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The Correlation Between Extreme Wind and Flood Events in Unregulated River Basins

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The aim of this investigation is to improve the method for calculating design wind speed used for wave run up at water reservoirs. It is focused on the relation between extreme flood and wind events, and between wind speed and duration.

Water flow data from fourteen Norwegian river basins and wind data from neighbouring airfields are correlated. Some positive correlation is found for areas situated at the coastal side of the mountains where a further analysis is carried out. Extreme value analysis of the wind and flood series provides estimates of T-year events for each of the two variables. The best-fitted equation linking the square of the maximum 10-minute wind speeds to the daily mean water flow is established. It is observed that the expected wind speed during the 1000-year daily flood event has approximately one year return period. The risk for higher wind speed is high, so the effect of adding 1 and 1.65 standard deviations of the maximum wind speed is assessed, increasing the expected return period to 5 and 20 years respectively.

Continuous records of 10-minute wind speed are used to establish transfer coefficients from the extreme 10-minute value to durations of 20 minutes to 6 hours.

Introduction

The vertical distance from a reservoir level to the dam crest, *i.e.* the freeboard, is designed to accommodate a combination of flood rise and wave run up. The current Norwegian design code states that the 1000-year flood shall be combined with a wave run up caused by a wind speed of 30 m/s, or alternatively by a wind speed of 1000-year return period. The duration of the windstorm (30 m/s) is always taken to be long enough to generate maximum wave height in the reservoir.

This investigation was carried out in order to quantify the wind speeds to be expected during extreme flood events. There is a common feeling of a connection between high floods and strong wind in Norway, but no scientific analysis of the problem has been made. However, many time series of wind and water flow exist, asking for an analysis.

The new engineering standard for estimating design wind speeds is based on the extreme wind of 10 minutes duration. For generating a fully developed wave situation, the necessary wind duration may be far more than 10 minutes. Therefore, the second objective of this investigation is to suggest a method for predicting wind speeds of duration longer than 10 minutes. The complete work is reported by Harstveit and Jenssen (2002) and Harstveit (2002).

Table 1 – Correlation coefficients, *r*, between daily mean wind speed from wind stations and daily water flow from neighbouring flow stations. The *r*-values are given for all data, and for samples of data from given seasons and wind directions in which precipitation frequently occur, *R*-sec. The stations used in further analysis are marked (M).

		All-year		Autumn		Spring		Definitions		
Wind station	Flow station	All sec	R-sec	All sec	R-sec	All sec	R-sec	Autumn	Spring	R-sec[°]
Rygge	Høgfoss	0.15	0.18	0.13	0.23	0.08	0.14	Jun-Nov	Apr	170-220
Rygge	Moss dam	0.08	0.12	0.04	0.12	0.00	–0.04	Jun-Nov	Apr	170-220
Gardermoen	Kråkfoss	0.11	0.14	0.11	0.21	0.00	0.13	Jul-Oct	Apr-May	130-190
Fokstua	Dombås	–0.05	–0.16	0.04	0.01	–0.01	0.04	Aug-Oct	May-Jun	150-190
Sola (M)	Hauge bru	0.14	0.22	0.32	0.48	0.05	0.14	Aug-Nov	May-Jun	200-310
Flesland (M)	Røykenes	0.35	0.50	0.38	0.51	0.26	0.41	Jun-des	Apr-May	200-310
Værnes (M)	Høggås bru	0.10	0.15	0.27	0.46	0.08	0.06	Jul-Nov	May-Jun	260-290
Ørland (M)	Krinsvatn	0.17	0.31	0.34	0.49	0.22	0.29	Jul-Oct	Apr-Jun	230-310
Bodø (M)	Strandå	0.19	0.43	0.33	0.56	0.20	0.36	Jul-Oct	Apr-Jun	230-310
Andøya (M)	Åelv	0.23	0.31	0.38	0.41	0.15	0.33	Jul-Oct	May	210-310
Bardufoss	Malangsfoss	0.10	–0.02	0.14	0.17	0.01	–0.20	Aug-Sep	May-Jun	250-310
Tromsø-Langnes	Jægervatn	–0.13	–0.13	0.09	0.26	0.08	0.07	Aug-Sep	May-Jun	270-280
Banak	Lombola	–0.11	–0.07	0.03	0.12	–0.03	0.03	Aug-Sep	May-Jun	350-360
Alta	Lombola	–0.01	–0.10	0.05	0.13	0.00	0.00	Aug-Sep	May-Jun	310-330
Fruholmen	Lombola	–0.15	–0.17	0.05	0.13	–0.03	–0.12	Aug-Sep	May-Jun	260-280
Kirkenes	Karpelv	–0.01	–0.02	0.08	0.27	0.07	0.10	Jul-Sep	May-Jun	320-360

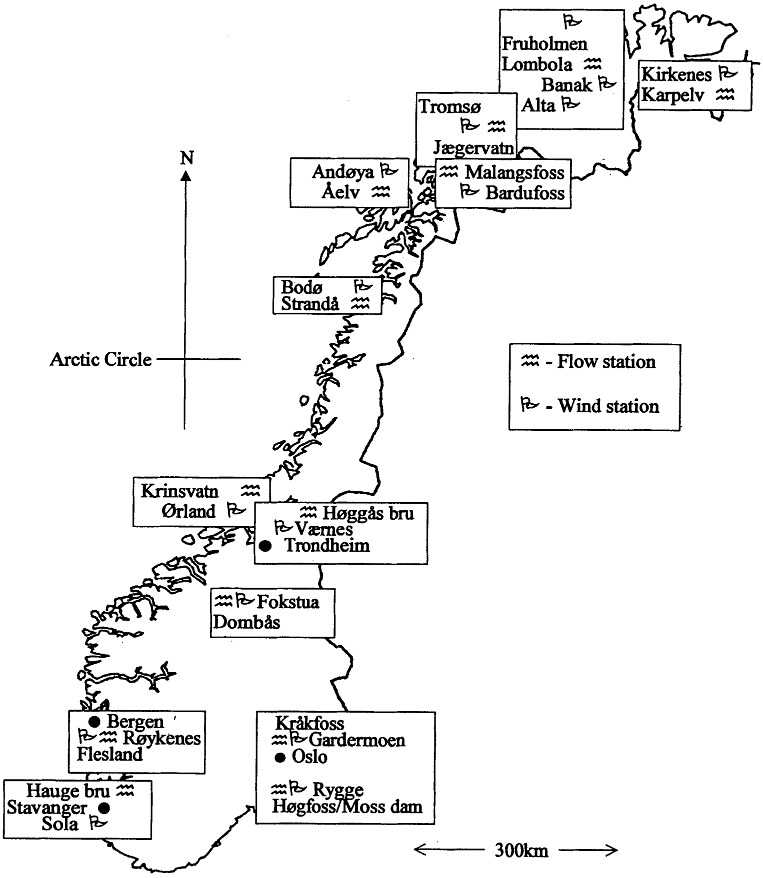


Fig.1. Location of flow stations and wind stations referred in text.

Correlating Water Flow and Wind Speed

Site Evaluations

Data from 14 water flow stations from different parts of Norway are compared to wind speed data from neighbouring wind stations, mainly airports, for the period 1957 – 2000, for some stations a shorter period was used (Fig.1).

Table 1 illustrates the low correlation between water flow and wind speed. However, the highest correlation coefficients are found for sites exposed to maritime, moist air at the western side of the mountains, marked (M) in Table 1. For those stations, $r\approx0.35$ for autumn (typically July-October/November), and $r\approx0.5$ if we sample only from westerly wind directions, typically 230-310°. The all-year value is lower due to the influence by snowmelt. This is best illustrated for the two high mountain fields, Ulla (Hauge bru) and Høggås bru, which show a distinct improvement from the all-year to the autumn season, due to large snow accumulation.

Table 2 – Recorded values of maximum 10-minutes mean wind speed (m/s) for the 10 days of highest water flow at the neighbouring flow station, ranked by the flow value. Average maximum wind speed, Uxm and average at the 10 episodes, Ux_{10H}. Average and scaled wind speed for daily flow above the 99.75 percentile, $Uxm|(Q \geq Q_{99.75})$.

	1	2	3	4	5	6	7	8	9	10	U_{Xm10H}	Uxm $(Q \geq Q_{99.75})$	Uxm	$Uxm|(Q \geq Q_{99.75})$ /Uxm
Sola	6.7	15.4	9.8	9.8	15.4	9.8	15.4	26.8	9.8	6.7	12.6	11.7	8.6	1.36
Rygge	16.5	10.8	13.9	7.7	4.1	7.7	15.4	4.6	8.7	8.2	9.8	8.7	6.5	1.34
Gardermoen	20.1	7.2	4.6	4.1	12.3	10.8	1.9	11.3	12.9	6.2	9.1	7.4	5.9	1.25
Fokstua	14.4	6.7	9.8	4.6	4.1	7.7	4.6	4.6	9.8	4.6	7.1	8.0	8.2	0.97
Værnes	12.3	7.7	9.3	12.3	9.8	9.8	9.8	6.7	4.6	9.8	8.4	9.3	8.2	1.14
Bardufoss	4.6	9.8	6.7	4.6	7.2	6.7	6.7	6.7	5.1	6.7	6.5	6.2	5.3	1.17
Tromsø-Langnes	6.2	12.3	6.2	5.1	9.8	12.3	5.7	9.8	6.2	9.8	8.3	8.9	8.2	1.08
Alta	7.2	5.1	6.2	9.3	6.7	7.2	6.7	4.6	8.7	15.4	7.7	7.7	8.6	0.90
Banak	9.3	6.2	7.7	10.8	4.6	9.3	6.7	4.6	18.0	6.7	8.4	8.4	9.1	0.93
Fruholmen	14.4	8.7	7.7	12.9	9.8	7.2	9.8	4.6	8.2	26.8	11.0	11.4	13.1	0.87
Kirkenes	12.3	8.2	12.3	7.7	9.8	17.0	12.3	12.3	15.4	10.3	11.8	10.5	9.2	1.14
Sola (autumn)	9.8	9.8	15.4	26.8	12.3	12.3	15.4	9.8	19.0	15.4	14.6	14.6	8.7	1.67
Flesland	9.3	9.8	8.7	9.8	7.7	15.4	12.3	19.0	9.8	9.8	11.2	11.3	7.1	1.59
Værnes (autumn)	12.3	12.3	6.7	16.5	22.6	11.3	15.4	11.3	12.3	12.3	13.3	12.3	7.7	1.60
Ørland	20.6	18.5	26.8	17.0	14.4	17.5	19.5	15.4	15.4	15.9	18.1	16.6	10.2	1.62
Bodø	15.9	17.0	22.6	15.4	19.0	19.0	15.4	10.8	19.0	15.4	17.0	17.0	10.2	1.66
Andøya	19.0	17.5	14.9	17.0	13.9	19.0	23.2	10.3	19.0	20.1	17.4	17.4	9.6	1.81

For inland stations, the transport of moist air combined with strong wind is less typical, and floods are most often connected to snowmelt. However, even in the autumn, there is less correlation between wind speed and water flow than at the coastal stations, with $r \approx 0.1$ (all sector) and $r \approx 0.2$ (R-sector).

Table 2 clearly shows that at the 6 stations having best correlation, the strongest winds occur at large water flows, $Uxm|(Q \geq Q_{99.75})/Uxm$ = 1.57 – 1.81, while 0.9 – 1.36 were found at the other stations. For Høggås bru (wind station Værnes) and Hauge bru (wind station Sola), only the autumn data are used due to the influence of the large snow storage at these sites.

Extreme Value Analysis

The extreme value analysis used here is from the Fisher – Tippett 1 distribution used by Gumbel (1958)

$$p(X>X_T) = 1 - p(X\leq X_T) = 1 - F(X_T) = 1 - e^{-e^{-\alpha(X_T-\beta)}} \tag{1}$$

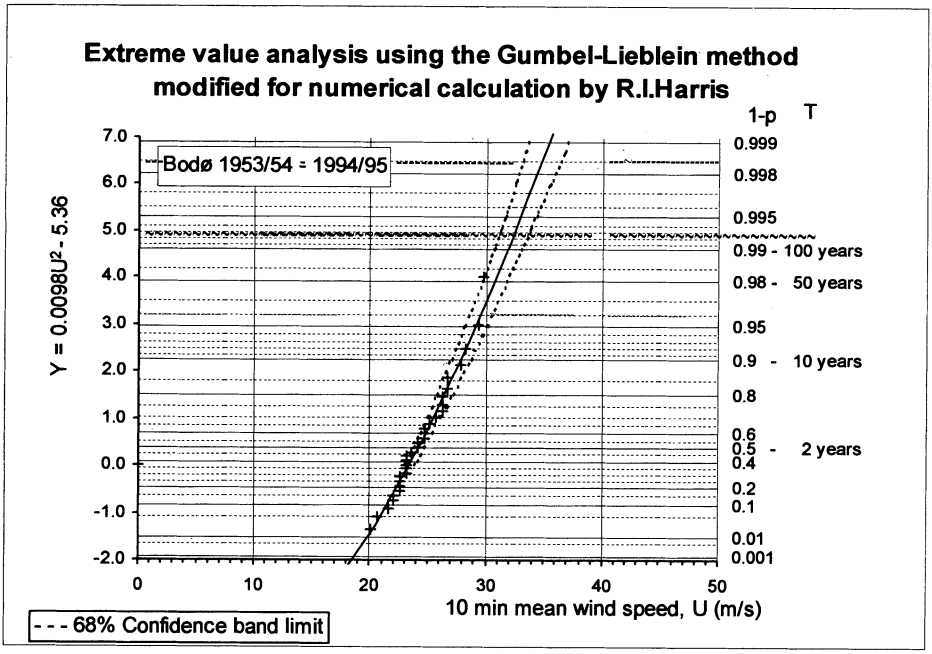
where X_T is the extreme T-years value of X; $X=Q$ (water flow), or $X=U^n$ (the wind speed). Cook (1982) showed that $n=2$ should be used for wind exposed stations in England where the parent distribution is the Rayleigh distribution, that is a Weibull distribution where the shape parameter, $n=2$. The authors have found the shape parameter at most of the exposed Norwegian wind stations to be close to 2, but for some of the stations it was closer to 1.5 (Sola, Flesland and Værnes airports), and correspondingly we have taken $X=U^{1.5}$ for those stations.

To optimize Eq.(1) the Lieblein technique (Lieblein 1974) is used, modified for numerical calculations by Harris (1996), and used by the author as a Visual Basic macro for Excel-sheet diagram visualization. The resulting diagrams for the flow stations, covering typically 70 years, except for the short record series at Andøya (21 years), were produced for all stations. For the wind stations data, existing data series from the period before 1994/95, covering typically 40 years were used. The probability diagrams for Røykenes flow station and the wind station Bodø airport are shown as examples in Fig.2, and the extreme values for the analyzed sites are summarized in Tables 3 and 4.

The Røykenes diagram illustrates a feature of the Lieblein method. The two "outliers" are not weighted as strongly as the less extreme situations. By a closer view of the data, we found that the water flow curve has not been calibrated for water flow above 40 m^{3}s^{-1}. This indicates that there are rather large inaccuracies connected to the highest values, and those values should not have too much effect on the curve. But also "outliers" due to extreme rare events happening to occur within the actual measuring period should not influence the results too much. Traditional automatic

Table 3 – Extreme value of 10 minutes mean wind [m/s] of 2 to 100 years return periods calculated for 6 wind stations by Gumbel's method using Lieblein's optimizing method.

		2 yrs	5 yrs	10 yrs	20 yrs	50 yrs	100 yrs
Sola	1958/59 – 1994/95	21.1	23.4	24.8	26.2	27.9	29.1
Flesland	1957/58 – 1994/95	18.6	20.6	21.9	23.1	24.6	25.6
Værnes	1965/66 – 1994/95	22.1	24.1	25.4	26.6	28.1	29.2
Ørland	1957/58 – 1994/95	26.1	28.7	30.4	31.9	33.8	35.1
Bodø	1953/54 – 1994/95	24.1	26.4	27.8	29.1	30.7	31.8
Andøya	1962/63 – 1994/95	25.0	27.8	29.5	31.1	33.0	34.4
Mean		22.8	25.2	26.6	28.0	29.7	30.9



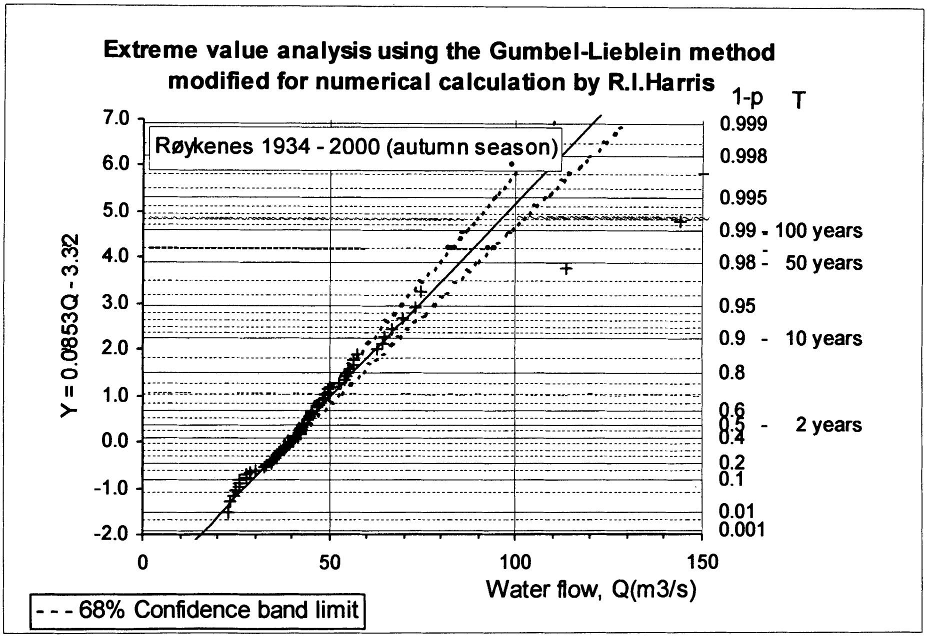


Fig.2. Probability for non-exceedance per year and the corresponding return period of wind speed and water flow.

Table 4 – Average, 70 percentiles and extreme values of 100, 200, 500 and 1000-year return period of daily mean water flow, calculated for 5 stations by Gumbel's method using Lieblein's optimizing method. Return periods of daily mean water flow scaled by the average water flow.

Station	Daily mean flow [m³/s]						Dimensionless flow			
	Mean	70p.	100 yrs	200 yrs	500 yrs	1000 yrs	100 yrs	200 yrs	500 yrs	1000 yrs
Hauge bru(autumn (1906-83)	31.8	35.7	414	455	511	552	13.0	14.3	16.1	17.4
Røykenes (1934-00)	4.9	5.2	93	101	112	120	18.9	20.6	22.8	24.5
Høggås bru(autumn) (1912-00)	18.7	144	276	303	339	366	14.8	16.2	18.1	19.6
Krinsvatn (1916-00)	13.0	13.1	267	290	321	344	20.5	22.3	24.7	26.5
Strandå (1916-81)	1.38	1.53	22.6	24.6	27.2	29.1	16.3	17.8	19.7	21.1
Åelv (1978-98)	2.27	2.57	27.3	29.9	33.3	35.8	12.1	13.2	14.7	15.8
Average							15.9	17.4	19.3	20.8

tuning using either the moment method, the least square minimizing method or the method of maximum likelihood all make the probability curve to respond more to the occurrence of an "outlier".

The Relation between Water Flow and Wind Speed

The floods at the western coast are related to heavy precipitation, which is connected to situations where moist air is transported to the Norwegian coast. Lifting the air requires energy because the air is usually weakly stable. The kinetic energy is proportional to U^2, where U is the wind speed. The relation between the wind speed and the water flow may thus be expressed by

$$Uxri = \frac{Uxi}{Uxm} \approx \frac{\sqrt{a'Qm}}{Uxm} \sqrt{\frac{Qi}{Qm} + \frac{b'}{a'Qm}} \equiv a\sqrt{Qri + b} \tag{2}$$

where *Uxri* is the average value of the maximum 10 min wind speed, *Ux*, scaled with the mean value, *Uxm*, at the i^{th} interval of the scaled water flow, *Qri*. Eq.(2) is only valid for intervals covering enough data to smooth out the noise. The coefficients a and b are calculated by the least square method for all daily water flow data above the 70 percentile value. (The wind conditions at low water flow are of no interest.)

In Fig. 3 two example plots of dimensionless water flow against dimensionless wind speed are shown. The figure shows that the curve is smooth when each data interval (plotted point) contains more than 30 data points (N), and that spread occurs when the number of data in the interval drops below 10.

For the *T*-year return flood event the expected value of the maximum daily wind speed, $Ux|Q_{T\text{years}}$ is easily calculated from Eq.(2), and is given in Table 5 for several

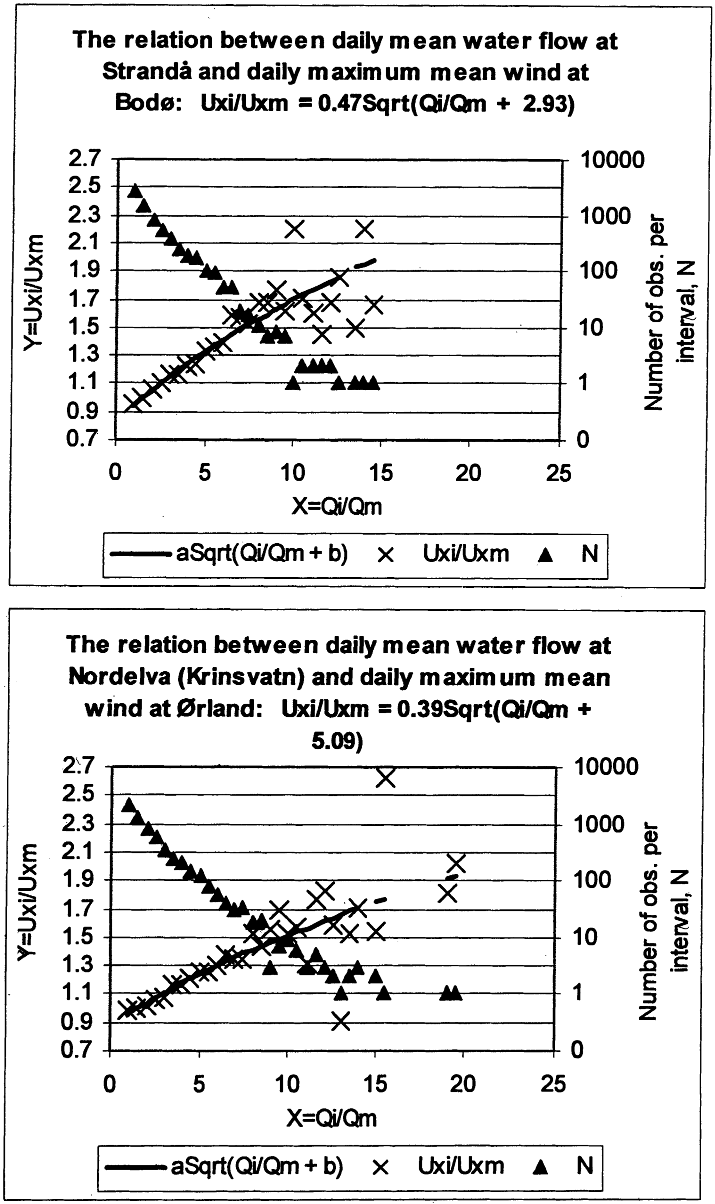


Fig.3. Plot of the dimensionless wind speed, *Uxi*/*Uxm* within each flow interval, *Qi*/*Qm* where *i*=1,2,3, *etc.* refer to values of *Qi*/*Qm*=1.0 (0.75-1.24), 1.5 (1.25-1.74), *etc.*, and the function, *a*· *Sqrt*(*Qi*/*Qm*+*b*). *N* is the number of data within each data interval. The average value of the data within each interval is used when plotting the observed *Uxi*/*Uxm* points.

Table 5 – Expected value and standard deviation of daily maximum 10-min mean wind speed (m/s) during flood events of 100 to 1000-year return period. Calculated upper limits of 84 and 95% confidence intervals during the 1000-year flood event, given as wind speed and as the corresponding return period regardless of the flood situation.

Wind station	$Ux\mid Q_{100yrs}$	$Ux\mid Q_{200yrs}$	$Ux\mid Q_{500yrs}$	$Ux\mid Q_{1000yrs}$	$\sigma_{Ux}, Q\geq Q70$	$Ux\mid Q_{1000yrs} + \sigma_{Ux}$	(84%)	$Ux\mid Q_{1000yrs} + 1.65\,\sigma_{Ux}$	(95%)
Sola (autumn)	18.5	19.3	20.2	20.9	3.9	24.8	10 yrs	27.3	40 yrs
Flesland	15.5	16.0	16.7	17.1	3.3	20.5	5 yrs	22.6	20 yrs
Værnes (autumn)	17.6	18.3	19.2	19.9	3.7	23.6	4 yrs	26.0	12 yrs
Ørland	20.1	20.8	21.7	22.4	4.7	27.0	3 yrs	30.1	10 yrs
Bodø	21.3	22.1	23.0	23.7	4.3	28.0	10 yrs	30.8	50 yrs
Andøya	18.4	19.0	19.9	20.5	4.4	24.9	2 yrs	27.8	5 yrs
Mean	18.6	19.2	20.1	20.7	4.1	24.8	5 yrs	27.5	20 yrs

return periods, T. The low correlation between Ux and Q, however, illustrates that the risk of higher wind speeds is rather high. See also Table 2 where the variable wind speed during the highest floods recorded is illustrated. The standard deviation of the maximum wind during high water flow should be a good measure of that variability. In the case of a normal distribution, the upper limit of the 84% confidence interval corresponds to adding 1 σ_{Ux}, and the 95% confidence interval to adding 1.65 σ_{Ux} to the expected value of Ux. Thus, the maximum wind speed in 84% and 95% of the T-year flood situations should be below those limits.

Tables 3 and 5 indicate that $Ux|Q_{1000yrs}$ roughly corresponds to a 1-year extreme value of the 10-minute wind speed regardless of the water flow situation, while $Ux|Q_{1000yrs} + \sigma_{Ux}$ corresponds to a 5 years value (2-10 years), and $Ux|Q_{1000yrs} + 1.65\sigma_{Ux}$ corresponds to a 20 years value (5-50 years).

This investigation was based on the wind and flow measurement stations having the best correlation, typically sites exposed to maritime conditions. For areas where the correlation between wind speed and water flow is less, the use of the results presented in this paper will lead to conservative estimates, but due to the lack of specific knowledge regarding extreme situations, caution is recommended.

Extreme Wind Durations

Continuous records of 10-minute wind speed from 5 exposed wind stations in Norway covering 1 to 4 years are divided into periods of 14 days and the highest value in each period is used. The material is also re-analysed giving corresponding maximum values of 20 to 50 minutes, and 1 to 6 hours duration.

We then calculate the average relation between the maximum wind speed of t

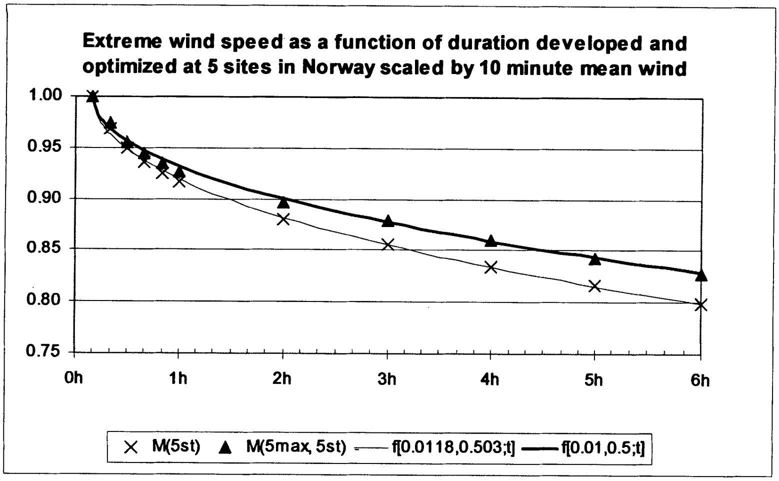


Fig. 4. Model tuning to the data for the mean maximum of each 14-day period M (5st) and the maximum of the five strongest wind storms, M(5max,5st) for five wind stations (5st).

minutes duration, Ux_t, and 10 minutes duration, $Ux_{10\text{min}}$, for each station. The maximum values are chosen in two ways. First, the highest values from each 14-day period were taken, giving an average relation during high wind speed. Second, only the five strongest values, independently chosen from the data set, but restricted to one t-value for each independent storm, were used.

The data points in Fig. 4 suggest that the extreme wind speed depends on the average time period according to the equation

$$f(c_1, c_2; t) = \frac{Ux_t}{Ux_{10\text{min}}} = e^{-c_1(t-10)^{c_2}} \tag{3}$$

where c_1 and c_2 are model parameters and t the time (min). For the five stations used, optimizing by the least square method gives c_1=0.0118 and c_2=0.503, $t \geq 10$ (min) when optimizing to an average of the maximum values over 14 days (M(5st)).

When using average values of the 5 strongest wind speeds (M(5max,5st)), slightly different values, close to c_1=0.01 and c_2=0.5, were found. Statistically, the last values should be somewhat less precise. On the other hand, we are looking for the situation during the most extreme situations, so c_1=0.01 and c_2=0.5 were chosen. Use of those numbers also means slightly less wind speed decrease with averaging time, consistent with a conservative design approach.

The model is verified by data from 5 stations (1996-2000), sited in somewhat different surroundings, and which were not used in model optimizing (Table 6).

Table 6 – Comparison of the highest wind speeds of duration 1, 3 and 6 hours to the highest values of 10 minutes at the 5 wind stations from which the model was developed, the model results, and the results for 5 verification stations.

Development.	1 h	2 h	6 h	Verification	1 h	3 h	6 h
Askøy (fjord station)	0.93	0.90	0.85	Lista lighthouse	0.95	0.91	0.87
Bu in Hardanger (fjord st.)	0.93	0.87	0.83	Finsevatn (1210 masl)	0.90	0.83	0.77
Hurum-N (hill top)	0.91	0.86	0.80	Fokstua (972 masl)	0.94	0.89	0.85
Hurum-S (hill top)	0.93	0.87	0.82	Skrova lighthouse	0.92	0.87	0.83
Vealøs (hill top)	0.93	0.89	0.84	Torsvåg lighthouse	0.90	0.86	0.82
Model (Eq.1;c_1=0.01,c_2=0.5)	0.93	0.88	0.83	Model (Eq.1;c_1=0.01,c_2=0.5)	0.93	0.88	0.83

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