

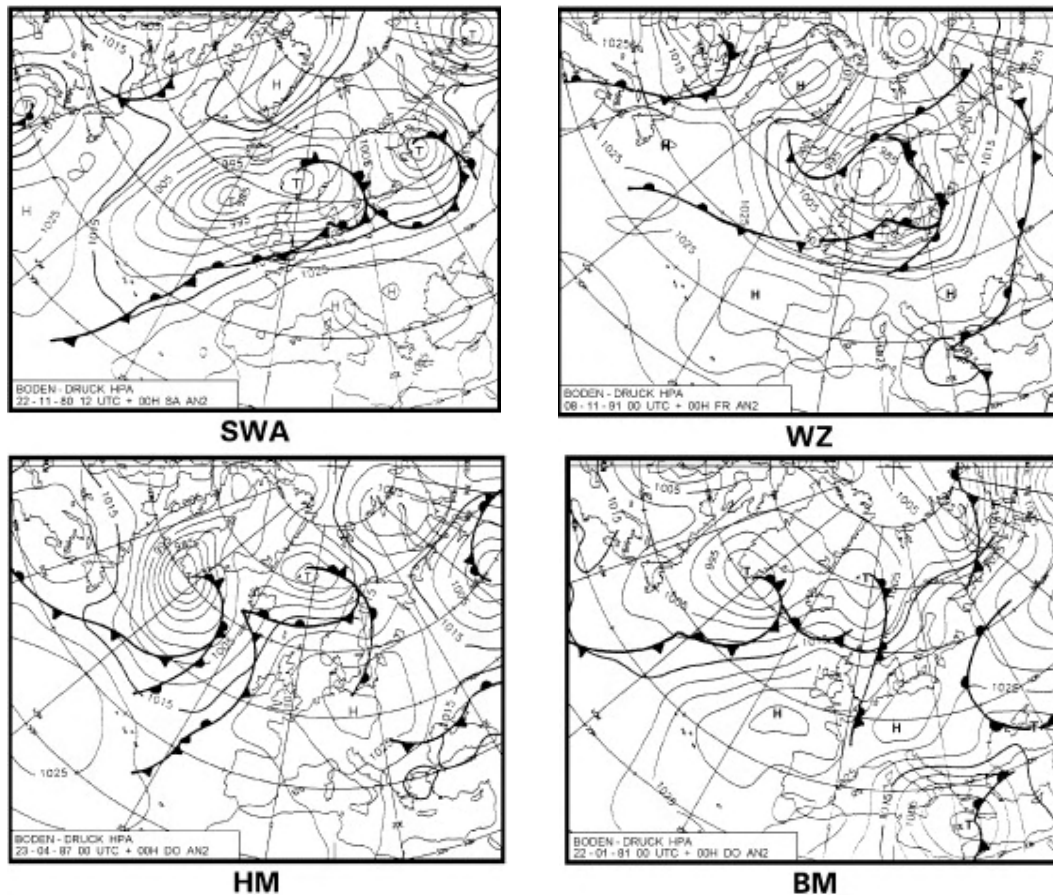


Figure 4.2 Weather types associated with rainfall floods in different regions in Norway (Source: Gerstengarber and Werner, 2005)

4.4 Lamb-Jenkinson (LWT)

Lamb (1972) has classified indices describing the pressure fields of daily weather maps from 1861 to 1972 based on his manual classification scheme. The Climate Research Unit (CRU) of the University of East Anglia has also reconstructed weather maps for selected earlier periods of special significance back to 1588 with the defeat of the Spanish armada. The reconstruction of daily weather maps of the 1780's (Kington, 1988) is of special interest for assessing the meteorological conditions causing two severe floods in Norway.

The classification is focussed on the British Isles and operates with 20 different circulation classes (Hulme and Barrow, 1997). The classification is based on three main groups of weather system, anticyclonic, zonal and cyclonic. Each main group comprises a number of subclasses describing the location of the anticyclone or cyclone relative to the British Isles or the direction of the zonal wind field. The classification is summarised in Table 4.2.

Table 4.1. The Grosswetterlagen classification scheme.

Zonalen Zirkulationsform			Merodinalen Zirkulationsform		
Number	Code	Description	Number	Code	Description
1	WA	Westlage, Antizyklonal	12	NA	Nordlage, Antizyklonal
2	WZ	Westlage, Zyklonal	13	NZ	Nordlage, Zyklonal
3	WZ	Südliche Westlage	14	NHA	Nord Hochmeer-Inland, Antizyklonal
4	WW	Winkelförmige Westlage	15	NHZ	Nord Hochmeer-Inland, Zyklonal
Gemischten Zirkulationsform			16	HB	Hoch Britische Inseln
Number	Code	Description	17	TRM	Trog Mitteleuropas
5	SWA	Südwestlage, Antizyklonal	18	NEA	Nordostlage, Antizyklonal
6	SWZ	Südwestlage, Zyklonal	19	NEZ	Nordostlage, Zyklonal
7	NWA	Nordwestlage, Antizyklonal	20	HFA	Hoch Fennoscandien, Antizyklonal
8	NWZ	Nordwestlage, Zyklonal	21	HFZ	Hoch Fennoscandien, Zyklonal
9	HM	Hoch Mitteleuropas	22	HNFA	Hoch Nordmeer-Fennoscandien, Antizyklonal
10	BM	Hochdrücksbrücke Mitteleuropas	23	HNFZ	Hoch Nordmeer-Fennoscandien, Zyklonal
11	TM	Tief Mitteleuropas	24	SEA	Südostlage, Antizyklonal
			25	SEZ	Südostlage, Zyklonal
			26	SA	Südlage, Antizyklonal
			27	SZ	Südlage, Zyklonal
			28	TB	Tief Britische Inseln
			29	TRW	Trog Westeuropas
			30	U	Übergang

Table 4.2. The Lamb classification scheme of circulation classes centered on the British Isles.

Anticyclonic			Zonal			Cyclonic		
Number	Code	Description	Number	Code		Number	Code	Description
0	A	Anticyclonic	11	NE	Northeast	20	C	Cyclonic
1	ANE	Anticyclonic northeast	12	E	East	21	CNE	Cyclonic northeast
2	AE	Anticyclonic east	13	SE	Southeast	22	CE	Cyclonic east
3	ASE	Anticyclonic southeast	14	S	South	23	CSE	Cyclonic southeast
4	AS	Anticyclonic south	15	SW	Southwest	24	CS	Cyclonic south
5	ASW	Anticyclonic southwest	16	W	West	25	CSW	Cyclonic southwest
6	AW	Anticyclonic west	17	NW	Northwest	26	CW	Cyclonic west
7	ANW	Anticyclonic northwest	18	N	North	27	CNW	Cyclonic northwest
8	AN	Anticyclonic north				28	CN	Cyclonic north

The circulation type can shift from one type to another in a day, these days are coded as -1 U and noted as Transitional

4.5 Van Bebber's classification of storm trajectories

The Lamb/Jenkinson and the Grosswetterlagen describes typical pressure configurations over Europe. Van Bebber (1882) made an earlier classification based on storm trajectories. Figure 4.3 show the five main trajectories identified by Van Bebber.



Figure 4.3 Van Bebber's classification of storm trajectories in Europe. (Source: www.zdf.de)

Most rainfall events in Nordland are linked to storm trajectory class I of Van Bebber. Class II is typical for many events in west and central Norway. These two classes are linked with anticyclones over central Europe and occasionally over Britain. Class III is linked to heavy rainfall in the southernmost part of Norway. Very heavy snowfall on the southernmost part of the coast is also associated with this storm trajectory.

Storm track type IV causes often heavy rainfall over Northwest Europe, e.g. Great Britain, Southeast Norway and Southwest Sweden. The air masses origins far south in the North Atlantic. The most intensive phases of "Storeflaumen" in 1860 (Johnson, 1861; Roald, 2000) and the large floods in Telemark and Gudbrandasdalen in 1927 and 1938 were caused by this storm track. The floods in October 1987, October-November 2000 and most recently in July 2007 were caused by frontal systems following this trajectory towards Southeast Norway. The resulting floods were more severe in Britain in 2000 and especially in 2007 (Marsh and Hannaford, 2007) and in Sweden in 2000 than in Norway.

The subclass Vb has caused most of the extreme floods in Central Europe (Rudolf and Rapp, 2003; Engel et al, 2002). The extreme floods in Oder in July/August 1997, in Elbe and Danube in August 2002, in Austria in August 2005 as well as the "1000-year flood" in Rivers Elbe, Danube, and Main of 1342 were all caused by this weather pattern. Storofsen, which ravaged Norway 21.-23.July 1789, is another example of an extreme flood caused by this weather pattern as described by Østmo (1985). Daily weather-maps have been published for the 1780's by Kington (1988). A secondary wave of the 1927

system changed into a full Vb-type event, which caused a severe flood in the upper Elbe basin with 160 casualties and extensive damage to roads and railways.

The “Vb-Tief” occurs typically in July or August, and is characterised by very warm and humid air masses from the Mediterranean streaming around the eastern parts of the Alps, towards northwest, with cold air masses linked to depressions further west forming a quasi-stationary front with extremely heavy rainfall. The situation is linked to blocking anticyclones in the North Atlantic and over Finland or the Kola Peninsula. The system may last for three days as in the case of Storöfosen or for weeks as in the case of some of the extreme floods in Central Europe.

A Vb-type event represents a worst case scenario for floods in southeast Norway, although the damages would differ considerably from 1789. The flood in 1789 occurred at the end of a severe spell of the Little Ice Age (LIA), causing numerous landslides because of layers of frozen soil in most slopes. The amount of frozen layers in the soil is substantially less with the present and projected future climate than in 1789. The vulnerability of the society is however much higher now, and the damages caused by an event of this type would exceed any previous flood.

4.6 Remnant of tropical cyclones from the Atlantic.

Tropical cyclones occur from late May to November at low latitudes in the Atlantic or the Caribbean Sea. They are most frequent in August to November and are formed over the sea when the sea surface temperature exceeds 26,5°C. Many cyclones have their origin in tropical waves from Africa between 5 and 20°N. Others are formed in the Caribbean or the Gulf of Mexico. Many cyclones move WNW towards the Antilles and Central or North America. Some storms curve northward and eventually northeast-ward as they merge with extra-tropical cyclones. These systems can reach Northwest Europe. The warm air from the tropical cyclone is usually found over the occluded front. When the warm and humid upper air masses approaches the Norwegian coast, further lifting can cause heavy rainfall and occasionally strong wind.

The National Hurricane Centre of NOAA has published the trajectories of tropical storms occurring North Atlantic since 1851 (www.nhc.noaa.gov). The number of storms varies considerably from year to year as shown in Figure 4.3. The number of remnants of tropical storms reaching North West Europe varies also considerably from year to year. The Hurricane Faith which occurred in September 1966 is a good example of a hurricane of this kind. The storm was formed near the Kapp Verde Islands 18.August, crossed over the Atlantic increasing in intensity to a type 3 hurricane on the Safir-Simpson scale. The weakening hurricane turned then toward northeast and became embedded in an extratropical low north of Scotland. The storm reached the west coast of central Norway 7.September and crossed over Sweden and Finland to end north of Novaja Semylya. The storm caused wind damages in Norway and more than 200 mm rainfall at locations in Sunnfjord. The warm and humid upper air masses caused intensive melting at some glacier resulting in record high runoff in some glacier streams.

The number of storms which have penetrated as parts of extratropical cyclones north of 50°N and east of 30°W has been identified. The data series is more unreliable in the early

part than in the most recent years, where the mapping of the trajectories is based on satellite observations. Years with many systems penetration towards Northwest Europe seem to cluster, with many years with hardly any storm in between. The number of events occurring from August 1883 to 1887 is remarkable. A similar cluster of events has occurred between 2004 and 2006. The final dates of more than 100 storms have been compared to the circulation types indicated by the Grosswetterlagen and the Lamb-Jenkinson indices as well as to rainfall and flood observations from Norway. The web-site www.senorge.no was also used in identifying possible rainfall and flood events caused by these storm remnants.

Some of the storm remnants has moved towards Iceland or Greenland, whereas other has reached the European mainland or stopped near Great Britain without penetrating further east. A considerable number of remnants has however been found to cause rainfall in parts of Norway, mostly close to the coast. The amount of rainfall can be in the range of 100 to 200 mm typically over 1 to 2 days.

Sorteberg has shown that some extreme rainfall events on the west coast can be attributed to warm and humid air masses from subtropical or tropical waters from southwest even if remnants of tropical storms are not embedded in the fronts arriving at the coast. The extreme weather Loke 14.November 2005 is an example of a rainstorm with this kind of origin. The trajectories of tropical hurricanes moving towards northwest Europe indicate years when these warm air-masses have the potential for reaching the coast of Norway, especially if several remnants follow in the same direction as in 1883, 1884, 1887, 1892, 1953, 1976, 1980, 1988, 2004, 2005 and 2006.

5 Identification of Norwegian rainfall floods

5.1 Comparison of rainfall, circulation indices and flood data.

Large rainfall events have been identified for around 100 long term rainfall series based on the Peak-Over-Threshold Method comprising 30 to 110 year of daily rainfall data. The threshold was selected based on the statistical properties of each series and varies regionally over Norway. The analysis required a minimum distance between individual events to be included of 10 days. The earliest events considered in the study occurred in 1896, the most recent in 2004. A total of almost 1000 events have been identified.

Large flood events were identified by a similar analysis of daily streamflow data. The lag between each flood event was conditioned on the size of the basin as well as the occurrence of upstream lakes in order to identify independent peaks. The analysis used data from basins, not affected by hydropower regulations. The data set was supplemented with naturalised data series where regulation changes the streamflow. The tables of rainfall events and flood events were compared to identify coinciding flood and rainfall peaks for the events occurring within each basin. A maximum time difference of ± 2 days was used to define coinciding rainfall and flood events. The GRW- index and LWT-index were assigned to the date each rainfall peak as measure of the rainfall producing circulation. The percentage of rainfall and flood-generating weather types has been determined for 24 regions in Norway. The snowmelt floods are dominating in some regions in the southeast and in northern Norway. The number of rainfall events differ therefore considerably between the regions. Only three rainfall floods were found in Troms and none in Finnmark. The number of rainfall floods in Østfold and Vestfold is low, but that reflects a scarcity of long runoff series in smaller basins. The large snowmelt floods in the major rivers dominate over the rainfall floods in Hedmark as well, although several severe rainfall floods are known in this county. Rainfall floods are most abundant in coastal basins from Agder to Nordfjord. The coastal basins on the Fosen Peninsula and in Helgeland to Lofoten have also many heavy rainfall events, causing occasional floods.

The seasonal distribution of the dominating weather types has also been examined for each region. It is preferable to use a classification scheme focussed directly on Norway. This would however require use of ERA-data which start in 1948. Since the study includes many flood events prior to the ERA-period, it was necessary to use the classifications focussed on Germany and the UK respectively which are available as daily indices to 1881 and 1861.

5.2 The southeast region

The Norwegian landscape in the southeast is characterised by low-lying areas near the Oslofjord, with a number of relative large rivers flowing from the inland from north and northwest. The western part is mountainous with alpine districts to northwest. The area is

exposed to frontal rainfall from southeast to southwest, but zonal wind from the west has caused most of the rainfall events in the region. The number of events selected by the POT-analysis and the monthly percentage for the counties comprising the region is shown in Table 5.1. The analysis yielded fewer rainfall floods than most of the other regions. The reason is that snowmelt floods are the dominating flood type in the region. The small number in the coastal districts is also caused by a scarcity of series from small coastal rivers where rainfall floods are the dominant flood type.

Table 5.1 The number of rainfall flood events per county in Southeast Norway 1895-2004 selected by Peak-Over-Threshold analysis of rainfall and streamflow data. The seasonal distribution is given as monthly percentages per county.

Region:	Southeast				
	Oslo/Akershus	Østfold/Vestfold	Buskerud	Hedmark	Oppland
Number	31	12	20	5	10
January	0	0	0	0	0
February	0	0	0	0	0
March	0	0	0	0	0
April	0	0	0	0	0
May	0	0	5	0	10
June	0	8,3	10	40	10
July	6,5	0	15	0	20
August	48,4	50	25	60	40
September	19,4	0	10	0	20
October	25,8	41,7	35	0	0
November	0	0	0	0	0
December	0	0	0	0	0

The larger rainfall floods occur typically from July to October in catchments close to the coast and from June to September in the inland rivers. The high percentage in June in Hedmark, is probably caused by that combined floods have been identified as rainfall floods because of high rainfall contributing to the snowmelt. The month with highest risk of rainfall floods is August, which is also known from historical records to have had many of the most severe rainfall floods prior the start of the observations.

The district can be subdivided into four sub-regions with different occurrence of rainfall floods. The most frequent flood type in the district around the Oslofjord including Vestfold, Østfold, Oslo, Akershus and the lowland part of Hedmark and Oppland is snowmelt floods, but moderate rainfall floods are also common. The maximum precipitation ranges from 40 to 100 mm; most in the hills north of Oslo. The district has suffered from heavy August rainstorms in 1740 and in 1860. The rainfall floods in October 1987 and 2000 is among the largest floods in the smaller natural basins occurring since 1970.

The sub-region west of the Oslofjord extending to Valdres have more severe rainfall floods than district further east. A number of large rainfall events in the 18th to the 20th Century have caused severe floods in this district, typically occurring in August as shown in Table 5.2. One of the most dramatic of these events occurred at Rjukan in 1927,

(Einung, 1927). The naturalised discharge in River Måna and the observed rainfall is shown in Figure 5.1. The circulation type was SWA as shown in Figure 4.2.

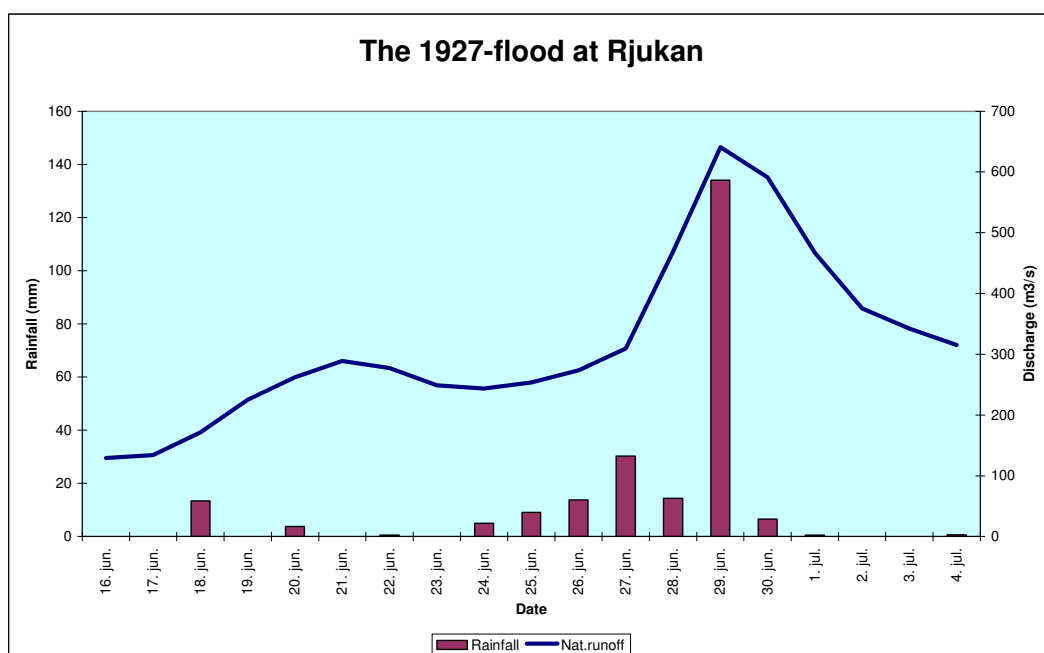


Figure 5.1 The 1927 flood at Rjukan triggered more than 250 landslides in the district with six fatalities in the town. The large upstream reservoir was not filled up and was able to contain most of the water from the large upstream basin.

Table 5.2 Overview of severe rainfall flood events in the western part of region Southeast caused by local thunderstorms or frontal systems moving in from southwest. Many of these events have caused landslides in steep terrain.

Year	Date	District	Type of event	Rainfall (mm)
1752	23/8	Sigdal and Tinn	Torr. rainfall, 28 slides in Tinn	
1822	23/8	Rivers Skienselv, Numedalslågen and Simoa	Torr. rainfall	
1858	7/7	Sigdal and Tinn	Torr. rainfall, 46 slides in Tinn	
1860	15-17/6	Hallingdal, Numedal, Tinn	Snowmelt, torr. rainfall, many slides	
1927	28-29/6	Rivers Numedalslågen and Skienselv	Torr. rainfall, 250 slides at Tinn	134 mm at Rjukan
1934	4-6/8	Rivers Numedalslågen and Skienselv	Torr. rainfall	150 mm at Tørdal

Two sub-regions further north is characterised by valleys running north to northwestwards with major rivers flowing towards the mountains. The flood regime is dominated by spring or early snowmelt floods. Many tributaries join the major rivers through steep side valleys. The annual rainfall is generally low, but rare events of high intensive rainfall occurs causing dangerous floods. These floods can cause severe damage because of erosion with subsequent deposition of eroded rocks, gravel and sand at the flood plain.

Both sub-regions suffered badly from Storofsen in July 1789. The eastern sub-region including River Glomma and River Trysilelv are dominated by large snowmelt floods. This region is also affected by rainstorms from the east, penetrating from Sweden. The region suffers from a number of intensive but mostly local rainfall events. The extreme Fulufjäll event in August 1997 caused also rainfall in Trysil although much less severe than in Sweden. The maximum intensity in Sweden was estimated to be just below 400 mm rainfall. This event occurred during very hot weather simultaneously with the large flood in Oder in Poland, Tsjeckia and Germany, caused by a Vb-low. Another event occurred at Folldal 28.June 1935, when a local thunderstorm produced 125,5 mm rain in one day. The region extends into the upper part of some of the larger rivers flowing northwards to the Trondheimsfjord, such as Orkla and Gaula. The late August flood in 1940 ravaged Gauldalen upstream Støren. The maximum one-day rainfall at the stations operated by the Meteorological institute was 70 mm. The maximum one-day rainfall observed at Atnasjø was however 110 mm, where it only caused a 10-year flood out of the lake. A local flood in the Rondane massif caused Atna to over-top a sediment station in 1996. There is no observation of rainfall at the time, but the cause of the flood is obviously a local rainstorm in the mountains. Trysil has suffered from several recent rainstorms such as the one in 2002.

The fourth sub-region comprises River Lågen with the high alpine area Jotunheimen and the upper part of Valdres. Vågåmo in Oppland has suffered from several severe floods in the 1340's, in 1789, in 1860 and in 1938. The floods occur in River Finna, a tributary from northwest with heavy transport of rocks and gravel during severe floods. The August-September flood of 1938 is the highest flood on record in rivers Otta and Sjøa and was caused by rainfall alone. The previous events were caused by a mixture of snowmelt and heavy rainfall. An early July event in 1932 at Dovre caused the largest observed flood in Driva and in Jora at Dombås. The flood in River Jora was estimated to be the largest since Storofsen. This flood was partly caused by snowmelt, but also by intensive rainfall. The rainstorm between Vågåmo and Lom 30.July 2006 is an example of a local rainstorm causing flooding in small brooks and multiple land slides.

Table 5.3 The distribution of the rainfall floods in region: Southeast into the three main classes: A anticyclonic, Z zonal and C cyclonic circulation type. The most frequent class of rainfall floods are shown for each region.

Region:		Southeast				
		Oslo/Akershus	Østfold/Vestfold	Buskerud	Hedmark	Oppland
GRW	A	3,6	0	0	0	0
	Z	60,7	53,8	52,6	75	50
	C	35,7	46,2	47,4	25	50
	Most frequent	WZ, TB	WZ, TRM	TRW, WZ	NWZ	WZ, TRW
LWT	A	19,3	7,7	20	25	60
	Z	35,5	15,4	20	50	20
	C	45,2	76,9	60	25	20
	Most frequent	C, W	CNE	C	-	C

Table 5.3 summarises the distribution of flood generating circulation classes for four subregions in region: Southeast.

The dominant flood generating type is the zonal WZ type with focus point in Germany as for the Grosswetterlagen for floods in the inland, with exception of upper Hedmark, where some of the larger rainfall events and floods are linked to precipitation penetrating from Trøndelag. Cyclonic weather types dominate in basins closer to the coast, especially in case of low pressures over or near Great Britain. The largest events in the region are linked to fronts from southeast to south. These events are however quite rare, and will therefore not appear among the more frequent events.

5.3 Coastal basin from the Oslofjord to Lista

The coastal region extends from Vestfold through Telemark to Lista in Vest-Agder. The region is exposed to weather systems from south to southwest. Local topography caused reinforced rainfall intensities at some locations such as the southwest slopes of Skrimfjell and in the Gjerstadelv and Vegårdselv basins, where one-day rainfall of 172 mm has been observed. Table 5.4 summarises the number of rainfall flood events in districts on the west side of the Oslofjord, south and the southwest coast. The threshold used in selecting rainfall events ranges between 40 and 80 mm in this region.

Table 5.4 The number of flood events per county in South and Southwest Norway 1895-2004 selected by Peak-Over-Threshold analysis of rainfall and streamflow data. The seasonal distribution is given as monthly percentages per county.

Region:	Southeast	South	Southwest	
	Telemark	Agder	Jæren	Ryfylke
Number	26	68	35	74
January	0	4,4	2,8	10,8
February	3,8	4,4	5,7	10,8
March	0	2,9	2,8	9,4
April	0	1,47	2,8	1,35
May	3,8	0	0	0
June	11,5	4,4	2,8	0
July	11,5	7,4	0	0
August	34,6	16,2	5,7	5,4
September	11,5	14,7	17,1	12,2
October	8,0	19,1	22,8	21,6
November	0	14,7	20	17,6
December	0	10,3	17,1	10,8

The largest river in Telemark drains a substantial part of the Hardangervidda plateau. The most common flood type is therefore caused by snowmelt. Hydropower regulations have reduced the flood magnitudes considerably since the regulation started in 1909. The district further south comprises a mixture of some long rivers draining mountainous areas in the inland and smaller coastal rivers. Snowmelt floods dominate also in the larger rivers e.g. Nidelva, Tovdalselv and Otra.

Historical data show that region South has been affected by many severe rainstorm floods just as in upper Telemark. These floods occur typically in August and have caused many landslides in the steep terrain in Setesdal, as shown in Table 5.5. The events are mostly different from the events in Telemark, showing the local nature of these floods. The Peak-Over-Threshold analysis has identified a typical rain-flood season from June to October. The larger rivers are mostly regulated, and the snowmelt flood was the most common type of flood in these rivers. The smaller rivers are frequently affected by rainfall floods. The dominant flood season is from late July to December. Coastal towns in the region have suffered from rainstorms, which not always have penetrated far into the inland.

Table 5.5 Overview over intense rainfall storms in region south, which can not be associated with remnants of tropical storms.

Year	Date	District	Type of event	Rainfall (mm)
1772 1773		Bygland and Valle in Setesdal	Flood, landslide	
1793	5/8	Valle in Setesdal	Torr. rainfall, flood, slides	
1799	14/10	River Hiså	Torr. rainfall, flood	
1837	20/9	River Vegårdelv – River Otra	Snow then, torr. rainfall	
1864	17/9	River Vegårdselv	Torr. rainfall	
1896	14/8	River Risørrelv – River Vegårdselv	Torr. rainfall	172 mm at Gjerstad
1939	27/8	River Herefosselv	Torr. rainfall	173 mm at Mykland

Towns on both side of the Oslo fjord have occasionally suffered damage because of local rainstorms. A rainstorm in 1996 caused damage of 15 mill. NOK in Kristiansand. The flood was caused by frontal rain from southeast. More recently Fredrikstad has experienced urban flooding because of heavy rainfall 17.August 2007. These events occur mostly in the late summer or autumn, but can also occur in the late autumn or early winter. Figure 5.2 and 5.3 shows two of the largest observed floods in the urban basin Sømkleiva in Kristiansand. These floods were caused by a July and a December rainstorm.

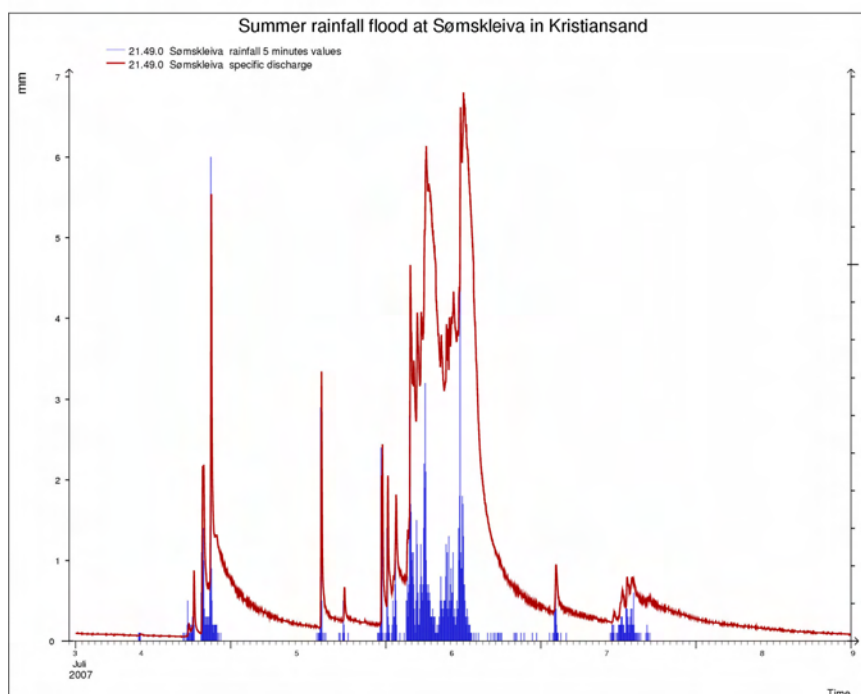


Figure 5.2 The rainstorms in July 2007 caused also flooding in Kristiansand, where the observed flood at Sømkleiva is one of the two largest on record.

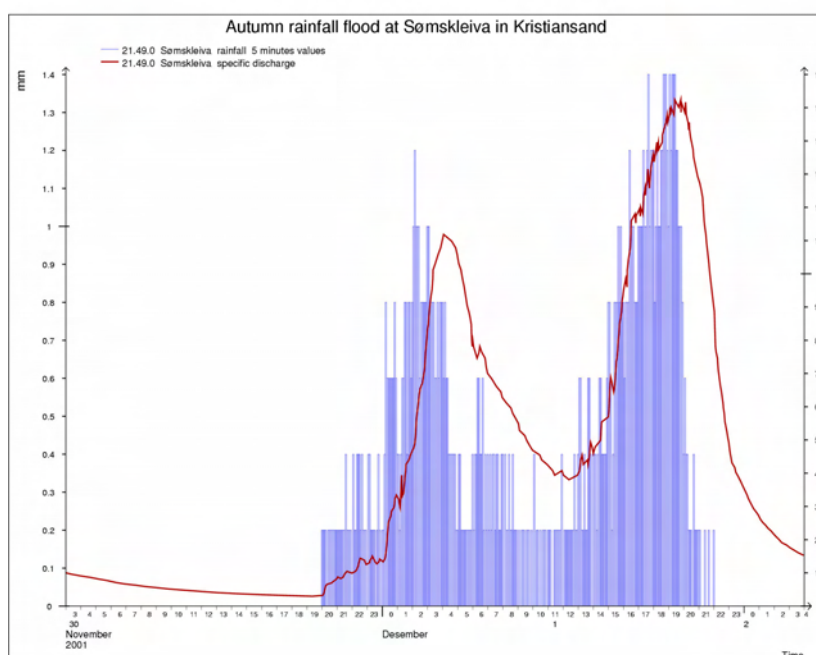


Figure 5.3 An example of a two-day rainstorm in the late autumn/early winter causing one of the largest floods observed at Sømskleiva in Kristiansand. The rainfall was caused by fronts from southwest, followed by an anticyclone over Britain on the 2nd of December.

Some of the urban floods on the south coast are probably caused by remnants of tropical storms. The trajectories of these systems show that some have penetrated into the North Sea and have caused heavy rainfall and local flooding, see Table 5.6.

Table 5.6 Overview of remnants of tropical storms causing heavy rainfall in coastal basins in region: South

Year	Date	Name	District	Rainfall (mm)
1950	18.-19.9	Doris	Åseral – Etne	106
1953	22.-23.9	Edna	Drangedal-Kvinesdal	92
1986	28.8	Charley	Risør-Arendal	115
1998	10.-11.9	Danielle and Earl	Tovdal-Fjotland	109
2000	Sep.-Nov.	Isaac, Leslie and Michael	Both sides of Oslo fjord	80
2004	17.-20.8	Alex	Vest-Agder	115
2004	5.10	Lisa	Jæren and Vest-Agder	122

The largest floods in the western part of the region occur in the late autumn or early winter resulting from mild weather and heavy winter rainfall. Figure 5.4 shows observed

rainfall and streamflow in early December 1992 in several rivers in Vest-Agder. This flood as well as a large flood 25.October 1929 and another flood 4.-5.November 1931 was caused by frontal systems from southwest. These events were all caused by rainfall exceeding 100 mm at one or more precipitation stations.

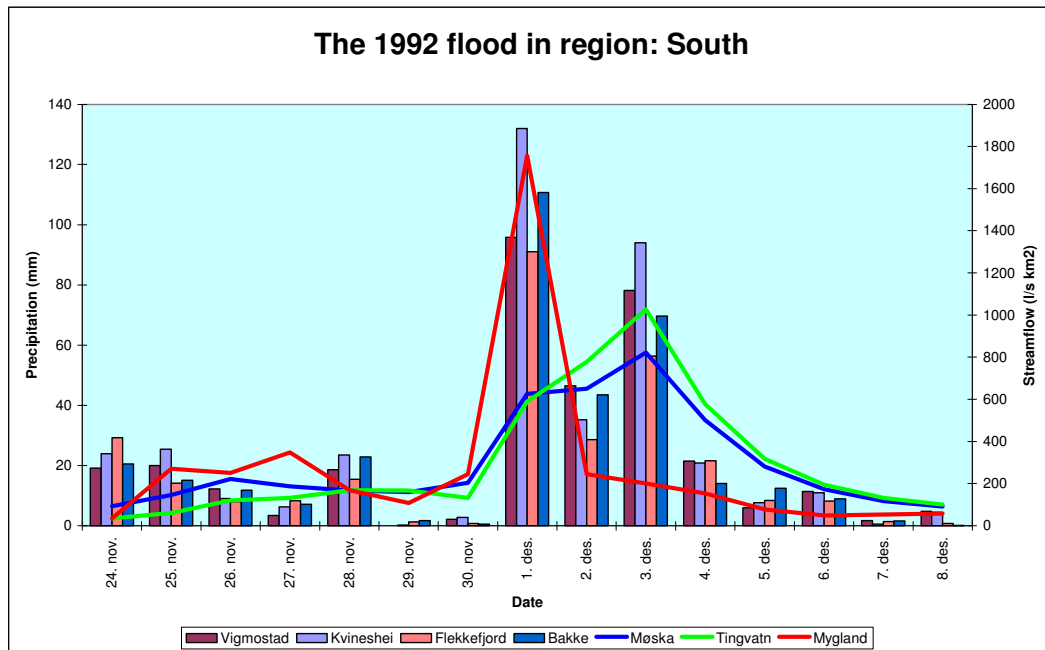


Figure 5.4 Observed rainfall and streamflow in rivers in the western part of region South during the large flood in December 1992. Snowmelt contributed initially to the flood, but rainfall was the main contributing factor to the magnitude.

The distribution of the main rainfall flood generating circulation types and the most common circulation indices are shown in Table 5.7

Table 5.7 The distribution of the rainfall floods in regions: South and Southwest into the three main classes: A anticyclonic, Z zonal and C cyclonic circulation type. The most frequent class of rainfall floods are shown for each region.

Region:		South		Southwest	
		Telemark	Agder	Jæren	Ryfylke
GRW	A	0	14,3	23,5	28,8
	Z	58,3	73	67,6	65,8
	C	41,7	12,7	8,8	4,1
	Most frequent	WZ, TB, WS, WW	WZ, SWA, WS, BM	WA, SWA, BM	WA, WZ, SWA, BM
LWT	A	11,5	16,2	8,6	28,4
	Z	26,9	47,0	74,3	59,4
	C	61,5	36,8	17,1	12,2
	Most frequent	C, SW, W	C, W, SW	W, SW, C, NW	W, SW, AW, NW

There is a well defined shift in the most frequent weather type close to Lista. Further east most large events are linked to low pressure areas near Britain. Weather systems from west and southwest dominates further west, but causes also several of the rainfall floods east of Lista.

5.4 Southwest Norway

The region from Lista to Ryfylke is exposed to weather systems from southwest to northwest. The dominant season for large rainfall floods is in the late autumn or early winter as seen in Table 5.3. The largest flood affecting the region was the large flood 3.-11.December 1743. This flood came at the end of a severe period, characterised by mild and wet winters, killing frost both in the spring and the autumn and cool summers, causing severe starvation. The flood was partly caused by snowmelt, but also large amount of rain. The flooded rivers caused severe damages in Årdal and Sauda.

The one day rainfall can exceed 150-200 mm especially in the northern part. The region has occasionally been hit by heavy rainfall caused by remnants of tropical hurricanes, forming the core of extra-tropical storms from the Atlantic. The remnants of tropical hurricane Faith affected a district from Ryfylke to Sunnfjord, causing heavy rainfall and glacier melting which resulted in large floods at many locations 7.-8.September 1966. The remnants of tropical storm Lisa reached Jæren 4.October 2004. The precipitation penetrated eastward to Kvinesdal where 122 mm rainfall was observed.

A typical example of a type IV storm trajectory was the extreme weather Loke 14.November 2005. The storm caused extensive damages at Jørpeland in Strand kommune in Rogaland. Table 5.7 summarises the most frequent circulation types within the region.

5.5 West Norway

The region from Sunnhordaland to Nordfjord includes the wettest parts of Norway. The dominant rainfall flood season is in the autumn to the early winter mostly linked to extra-tropical depressions from the Atlantic and Norwegian Sea. The number of flood events selected by the POT-analysis is shown for five districts in West Norway in Table 5.8.

Table 5.8 The number of flood events per district in West Norway 1895-2004 selected by Peak-Over-Threshold analysis of rainfall and streamflow data. The seasonal distribution is given as monthly percentages per district.

Region:	West				
	Sunnhordaland	Nordhordaland	Sogn	Sunnfjord	Nordfjord
Number	157	117	86	138	85
January	14,0	16,2	11,6	17,6	16,5
February	14,6	11,1	10,5	13	9,4
March	8,9	7,7	3,5	8	7,0
April	2,5	1,71	2,3	1,45	2,4
May	0	0	2,3	0,72	1,18
June	0,63	0,85	0	0,72	1,18
July	1,27	0,85	1,16	1,45	0
August	5,7	4,3	4,6	2,9	2,4
September	11,5	12,0	13,9	12,3	12,9
October	15,3	17,9	18,6	13,8	20,0
November	13,4	12,8	15,1	16,7	11,8
December	12,1	14,5	16,3	12,3	15,3

The extreme flood in December 1743 caused extensive damage in the region. The flood occurred after a cold October succeeded by snowfall in November. The subsequent rainfall event lasted from 3.-11.December. The temperature was very high for the season, a major ice-run started in 1000 m.a.s.l in Bøverdalen in Lom. The flood level 4.-5. December was the highest known at Voss. A wooden church was washed to the sea in Etne, and rivers shifted their course in many rivers. The flood caused numerous landslides, after a number of initial avalanches as the extreme weather started. Another rainfall event occurred 20.December in coastal basins in the region.

Another long duration rainstorm in late November 1940 produces 448 mm rainfall during four days at Indre Matre in Sunnhordaland. The one-day rainfall exceeded 200 mm at two stations and 100 mm at least at 15 stations, resulting in severe flood at many locations. A two-day event produced 156 and 155 mm rainfall 10.-11.October 1953, causing a record-breaking flood in River Oselv on the south of Bergen, as shown in Figures 5.5 and 5.6. The remnant of an unnamed tropical storm was approaching the coast on the 10.October and may have contributed to the intensive rainfall.

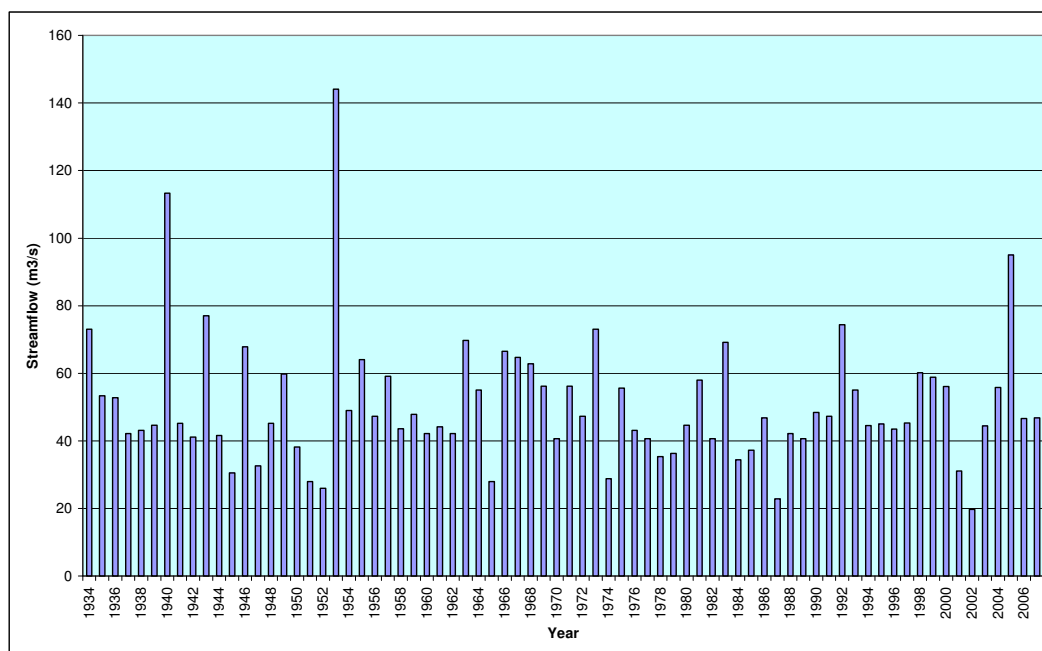


Figure 5.5. Observed floods in Oselv in Hordaland 1934-2007. The three largest floods are all caused by heavy rainfall.

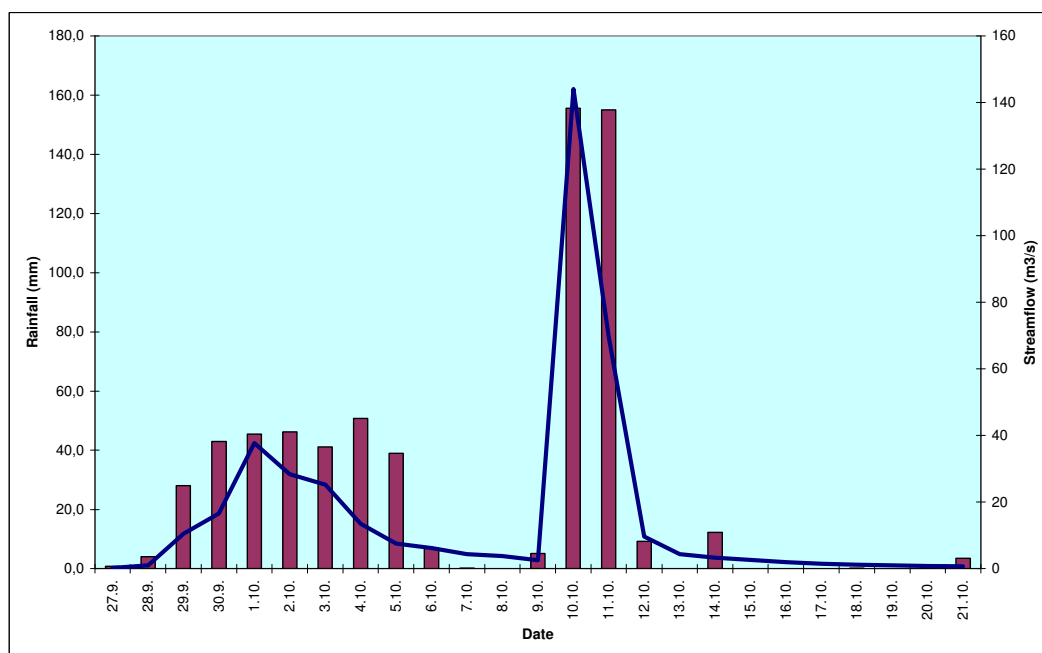


Figure 5.6 Observed rainfall at Samnanger and daily mean streamflow at Røykenes in Oselv during the extreme rainfall flood event in October 1953. The specific discharge was close to 3000 l/s km^2 .

The remnants of tropical hurricanes can also reach this region, typically from late August to early November. This is possibly the cause of an extreme rainfall flood in Vosso and in Ryfylke which occurred in mid August 1719. These depressions have a core of warm and humid air in combination with strong wind, often at the level of the upper part of the glaciers. This produces heavy melting, which causes additional runoff to the runoff

caused by the rainfall. The discharge in rivers from Folgefonna glacier and from the glaciers in Fjærland and northern Sunnfjord was record high as a result of Faith in 1966, as shown in Figure 5.7. The severe flood in Jostedalen 14.August 1979 was not caused by remnants of a tropical storm but the warm air-masses causing the flood had also at least subtropical origins. The remnants of the tropical hurricanes Maria and Nate joined to cause the extreme weather Kristin, which hit the Bergen district 18.September 2005. The one-day rainfall was up to 165 mm, and the resulting flood caused landslides which caused three fatalities at Hatlestad Terrasse. The distribution of rainfall is shown in Figure 5.8. Figure 5.9 and 5.10 show observed flood and rainfall at Sandsli in Bergen.

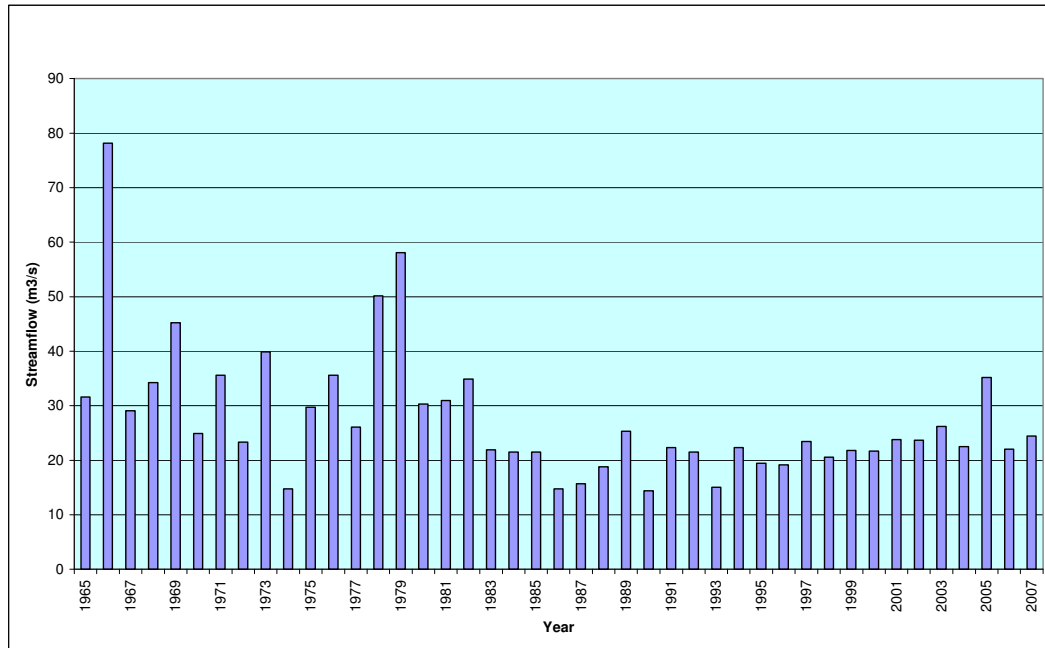
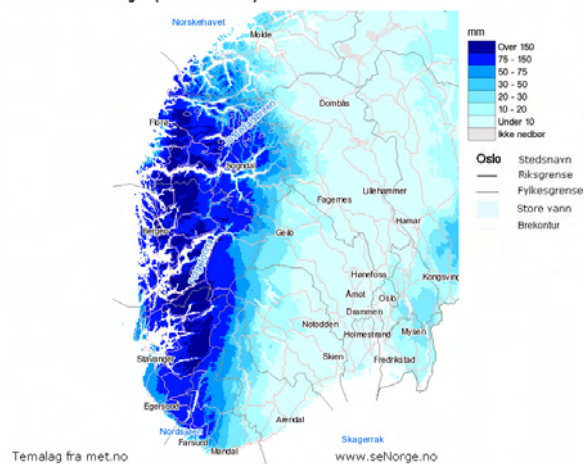


Figure 5.7 Annual maxima at Bøyumelv in Fjærland. The largest event in 1966 was caused by the remnants of tropical hurricane Faith (GRW: BM, LWT: W), and the second largest, which caused severe damages in Jostedalen in 1979, by warm air-masses moving along the coast (GRW: HFA, LWT: C).

Nedbør siste døgn (14.09.2005)



Nedbør siste døgn (15.09.2005)

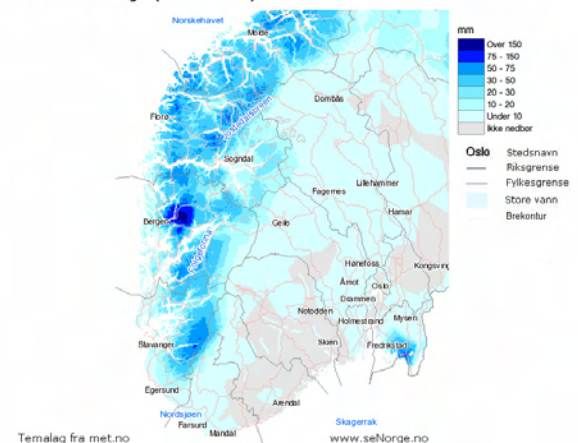


Figure 5.8 Rainfall caused by the extreme weather Kristin 14. 15.September 2005.

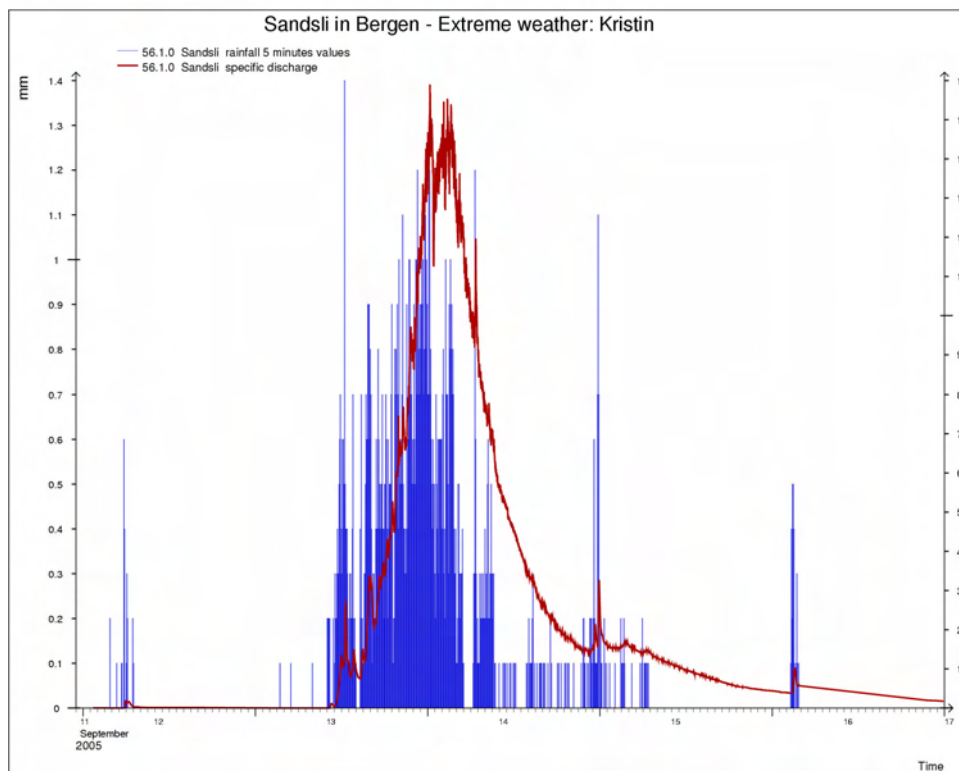


Figure 5.9 Observed rainfall and discharge at the semi-urban basin Sandsli in Bergen during the extreme weather Kristin, caused by the remnants of tropical hurricanes Maria and Nate.

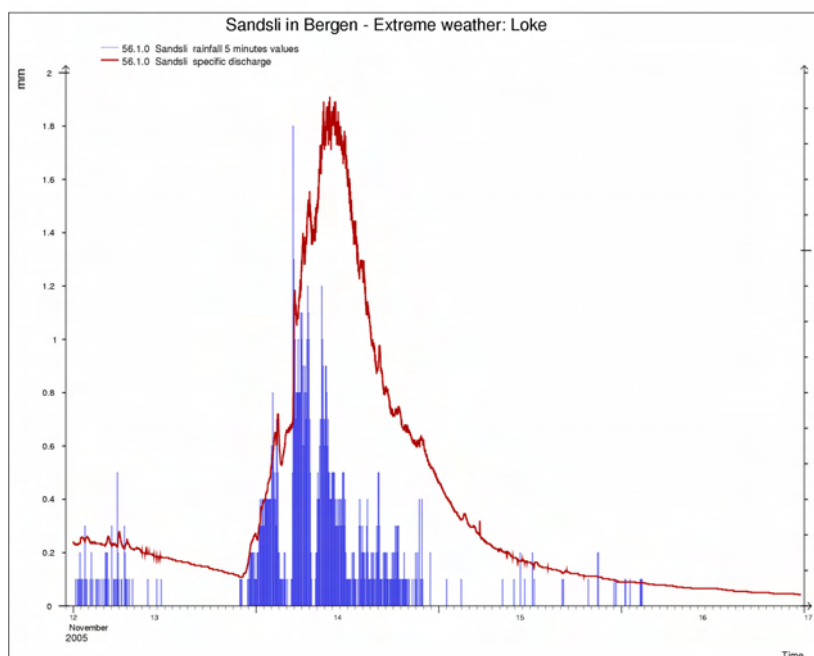


Figure 5.10 Observed rainfall and discharge at Sandsli in Bergen during the extreme weather Loke.

Table 5.9 summarises the distribution of the circulation classes in the region.

Table 5.9 Summary of the percentages of anticyclonic, zonal and cyclonic circulation classes and the most common weather type for all rainfall flood events in the region for both classification schemes.

Region		West				
		Sunnhordaland	Nordhordaland	Sogn	Sunnfjord	Nordfjord
GRW	A	35,6	33,9	40,2	39,8	40,7
	Z	62,4	63,3	56,1	57,9	56,8
	C	2,0	2,7	3,6	2,5	1,2
	Most frequent	WA, HM	WA, HM	HM, WA	WA, HM	HM, WA
LWT	A	36,9	40,2	40,7	42,8	45,9
	Z	55,4	52,1	50	50	48,2
	C	7,6	7,7	9,3	7,2	5,9
	Most frequent	W, SW	SW, AW	W, AW	W, SW	W, AW

The dominant flood generating weather type is frontal systems moving in from the west. The circulation class WA is the northernmost of the three western zonal classes of Grosswetterlagen, and this class is also found among the more frequent classes for all regions northward along the coast to Nordland. The class HM indicates an anticyclone over Germany and is strongly associated with strong westerlies further north. The Lamb indices W and SW indicates zonal wind direction between southwest or west over Britain, whereas AW indicates an anticyclone west of Britain with westerlies further north.

5.6 Central Norway

The region includes Møre og Romsdal and the rivers in Trøndelag draining northwards to Trondheimsfjorden. The region includes coastal basins at Sunnmøre as well as inland basins starting at the water divide towards the major rivers in Southeast Norway. The major rivers reaching the bottom of the fjords such as Geirangerelv, Rauma, Driva, Orkla, Gaula and Nidelva have a dominant snowmelt flood regime and many of the largest floods in the mountain catchments to the Southeast are also among the largest in these rivers. Several severe floods have occurred in the late autumn in rivers draining to the fjords as a result of abrupt raise in temperature linked intensive rainfall falling on snow. This has been a particular problem in Valldøla, Øksendalselva and Surna. There is a lack of stations in many of the coastal rivers which have suffered badly from severe rainstorms. It is nevertheless possible to identify some large rainfall floods in the past.

Romsdal was affected by a severe rainstorm and extensive damages in 1650. The 1743 event caused locally severe damage at Sunnmøre, Romsdal and Nordmøre. A 8 day rainstorm in February 1756 resulted in the largest rock-fall into a fjord in historical times and caused 32 fatalities. Several rainstorms have caused local flooding and rock-fall in smaller rivers at Sunnmøre in the 19th and 29th Century.

The number of rainfall floods is shown in Table 5.10 for this region. The number of events is much smaller than in region west because of the dominance of snowmelt floods within the region.

Table 5.10 The number of rainfall flood events per county in Mid-Norway and in Fosen and Helgeland 1895-2004 selected by Peak-Over-Treshold analysis of rainfall and streamflow data. The seasonal distribution is given as monthly percentages per county.

Region:	Mid-Norway				Fosen/Helgeland	
	Sunnmøre	Romsdal	Nordmøre	Sør-Trøndelag	Fosen	Nordland
Number	18	8	13	10	22	55
January	16,7	0	7,7	0	22,7	12,7
February	0	0	0	10	13,6	10,9
March	5,6	12,5	0	0	9,1	7,3
April	5,6	0	0	0	4,5	5,4
May	0	0	0	10	0	0
June	5,6	12,5	7,7	20	4,5	0
July	5,6	0	0	10	0	3,6
August	11,1	25	30,8	20	9,1	7,3
September	22,2	37,5	15,4	20	13,6	10,9
October	5,6	0	7,7	10	13,6	14,5
November	11,1	0	7,7	0	4,5	14,5
December	11,1	12,5	23,1	0	4,5	12,7

The dominant rain-flood season in Mid-Norway is from July to December, but rainfall floods occur occasionally in coastal basins in the winter, except in the larger rivers in Sør-Trøndelag where snowmelt floods in the spring dominates.

Some of the largest rainfall floods in Southeast Norway have penetrated into the larger rivers in the region. The rainfall flood in August-September 1938 occurred also the upper part of Rauma. “Storofsen” caused extensive damages in Driva, both in Oppdal and in Sunndalen in July 1789. This flood caused also damages in Surna. The worst damages of “Storofsen” in the region occurred however in Orkla, where 173 farms were granted tax deductions because of flood damages. The copper mine at Kvikne was flooded from the river, and was subsequently abandoned. The flood caused also damages in Gaula, limited to farms around Sokna and Støren. The rainfall flood 24.August 1940 caused extensive damages in Gaula and was also large in Orkla. The rainfall was probably more intensive in the Atnasjø basin where a one-day rainfall of 110mm was observed. The reason for the damages in Gaula is that this basin has a short concentration time because it lacks great lakes and reservoirs.

Remnants of tropical hurricanes have also caused floods in the region. The remnants of Frances reached Trondheim 22. September, and the remnants of Karl caused extensive damages at Sunnmøre 27. September 2004. Rainfall storms have caused substantial damage in coastal basins south of Storfjorden at Sunnmøre 16.July 1873, 3.October 1878, 18.September 1948 and 21.-22.August 1980. Other storms have caused inundation and damages in Romsdal and Nordmøre, such as the flood at Oppdal 19.-20.July 1698 and 14.August 2003. The latter extended to Sunnmøre and Romsdal causing landslides several places. The maximum one-day rainfall was 172 mm at Sunndalsøra causing the second largest flood in Driva since 1907. A similar flood occurred in the district 14.August 1909.

Trøndelag has suffered from major clay-slides causing many fatalities. The worst disaster occurred at River Gaula in September 1345, when the main River was dammed by a large slide. The subsequent dam-break destroyed 48 farms and killed around 500 persons according to Icelandic sources. It is likely that this slide was finally triggered by rain and a subsequent flood.

Table 5.11 Summary of the percentages of anticyclonic, zonal and cyclonic circulation classes and the most common weather type for all rainfall flood events in the region for both classification schemes.

Region:		Central Norway				Region: Fosen/Helgeland	
		Sunnmøre	Romsdal	Nordmøre	Sør-Trøndelag	Fosen	Nordland
GRW	A	42,8	16,7	25	30	55	77,6
	Z	50	83,3	75	50	45	26,3
	C	7,2	0	0	20	0	2,0
	Most freq.	HM, NWA	HM, NWZ	NWA, NWZ, HM	HM, NWZ, TRM	HM, WA, NWA	HM, BM
LWT	A	72,2	75	69,2	50	72,7	69,1
	Z	27,8	25	30,8	40	27,3	27,3
	C	0	0	0	10	0	3,6
	Most freq.	A, AW, W	W	A, W	A	A, ASW, SW	A, ASW

Table 5.11 summarises the most common circulation types associated with rainfall floods in the region. The large events occur when anticyclones are present on the European mainland as well as near Britain with strong westerlies further north. Note that zonal weather types indicating northwest wind are also quite common. The two northernmost

districts can have very heavy rainfall with southeast to southwesterly wind field along the coast.

5.7 Trøndelag north of the Trondheimsfjord to Lofoten

The region comprises coastal basins with 100- 150 mm one-day precipitation events caused by the vicinity to the Norwegian Sea. The dominant flood season is late autumn and early winter as seen from Table 5.10. Large rivers in the inland have mostly snowmelt floods, but winter rainfall can penetrate into these basins causing minor winter floods. Many of the winter precipitation events have not caused large in spite of the high intensities. Many catchments are fairly steep. The precipitation falls frequently as snow in the upper parts of the catchment under the present climatic conditions. The Fosen Peninsula is rather flat. Heavy rainfall events in Jan.-Feb. 1932 and 2006 demonstrate the magnitude of the floods if all the winter precipitation occurs as rain.

The dominant flood generating weather type is characterised by the GRW-classes HM and BM, as seen from Table 5.11. Some events are alternatively classified as the northernmost Westlage class WA as in region: West. Most of the events belong to the Anticyclonic classes in the LWT-classification. This implies that anticyclones are present over the European mainland or over Great Britain with strong westerlies further north. Some large rainfall events in Nordland are linked to south to southwest wind along the coast.

5.8 Troms and Finnmark

This region is dominated by snowmelt floods, although the largest observed flood occurring in Salangselv 7.October 1959 was a rainfall flood. The heaviest rainfall fell in Vesterålen with 50-100 mm further east. The event was caused by a southerly circulation type lasting from 30.September to 8.October. The rainfall may have been caused by remnants of the tropical hurricane Hannah, but it is more likely that the warm air stream from the subtropics were set up earlier in September when the hurricane Flora dissipated west of Ireland.

Other rainfall floods in the region are so small that they are not selected by the Peak-over-threshold analysis. The distance to the focussing point of either the Grosswetterlagen or the Lamb-Jenkinson indices is also too large to yield a consistent pattern.

6 Future rainfall floods

Daily streamflow series have been developed for the control period 1961-90 and the scenario period 2071-2100 based on climate scenarios and use of a hydrological model for 33 basins in Norway (Roald et al, 2006). They performed flood frequency analysis for the control and the scenario period in order to identify changes in the occurrence of floods in a future warmer climate. The most important factor for changes in the occurrence and magnitude of floods is changes in the amount and duration of the snow cover. The scenarios indicate a rise in the temperature of almost 3°C in the winter temperature. This corresponds to a lifting of the transition level from rain to snow nearly 500 m which has important consequences for the flood regime.

The scenarios indicate more warm spells in the winter with more floods, especially in the lowlands. The snow reservoir may increase in mountainous areas in the inland because of increasing winter precipitation before the warming causes more melting event even in the mountains. The snowmelt flood will occur earlier and will be over in the low lands early in the spring. The flood season will move from the early summer into the spring in the mountains. The magnitude of the summer floods will decrease. The scenarios indicate increasing risk of autumn floods in many basins, especially in basins along the coast.

The projections of future rainfall intensities are highly uncertain especially for small scale summer storms which the present climate models hardly can capture. The historical data demonstrates that there are more summer rainstorms in warm year than in cold. The Norwegian terrain with long mountain ranges along the coast introduces another uncertainty, because of the high sensitivity of the rainfall distribution to even small shifts in the trajectories the storms. The two models underlying the scenarios used by Roald et al. (2006) produce different dominant storm trajectories, causing significant differences in the distribution of floods in various parts of Norway.

Some mountainous basins near the coast of west Norway to Nordland can have one day winter precipitation exceeding 100 – 150 mm. Some of these basins cover altitudes from the sea level to 1200-1600 m. The precipitation has fallen as sleet or snow in the greater part of these basins during many events, and have therefore only caused small if any floods. A raise of 500 m in the transition level from rain to snow will have dramatic consequences for sharp winter floods. These events cause wet snow avalanches and land slides at new locations, threatening roads, railways and built up areas.

Sorteberg and Kvamstø (2008) discuss the huge variability of the rainfall in Norway, relating it to a tendency of storms to cluster with large differences from year to year and decade to decade. This makes comparison with observed trends difficult. They refer to results of the PRUDENCE project which indicates that the increase in observed rainfall intensities may exceed those of the climate models.

The most dramatic flood events in Norway seem to be linked to cold episodes during the Little Ice Age. This has also been noted in Germany (Glaser, 2001). Storofsen occurred at the end of a very severe cold period as mentioned in Chapter 4.3. This cold spell started in 1773 after a previous severe flood in River Glomma. Midway in the period Iceland

suffered from the worst natural disasters in its history, the volcanic eruption at Laki in 1783-84. The emission of sulphur dioxide to the atmosphere caused an extremely cold winter in much of Europe in 1784, and the subsequent ice runs caused record high flood levels in many European rivers. The cold spell between 1740 and 1742 ended with the extreme December flood in west Norway in 1743. Trøndelag suffered from several severe floods from 1688 to 1692, just prior to the most severe phase of the Little Ice Age in 1695-97. Although several of these events have occurred in cold periods, warm air linked to rather unusual weather types have caused these floods. They seem to occur at the end or prior to spells of rather stable cold circulation types, typically lasting three years.

8 Conclusions

The largest rainfall floods in Southern Norway are caused by meridional circulation types e.g. circulation types with transport of warm and moist air northwards from a sector between from southeast to southwest. Some of the most severe rainfall floods are caused by the Vb-low circulation type, which are linked to blocking highs both in the Atlantic and to the east over Finland or Northern Russia. Severe floods can be more common in Southeast Norway, should this rare circulation type become more common as seen in Central Europe in recent years.

Most large rainfall floods along the Southeast coast of Norway are caused by cyclonic circulation near the British Isles. Some of these events are caused by remnants of tropical storms. Further inland more rainfall events are linked to zonal circulations types e.g. frontal systems moving in from west. A zone with a potential of intensive local rainfall events extending from Sweden over Trysil, Østerdalen, Rondane, Folldal to the upper Gaula, Orkla and Driva basins.

Summer thunder storms cause a lot of damage in steep mountainous terrain in Gudbrandsdalen and in Telemark. Some of these storms are caused by major systems moving in from southeast to southwest. Others are local phenomena and cannot be attributed to any large scale weather type.

Rainfall floods in West Norway are mostly linked to zonal wind in the sector between southwest and northwest. The basins affected by each event are dependent on the actual direction of the wind field because of local topography and exposure. Remnants of tropical hurricanes can cross over the Atlantic as a core of an extra-tropical low. There have been a number of such events in recent years.

Rainfall floods in Northern Norway up to the Lofoten Isles occur mostly in the autumn when there is a high pressure ridge from Britain to the European mainland with a strong westerly wind field to the north. Some 100+ mm rainfall events are caused by warm air following the coast of Nordland from the south.

The annual flood is usually caused by snowmelt and occurs in the late spring or early summer in the two northernmost counties, Troms and Finnmark. Rain floods occur rarely and cannot be related to the GRW- or LWT indices, which are focussed on Germany and Great Britain respectively.

References

- Beldring, S., Førland, E.J. and Sælthun, N.R. (1989) Store flommer – En sammenlikning mellom nedbørepisoder og flommer I en del norske vassdrag. DNMI-rapport 24/89 Klima/NVE-VH oppdragsrapport 12-89.
- Einung, H.H. 1927. Storflommen i Tinn. Rjukan kommune.
- Engel, H., Krahé, P., Nicodemus, U, Heininger, P, Pelzer, J., Disse, M. and Wilke, K. (2002) Das Auguthochwasser 2002 im Elbegebiet. Bundesanstalt für Gewässerkunde, Koblenz.
- Fagan, B. (2000a) Flood, Famines and Emperors. Plimlico, London. ISBN 0-7126-6478-5.
- Fagan, B. (2000b) The Little Ice Age. Basic Books, New York. ISBN 0-465-02271-5.
- Førland, E.J., Roald, L.A., Tveito, O.E. and Bauer-Hanssen, I. (2000) Past and future variations in climate and runoff in Norway. *DNMI Report no. 19/00*.
- Gerstengarbe, F.-W. and Werner, P.C. (2005). Katalog der Grosswetterlagen Europas (1881-2004) nach Paul Hess und Helmut Brezowsky 6., Verbesserte und Ergänzte Auflage. PIK Report No.100, Potsdam, Germany.
- Glaser, R. (2001) Klimageschichte Mitteleuropas, Primus-Verlag, Darmstadt. ISBN - 89678-405-6.
- Hanssen-Bauer, I. and Førland, E.J. 1994a: Homogenizing long Norwegian precipitation series. *J.Climate*, 7, 1001-1013
- Hanssen-Bauer, I. and Førland, E.J. 1998: Annual and seasonal precipitation variations in Norway 1896-1997. DNM-Rapport 27/98 KLIMA, 37pp
- Hanssen-Bauer, I. and Nordli, P.Ø. 1998: Annual and seasonal temperature variations in Norway 1876-1997. DNM-Rapport 27/98 KLIMA, 29pp
- Hulme, M. and Barrow, E. (1997). Climate of the British Isles – present, past and future. Routledge, London and New York.
- Johnson, G.B. (1861) Mine Erfaringer og Anskuelser om Communicationsvæsen, J. Dydwad, Christiania.
- Jonsdottir, J.F. and Uvo, C.B. (2006). Long term variability in Icelandic hydrological series and its relation to variability in atmospheric circulation. EURENEW, Iceland, June 5-9,2006.

- Kington, J. (1988). *The Weather of the 1780s over Europe*, Cambridge University Press, Cambridge, UK.
- Lamb, H.H. (1972). British Isles Weather types and a register of daily sequence of circulation patterns. *Geophysical Memoir* 116, HMSO, London, 85 pp.
- Lamb, H.H. (1982). *History, Climate and the Modern World*. Methuen, London and New York.
- Lamb, H.H. (1991). *Historic Storms of the North Sea and the British Isles and Northwest Europe*. Cambridge University Press, Cambridge, UK.
- Marsh, T. and Hannaford J. (2007) The summer 2007 floods in England & Wales – a hydrological appraisal. National Hydrological Monitoring Programme. Centre for Ecology and Hydrology. 32 pp.
- Norges Vassdrags- og Elektrisitetsvesen (1895-1977) Vannstander i Norge.
- Det Norske Meteorologiske Institutt (1895-1976) Nedbøriattagelser i Norge
- Pfister, C. (1999). *Wetternahhersage – 500 Jahre Klimavariationen und Naturkatastrophen. Haupt*, Bern.
- Roald, L.A. (2000): The large flood of 1860 in Norway. *Proceedings of the Conference: Extreme of extremes*, Reykjavik, Iceland, July 2000. *IAHS Publication no. 271*.
- Roald, L.A. (2003) Two large 18.Century flood disasters in Norway. In: V.R. Thorndycraft, G. Benito, M. Barriendos & M.C. Llasat (ed) *Palaeofloods, Historical Data & Climatic Variability: Applications in Flood Risk Assessment*. Proc. of the International Workshop PHEFRA (Palaeofloods, Historical Data & Climatic Variability: Applications in Flood Risk Assessment) held at Barcelona, Spain, October 2002.
- Roald, L. A., Beldring S., Skaugen T. E., Førland E.J. and Benestad R. (2006). Climate change impacts on streamflow in Norway, NVE-Oppdragsrapport A 1 2006.
- Rudolf, B. and Rapp, J. (2003) *Das Jahrhundert Hochwasser der Elbe. Synoptische Wetterentwicklungen und klimatische Aspkte*. Abdruck aus *Klimastatusbericht*, DWD Offenbach 2003.
- Sorteberg, A. and Kvamstø, N.G. (2008) Hvor mye vil nedbøren øke i et varmere klima? *KLIMA* 4-8, p 36-38.
- Taksdal, S. (1999). Hydrologiske data i Norge. (Hydrological data in Norway). *Rapport nr 9/1999, Norges vassdrag- og energidirektorat, Oslo*. In 3 Vols.

Tveito, O.E. and Roald, L.A. (2005). Relations between long-term variations in seasonal runoff and large scale atmospheric circulation patterns. Met.no report no 7/2005 Climate.

Van Bebber J. (1882) Typische Witterungs-Erscheinungen. Aus Arch dt Seew, Hamburg, 5, No. 3, 1882, pp.1-45.

Østmo, A. (1985). Storofsen. Oversiktsregisteret. Infotrykk, Ski.

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