How extreme can unit discharge become in steep Norwegian catchments?

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ABSTRACT

This study presents results of observations and analysis of the flood event in Utvik on 24 July 2017. Observations during and after the event, hydraulic simulations and hydrological modelling along with meteorological observations, are used to estimate the peak discharge of the flood. Although both observations and hydraulic simulations of flood extremes are uncertain, even the most conservative assumptions lead to discharge estimates higher than 160 m^3/s at culmination of the flood from the 25 km^2-large catchment. The most extreme assumptions indicate it may have been up to 400 m^3/s, but there is also strong evidence for the discharge at culmination being between 200 and 250 m^3/s. Observations disclosed that the majority of water came from about 50% of the catchment area giving unit discharges up to 18 to 22 m^3/s,km^2. If the entire catchment contributed it would be from 9 to 11 m^3/s,km^2. This is significantly higher than previously documented unit discharges in Norway and in the range of the highest observed peak unit discharges in southern Europe. The precipitation causing this event is estimated to be three to five times higher than a 200-year precipitation taken from the intensity–duration–frequency curves for the studied region.

Key words | flash flood, hydrological extremes, Norway, unit discharge

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INTRODUCTION

On 24 July 2017, the river Storelva in Utvik, Norway, grew from less than 1 m^3/s to extreme ranges, which led to severe detrimental consequences within a 4-hour time frame. The event was documented through onsite observations of the course of the flood by the author. The purpose of this paper, besides documenting the event, is to assess how extreme this flood was in a Norwegian and European context.

Flash floods are floods caused by heavy and excessive rainfall of duration generally less than 6 hours or sudden release of water from, for example, dam breaks or ice jams (NOAA 2017). They are of the most dangerous and common natural hazards (Barredo 2007) and, as such, the threats that have the highest impact and likelihood of occurrence (World Economic Forum 2018). In the period 1950–2005, 2,764 casualties were documented in southern and continental Europe due to flash floods, representing about 40% of all flood-related casualties in Europe (Barredo 2007). In Norway alone, the yearly costs due to floods are close to 1 billion Norwegian krones (NOK) or about 100 million € (Finans Norge 2018). This does not include the rehabilitation cost of damage in water courses and on public infrastructure. Over the last 50 years, there has been an increase in the frequency and intensity of short duration rainfall (Sorteberg *et al.* 2018) and climate change will further enhance this. It is expected that

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precipitation-dominated catchments will experience an increase of flood frequency of up to 60% and that the challenges will be particularly pronounced in small, steep rivers and streams, as well as in urban areas (Hanssen-Bauer *et al.* 2015). This will have a significant influence on the design of infrastructure and the risk level and the risk assessments all Norwegian municipalities are required to carry out. Observations of floods in small, steep rivers are very sparse and extreme local precipitation is rarely captured by a coarse network of rain gauges, thus the basis for analyses and estimates necessary to estimate the risk from floods in such areas are very limited. As combinations of high water velocities and water levels can increase the risk acceptance level from a 200- to a 1,000-year return period (Ministry of the Environment 2008), the risk related to steep rivers is particularly relevant to study. In this context, extreme events like the Utvik flood can provide useful insights into how extreme such natural hazards can also be at these latitudes.

Can the observations carried out during and after the flood in Utvik be used to estimate the discharge and can this, based on a precipitation-runoff model, be used to estimate the intensity of the precipitation and finally reveal how extreme this event was in a Norwegian and international context?

Following Borga *et al.* (2008), there are several ways to approach a post-event analysis of floods. Traces left by water, such as erosion and deposition, images and reports from eyewitnesses and other observations, not only along the flooded water courses, but within the hit region, can provide valuable information for quantifying the peak discharge and the extent of the flood, especially if these can be combined with hydrodynamic 1 or 2D modelling of flow over a dam or through a culvert. They also suggest use of radar data and rain gauge observations in the region combined with mesoscale meteorological modelling and distributed hydrological modelling. They state that successful implementation of such flash-flood response surveying methodology could transform our understanding of extreme floods and provide significant visibility for the scientific community.

In this paper, several of the methods described by Borga *et al.* (2008), adapted to the available observations, are used to document and assess the magnitude of the Utvik flood.

The aims of this paper are: to use the *in-situ* and post-observations of the flood and flow over a dam crest together with hydraulic 2D simulations to estimate the discharge at culmination; to use rain gauge and radar observations together with hydrological modelling, observed lightning and eyewitness reports to assess how this event occurred, how extreme it was and to recreate the flood hydrograph and estimate the rainfall intensities causing the event; finally, to compare the peak unit discharge estimate for this flood to unit discharges of observed and reported floods in Norway over the last decade and to floods reported in southern Europe since 1950.

Norwegian floods

Based on historical sources, Lars Roald (2013) provides an overview over major floods back to the 14th century. He mainly describes impacts and not discharges. Only at a few locations are flood discharges given. Thus, it is difficult to use these in a quantitative analysis without further knowledge and assumptions. Only since 2008, all floods observed at gauging stations in Norway and with a return period higher than ten years, have been systematically documented (Figure 1). In November 2009, south-western Norway was exposed to high precipitation and several rivers flooded (Haddeland 2009). The highest observed precipitation was 143 mm over less than 12 hours. The highest unit discharge was 2.9 $m^3/s,km^2$. Locally reported damage indicate that in some areas the intensity probably was higher (Aftenposten 2009). In October 2010, a heavy rainfall event following several days of precipitation caused flooding in numerous rivers in the south of Norway, and the highest observed unit discharge was 3.04 $m^3/s,km^2$ (Pettersson 2010). A rain event of up to 110 mm in 24 hours affected central Norway in August 2011 and caused, at some locations, 100-year floods (Pettersson 2011). The highest observed unit discharges was 1.3 $m^3/s,km^2$. In June 2011, snowmelt combined with heavy rain caused a flood with severe consequences in Kvam (NRK 2011). This event was not quantified, but is a major flash flood in a Norwegian context. The same location experienced a similar flood in 2013. Later in the summer of 2011, another event hit southern Norway with observed precipitation up to 97 mm over 2 days, and caused flooding

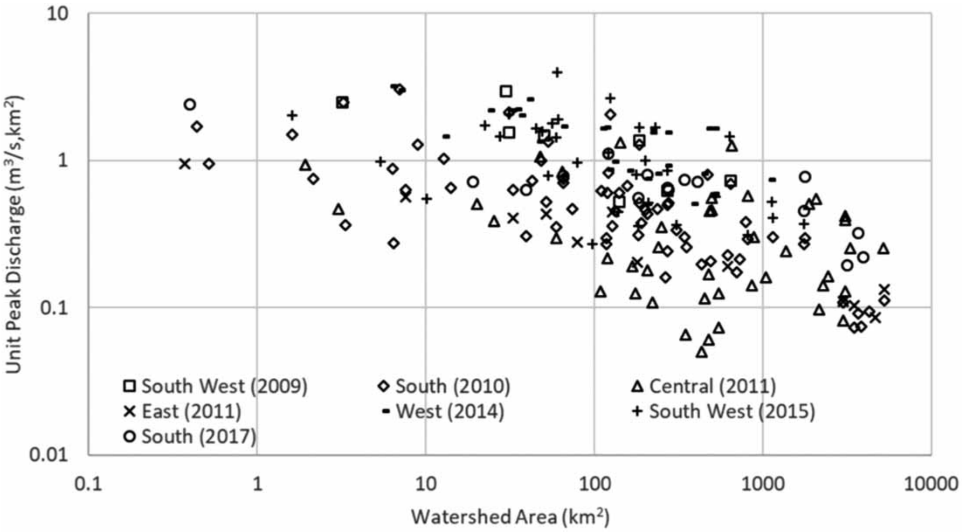


Figure 1 | Scatterplot of unit peak discharge (m^3/s,km^2) from registered flood events in Norway since 2008 versus watershed area (km^2) and grouped by region and year.

in regions with the highest registered unit discharge of 0.95 m^3/s,km^2 (Haddeland 2011). In October 2014, precipitations of 200 to 300 mm over 2 days caused severe flooding in west Norway. Damage to over 1,000 properties was reported and there was considerable damage to infrastructure (Langsholt *et al.* 2015). The highest observed unit discharge in this event was 3.2 m^3/s,km^2. In December 2015, south-western Norway was again exposed to floods with severe consequences. Up to 190 mm of precipitation over 24 hours was recorded and the highest observed unit discharge was 4.0 m^3/s,km^2 (Holmqvist 2016). A precipitation of 300 mm over 3 days and up to 173 mm over 24 hours in October 2017 caused flooding in south Norway, with a unit discharge of up to 2.4 m^3/s,km^2 and damage to 3,300 properties and reported repair costs of over 500 million NOK (Langsholt & Holmqvist 2017).

Stenius *et al.* (2015) compiled the maximum observed streamflow from Norwegian gauging stations with catchments smaller than 50 km^2 (Figure 2). The unit discharge shows a wide variability, ranging from 0.15 m^3/s,km^2 to 5.3 m^3/s,km^2. The highest unit discharge is observed in east Norway, but the highest average and variability is in west Norway.

All these floods have been possible to study quantitatively as they all cover gauged catchments. However, flash floods are characterized by intense rainfalls affecting small areas (Barredo 2007) and taking place very locally where there are, in most cases, no observations, as in Utvik and

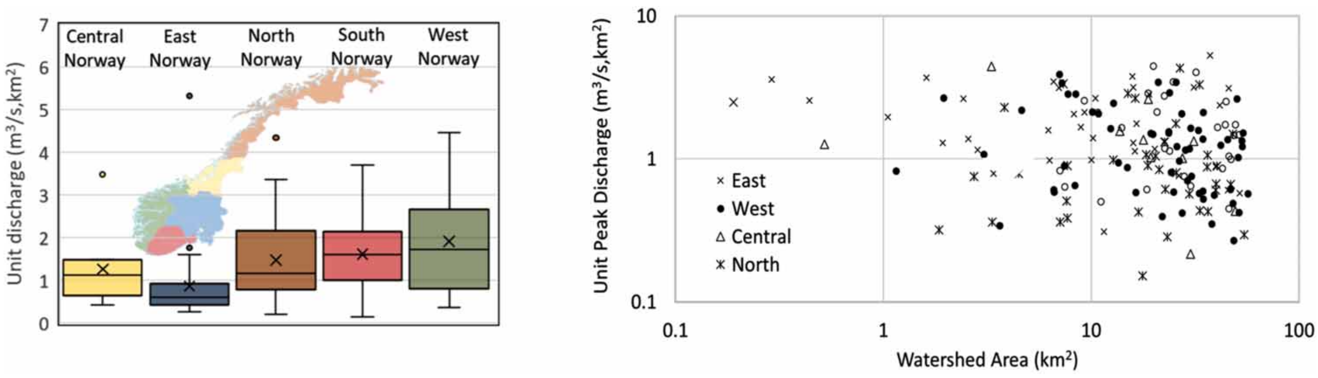


Figure 2 | Unit discharge in Norwegian catchments smaller than 50 km^2, compiled from Stenius *et al.* (2015).

Kvam described above. Since the observation network of precipitation and streamflow is usually too sparse to capture local flash floods and the flood generating precipitation, it is most likely that several of the events described above can have been far more extreme locally than the documentation indicates. In this respect, the event at Fulufjället in central Sweden is a rare exception in Scandinavia, not only in extremity, but also how well this was documented (Vedin *et al.* 1999). They investigated the meteorological situation causing the event and found that the precipitation was close to 400 mm over 24 hours and that the event had a return period of 10,000 years. Based on their observations, Lundquist (2000) estimated the peak unit discharge for this event to be 9 m^3/s,km^2.

European flash floods

Even in southern Europe, where flash floods annually cause close to 60 casualties, flash floods are a poorly understood and documented natural phenomenon (Gaume *et al.* 2009). Barredo (2007) studied 47 major flood events from 1950 to 2006 in the European Union, Bulgaria and Romania based on casualties and direct damage. Twenty-three of these are characterized as flash floods. He concludes that major floods have become more frequent and the damage has increased in the last decades prior to the study. Gaume *et al.* (2009) compiled data to develop a catalogue that includes the most extreme flash flood events registered between 1946 and 2007. Their collection consists of 550 extreme flash floods affecting catchments smaller than 500 km^2 in southern Europe. Based on these data, they found envelope curves for the peak unit discharges as a function of area that summarizes floods in the studied regions. Building on this study, Marchi *et al.* (2010) examined more closely the control of the watershed physiography and channel network on the flood response for a selection of the floods. In their study, they characterized initial soil moisture status, climate and the river response to identified extreme flash flood events representative of different hydro-climatic European regions, and characterized the morphological properties of the catchments, land use, soil properties and geology. The unit peak discharges they reported are in the range around 0.4 m^3/s,km^2 to about 20 m^3/s,km^2. They found an envelope curve that was in accordance with Gaume *et al.* (2009) (Equation (1)):

$$Q_u = 97.0 \cdot A^{-0.4} \quad (1)$$

where Q_u is peak discharge in m^3/s,km^2 and A is catchment area (km^2).

Moreover, Parajka *et al.* (2010) studied floods across the Alpine-Carpathian range (from France to Romania) and found support for a spatial and temporal clustering of floods. They suggest that extreme events in this region are often produced by one main mechanism – extreme storms during southerly circulation patterns. Bárdossy & Filiz (2005) found similar tendencies in the northern Alpine region.

The study area and the flood event

Utvik is a small village of about 400 inhabitants located at 61.8°N, 6.52°E, with the river Storelva passing through the centre of the village, flowing northwestwards and with its tail waters in the fjord (Figure 3, left). Storelva has a watershed of 25 km^2 ranging from 0 to 1,553 masl where about 25% of the landcover is forested, 62% is open alpine landscape, about 5% is marsh and 3% is glaciated. The soil types are mainly moraine deposits (Figure 3, right). The river is steep, with an average gradient of 12% and a maximum of 18%.

For the normal period 1961 to 1990, the average yearly precipitation is estimated to be 1,300 mm with 430 mm during the summer months (1 May to 30 September). The average yearly temperature is 2.3 °C, with July being the warmest month with an average of 8.7 °C. The average flow in Storelva is estimated to be about 1.6 m^3/s or 65.3 L/s,km^2 (Nevina 2018).

It started to rain heavily from about 4 a.m. on the morning of 24 July 2017 and continued with varying intensity until around 2 p.m. in the afternoon. The intensities were highest in the morning and in the upper part of the catchment. Following the warmest day of the summer, the discharge in Storelva was initially very low, but grew rapidly from 6 a.m. and culminated some time between 8 and 9 a.m. During this period, Storelva shifted its course at several

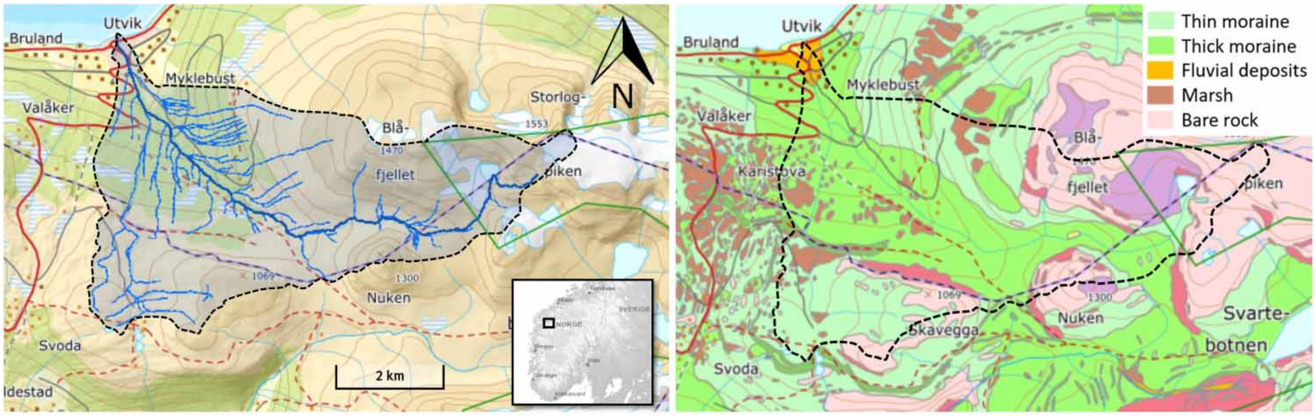


Figure 3 | Storelva watershed and watercourses are presented in the left panel. Land surface types are pictured in the right panel (NGU 2019).

locations, eroded away the county road, a bridge, and left the village isolated (Figure 4).

The total cost of damage to private property due to the flood was estimated to be at least 7 million € and the repair cost of the affected road was estimated to be at least 5 million € (Sunnmørsposten 2017). In addition, there were large costs in rehabilitating and securing the watercourse. Also, local businesses incurred the loss of millions € due to the closing down of the road (Fjordingen 2017). A 100-year-old hydropower station was also destroyed. The rebuilding of this and the loss of income is severe. Additionally, comes all the intangible costs of the devastation the flood caused to the local community, i.e., losing the historical value of several hundred-year-old buildings.

METHODS AND DATA

Hydraulic modelling and data for estimation of the peak flood discharge

Storelva is an ungauged river and, even though traces of the maximum water level during the flood are visible at several locations, it is challenging to estimate the culmination discharge since the river is steep and the topography makes it

Figure 4 | Overview picture showing the new watercourse and damage caused by the flood in Utvik (*source*: Hallgeir Vågenes, VG 2017).

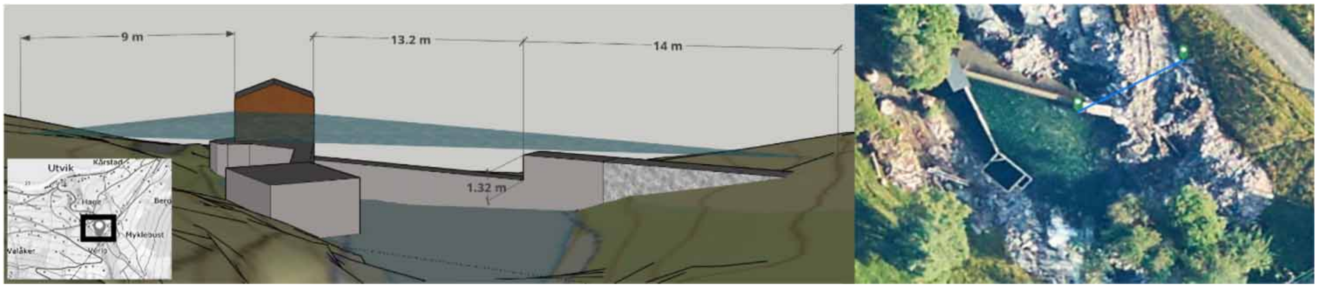


Figure 5 | Drawing (left) and picture (right) of the dam crest showing the eroded area and areal extent of the flood.

difficult to use hydrodynamic models. The best location to estimate the discharge is a dam crest (Figure 5) at about 86 masl, where it can be estimated by Equation (2):

$$Q_e = L \cdot C \cdot H_0^{\frac{3}{2}} \tag{2}$$

where Q_e is estimated discharge in m^3/s, L (m) is the length of the dam crest, C is the crest coefficient and H_0 (m) is the water level upstream of the dam crest at negligible flow velocities. For this short section of the river it is also possible to use a hydrodynamic model. During the flood, the main section of the dam was overtopped, and both sides of the dam crest were flooded as well. The water velocities over these sections are estimated by a 2D hydrodynamic model.

As displayed in Figure 5 (left), the dam crest is 13.2 m and observations showed that the river extended about 14 m to the right of the main crest and 9 m to the left. The maximum water level behind the dam crest was estimated based on the damage and traces of the flood on the wall of the aforementioned building at the left side of the crest (Figure 6) and traces in the terrain along the riverbanks upstream of the crest (Figure 5).

At maximum discharge, the water velocity upstream of the dam crest was significant. To account for this, the velocity has to be transformed into kinematic energy using the relation $v^2/2\,g$ – where v (m/s) is the velocity upstream of the crest and g (m/s^2) is gravity, and added to the potential energy, H_0, in Equation (2). The velocity upstream is estimated using Manning's equation for open channel flow, $v = M \cdot R^{2/3-} \cdot I^{1/2}$, where M is Manning number (m$^{1/3}$/s) and a measure for river bed roughness (often also given as 1/n), R (m) is hydraulic radius and I (m/m) is gradient of the river. As the picture in Figure 6 shows, the flow over the crest is highly turbulent and together with a high gradient, a river bed varying from bare rock, course gravel and large stones, as well as with vegetation at the banks at high water levels, this makes water velocities difficult to estimate (Yochum *et al.* 2012).

To validate the calculations, a 2D hydrodynamic model was established for the site in Hec-Ras v5.0 (Brunner 2016b). The terrain used in the model is based on high resolution lidar measurements from after the flood (Høydedata 2019). The 2D simulation flow area (Figure 7) was selected to ensure stable inflow conditions. The gradient within the area is lower than 10%, the selected grid cell size was

Figure 6 | Illustrated water over the crest level, and picture of upstream of the crest and of the flow over the crest during the event.

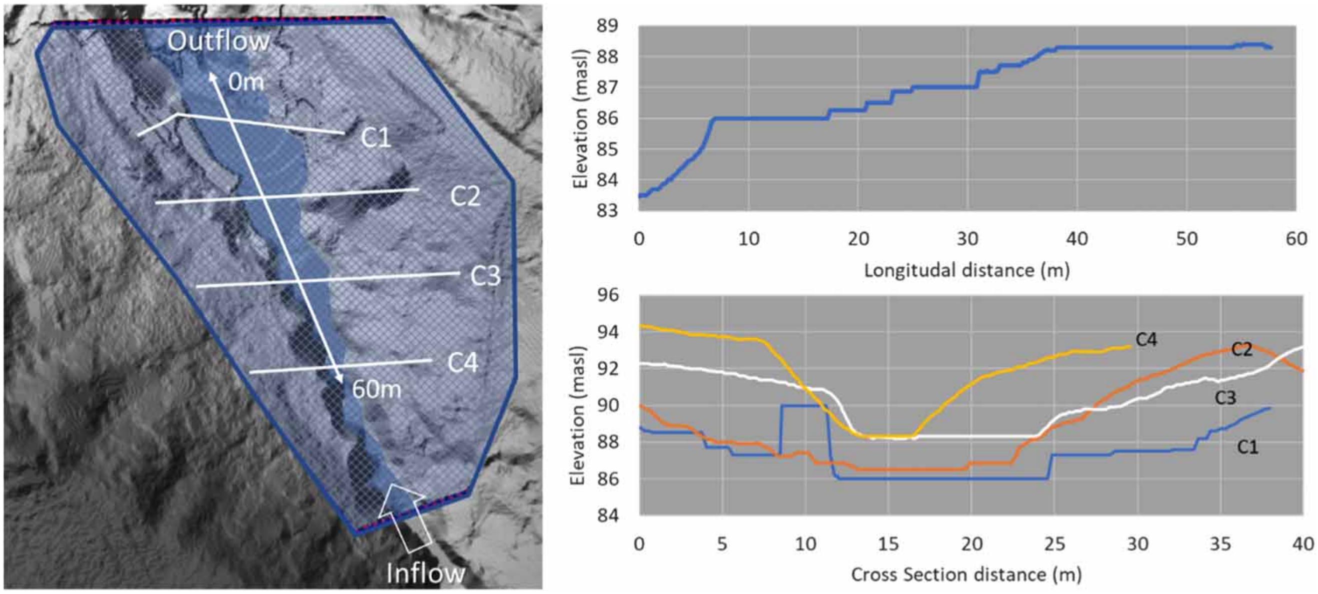


Figure 7 | 2D flow area in Hec-Ras (left). Longitude cross section and cross sections of the river stretch (right).

0.5 m and the simulation steps were 0.1 second. This is within the recommendations given by Brunner (2016a) for stable simulation conditions. The upstream Manning numbers at the peak flow are not known but can be estimated by Manning's equation at known velocities and corresponding water depths. Recently, after the flood, the mean upstream surface velocity was measured (using floating devices) to about 2.5 m/s at a discharge of about 10 m^3/s (using Equation (2)) and a water level over the dam crest of 0.3 m and between 0.3 and 0.5 m upstream of the crest. The width of the channel was from 10 to 12 m. The gradient upstream of the dam crest is about 5% at normal discharges. This gives Manning numbers of 18 to 25. During the flood, the upstream depth was from 2.3 m at the dam crest to about 4 m further upstream, and the width was 25 m to 30 m. The additional flooded area compared to the situation at 10 m^3/s will have a higher roughness due to vegetation and structures at the riverbanks. Compared to suggested roughnesses in Chow (1959), Barnes (1969) and Yochum *et al.* (2014), a Manning number for the simulated river section should be between 10 and 20. A value of 7 is included in the analysis, but this is extremely low and representative for floodplains with high and dense vegetation. Even a value of 10 is very low for this river section, but due to high bed load transport this is more likely than a value of 7. The different Manning values are used in combination with different, but stable inflows. According to Pappenberger *et al.* (2005), the roughness parameter together with geometry has the highest impact on the hydrodynamic simulation results. Using high density lidar data for the geometry leaves the roughness parameter as the most uncertain parameter. By varying the Manning number for each tested inflow, it is possible to test the sensitivity to the roughness parameter and, thus, by comparing the simulated water levels at profile C1 (Figure 7) to the highest water levels during the flood, the uncertainty of the estimated discharge.

Methods and data for estimating the precipitation

Observations from precipitation gauges and weather radar show that the precipitation was very local (Figure 8). The highest 24-hour precipitation measured in a rain gauge was 87 mm at the NIBIO station (A) at Sandane (NIBIO 2019) about 18 km west of Storelva watershed and 55 mm at Innvik (B), about 5 km to the north-east. Whereas Kroken station (C) in Stryn, 9 km further north, observed 34 mm in the same period, 17 mm of these in the morning.

The 24-hour accumulated radar observation shows that the precipitation was concentrated over the upper part of

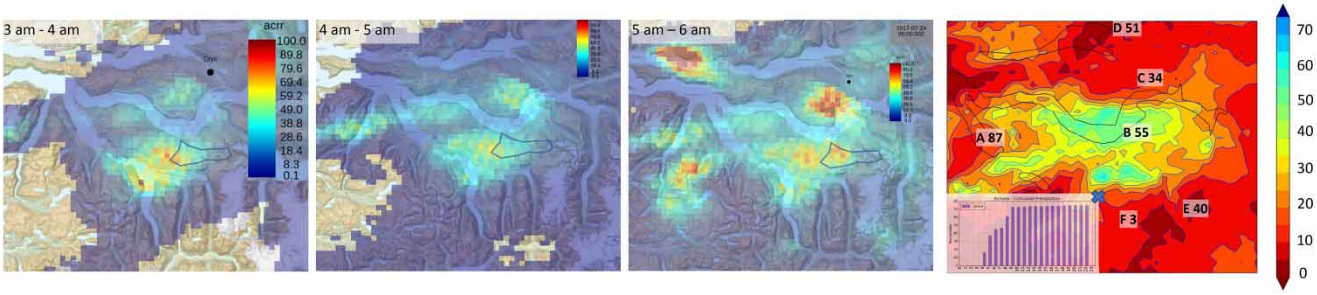


Figure 8 | Observed hourly precipitation from 3 a.m. to 6 a.m. by the radar in the three figures to the left and total observed over 24 hours by the radar and at meteorological stations in the region (right). The graph is accumulated values at the location of the cross (data acquired from Met.no).

the catchment (known as Utvikfjellet). Based on the values of the radar pixels (each of 1 km^2) covering Utvikfjellet, it is estimated that 72 mm of rain fell over 4 hours in the most intense areas. However, the rain gauge observations show that the accumulated radar values are too low. Kroken and the NIBIO station are the only ones with available hourly observations. Both showed that most of the precipitation occurred within 1 hour. The NIBIO station recorded 44 mm within 1 hour, 55 mm within 4 hours and 87 mm from 5 a.m. to 6 p.m. (Figure 9), whereas the radar pixel covering the same location gives 30 to 50 mm over the same period. At Kroken, 34 mm of rain fell compared to 10–20 mm from the radar. In Hornindal (D) and Olden (E), precipitation was 51 mm and 40 mm, respectively, while the radar shows 10 mm or less. The radar pixel covering Innvik shows 40 to 50 mm over 24 hours and this is in better accordance with an observed precipitation of 55 mm. Station F, Myklebustdalen, 5 km south of Utvikfjellet, measured only 3 mm which is coherent with the radar observations. Even though this station might be located in a rain shadow between high mountains and in a narrow valley, this observation shows how extremely local the precipitation was during this event.

Based on registered lightning (Figure 10), Bjart Eriksen, a meteorologist at Norwegian Meteorological Institute (Met.no), found that three heavy storm centres met at Utvikfjellet. The storm centres arrived at Utvikfjellet during the morning hours, first from west and north, later from south east, merged and were stable for some hours before dissolving. This indicates that the duration of the event at Utvikfjellet was longer and produced more precipitation than observations at stations in the region alone suggest. Observed precipitation and wind directions at meteorological stations in the region support this finding.

Observations of erosion along streams in the catchment and along the main river coincide with the radar observations and indicate that the precipitation was not evenly distributed

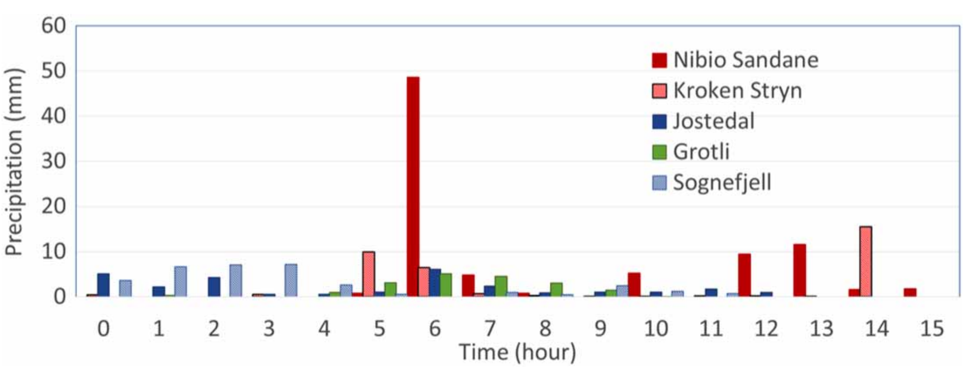


Figure 9 | Hourly observed precipitation at Nibio Sandane and at Kroken Stryn gauging stations and at stations with representative corresponding observed wind directions in Figure 10.

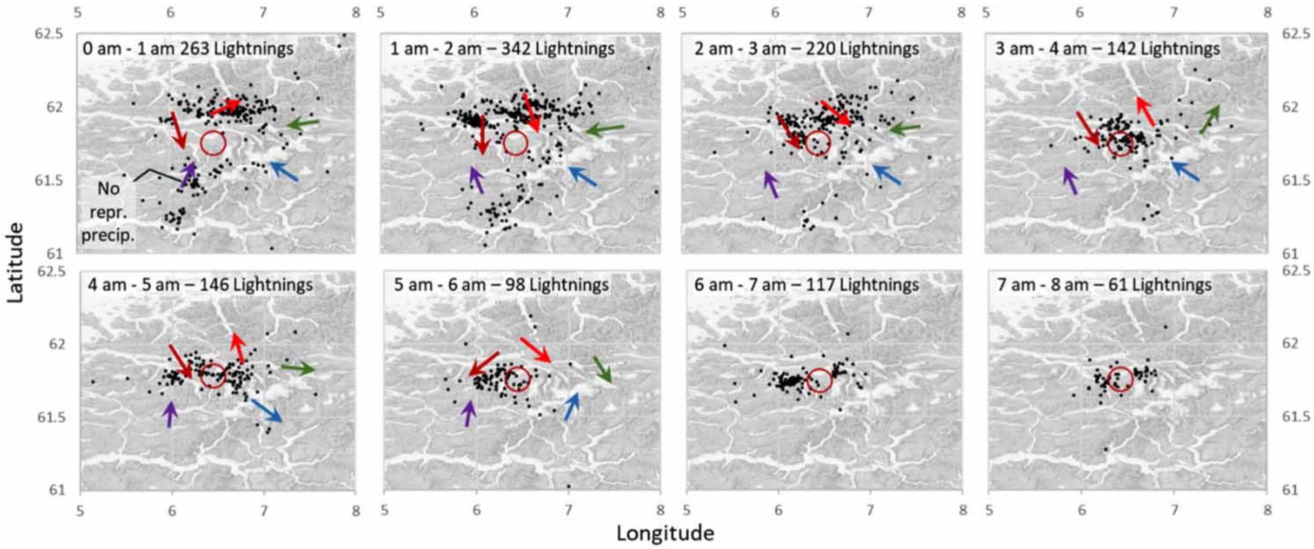


Figure 10 | Observed lightning on 24 July 2017. Arrows indicate wind directions at the location of the precipitation gauges in Figure 9. (Data from Frost.met.no and SeNorge.no).

over the 25 km^2 watershed, but rather was more concentrated in the upper part of the catchment and that this part of the catchment contributed the majority of the discharge.

Eyewitness observations in the hours between 8 and 10 a.m. revealed a 60 to 80 m-wide waterfall, not known to be observed before, in a mountain slope in the upper part of the catchment. This mountain is located where the storm centres are assumed to have coincided.

Rainfall-runoff modelling and data for estimating the peak discharge

A distributed hydrological model with a domain as shown in Figure 11 and a resolution of 0.5 km by 0.5 km was used to estimate the precipitation causing the flood. When considering the observed precipitation during the event and the topography, the observations at NIBIO Sandane and Innvik are considered the most representative for this event. These are interpolated to the domain using inverse distance weighting and an increase of precipitation with elevation of 5% per 100 masl. As the precipitation at Innvik is only a daily value, this is distributed into hourly values using the temporal precipitation distribution observed at NIBIO Sandane and Kroken. The radar images indicate that the precipitation came earlier and lasted longer at Utvikfjellet than at the surrounding precipitation stations. This is accounted for by extending the duration of the rainfall at Utvikfjellet by 2 hours compared

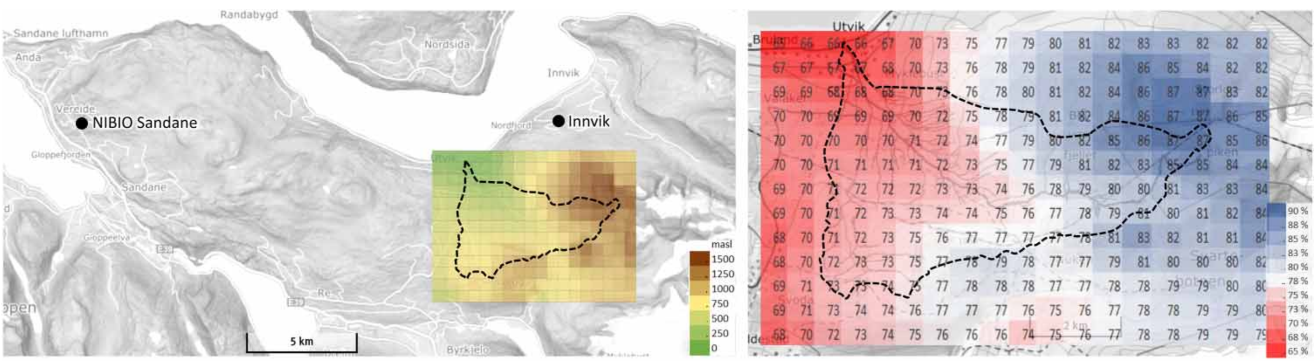


Figure 11 | Modelled region and a DTM with grid cells of 500 × 500 m overlapping the study area (left) and initial soil saturation before the event ranging from 65% to 90% (right).

to the durations at NIBIO Sandane and Stryn. The intensity of the rainfall for these hours are tuned until the timing of and discharge at culmination is in accordance with the estimated peak discharge and the observed course of the event.

The hydrological simulation for each grid cell is based on the principles summarized within the HBV model (Bergstrøm & Forsman 1973). The runoff from each grid cell is routed to and accumulated in downstream grid cells based on the slope of the grid cell. As there are no calibration data, only an estimated peak flow and a visually observed development and duration of the flood, the runoff parameters are based on previous regional model calibrations and recommendations in Stenius *et al.* (2015). The model was run on an hourly time step with a warmup period of two months.

RESULTS

Calculated discharge at the dam crest

As the dam crest was severely overtopped and there were no observations of the discharge, it was necessary to assume a velocity distribution out of the dam in order to estimate the peak discharge of the event. The assumption is based on Hec-Ras 2D simulations with discharges ranging from 130 to 270 m^3/s combined with Manning numbers ranging from 7 to 20. The results of the Hec-Ras simulations show that the velocities were reduced to 20% to 46% over the 9 m-long section at the left bank side and to 25% to 70% over the 14 m-long section at the right bank, compared to the velocities at the main section. The velocities at the main section simulated by Hec-Ras ranged from 4 to 8.9 m/s on average over the cross section C1.

Manning equation with Manning numbers, M, of 10 to 20 gives velocities of 5.3 to 8 m/s for gradients of 5 to 10%. By using Equation (2) with velocities v from 4 m/s to 9 m/s, depth d at the main section of 2.36 m and average velocity reductions from the Hec-Ras simulations of 60% and 66% velocity reduction at the right and left side sections, respectively, the discharges, Q_e, will be from 165 to 380 m^3/s (Figure 12). The sensitivity to uncertainties in depth and velocity distributions are tested by varying the depth at the main section with ±10% and the velocities at three sections in accordance with the variations found by the Hec-Ras simulations. This gave mean discharge values ranging from 172 m^3/s for the lowest estimated upstream velocities to 390 m^3/s for the highest and standard deviations of 9% to 6%, respectively (Figure 12).

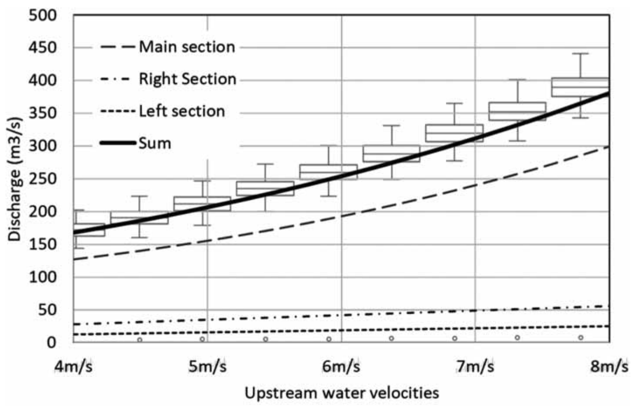


Figure 12 | Discharge (m^3/s) at different upstream water velocities (m/s) and for the different sections of the dam with main section depth of 2.36 m and 60% and 66% reduction of velocity at right and left sections, respectively. Box plot shows sensitivity to variations in depth and to velocities at the side sections.

Figure 12 shows that the major volume passes the main section when compared to the left and right sections and thus, that the sum discharge is not strongly influenced by uncertainty in the discharges at the side sections.

Hec-Ras gave simulated water levels at the left side of the dam crest between 1.93 m and 2.86 m for discharges between 130 and 230 m^3/s and Manning numbers between 7 and 20 (Figure 13). The right graph of Figure 13 shows that inflows larger than 160 m^3/s give water levels higher than 220 cm and that Manning number of 20 will give water levels of maximum 243 cm also for inflows up to 260 m^3/s.

The simulated water surface profile along the crest shows a significant variation between the different combinations of inflow and roughness factor (Manning number). The lowest roughnesses give the highest water velocities (Figure 14) and most variable water surface levels, up to 1.5 m, along the crest. Except from the highest discharge combined with the lowest roughness, the water levels over the crest were stable over time in the simulations.

The simulated flooded area in Hec-Ras for inflows from 150 to 230 m^3/s with roughness of $M = 10$ is shown in Figure 15. With some exceptions, the simulated water-covered area was in coherence with the area where traces of the flood and erosion due to high water velocities were

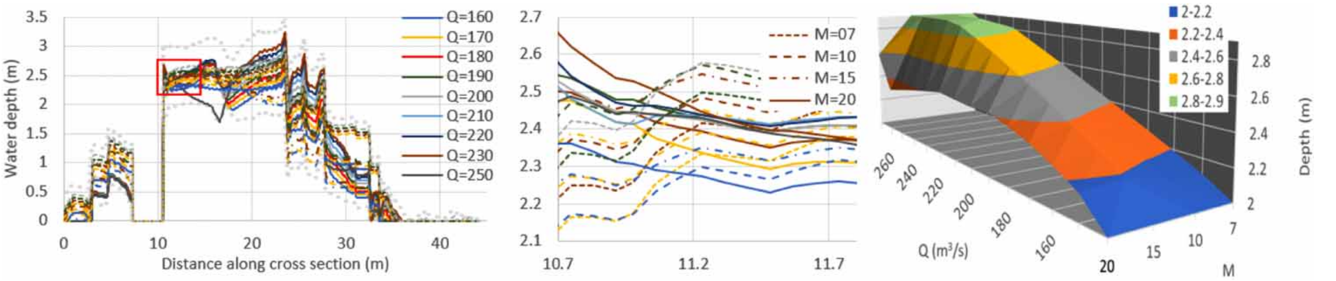


Figure 13 | Resulting water depths at dam crest from Hec-Ras simulation with discharges from 130 to 250 m^3/s and Manning number from 7 to 20. Left graph shows results that are within ±15 cm of observed water levels and maximum and minimum water levels for all simulations as the dotted grey line. The centre graph shows an enlargement of the marked segment. The right graph shows the relation between simulated depth at the left side of the crest, inflow in m^3/s and Manning number.

evident. The upper part of the simulated section is a narrow, tree-covered gorge (particularly at the left bank), that is not fully captured in the digital terrain model. This can explain the discrepancies at the left bank of the upper part of the river section.

At the right bank, there is an elevation where the erosion was significant. It is not likely that the water level in the dam was this high, but that an increasing upstream water level diverted a part of the flow in this direction which caused this erosion. None of the simulations were able to recreate this as erosion was not included, but the water level and velocities must have been high around this elevation. Simulations with $Q = 200$ m^3/s to 230 m^3/s gives about 50 to 80 cm higher water level around this elevation than simulations with $Q = 180$ m^3/s and lower.

Simulated precipitation and discharge

To reconstruct the hydrograph of floods in the range found plausible by the calculations and the Hec-Ras simulations, the areal precipitation needed to be from 80 to 140 mm in total over the three most intense hours (Figure 16, right). In the simulations, this was achieved by increasing the observed precipitation the hour before and the hour after the observed maximum. The base case with no increase of the precipitation gave a peak discharge of 143 m^3/s. A total increase of the precipitation from 14 to 50 mm over the 3 hours gave discharges from 164 up to 243 m^3/s. The increased duration of the rainfall is coherent with the indicated intensities and duration observed by the radar (Figure 8). The accumulated estimated 3-hour precipitation at Utvikfjellet is up to two times higher than precipitation accumulated from the radar data, but the difference is less than the difference between precipitation observed by rain gauges and by the radar. The gauges showed 1.5 to 5 times higher 24-hour precipitation than estimates from the radar pixels (1×1 km^2) covering the gauge locations.

The runoff generation and accumulation from grid cell to grid cell and finally to the water courses within the region is also coherent with field observations and where

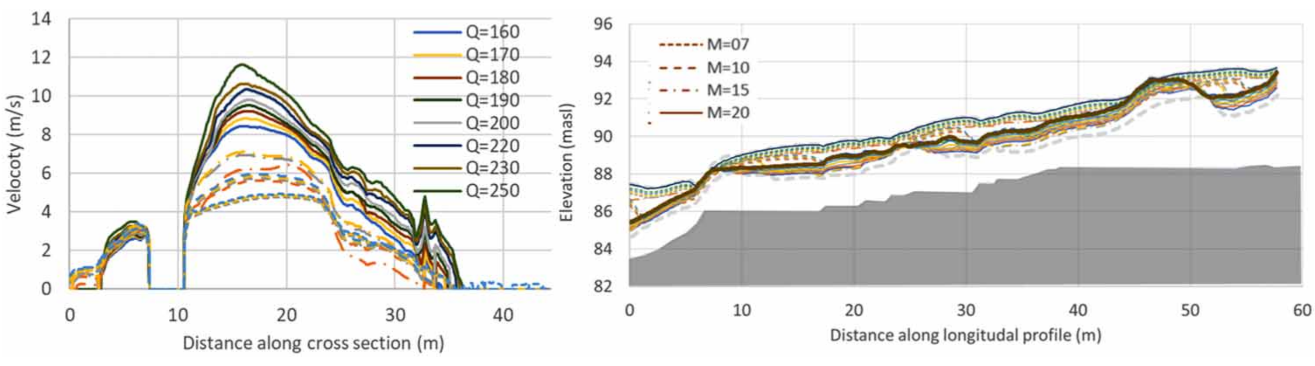


Figure 14 | Water velocities (left) and longitudinal profile of water surface profiles from Hec-Ras simulations. Type of line indicates Manning number used in simulations.

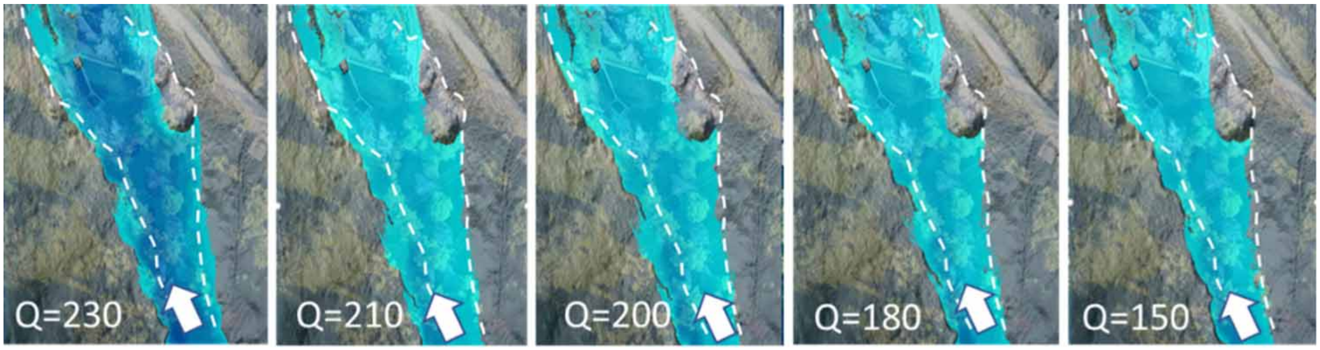


Figure 15 | Simulated water-covered area in Hec-Ras compared to areas with significant erosion observed.

damage due to flooding occurred. In addition to the damage along the main course of Storelva, there was significant damage along the two rivers, denoted a and b, east of Storelva catchment and along the tributary river (c) to Storelva (Figure 16, centre).

The damage was of the same order in the upper part of these rivers as further downstream. This indicates that discharge was relatively higher in the upper part of their catchments than the simulation shows. Another observation supporting the indication of locally very high rainfall intensities and runoff generation, is the observed presence of the waterfall in the mountain slope in the upper part of the catchment. The watershed generating the runoff for this waterfall is 0.15 km^2, with mostly bare rock and areas with thin soil layers. Visibility of a waterfall depends on how it is cascading and the discharge in L/s per meter waterfall (Simensen *et al.* 2011). The database of waterfalls (World Waterfall Database 2019) provides pictures, average discharge and width for different waterfalls and gives thereby an indication of discharge per meter waterfall versus visibility. The average discharge of some selected waterfalls comparable to the one observed at Utvikfjellet is about 200 L/s per metre width. To create discharges like this in this waterfall, it is necessary to have a precipitation of over 100 mm prior to the event over the concentration time of the drainage area. According to the definition of concentration time given by Stenius *et al.* (2015), this is less than an hour for this watershed. This indicates that the rainfall intensities in this area must have been extremely high. This can explain the severe local damage in the upper parts of these rivers.

Observations along the Storelva river and in its catchment indicate that the upper part of the catchment contributed to most of the discharge also for Storelva (Figure 17, left). Based on these observations and the accumulated radar observations, the major contributing area is estimated to be about 50% of the catchment. A discharge of 200 m^3/s and a contributing area in the range of 100% to 50% of the catchment, gives a unit discharge of this event from 9 m^3/s,km^2 to over 17 m^3/s,km^2. In the most intense areas, the unit peak discharge can have been as high as 20 m^3/s,km^2.

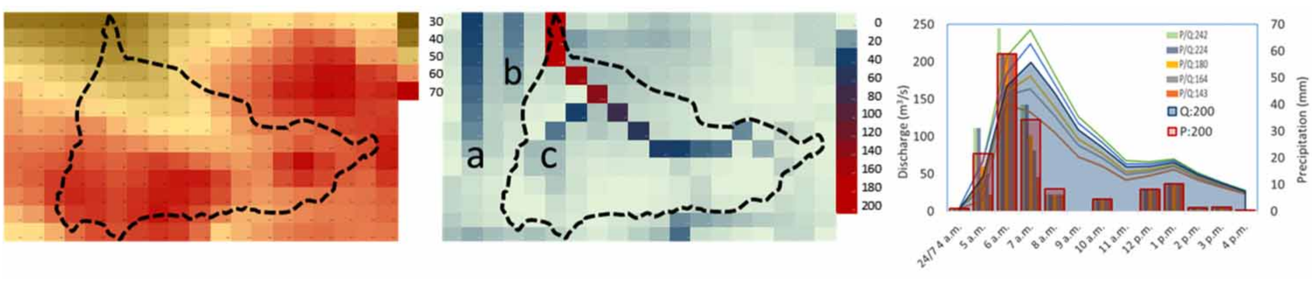
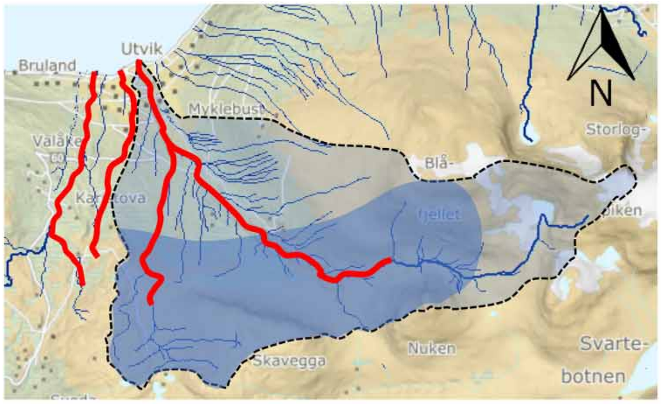


Figure 16 | Precipitation distribution (left) at maximum intensity (5–6 a.m.), maximum runoff (7–8 a.m.) (centre), and precipitation intensities for different simulated peak discharges with corresponding hydrographs (right).



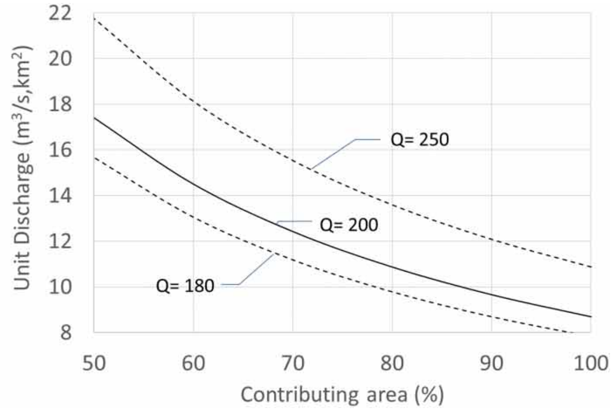


Figure 17 | River stretches with high erosion and the estimated contributing area are presented on the left-hand side, and peak unit discharge (m^3/s, km^2) depending on the contributing area (%) for culmination discharges of 180, 200 and 250 m^3/s on the right-hand side.

DISCUSSION

There are several uncertainties related to the calculation of the unit peak discharge for the flood in Utvik in July 2017. The dam crest is not ideal for the estimation as it is not perpendicular to the flow and, due to the high water level, the flow passes through sections without a defined crest. As the picture in Figure 6 shows, the flow was very turbulent, which makes it difficult to define maximum water levels and water velocities and as Figure 12 shows, the discharge estimates are dependent on the upstream water velocity. In addition, unknown Manning numbers and a significant sediment load and bed load at peak discharge influences also the estimates of water velocities (USDA 2007). However, even though the river stretches far outside its original course and the bed load is significant, with a Manning of 10 which is low for a river with a clear defined channel, some pools and a rough bed (Chow 1959; Barnes 1969; Yochum *et al.* 2014), an upstream slope between 5 and 10% and a depth of more than 2 m, it is not likely that the water velocity was any lower than 5 m/s. Even if there are uncertainties regarding the flow through the side sections, the calculations show that more than 70% of the flow is where the crest is well defined and, and even with very conservative assumptions on the upstream water level and water velocities, the discharge would need to be higher than 200 m^3/s.

The calculations using the dam crest formula (Equation (2)) give discharges that are coherent with the Hec-Ras simulations. According to Pappenberger *et al.* (2005), the uncertainties of hydrodynamic simulations are mainly related to the representation of the topography and the roughness, and according to Brunner (2016a), the 2D simulation in Hec-Ras is reliable at slopes lower than 10%. The slope is between 5 and 10% for the actual river section, the topography is detail mapped by lidar and the sensitivity to roughness is tested with Manning numbers from 7 to 20. For inflows of 160 to 250 m^3/s Hec-Ras gave water levels of ± 15 cm compared to the observed depth at the same section of the river. As Figure 6 shows, there is significant damage higher up at the wall than the indicated maximum water level during the flood. Furthermore, the erosion extends higher up at the riverbanks than the simulated water levels. It is therefore likely that the water level at culmination used to determine the discharge is conservative. Compared to pictures of reference rivers for roughnesses (Barnes 1969; Yochum *et al.* 2014), the roughness of the simulated river section is most likely in the range 10 to 20, which gives upstream velocities higher than 5 m/s. Hec-Ras gives velocities from 5.39 to 6.25 with these roughnesses. From Figure 12 this gives discharges from 223 to 267 m^3/s. The sensitivity to water level and velocity reductions at the side sections indicate that these estimates can vary with up to $\pm 9\%$. As the water level estimate used in the dam crest formula and comparison with Hec-Ras simulations is conservative, the upper range of the confidence interval, indicated in Figure 12, is more likely than the lower, at least for the lowest probable discharges.

Also, the rainfall-runoff simulation supports a peak discharge higher than 200 m^3/s. The radar images show that the duration and intensity of the rainfall was higher at Utvikfjellet than anywhere else in the region. The registered damage in the region due to flooding also indicates this. Based solely on the observations at rain gauges and a normal increase in precipitation due to elevation, the peak discharge reached 143 m^3/s. A rainfall duration and intensity more coherent with site observations and in accordance with the radar observations, give peak discharges higher than 200 m^3/s. To give a peak discharge over 200 m^3/s and a duration in accordance with the observed course of the event, the areal precipitation had to be at least 60 mm in the most intense hour and 114 mm over 3 hours. In the upper part of the catchment, the intensity was up to at least 144 mm over 3 hours. For the simulations giving peak discharges of 230 m^3/s, the areal precipitation was over 130 mm and the highest intensities up to 170 mm over 3 hours. Field observations and observed damage along rivers show that the rainfall and runoff generation was more concentrated than the simulations suggest. This indicates that the rainfall intensity in the area giving the major contribution to the flood, can have been even higher than the highest simulated intensities.

According to the IDF curves for the region (Norsk Klimaservicesenter 2019), intensities between 114 and 170 mm over 3 hours is about three to five times higher than a 200-year return period rain event (P_{200}) for similar duration. How this extreme precipitation could occur is a question open for discussion, but it is reasonable to believe, based on wind directions in the region and observations of lightning in the hours prior to the flood, that three storm centres, each producing rainfalls of 40 mm/hour or more, merged at Utvikfjellet. This can explain the longer duration and higher intensities here than in the surrounding areas. Furthermore, post-processed rerun from MetCoOp Ensemble Prediction System shows a southerly located low pressure meeting a high pressure in the north and northeast (Figure 18), somewhat similar to the pattern reported by Parajka *et al.* (2010) and Bárdossy & Filiz (2005) that caused extreme floods across the Alpine-Carpathian range. This was also the case for the event at Fulufjället in 1997 (Vedin *et al.* 1999). The weather as they described it, with very warm humid air prior to the event, was also comparable to the weather prior to the event in Utvik.

The radar observations support that the most intense area of precipitation covered a limited part of the catchment and that the total rainfall during the event was at least 70 mm in this region. Comparing the radar images with

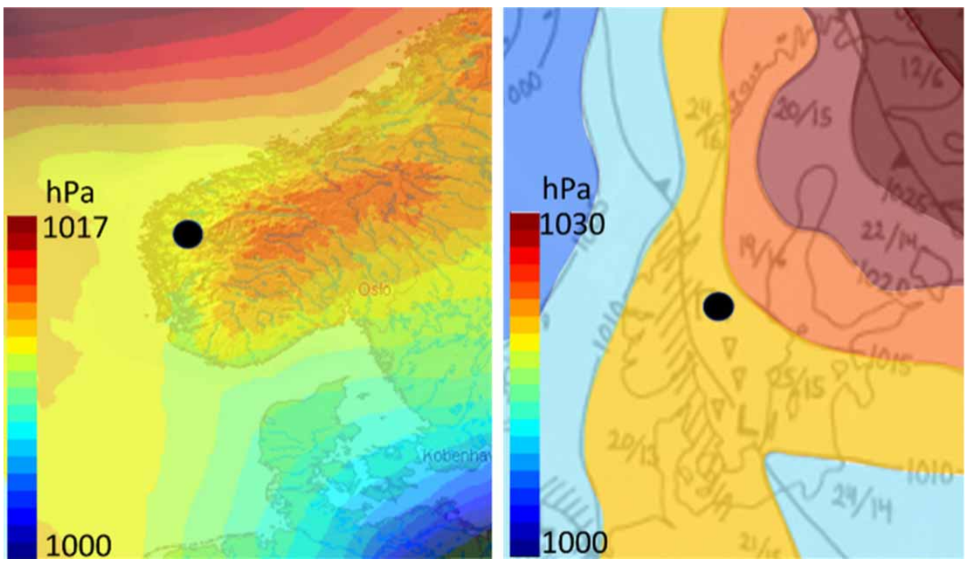


Figure 18 | Sea surface air pressure at 3 a.m. in the morning on 24 July 2017 prior to the Utvik flood to the left (Met.no 2019) and prior to the Fulufjället flood on 30 August 1997 from Vedin *et al.* (1999) to the right. The black dots indicate the location of Utvik and Fulufjället.

local observations confirms that the radar is underestimating the precipitation. Although the radar underestimates the intensity of the precipitation, it is able to locate the event quite well. The radar observations and the suggested extent of the contributing area based on observed extent of erosion along the river coincide quite well and reinforces the assumption of a contributing area down to 50% of the entire catchment. With a peak discharge between 200 and 250 m^3/s, this gives an estimated unit discharge from 9 to 13 $m^3/s,km^2$ if the entire area contributed up to 17 to 23 $m^3/s,km^2$ if the major contribution came from 50% of the catchment. In the most intense area, it will have probably been higher. This is significantly higher than any documented peak unit discharges in Norway so far and even higher than the peak unit discharge reported for the 22 km^2-large catchment at Fulufjället in 1997 (Lundquist 2000) that was estimated to be a 10,000-year event. Both these events are in the same range as peak unit discharges for extreme floods documented for southern Europe (Figure 19).

Even when taking the identified uncertainties into consideration, the findings from the flood in Utvik in 2017 suggest that previous observed peak unit discharges in Norway are low compared to what can, in fact, be expected. Although extraordinary claims require extraordinary evidence, all observations during and after the event indicate that this event is, beyond doubt, very extraordinary. Traces of the flood give a strong indication of the maximum flood level. Even with conservative estimates of this and the Manning coefficients, the peak discharge estimates become higher than 200 m^3/s and the corresponding peak unit discharge is in the range from 9 to 17 $m^3/s,km^2$. Hydraulic simulations support this conclusion. The most conservative estimate possible of the water level and velocity distributions would give discharges down to 160 m^3/s. Even this would give significantly higher unit discharges than previously observed in Norway. Radar images of the precipitation compared to rain gauge observations support the conclusion that the accumulated precipitation must have been at least 1.5 times higher than the 70 mm the radar gives at the most intense area of the catchment.

In a post-event flood frequency analysis, Q_{200} for Storelva in Utvik is suggested to be 140 m^3/s (5.68 $m^3/s,km^2$) and increased to 193 m^3/s (7.95 $m^3/s,km^2$) when including climate correction (Leine 2017b). However, an estimate of the areal precipitation causing a flood of this size is, according to the IDF curves for the region, at least two to three times higher than a 200-year return period rain event

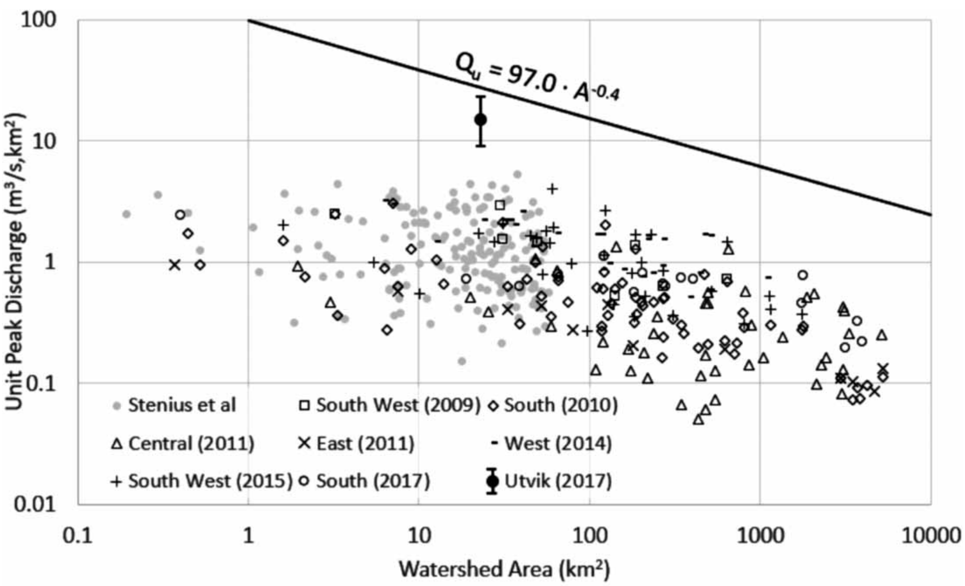


Figure 19 | Unit peak discharges observed in Norway compared to the estimated most likely range of unit peak discharges for the Utvik flood, including the envelope curve suggested by Marchi *et al.* (2010).

(P_{200}) for similar duration. This indicates that the Utvik flood event was significantly higher than a 200-year event. Prior to this event, Q_{200} for a neighbouring, hydrologically similar, catchment was estimated to be 2.82 m^3/s,km^2, and 3.95 m^3/s,km^2 including climate correction (Leine 2017a). Besides exposing the uncertainty of the Q_{200} estimates, this indicates also that the suggested Q_{200} for Storelva in Utvik is too high. Flood frequency analysis has significant impact on dimensioning and thus the cost of future infrastructure and also where people can live. Uncertainties like those identified in this case, illustrate the need of more information to base these analyses on to make them more reliable.

CONCLUSIONS

The Utvik flood is one of very few flash floods in Norway that are documented and quantified based on onsite observations during and after the flood combined with hydraulic and hydrological modelling. Analysis based on these observations and presented in this paper, shows that the discharge at the culmination of the Utvik flood most likely was in the range between 200 and 250 m^3/s corresponding to a unit discharge of 9 m^3/s,km^2 to 11 m^3/s, km^2. Assuming that the main contribution of the flood came from 50 to 100% of the catchment area, the peak unit discharge was from 9 m^3/s,km^2 to 22 m^3/s,km^2. Hydrological analysis based on gauge and radar observations tuned to the estimated peak discharge and observed flood propagation, shows that the areal precipitation causing the event probably was higher than 114 mm over 3 hours and between 140 and 170 mm in the most intense areas of the catchment. It is also found that the peak unit discharges for the Utvik flood are significantly higher than for previous floods observed at gauging stations in Norway and comparable to the most intense flash floods observed in southern Europe.

Floods like this have a high societal impact and this paper documents how extreme they can also become at these latitudes. Their impact is not only through the damage they cause, but also indirectly as they influence design criteria for infrastructure. In respect to how important but uncertain estimates of design floods (Q_{200}) are in rivers like Storelva, as also documented herein, this paper tries to point out that there is clearly a need for more information about floods in small, steep and fast responding catchments in order to have a better basis for future decision-making in regard to infrastructure and societal and economical optimized mitigation measures.

This paper may also indicate that we are experiencing a new hydrological regime that makes previous observations less relevant and thus new ones are more urgently needed.

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Discussion with Bjart Eriksen and Jørn Kristiansen at the Norwegian Meteorological Service (Met.no), as well as their input on precipitation, have been valuable for this analysis. Acknowledgement also to Adina Moraru who gave constructive feedback on the analysis and the presentation.

REFERENCES

Aftenposten 2009 *Flomkaos i Egersund* (Floodcaos in Egersund) Aftenposten, November 20, 2009. https://www.aftenposten.no/norge/i/jB5Jw/flomkaos-i-egersund

Bárdossy, A. & Filiz, F. 2005 Identification of flood producing atmospheric circulation patterns. *Journal of Hydrology* **313**, 48–57. https://doi.org/10.1016/j.jhydrol.2005.02.006.

Barnes, H. H. 1969 Roughness characteristics of natural channels. *Journal of Hydrology* **7** (3), 354. https://doi.org/10.1016/0022-1694(69)90113-9.

Barredo, J. I. 2007 Major flood disasters in Europe: 1950–2005. *Natural Hazards* **42** (1), 125–148. https://doi.org/10.1007/s11069-006-9065-2.

Bergstrøm, S. & Forsman, A. 1973 Development of a conceptual deterministic rainfall-runoff model. *Hydrology Research* **4** (3), 147–170. https://doi.org/10.2166/nh.1973.0012.

Borga, M., Gaume, E., Creutin, J. D. & Marchi, L. 2008 Surveying flash floods: gauging the ungauged extremes re-analysis of radar-based precipitation estimates of the flash-flood producing storm. *Hydrological Processes* **22** (18), 3883–3885. https://doi.org/10.1002/hyp.7111.

Brunner, G. W. 2016a *HEC-RAS River Analysis System 2D Modeling User's Manual*. US Army Corps of Engineers, Davis, CA. www.hec.usace.army.mil

Brunner, G. W. 2016b *HEC-RAS River Analysis System Hydraulic Reference Manual*. US Army Corps of Engineers, Davis, CA. www.hec.usace.army.mil

Chow, V. T. 1959 *Open-Channel Hydraulics*. McGraw-Hill, New York, USA. http://web.ipb.ac.id/~erizal/hidrolika/Chow

Finans Norge 2018 Norsk Naturskadestatistikk (Nask) (Natural Damage Statistics). https://www.finansnorge.no/statistikk/skadeforsikring/Naturskadestatistikk-NASK/. Last accessed 30 December 2019.

Fjordingen 2017 *Bestilte og betalar asfaltering i Utvik sjølv* (Ordered and paid for asphalt in Utvik at own initiative) Fjordingen, August 10, 2017. https://www.fjordingen.no/nyhende/2017/08/10/Bestilte-og-betalar-asfaltering-i-Utvik-sjølv-15136446.ece.

Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., Blaškovičová, L., Blöschl, G., Borga, M., Dumitrescu, A., Daliakopoulos, I., Garcia, J., Irimescu, A., Kohnova, S., Koutroulis, A., Marchi, L., Matreata, S., Medina, V., Preciso, E., Sempere-Torres, D., Stancalie, G., Szolgay, J., Tsanis, I., Velasco, D. & Viglione, A. 2009 A compilation of data on European flash floods. *Journal of Hydrology* **367** (1–2), 70–78. https://doi.org/10.1016/j.jhydrol.2008.12.028.

Haddeland, I. 2009 *Flommen på Sør-og Vestlandet november 2009* (The flood in South and West Norway November 2009) NVE Report 3–2009. http://publikasjoner.nve.no/dokument/2010/dokument2010_03.pdf

Haddeland, I. 2011 *Flommen Østafjells juli* 2011 (The flood in East Norway July 2011) NVE Report 9–2011 http://publikasjoner.nve.no/dokument/2011/dokument2011_09.pdf.

Hanssen-Bauer, I., Førland, E. J., Haddeland, I., Hisdal, H., Mayer, S., Nesje, A., Nilsen, J. E. Ø., Sandven, S., Sandø, A. B., Sorteberg, A., Ådlandsvik, B., Andreassen, L. M., Beldring, S., Bjune, A., Breili, K., Dahl, C. A., Dyrrdal, A. V., Isaksen, K., Haakenstad, H., Haugen, J. E., Hygen, H. O., Langehaug, H. R., Lauritzen, S.-E., Lawrence, D., Melvold, K., Mezghani, A., Ravndal, O. R., Risebrobakken, B., Roald, L., Sande, H., Simpson, M. J. R., Skagseth, Ø., Skaugen, T., Skogen, M., Støren, E. N., Tveito, O. E. & Wong, W. K. 2015 *Klima i Norge 2100. Kunnskapsgrunnlag for Klimatilpasning Oppdatert i 2015 (Climate in Norway 2015. Knowledge Base for Climate Adaptation Updated in 2015)*. Norwegian Environment Agency, Trondheim, Norway.

Holmqvist, E. 2016 *Flommen i Rogaland og Agder desember 2015* (The Flood in Rogaland og Agder December 2015) NVE Report 5–2016. www.nve.no.

Høydedata 2019 Høydedata. https://hoydedata.no/LaserInnsyn/ (accessed 18 December 2019).

Langsholt, E. & Holmqvist, E. 2017 *Flommen På Sørlandet 30.9–3.10.2017* (The flood in South Norway 30.9–3.10.2017) NVE Report 80–2017. www.nve.no.

Langsholt, E., Roald, L. A., Holmqvist, E. & Fleig, A. 2015 *Flommen På Vestlandet Oktober* 2014 (The flood at West Norway October 2014) NVE Report 11–2015 www.nve.no.

Leine, A.-L. Ø., 2017a *Flomberegning for Storelva i Utvik (087.4Z)* (Flood estimates for Storelva Utvik (087.42)) NVE Report 94–2017. www.nve.no.

Leine, A.-L. Ø. 2017b *Flomberegning for Storelva* (Flood estimates for Storelva) NVE Report 51–2017. www.nve.no.

Lundquist, D. 2000 What is an extreme flood and for whom? In: *The Extremes of the Extremes: Extraordinary Floods* (A. Snorrason, H. Finnsdottir & M. E. Moss, ed.). IAHS Press, Reykjavik.

Marchi, L., Borga, M., Preciso, E. & Gaume, E. 2010 Characterisation of selected extreme flash floods in Europe and implications for flood risk management. *Journal of Hydrology* **394** (1–2), 118–133. https://doi.org/10.1016/j.jhydrol.2010.07.017.

Met.no 2019 TdsStaticCatalog. http://thredds.met.no/thredds/catalog.html (accessed 26 December 2019).

Ministry of the Environment 2008 Planning and Building Act (2008), June. https://www.regjeringen.no/en/dokumenter/planning-and-building-act/id173817/

NEVINA 2018 NEVINA Nedbørfelt-Vannføring-INdeks-Analyse (NEVINA Catchment-Discharge-Index-Analysis). http://nevina.nve.no/. Last accessed 17 April 2019.

NGU 2019 NGU Løsmasser – Nasjonal løsmassedatabase (NGU Soil cover – National Soil Cover database). http://geo.ngu.no/kart/losmasse_mobil/. Last accessed 18 April 2019.

NIBIO 2019 NIBIO – AgroMetBase. https://lmt.nibio.no/agrometbase/getweatherdata.php (accessed 30 December 2019).

NOAA, NWS 2017 Flash Flooding Definition. NOAA's National Weather Service. 2017. https://www.weather.gov/phi/FlashFloodingDefinition

Norsk Klimaservicesenter 2019 Norsk Klimaservicesenter. https://klimaservicesenter.no/faces/desktop/index.xhtml (accessed 1 April 2019).

NRK 2011 - Skader for 200 millioner kroner – NRK Norge – Oversikt over nyheter fra ulike deler av landet [WWW Document]. https://www.nrk.no/norge/–skader-for-200-millioner-kroner-1.7671294 (accessed 20 August 2019).

Pappenberger, F., Beven, K., Horritt, M. & Blazkova, S. 2005 Uncertainty in the calibration of effective roughness parameters in HEC-RAS using inundation and downstream level observations. *Journal of Hydrology* **302** (1–4), 46–69. https://doi.org/10.1016/j.jhydrol.2004.06.036.

Parajka, J., Kohnová, S., Bálint, G., Barbuc, M., Borga, M., Claps, P., Cheval, S., Dumitrescu, A., Gaume, E., Hlavkova, K., Merz, R., Pflaundler, M., Stancalie, G., Szolgay, J. & Blosch, G. 2010 Seasonal characteristics of flood regimes across the Alpine-Carpathian range. *Journal of Hydrology* **394** (1–2), 78–89. https://doi.org/10.1016/j.jhydrol.2010.05.015.

Pettersson, L.-E. 2010 *Flommen i Sør-Norge oktober 2010* (The flood in South Norway October 2010) NVE Report 10–2010. www.nve.no

Pettersson, L.-E. 2011 *Flommen i Trøndelag august 2011* (The flood in Trøndelag August 2011) NVE Report 12–2011. http://publikasjoner.nve.no/dokument/2011/dokument2011_12.pdf.

Roald, L. A. 2013 *Flom i Norge. (Flood in Norway)*. Tom & Tom, Norway.

Simensen, T., Hiller, P. H. & Vaskinn, K. 2011 *Vassdrag, Vannføring og Landskap. (Water Course, Discharge and Landscape)*. NVE-Report 1-2011, Trondheim, Norway. http://publikasjoner.nve.no/rapport_miljoebasert_vannfoering/2011/miljoebasert2011_01.pdf

Sorteberg, A., Lawrence, D., Dyrrdal, A. V., Mayer, S. & Engeland, K. 2018 Climatic Changes in Short Duration Extreme Precipitation and Rapid Onset Flooding – Implications for Design Values. https://cms.met.no/site/2/klimaservicesenteret/rapporter-og-publikasjoner/_attachment/13537?_ts=163df95ff7b

Stenius, S., Glad, P. A., Wang, T. K. & Væringstad, T. 2015 Veileder for Flomberegninger i Små Uregulerte Felt. (Guide for flood calculations in small unregulated fields) NVE. www.nve.no

Sunnmørsposten 2017 Prislapp for Flommen i Sogn Og Fjordane: 120 Millioner Kroner. (Price tag for the flood in Sogn og Fjordane: NOK 120 million) Sunnmørsposten, Norway.

USDA 2007 Natural Resources Conservation Service-Stream Restoration Design (National Engineering Handbook 654). NRCS. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/water/manage/restoration/?cid=stelprdb1044707

Vedin, H., Eklund, A. & Alexandersson, H. 1999 The rainstorm and flash flood at Mount Fulufjallet in August 1997: the meteorological and hydrological situation. *Geografiska Annaler, Series A: Physical Geography* **81**(3), 361–368. https://doi.org/10.1111/1468-0459.00065.

VG 2017 Flere bygninger flyttet av flommen i Utvik: – Dette er forferdelig (Several buildings moved by the flood in Utvik: – This is terrible) VG, 24 July 2017. https://www.vg.no/nyheter/innenriks/i/LVG6V/flere-bygninger-flyttet-av-flommen-i-utvik-dette-er-forferdelig

World Economic Forum 2018 *The Global Risks Report 2018 – Reports – World Economic Forum*. Geneva, Switzerland.

World Waterfall Database 2019 *World Waterfall Database*. https://www.worldwaterfalldatabase.com/ (accessed 27 December 2019).

Yochum, S. E., Bledsoe, B. P., David, G. C. L. & Wohl, E. 2012 Velocity prediction in high-gradient channels. *Journal of Hydrology* **424–425**, 84–98. https://doi.org/10.1016/J.JHYDROL.2011.12.031.

Yochum, S. E., Comiti, F., Wohl, E., David, G. C. L. & Mao, L. 2014 Photographic guidance for selecting flow resistance coefficients in high-gradient channels. *Gen. Tech. Rep.* RMRS-GTR-323. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 91 p.

First received 19 April 2019; accepted in revised form 4 March 2020. Available online 13 April 2020