Uncertainty on coastal flood risk calculations, and how to deal with it in coastal management. Case of the Belgian coastal zone.

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Abstract

A coastal flood risk calculation estimates the damage by coastal flooding for a certain time horizon. Five different sources of uncertainty can be distinguished: unpredictability of the weather; uncertainty on the extreme value probability distribution of storm surges; unknown future values of economic growth rate, population growth rate, sea level rise rate and discount rate; limited knowledge of the behaviour of the coastal system; limited amount of measurements about the state of the coastal system. From a preliminary analysis for the Belgian coastal zone it is clear that the combined effect of these different sources of uncertainty results in a very large uncertainty on the calculated risk, namely a sigma of a factor more than 10. Some important sources of uncertainty are impossible to decrease substantially by doing research or measurements. Therefore the only option for coastal management is to deal with these large uncertainties. It is suggested to use calculation results relatively, namely to compare scenarios of coastal management in order to determine which scenario can best use an available budget for investment. Also it is concluded that risk calculation results would best be compared as ratios between scenarios (in %), not as differences (in euro/year).

1. The Belgian coastal zone

The Belgian coastal zone is part of the North West European low-lying coastal areas along the Southern North Sea, with a length of 65 km. In Belgium this area has an average width of 20 km and is located an average of 2 m below the surge level of an annual storm. The natural sea defences are sandy beaches and dunes. However, hard defence structures have replaced the dunes almost everywhere in the coastal towns and ports, and hence representing approximately two thirds of the Belgian coastal defence line. The Belgian standard of coastal protection is to be safe against a surge level with a return period of 1000 years. At present it is investigated if and how this standard could be modified using risk calculations.

2. Sources of uncertainty on coastal flood risk calculations

A coastal flood risk calculation aims at estimating the damage by coastal flooding for a certain time horizon. It is important to distinguish the different sources of uncertainty which influence a prediction of damage for a certain time horizon, for a given coastal zone. Five different sources of uncertainty are being distinguished in this paper:

1) the unpredictability of the weather
2) the uncertainty on the extreme value probability distribution of extreme storm surge events
3) unknown future values of economic growth rate, population growth rate, sea level rise rate and discount rate, for the time horizon under consideration
4) the limited knowledge of the behaviour of the coastal system during a coastal flooding event
5) the limited amount of measurements about the actual state of the coastal system.

In the following sections a method will be presented to estimate the impact of these five sources of uncertainty on the damage, with a preliminary application for coastal flood risk assessment of the Belgian coastal zone.

3. Uncertainty caused by the unpredictability of the weather

The predictability of the weather is very limited (~a few days), compared to the time horizon *T* considered when doing coastal flooding risk calculations (~100 years). The chance of occurrence of a coastal flooding is very small (for the Belgian coast ~1/10000 years) compared to the time horizon considered in actual coastal zone management (~100 years). So for the Belgian coast in 99 out of 100 possible futures there is no coastal flooding damage during the time horizon under consideration. Coastal flooding damage in a specified time horizon T is the result of a Poisson process. Weather systems change each few days. For every independent weather system there is a chance of occurrence of an extreme storm surge that results in coastal flooding. Because the considered time horizon T (~100 years) is much smaller than the return period R of coastal flooding (~10000 years) the expected damage $E(D)$ can be calculated as $E(D)=T/R\times S$ in which S is the damage in case of a coastal flooding. For clarity of the arguments the damage due to coastal flooding is simplified to a constant value S. In other words, the relation between damage S and return period R is simplified as a step-function. This binary approach is to be generalised for a more realistic case in which the damage S is an increasing function of the return period R, but this is out of the scope of this paper. So in this paper the expected damage (euro) and risk (euro/year) are defined by the following equations (3.1) and (3.2).

$$E(D) = \frac{T}{R} \cdot S \tag{3.1}$$

$$risk = \frac{E(D)}{T} = \frac{S}{R} \tag{3.2}$$

The variation around the expected value for damage during the time horizon considered can be expressed by the coefficient of variation valid for a Poisson process $\mu = \sqrt{R}/\sqrt{T}$.

For the Belgian coast typical values are R ~10000 years and T ~100 years, so μ ~10. This means a very large uncertainty on the damage, namely a factor ~10.

4. Uncertainty on the extreme value probability distribution of extreme storm surges

The extreme value probability distribution is essentially the result of an extrapolation of storm surge events recorded during the past decades/century. For the Belgian coast almost 100 years of reliable storm surge measurements are available. However, such a dataset remains very limited when one has to determine storm surge levels of extreme events with return periods of ~10000 years. Because of the importance of extreme storm surge levels in coastal management, in Belgium several detailed statistical studies were carried out in previous years. Extreme value probability distributions were determined, and also the uncertainties on the distributions. The results of Probabilitas (1999) are shown in Figure 1.

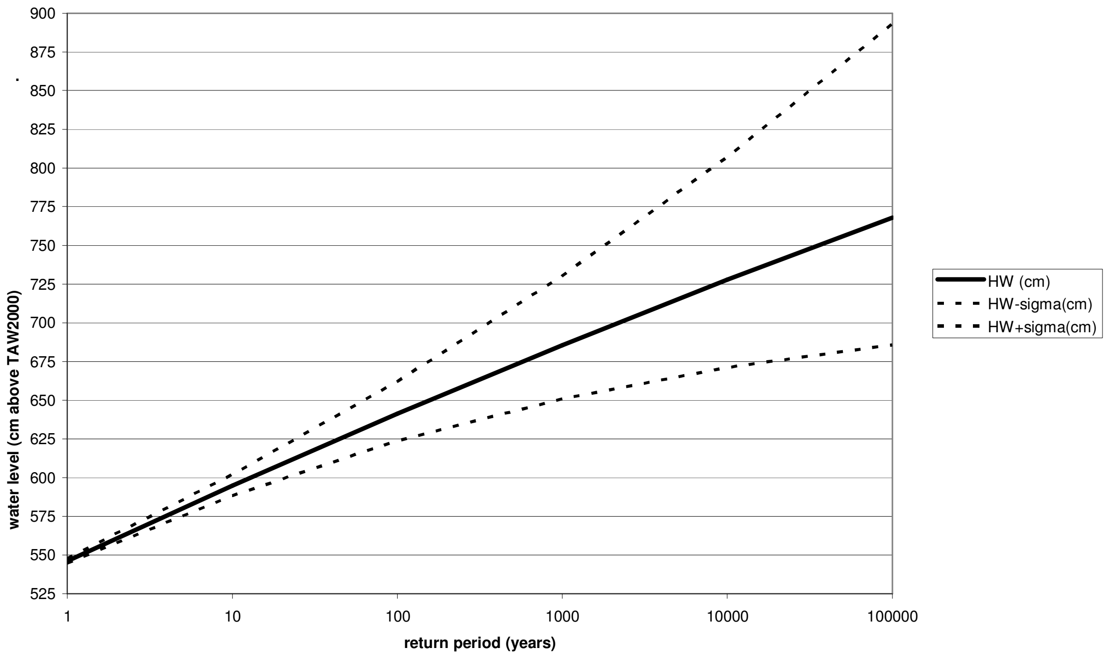

FIGURE 1. Probability of exceedance of storm surge level in Oostende including uncertainty estimate (Probabilitas 1999).

It is obvious that the uncertainty is larger for higher storm surge levels. For a typical level causing coastal flooding (return period of 10000 years) the uncertainty on the return period is approximately a factor 10. This results in a very large uncertainty on the expected damage during a considered time horizon, namely a sigma of a factor of ~10.

5. Uncertainty on the future values of economic growth rate, population growth rate, sea level rise rate and discount rate

When considering a time horizon for a coastal flooding risk calculation, e.g. T = 100 years, it is essential also to consider some continuously evolving system characteristics. Namely, four elements are continuously changing: the economic value and the size of the population in the coastal zone prone to flooding, the sea level -which is rising with or without an effect of climate change-, and the discount rate. For sake of clarity a constant rate for these parameters is assumed.

A first systematic changing element is the amount of values at risk of coastal flooding. More specifically is meant the rate of growth of the economical values and also the rate of population growth in the coastal zones prone to flooding. For the Belgian coastal zone the actual (at present) rates are measured to be 2 % per year for economical growth and 0,2 % per year for population growth (especially elderly enjoying retirement at the coast). Predictions of these socio-economic rates for the coming ~100 years are very uncertain. Estimates of the expected variation can be determined from the rates in the previous century, or by using results of global scenario studies which are regularly performed by planning bureaus.

A second systematic changing element is the sea level rising. For the Belgian coast the actual rise of the high water level (relative to the height of the coastal defences) is 1.8 mm per year (see Verwaest & Verstraeten, 2005). A rising of the average sea level results in a rising of the probabilities of extreme storm surge levels, and thus also a rising of the coastal flooding risks. For the Belgian coast the risks have been rising with 0.7 %/year due to the sea level rise of 1.8 mm/year. Predictions of sea level rise in the 21st century are very uncertain. Depending on the size of the impact of the global warming different scenarios are foreseen, ranging from a very optimistic scenario of no acceleration of sea level rise, to a very pessimistic scenario of an acceleration to a 5 times higher rate of sea level rise (~90 cm/100 years = 5 x 1.8 mm/year). This very pessimistic scenario results in a yearly increase of the coastal flooding risks with 3.5 % (3.5 % = 5 x 0.7 %).

A third systematic changing element is the discount rate. In our capitalist economies money brings more money, thanks to the interest rate. This also means that future costs have to be valued less at present day. In Belgian the actual discount rate is about 4 % (corrected for inflation). Predictions of the discount rate for the coming century are very uncertain. An estimate of the expected variation can be determined from the discount rates in the previous century or from socio-economic projections.

Combining the different rates of change, considering them to be independent of each other and small (<<1), results in a net rate of change. Estimates for the different rates for the Belgian coastal zone are summarised in Table 1.

	Expected value ([+] means resulting in larger coastal flooding risks, [-] means the opposite)	Estimate of uncertainty on the rate of change (+- sigma)
Rate of change of economic assets at risk	2 %/year [+]	σ = +- 2 %/year
Rate of change of population at risk	0.2 %/year [+]	σ = +- 1 %/year
Rate of sea level rise	2 %/year [+]	σ = +- 1 %/year
Discount rate	4 %/year [-]	σ = +- 2 %/year
Net rate of change from an economical point of view (excluding population change)	0 %/year	σ = +- 3 %/year

TABLE 1. Rates of change for the 21^{st} century: expected values and uncertainties for the Belgian coastal zone

According to the estimates above, the expected value of the net rate of change from an economical point of view (excluding population change) for the Belgian coast is "no change". However, positive or negative net change rates are possible, most probably less than +- 6% (~ +- 2 x sigma).

Considering a constant net rate of change *r* (positive means increasing flooding risks), the calculation of the expected damage in a certain time horizon *T* is with the following equation (5.1).

$$E(D) = \frac{T}{R} \cdot S \cdot \frac{(1+r)^T - 1}{rT} \tag{5.1}$$

This equation (5.1) is a modification of the equation (3.1) to take into account the effect of changing conditions during the time horizon *T* considered. It differs from the classical risk formula only by the multiplication with a so called rate factor. The rate factor is thuss defined by equation (5.2).

$$ratefactor = \frac{(1+r)^T - 1}{rT} \tag{5.2}$$

For typical values of the time horizon *T*, the rate factor is calculated for different values of *r*. The results are given in Table 2.

	T = 50 years	*T* = 100 years	*T* = 200 years
r = -6 %/year	0.32	0.17	0.08
r = -5 %/year	0.37	0.20	0.10
r = -4 %/year	0.44	0.25	0.12
r = -3 %/year	0.52	0.32	0.17
r = -2 %/year	0.64	0.43	0.25
r = -1 %/year	0.79	0.63	0.43
r = 0 %/year	1	1	1
r = +1 %/year	1.29	1.70	3.16
r = +2 %/year	1.69	3.12	12.87
r = +3 %/year	2.26	6.07	61.39
r = +4 %/year	3.05	12.38	318.72
r = +5 %/year	4.19	26.10	1729.16
r = +6 %/year	5.81	56.38	9593.74

TABLE 2. The rate factor calculated with equation (5.2) for different values of *T* and *r*.

One can observe from Table 2 that for larger values of the net rate of change *r* and/or larger values for the time horizon *T* the rate factor becomes largely different from 1.

For the case of the Belgian coastal zone (*r*= 0 % +- sigma 3%) the coefficient of variation of the rate factor is of the order of ~10. This results in a very large uncertainty on the expected damage for coastal flooding, namely a sigma of a factor ~10.

6. Uncertainty caused by the limited knowledge of the behaviour of the coastal system during an extreme storm surge event

Coastal flooding events are very rare. For the Belgian coastal zone ~1/10000 years. So, not much empirical evidence can be gathered easily to understand the behaviour of the coastal system during extreme storm surge events. Scientific progress is made by combining empirical studies of worldwide occurring coastal flooding events, and model studies of the local coastal system under consideration (mathematical modelling as well as physical model experiments). Present scientific understanding of the behaviour of the coastal system during a coastal flooding event is limited. From experts (see for example Oumeraci 2005) it is clear that especially on the failure behaviour of sea defences and the process of breach growth a lot more scientific research is needed. Anyway calibration of models will remain difficult due to the lack of in situ measurements (wave impact, breaching and breach growth, flood propagation) of extreme events having a very low probability of occurrence.

Estimating the uncertainty on the coastal flooding risk caused by the present lack of scientific understanding about the failure behaviour of sea defences is only possible by questioning experts. For the

Belgian coastal defences an uncertainty of 0.5 m on the storm surge level at which a certain coastal defence fails resulting into breach formation and coastal flooding, corresponds to an uncertainty of approximately a factor 10 on the flooding risks. From expert opinions one may preliminary estimate that this source of uncertainty is resulting in an uncertainty on the expected damage with a sigma of a factor ~3 (corresponding to a storm surge difference of ~0.25 m).

7. Uncertainty caused by the limited knowledge of the behaviour of the coastal system during an extreme storm surge event

Many measurements are needed to characterise the state of the coastal system with respect to its vulnerability for coastal flooding damage. Measurements are needed on the one hand for characterising the coastal defences, and on the other hand for characterising the zones prone to flooding. Main characteristics of the coastal defences are its height (relative to storm surge level), its erosion resistance and its structural stability. Main characteristics of the zones prone to flooding are its height (relative to storm surge level), its area, its land use and its population density.

For the Belgian coastal zone detailed measurement results are available for all main characteristics of both the coastal defences and the zones prone to flooding. The least information is existing regarding the erosion resistance and the structural stability parameters of the hard coastal defence structures. Therefore a measurement campaign is being carried out in which geotechnical parameters and structural parameters are determined for the hard coastal defence structures along the Belgian coastline (mainly sea walls).

In previous studies estimates were made of the uncertainty on coastal flooding risks in Belgium caused by a lack of data (e.g. Verwaest, 2000). From these studies it can be preliminary estimated that for the Belgian coastal zone a coefficient of variation of ~3 results for the expected damage, mainly caused by the aforementioned lack of detailed measurements on the composition of the hard coastal defence structures.

Other parameters which are less well known are the hydraulic roughness of the flooding zones (e.g. urban areas in which flooding concentrates in streets, or the effect of the flow via existing drainage systems in the polders) and the damage functions for different types of valuables (e.g. the relation between the flood water level and the proportion of the value of a house damaged by flooding, or the damage to point objects –not detectable from land use maps- with a very high localised value such as drinking water wells, historical buildings etcetera). Ongoing research aims at further reducing uncertainties on these parameters.

8. The combined effect of the different sources of uncertainty

From the analysis of the effect of the five different sources of uncertainty on the coastal flooding damage for a given time horizon, it is clear that the combined effect results in a very large uncertainty on the expected coastal flooding damage for the Belgian coastal zone, namely a sigma of a factor more than 10. In Table 3 the effect of all uncertainty sources is summarised.

	Source of uncertainty	Resulting uncertainty on the expected damage in terms of a sigma factor.
1	Unpredictability of the weather	~10 (coefficient of variation)
2	Extrapolated values for exceedance frequencies of extreme storm surge levels	~10
3	Future net rate of change (combined effect of economical growth, population growth, sea level rise and discount rate)	~10
4	Limited understanding of the behaviour of the coastal system during an extreme storm surge	~3
5	Limited understanding on the state of the coastal system	~3
	All uncertainty sources combined	more than 10

TABLE 3. Summary of the effect of the different sources of uncertainty for a risk calculation. Estimates from preliminary analysis for the Belgian coastal zone.

Given the nature of the stochastics the result of a flood risk calculation can be tentatively assumed to be lognormal. This is a simple distribution that can represent a sigma of a factor e.g. 10 or more. An important characteristic of a lognormal stochast is the large difference between the median value (50% probability to have a higher value, 50% probability to have a lower value) and the expected value (weighted average). It can be shown that the expected value is a factor *m* larger than the median value, with *m* given by equation (9.1) in function of the sigma factor σ.

$$m = \sqrt{\sigma}^{\ln(\sigma)} \tag{8.1}$$

For larger values of σ the factor *m* becomes increasingly larger, as can be seen from Table 4.

sigma factor σ	factor *m*
2	1.3
5	3.7
10	14.2
20	88.9
50	2104.8

TABLE 4. Lognormal distribution with sigma factor σ, resulting in a factor *m* difference between expected value and median value.

For the Belgian coastal zone the factor *m* is at least 10, given the estimate of a sigma factor of more than 10.

9. How to use coastal flood risk assessment results in coastal management?

Some important sources of uncertainty are impossible to decrease substantially by doing research or measurements, e.g. the uncertainty on the extreme value probability distribution of storm surge levels. Therefore the only option for coastal management is to deal with these large uncertainties with a sigma of a factor more than 10. Because the uncertainty on a risk calculation is that large, it is concluded that coastal flood risk calculations would best be used relatively, namely to compare scenarios of coastal management in order to determine which scenario can best use an available budget for investment.

For a given coastal zone, there is a complete correlation between different scenarios for three of the five sources of uncertainty (namely the first three in the Table 3). Also there is partial correlation between scenarios for the other two sources of uncertainty (the last two in Table 3). Taking into consideration the estimates of the different sources of uncertainty (see Table 3), a justifiable assumption is to simplify the degree of correlation between different scenarios as full (100 %) correlation.

The difference in risk between two scenarios “1” and “2” then has :

- an expected value : $E = E_1 - E_2 = m \cdot (median_1 - median_2)$
- a standard deviation : $\sigma_E = E \cdot \sqrt{m^2 - 1} \cong m \cdot E$ $(m >> 1)$
- a coefficient of variation : $\mu_E = \dfrac{\sigma_E}{E} \cong m$

The ratio of risks of two scenarios “1” and “2” then has :

- an expected value : $\varepsilon = \dfrac{E_1}{E_2} = \dfrac{median_1}{median_2}$
- a standard deviation : $\sigma_\varepsilon = 0$
- a coefficient of variation : $\mu_\varepsilon = \dfrac{\sigma_\varepsilon}{\varepsilon} = 0$

Because we estimated the factor *m* to be at least 10 for the Belgian coastal zone it is concluded that risk calculation results would best be compared as ratios between scenarios (in %), not as differences (in euro/year).

For example, if for a certain scenario of coastal defence improvement works the risk is calculated to be 1 million euro/year, while in the reference situation the risk is calculated to be 2 million euro/year, then it can be stated quantitatively that the improvement scenario has reduced the risk with 50 %. Contrary to this, the avoided risk by the improvement scenario (in euro/year) cannot be given with accuracy.

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