Chapter 8
Extreme sea levels

8.1 Return periods and risk

One of the main reasons for studying sea level changes is to predict flooding risks, and especially how these might change in future. Before looking at possible future changes we should look at the general concepts of risks and how these are calculated for extreme sea levels. The first two sections in this chapter may be omitted by readers who do not need to understand the mathematical concepts. The remainder of the chapter looks at observed trends and some of the potential coastal impacts.

Increasingly, coastal planners have to include estimates of flooding risk into their designs, and allow for an appropriate measure of protection against expected extreme sea conditions during the lifetime of any proposed development. Careful assessment of the probabilities of extreme sea levels is a necessary part of the design of modern coastal infrastructure systems. Estimating these risks needs to be based on good data and a range of analysis techniques.

There is a necessary and important distinction between knowing the risks and ignoring them. Known risks can be assessed from observations using probability theory and can be incorporated into planning, investment and defence design; if the risks are not known there is no basis for making decisions, other than 'trusting to luck'.

The probabilities of extreme sea levels and coastal flooding may be specified in several different ways. These levels, including the tide, surge and mean sea level elements, are sometimes called *still water levels* to distinguish them from the total levels, which include waves. Waves are usually accounted for separately in risk analyses, although more elaborate procedures may allow for some correlation between storm surges and high-wave conditions.

If the probability of a level z being exceeded in a single year is $Q(z)$, that level is often said to have a return period, which is in the inverse of $Q(z)$ in years. For example, a sea level having a probability of being exceeded in a year of 0.05 would be said to have a return period of 20 years. Similarly the level that has a probability of being exceeded once in a hundred years is called the *100-year return level*. This inversion of annual exceedance probabilities to give return periods makes the implicit assumption that the same statistics are valid for the whole period specified; since for very small probabilities this may be many tens or hundreds of years, this can be a very big assumption. It would be absurd to say the 10^{-4} level has a 10 000-year return period because MSL conditions would have changed substantially over that period.

The appropriate value of $Q(z)$ chosen for coastal planning will depend on the value of the property at risk. Nuclear power stations may specify 10^{-5} or 10^{-6}. For the coastal protection of the Netherlands a value of 10^{-4} is adopted, but for many British coastal protection schemes values of 10^{-3} or greater are accepted.

One way of presenting the risks of extreme still water levels is as the probability that a stated extreme level will be exceeded at least once during the specified design life of the structure. This is called the *encounter probability* or *design risk*. For the first year the risk is $Q(z)$, and the probability of not reaching that level is $(1 - Q(z))$. The probability of not reaching the level z in either of the first two years is $(1 - Q(z))^2$ and the risk of reaching the level is $[1 - (1 - Q(z))^2]$. As a simple comparison, this is the same as calculating the chance of throwing two dice and not showing a six on either. For a sea level example, if $Q(z)$ is 0.1, the risk of exceeding the level z in the first two years is 0.19. Over several years the *design risk* is related to the annual exceedence probability according to the statistical relationship:

$$\text{Risk} = 1 - (1 - Q(z))^{T_L} \tag{8.1}$$

where T_L is the design lifetime. This is plotted in Figure 8.1 for $Q(z) = 0.01$ (100-year return period). It shows that designing for a level which has an expected lifetime equal to the return period is generally not an acceptable criterion. It should be remembered, as illustrated by the dotted line for the 100-year design level in Figure 8.1, that a structure has a through-life probability of 0.63 of encountering a level that has a return period equal to its design life. For good design, the *design level* must

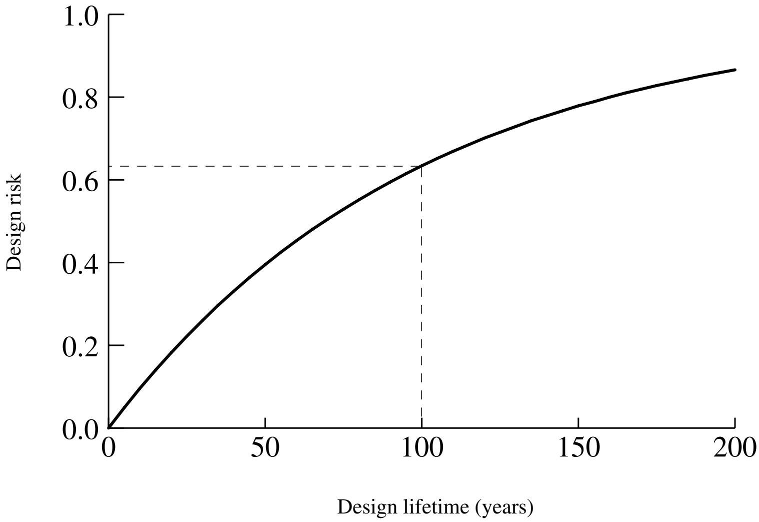

Figure 8.1. The relationship between the risk of encountering an extreme level with a return period of 100 years and the expected lifetime of a structure. For example, the dotted line shows that if the structure is to last for 100 years then there is a 0.63 probability of encountering the hundred-year level during its lifetime.

have a return period that considerably exceeds the expected lifetime of the structure. As an example, suppose that the envisaged life of a structure is 100 years, then for a risk factor of 0.1 of exceedence during this period, the design level should have a return period of 950 years.

When estimating $Q(z)$ it is very unusual for an engineer or coastal scientist to have access to the quantity or quality of data that many of the theoretical techniques described in this chapter require. Estimates must be based on only limited observations at the site proposed, so that extrapolation of the available data in both time and space is inevitable. Skill is necessary to decide how valid it will be to use data from another location, and the best way to make the transfer.

8.2 Ways of estimating flooding risks

Here we outline briefly the ways in which sea level data can be used to estimate risks of flooding. The methods which we will discuss are most effective for calculating extremes for regions outside areas influenced by hurricanes. In these extra-tropical regions extreme sea levels are usually due to a combination of high astronomical tides and extreme weather effects.

For very expensive structures the most elaborate available statistical methods should be used to estimate extremes. For less expensive schemes approximate methods of estimating have been developed as cheaper alternatives. The methods below are applied assuming mean sea level trends have been removed before analysis. For details of the application of the methods, readers should consult specialised publications.

8.2.1 Regional factors

The simplest approach is to compute the ratio between some normal tidal parameter and the level having the specified return period of years (typically 100 years) for a standard port in a region. One such factor is defined as:

$$\alpha_{100} = \frac{\textit{100-year highest sea level}}{\textit{Highest astronomical tide} + \textit{100-year surge level}} \tag{8.2}$$

The 100-year surge levels may be estimated from a long series of meteorological residuals with suitable extrapolation, or by analytical or numerical models, which relate them to 100-year winds. Clearly α_{100} has a maximum value of 1.0, but this is the most pessimistic case where the 100-year surge level is assumed always to coincide with highest astronomical tide. Building structures for $\alpha_{100} = 1.0$ will almost certainly lead to expensive over-design. In practice the values are lower than this because extreme surges will probably occur with more normal tidal levels (see Section 8.2.3). Around the British Isles α_{100} is typically in the range 0.8 to 0.9, except in the southern North Sea, where the value falls to around 0.72. This reduction is because the local shallow-water dynamics, discussed in Chapter 5, cause large surges to avoid times of high water of astronomical tides; this is a very fortunate interaction as it substantially lowers the levels of potential flooding of London and the Netherlands.

8.2.2 Annual maxima

In order to determine the value of $Q(z)$, the annual exceedence probability at a coastal site, from which return periods and risk factors may be estimated, it is necessary to tabulate the maximum levels reached in each of as many years as possible. Extreme levels have a seasonal cycle (weather effects are generally greatest in winter and the tides are often biggest in March and September) so it would be wrong to use values from periods shorter than a year.

The annual maxima of Newlyn data over 84 years are plotted as a histogram in Figure 8.2. The level of highest astronomical tide (3.0 m) was exceeded in only 28 of those years. The broken curve in Figure 8.2 shows the probability of a particular level being exceeded in any single year. For example, the probability of an annual maximum level exceeding 3.0 m at Newlyn is 0.33, because 28 yearly maxima in the set of 84 were higher than this. Expressed in a different way, an annual maximum in excess of 3.0 m has a return period of three years. Plots like Figure 8.2 are useful for representing the general characteristics of

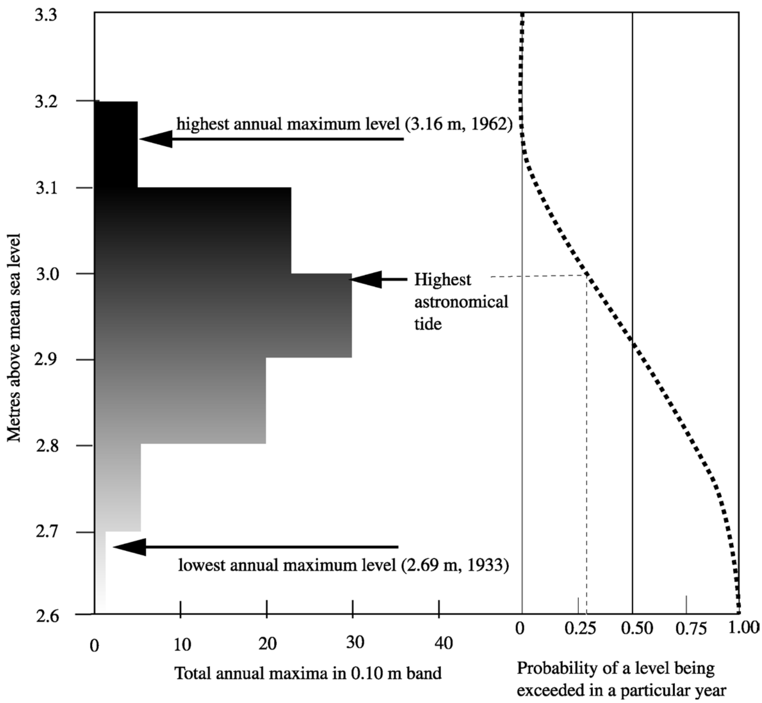

Figure 8.2. Observed annual maximum sea levels at Newlyn, 1916–2000, and the probability of a level being exceeded in a particular year. Mean sea level trends are removed from the data. The most probable annual maximum level lies in the band 2.9 to 3.0 m above mean sea level. The fine dotted line shows that the highest astronomical tide (3.0 m) has a probability of 0.33 of being exceeded in a particular year.

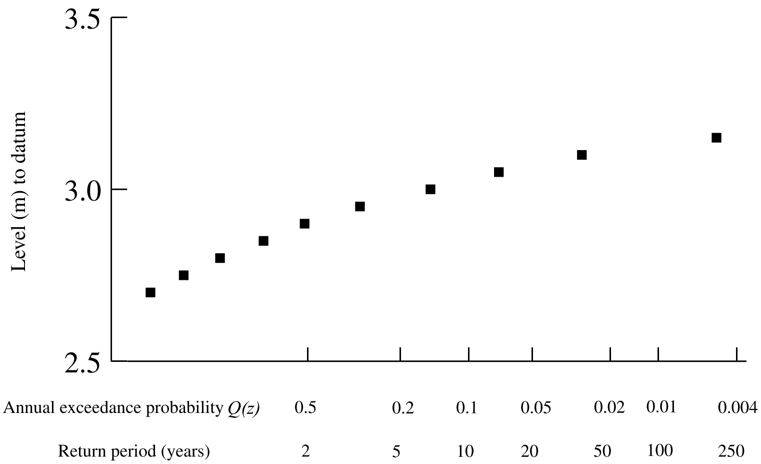

Figure 8.3. A different way of showing the information in Figure 8.2. This shows the probabilities of annual maximum levels at Newlyn falling below a specified level. Mean sea level trends have been removed.

annual maxima, but they cannot be used for the extrapolations necessary when estimating for extreme events which, by definition, have a very low probability and value of $Q(z)$.

The usual procedure is to fit a curve to values of z plotted against the probability of annual exceedence, as in Figure 8.3. Plotting the levels against an x-axis logarithmic scale for probability has the advantages of opening out the two ends of the probability curve ($P = 0$ and $P = 1$) relative to its central position, and of making the transformed curve approximately linear. (For fuller details of the process, consult the publications recommended in the Further reading section at the end of this chapter). The family of curves used for fitting and extrapolating to very low probability events is known as the generalised extreme value (GEV) distribution. The most appropriate curve is usually obtained by the method of least-squares fitting to the data.

Although as few as ten annual maxima have been used to compute probability curves, experience suggests that at least 25 annual values are needed for a satisfactory analysis. As a general rule extrapolation should be limited to return periods not longer than four times the period of annual maximum levels available for analysis, but even within this limit extrapolated values should be interpreted with caution. Experience also shows that the form of the extrapolated curve is almost always strongly controlled by the last few points of the plotted values; it is often found that one or two extreme levels observed during the period appear to lie outside the usual distribution pattern. The degree of weight given to these becomes a matter for subjective judgement. They cannot be discounted easily: the dangers of omitting the most extreme, genuine sea level values from an analysis are obvious.

The major disadvantage of the annual maxima method is the waste of data, because a complete year of observations is being represented by a single value. If the largest meteorological surge for the year coincides with a low tidal level, the information is ignored despite its obvious relevance to the problem of estimating extreme level probabilities (see Section 8.2.4).

8.2.3 Joint tide–surge probability estimates

An alternative way of estimating probabilities of extreme levels is to make use of the separate distribution of tidal and surge frequencies. Tidal probabilities can be determined from quite short periods of data by tidal analysis because the range of tidal forcing is well known from the astronomy. Figure 8.4 shows the statistical distribution of predicted tidal level at Newlyn over an 18.6-year period. The double-humped distribution, with the most frequent levels near to mean high and mean low water on neap tides, is typical of semidiurnal tidal regimes. The frequency distribution of non-tidal (surge) levels is plotted in a similar way in Figure 6.1.

Table 8.1 shows how joint tide–surge probabilities can be calculated in practice. In this example we assume that the extreme levels occur

Table 8.1. *Example of high water and high water residual probabilities for calculating joint probabilities. For example, a surge of 0.1 m represents all surges in the range 0.05 to 0.15 m.*

		Non-tidal residual (m)				
Tidal HW		−0.2	−0.1	0.0	0.1	0.2
level (m)	*Normalised frequency*	*0.1*	*0.2*	*0.4*	*0.2*	*0.1*
3.2	*0.1*	0.01	0.02	0.04	0.02	0.01
3.1	*0.2*	0.02	0.04	0.08	0.04	0.02
3.0	*0.3*	0.03	0.06	0.12	0.06	0.03
2.9	*0.3*	0.03	0.06	0.12	0.06	0.03
2.8	*0.1*	0.01	0.02	0.04	0.02	0.01

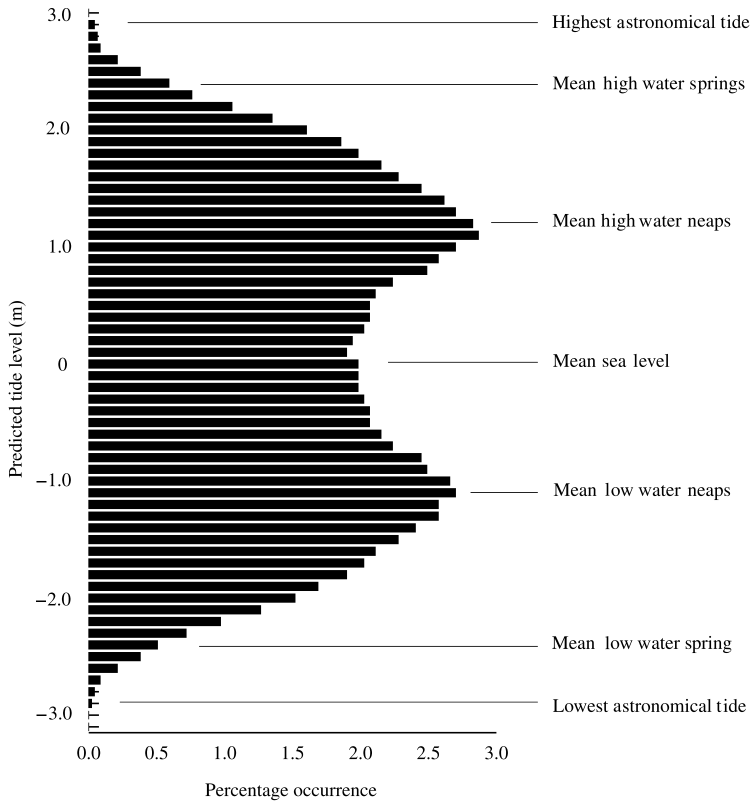

Figure 8.4. The frequency distribution of hourly tidal levels at Newlyn over an 18.6-year nodal period. The intervals are 0.1 m. The most probable levels are at mean high water neaps and mean low water neaps.

on a high tide, when there is also a large positive surge. The residual (surge) and predicted (tidal) high water levels over a complete number of years are tabulated to produce normalised frequency distributions. An appropriate tabulating interval is 0.1 m. In the example shown in Table 8.1 the tidal high water levels and the meteorological distributions have been artificially restricted to five 0.1 m class intervals in each case. Forty per cent of the observed residuals were in the range of -0.05 m to $+0.05$ m whereas 10 per cent were in the range 0.15 m to 0.25 m. The highest tides lie in the range 3.15 m to 3.25 m above the defined datum, represented by the 3.2 m band.

The frequency distributions of the surge observations and the tidal predictions are then assumed (this is not a trivial assumption) to be representative of the probability of future events. The joint probability of a 3.2 m predicted tide and a 0.0 m surge is 0.04, the product of their individual probabilities. Similarly, a 3.1 m tide and a 0.1 m residual have a joint probability of 0.04. For a 3.0 m tide with a 0.2 m residual the probability is 0.03. Any of these three joint events will produce a total observed high water level of 3.2 m, and so the total probability of a 3.2 m level, obtained by scanning along the diagonal line in Table 8.1, is the sum of the three probabilities, 0.11, i.e. 11 per cent of all observed sea levels will lie between 3.15 m and 3.25 m.

In this example the highest total level, 3.4 m, can only occur when a 3.2 m tide and a 0.2 m residual coincide, which has a joint probability of 0.01. When this method is applied to real data much smaller probabilities of extreme joint events are calculated, because the probabilities are distributed over many more class intervals.

In this case there is a natural way of relating these probabilities to the time interval between tidal high waters. For example, 3.4 m levels occur on average once in every 100 tides. More generally these dimensionless probabilities are converted to return periods using time-scaling factors related to the persistence of extreme events (see the Further reading section).

The principal advantages of the joint tide–surge probability approach may be summarised as follows.

- Stable values are obtained from relatively short periods of data. Even a single year can yield useful results, but four years is desirable, to sample several storms.
- There is no waste of information.
- The probabilities are not based on large extrapolations.
- Estimates of low water level probabilities are also produced.

However, data must be of good quality, with timing accuracy to better than a few minutes. If there are timing errors (old chart recorders were especially prone to these) tidal variations will appear in the non-tidal residuals. Joint tide–surge probability estimates of extremes require a high degree of analytical skill; extra computational effort is also involved.

8.2.4 Other methods

Other methods, either similar to or extensions of the annual maxima and joint probability methods described briefly above, are often applied. One method looks at a fixed number of the maximum extreme levels in a year, typically up to ten, instead of just the single annual maximum value. Sometimes this will mean including some highest levels from one year, which are less than those not included for another year. Care is necessary to make sure that each storm is a separate and independent event, which is sometimes taken to mean that they occur at least three days apart. These storm levels are then fitted with an appropriate extreme value distribution.

Another method, developed for river hydrology, is to look at the number of times a level exceeds some stated threshold level. Unlike the previous method, this may result in several storms being recorded in one year and few or none in another year. Total sea levels (tides plus weather effects) could be influenced by the 18.6-year cycle in tidal amplitudes (Figure 3.2). A better approach is to apply this peaks-over-threshold method to the non-tidal residuals, after removing the tides, and to use the resulting probabilities in a joint probability calculation.

The reliability of all estimates is limited by the available data and by possible trends and changes in the regional meteorology and oceanography. The possibility of some rare unsampled event, such as a tsunami, cannot be ignored nor is it easily incorporated into the estimates. Tsunamis are more common in the Pacific than in other oceans, but even for the Atlantic, well-documented tsunamis have occurred (Section 6.7). On the west coast of the United States and in Japan, tsunamis are recognised as the most important cause of extreme levels.

In tropical areas, for example, the Atlantic and Gulf Coast of the United States, extreme sea levels are produced by hurricanes; however, these are too rare at any particular place to permit the calculation of reliable probabilities from observations. The tidal contribution is usually a much smaller factor than the weather (see Section 6.5). A modelling approach, where all possible hurricane characteristics and tracks are simulated, is often used to estimate the very small probabilities.

8.3 Risks and climate change

Popular interest in increased risks of coastal flooding in future warmer climates usually concentrates on the effects of MSL changes. However, as we know from previous chapters, MSL is just one of the three factors, with tides and weather, that affect total observed sea levels. In this section