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Probability of Tidal Surge Levels in Reykjavik, Iceland

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ABSTRACT

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The tidal record from the Reykjavik Harbour in Iceland is analysed for extremes. For this analysis the annual maxima of recorded high tide of the 37 recorded years are used. In addition predicted high tides from the calendar years 1–2950 are used. This number of predicted years is considered sufficient data for a fairly accurate probability distribution of the astronomical tide, but the prediction is based on astronomical constituents. The astronomical tide deviates from the recorded, and three possible deviations are discussed, two deviation series that are differences of simultaneous values and one that is differences of annual maxima. It is found that a cross-correlation has to exist between the recorded and predicted series, if a stochastic model, expressing the recorded value as the sum of the prediction and the deviation, is to be applied. One of the deviation series fulfils this requirement, its recorded and predicted series are correlated. The deviation can be separated in two parts, one correlated to the prediction and another independent of the prediction. Using this, a probability integral is derived that gives the expected value of the tidal surge level as a function of return period. This result is compared to historical flood record, and it is found that the results are reliable for return periods 30–100 years. Finally, it is recommended that a hydrodynamic computational model of the tidal motion is constructed in order to investigate the tidal surge from rare meteorological situations that may not be represented in the 37 years of record.

INTRODUCTION

Tides in Iceland (Figure 1) are primarily governed by a Kelvin wave that migrates clockwise around the island. The Kelvin wave is induced by the astronomical equilibrium tide with M_2 and S_2 (GODIN, 1972) as the major constituents (GUÐMUNDSSON and EINARSSON, 1991). Tidal amplitudes are from a 4–5 m spring tide in the bays, Faxafloi and Breidafjoerdur, to approximately 2 m in the eastern and southern parts of the country, see Figure 2. The tidal period is 12 hr 25 min everywhere corresponding to M_2 (ICELANDIC HYDROGRAPHIC OFFICE, 1993). Figure 3 shows the time difference of the tide measured by the Reykjavik gauge. Note that the +6¼ hours and the −6¼ hours lines shall be the same line.

Prior investigations have shown clearly that the astronomical component is the main component of the tide (GUÐMUNDSSON and EINARSSON, 1991). This component alone is responsible for more than 80% of the tidal amplitude (see Table 1), and the probability distribution of all maxima of this component can easily be determined as the astronomical tide is a predictable series of astronomical constituents (GODIN, 1972).

The predictability of the astronomical tide is often used in extreme value estimation (DOUGLAS, 1992). In considering maximum tidal surge level as a function of return period, the question, therefore, arises whether the surge levels can be expressed as the sum of a deterministic component (the astronomical tide) and a stochastic component (the deviation of recorded values from predicted values).

In order to find a suitable stochastic model, it is necessary to analyse the possible serial correlation in the deviation and the cross-correlation between the stochastic and deterministic components. The dependence of tidal surge on meteorological conditions such as wind and wave set-up and barometric set-up are well known. MOSES and BLAIR (1988), demonstrate an efficient regression model, and WESTERINK, *et al.* (1992) the power of numerical computation in a hydrodynamic model. KARLSSON (1977) shows a one-dimensional model for wind set-up in Faxafloi Bay. The techniques of analysis utilised in these papers and treatments of similar problems render qualitative information about the nature of serial correlation and cross-correlation in predicted and recorded series. Quantitative information, up to a certain point, can be obtained from the available 37-year record.

TIDAL OBSERVATIONS IN REYKJAVIK

An automatic water-level recorder has been in service in Reykjavik Harbour since 1956. The present investigation is based on the 37-year record, 1956–1993. Instrumental accuracy is one cen-

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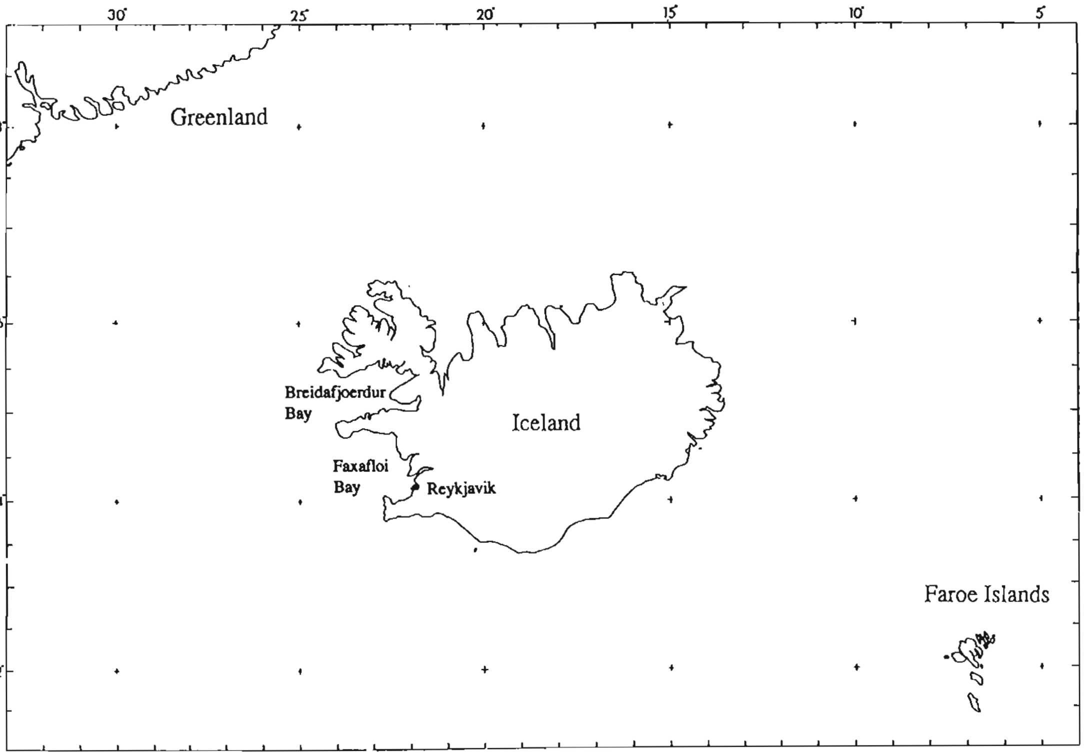

Figure 1. Location map (Courtesy of the Icelandic Hydrographic Service).

timetre. Observation errors do occur, but they are corrected by comparing observations to tidal tables, sorting out suspect values and correcting them (ELIASSON and VALDIMARSSON, 1993).

The observations produced the characteristic values listed in Table 1. Zero is the reference datum of the Icelandic Hydrographic Service's nautical charts, approximately equal to mean spring low tide (MLWST or MSLT).

Table 1. *Tides in Reykjavik, Iceland (meters ref. to Icelandic Nautical Zero Datum).*

Highest high water (obs.)	4.97
Highest high water (pred.)	4.68
Mean spring high tide	3.99
Mean neap high tide	2.98
Mean sea level	2.15
Mean neap low tide	1.32
Mean spring low tide	0.22
Lowest low water (obs.)	−0.54
Lowest low water (pred.)	−0.44

ASTRONOMICAL TIDE IN REYKJAVIK

The Reykjavik recorder is the base station for tidal observations in Iceland. Astronomical Tide is predicted for Reykjavik once a year and pub-

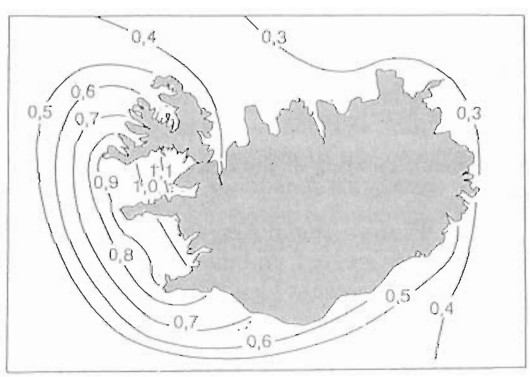

Figure 2. Tidal amplitude (Courtesy of the Icelandic Hydrographic Service).

Table 2. *Data series.*

No.	No. Values	Highest (m)	Lowest (m)	Mean (m)	St. Dev. (m)	Comment
1	37	4.97	4.44	4.71	0.11	Annual HHWinst
2	38	4.92	4.67	4.71	0.07	POT (4.67) hourly
3	37	4.92	4.43	4.67	0.11	Ann. HH hourly
4	37	4.60	4.07	4.38	0.12	Pred. no. 3
5	37	4.68	4.41	4.57	0.07	Pred ann. HHW
6	37	4.80	4.06	4.45	0.17	Measured no. 5
7	2,950	4.68	4.37	4.56	0.07	Pred ann. HHW
8	27,700	4.68	4.37	4.48	0.07	Pred POT (4.37)
e1	37	0.34	−0.51	−0.12	0.18	No. 1–no. 5
e2	37	0.58	0.09	0.29	0.14	No. 3–no. 4
e3	37	0.4	−0.13	−0.07	0.13	No. 6–no. 5

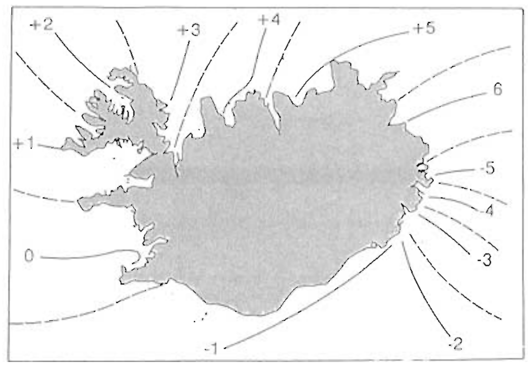

Figure 3. Tidal phase difference in hours (Courtesy of the Icelandic Hydrographic Service).

lished as tidal tables (Tidal Tables for Reykjavik, 1993). Tidal times and amplitudes in other locations refer to this base (Figures 2 and 3).

A prediction program calculated prediction values for the 37 observation years. The agreement with observation is very good, but there are certain differences. The differences are independent of neither the absolute time nor the phase of the tide. Two factors explain this:

Meteorological Constituents

Average barometric pressure in the North Atlantic is lower in the winter than in the summer. Guðmundsson and Einarsson (1991) established that 83% of atmospheric pressure variations longer than 4–8 days are reflected in the tide. This makes the astronomical tide higher in winter, the highest predicted tide being normally in February. This in turn makes the differences between predicted and observed tides depend on the average barometric pressure during the observation period and its variation during the year. This creates a certain autocorrelation in the deviation series on an hourly basis.

Non-Linear Shoaling of the Principal Tide (M_2 and S_2)

It is well known, that during this process higher harmonics are created, and they depend on water depth that is greater at high tide than at low tide, hence the dependency on phase.

PROBABILITY OF EXTREME HIGH TIDE

The following data series were extracted from the original data:

No. 1. Annual Highest High Water, instantaneous values 1956–1992, 37 values
No. 2. Peak Over Threshold series, the 38 mean hourly values exceeding el. 4.67 m
No. 3. Ann. Highest High Water hourly means, *i.e.*, annual maxima of the original data
No. 4. Predicted annual Highest High Water, 1956–1992, hourly means
No. 5. Predicted annual Highest High Water 1956–1992
No. 6. Values observed at times simultaneous with the values in No. 5
No. 7. Predicted annual Highest High Water for the years 0–2950, 2,950 values
No. 8. Predicted Peak Over Threshold (4.37 m) series, 27,700 values

Characteristic values of these series are listed in Table 2. Series 1 and 3 are almost identical, the values in No. 1 are on average 4 cm higher, as was to be expected. Nos. 2 and 3 are also very similar, the lowest value higher in No. 2 and the standard deviation slightly less.

The straightforward procedure to obtain probabilities of extreme HHW, *i.e.* to fit a known distribution to the series 1, 2 or 3, was rejected for several reasons. The data series are very short, but even more important is the possibility of using the tide's deterministic astronomical series that is predictable far into the future such as the series 7 and 8. We, therefore, write:

$$H(t) = A(t) + e(t) \tag{1}$$

$H(t)$: Observed tide

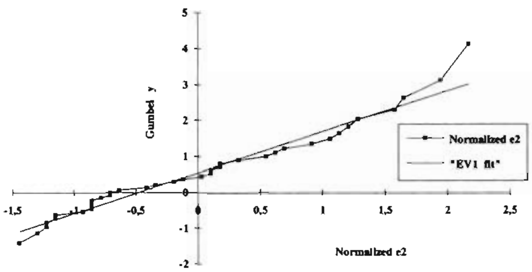

Figure 4. Distribution of normalised difference series e_2.

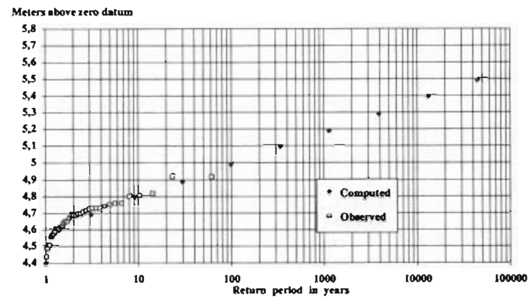

Figure 5. Return periods of extreme tides in Reykjavik.

$A(t)$: Astronomical tide (deterministic component)

$e(t)$: Stochastic deviation.

The reason for the stochastic deviation $e(t)$ is climate and bathymetry. These effects will be discussed more thoroughly in the next section.

Maxima of $H(t)$ are represented by the series nos. 1, 2, 3 and 6 in Table 2. Maxima of $A(t)$ are represented by the series nos. 4, 5, 7 and 8. Comparison with the deviation series, e_1, e_2 and e_3, shows that $A(t)$ is the principal component of $H(t)$, so HHW events will occur when $A(t)$ is close to maximum. The e-series in Table 2 are the following:

$$e_1 = Hm - Am \quad (2)$$

$$e_2 = Hm - A \quad (3)$$

$$e_3 = H - Am. \quad (4)$$

Hm and Am in (2)–(4) in the e-series are annual maxima. Normally their two maxima do not occur at the same time. The e_2 and e_3 series are differences of simultaneous values. Due to the reasons discussed earlier, $A(t)$ and $e(t)$ will exhibit an unknown time-dependant serial correlation. But the e_1–e_3-series will be free of this correlation as their elements are approximately one year apart in time.

We want a stochastic model where we can use predictable maxima *i.e.* a model that reproduces annual maxima of (1). This stochastic model has to account for possible cross-correlation between A and e as well as the statistical distribution of e. We, therefore, write e as:

$$e = rA + \epsilon \quad (5)$$

Where the ϵ-series is independent of A. Inserting (5) in (2), (3) or (4) gives

$$H = A + rA + \epsilon$$

Taking the mean of this equation and subtracting gives

$$\begin{aligned}\Delta H &= \Delta A + r\Delta A + \Delta\epsilon \\ &= (1 + r)\Delta A + \Delta\epsilon \quad (6)\end{aligned}$$

To use the model, one of the e-series equations, ((2), (3), or (4)), must be selected as a basis for the calculations. Examination of (6) gives the following dependency relations

$$\sigma_\epsilon^2 = \sigma_H^2 - (1 + r)^2\sigma_A^2 \quad (7)$$

$$r = \rho_{A\epsilon}\sigma_e/\sigma_A \quad (8)$$

$$\rho_{AH} = (1 + r)\sigma_A/\sigma_H \quad (9)$$

ρ_{AH}: Cross-correlation between A and H

σ: Standard deviation, index referring to series.

Equation (7) defines σ_ϵ and (8) defines r. Equation (9) brings the result that there is a correlation between A and H whether e depends on A or not, *i.e.*, whether $\rho_{A\epsilon}$ is zero or not. The A and H series we use, therefore, must not be uncorrelated. The only series with a significant correlation are the series in (3). The correlation between them is 0.285 while similar correlations for the other series pairs are lower than 0.1. Further calculations, therefore, are based on (3). In view of (3), (5) and (6), we can write

$$Hm = (Hm)_{av} + (1 + r)\Delta A + \Delta\epsilon_2 \quad (10)$$

The ϵ_2 series, is used as an independent stochastic variable. It must have a zero mean and standard deviation according to (7). The probability distribution must be the same as the distribution of e_2. It was found that the Extreme Value Type 1 distribution (Gumbels distribution) fitted e_2 reasonably well. Figure 4 shows the fit.

The *A* series in (3) is represented by series No. 7, the annual extremes of calendar years 1–2950. A max, min, average and standard deviation are easily obtained from a series with that number of values, but to represent the probability distribution of *A*, series No. 8 was chosen, it is the peak-over-threshold series for the same period. The threshold used was the minimum number in series No. 7. In this way a series with 27,700 values that all represent a possible maximum was obtained. It is believed that this series gives a stable estimate of *A*'s probability density function, because the only visible difference on the two series is 8 centimetres difference in average value. Accordingly, the probability distribution of extreme high waters is found by the following numerical integration:

$$P(H \le x) = \int_{A_{min}}^{A_{max}} p(z)EV1(x - (H)_{av} - (1 + r)(z - (A)_{av}))\, dz \qquad (11)$$

$P(H \le x)$: Probability distribution function of extreme H

$p(z)$: Probability density function of extreme $A = \dfrac{dP(A \le z)}{dz}$

$EVI(e)$: EVI function, $\{\mu, \sigma_\epsilon\} = \{0, \sigma\}$.

The results are in Figure 5.

The computed values show a log-line variation with return period. They are somewhat higher than the most probable extrapolation of the observed values. Whether or not the computed values are to be trusted will be discussed in the next sections.

COMPARISON TO HISTORICAL FLOOD RECORDS

In an appendix the historical records are listed that were compiled from the observations, newspapers, old annals and other written sources from the last 200 years. Unfortunately, there are very few reliable measurements of the actual flood levels in the oldest observations. The greatest event is an exception; there an estimate was made of how many alen (approximately 0.6 m) this flood exceeded MHWS. There is evidence that it has been more than 6 m above MLWST in Reykjavik and probably 7 m above at Basendar, a locality on the Reykjanes peninsula in southern Faxafloi.

The historical flood record estimates of return periods compare favourably for return periods of 100 years or less. This may be stated as the level estimates for 1894, 1867 and 1936 might very well have been lower than 5 m. This would leave only 3 events greater than 5 m in the last 200 years, very much in accordance with the computations. But for events above 5 m there is a difference in the computed and historical values that must be explained. This will be further discussed later in the paper.

BAROMETRIC- WIND- AND WAVE-SET-UP

Extreme winds in Iceland are caused by low-pressure areas migrating from south-west to north-east directions. One, therefore, would expect a strong positive correlation between high water levels due to wind or waves and barometric lows.

The recorder is inside Reykjavik Harbour in a rather sheltered position. Local wind and wave set-up, therefore, is not recorded, but regional wind set up in Faxafloi Bay and sea level rise due to barometric low pressures are. The waves depend upon the wind, and the wind depends upon barometric pressures so the deviation function $e(t)$ must be a complicated function of the time-history of the barometric pressure field in Iceland and vicinity.

Storm surge has been related to variations in pressure field variations in many places. MOSES *et al.* (1988) show how atmospheric pressure variation and surge level may be correlated using pressure values measured in several places at the same time to account for wind direction. Attempts to do the same for Faxafloi Bay have failed.

The only correlation found so far is the above correlation reported by GUÐMUNDSSON and EINARSSON (1991). They report an 83% correlation in 4–8 days averages of the time series of barometric pressure in Reykjavik and $H(t)$. This is 0.83 cm/Mb. But extreme $e(t)$ shows little correlation with simultaneous atmospheric pressure.

Calculation of wind and atmospheric pressure set-up in FEM models (WESTERINK *et al.*, 1992) is difficult, but certainly possible. This has not been tried for Faxafloi Bay, as a proper calibration situation is difficult to find. However, this may be

Table 3. *Computed surge levels.*

H, m	4.8	4.9	5.0	5.1	5.2	6.0
T comp.	12	30	100	300	1,000	1,000,000
T hist	12	16	30	?	?	70–200

the only way to analyse the potential danger of surge levels higher than 5 m in the bay.

PROBABLE MAXIMUM TIDAL SURGE

According to the statements above, the probable maximum surge would come if a low (or a series of lows) would migrate from WSW to ENE over Iceland inducing heavy westerly storms in Faxafloi Bay. This would have to happen during a large spring tide in January or February. But storms and high astronomical tides are frequent in these months. It is possible, that water levels from such an occurrence could reach more than 6 m. Prior attempts to estimate (KARLSSON, 1977) storm surge indicate this, even though the older results are probably too high. The computed return period of a surge higher than 6 m in Table 3 is ten million years which is an astronomical value, but three events similar to that are reported in the annals, the exact surge level of these events being, however, uncertain. From the above it can be seen that the probable maximum surge level may exceed the values in Figure 5 by as much as a metre.

CONCLUSIONS

It is possible to separate high surge level events in Reykjavik Harbour into deterministic and stochastic components. Correlation analysis of the stochastic component makes it possible to eliminate the random factor independent of the deterministic component. Statistical analysis of both components makes it possible to combine them into one distribution of extreme surge levels.

In this way, the quality of the computed return periods of extreme surge levels can be increased, and probability of levels higher than those encountered in the observation period can be analysed.

Comparison with historic records of tidal surge levels in Reykjavik for the last 200 years seems to confirm the validity of the calculation up to a return period of approximately 100 years. However, surge levels of longer return periods may be outside the distribution so computed. The highest possible surge levels are a result of a situation that is most likely not represented in the observation data. It is suggested that tidal surge events above 5 m should be analysed by numerical modelling of the area in question.

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Appendix. *Historical flood record.*

Year	M/Day	m		Comment
1991	1/31	4,89	Obs.	
1991	1/2	4,97	Obs.	
1986	11/3	4,84	Obs.	
1982	2/9	4,88	Obs.	Deepest Low since 1933 935 mb.
1974	1/9–11	4,89	Obs.	Jan. 11. Recorder out of service the other days.
1970	2/6	4,62	Obs.	Reports of higher surge from both sides of the harbor
1959	12/3	4,96	Obs.	
1947	1/9	4,9	?	
1945	12/19	4,9	?	
1938		4,9	?	
1936	10/30	<5	??	
1925	1/25			Damage reports only
1894	12/28			Damage reports only
1888	11/22			Reported similar to 1867
1877	1/15–17			Center of town flooded
1867	12/11			Reported similar to 1799
1799	1/9	6–7	??	Largest historical surge in Iceland. Reported more than 5 alen (3 m) over normal spring tide.

? means reliable estimate (±0.1 m); ?? less reliable estimate