CHAPTER 33

ON THE USE OF FREQUENCY CURVES OF STORMFLOODS

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1. THE PROBLEM

In coastal engineering we often have to face the problem of high stormfloods. Especially if the land near the coast is flat and low, if it is densely populated or if high economic values have to be protected.
In all these cases, where life and economic values are at stake, a design flood has to be established as a basis for the construction of the works of protection.

Obviously the height of the design flood will be dependent on two factors. On one hand it depends on the characteristics of the sea, on its probable and possible heights. On the other hand it depends on the values of human and economic nature, threatened by the sea. So the design flood may be regarded as a balance between the threatening force of the sea and the values at stake.

In this paper we will investigate the nature of this balance. This will lead us to a close examination of the frequency curves of stormfloods, to a discussion of the question: What is a reasonable risk and to a discussion of the question: What is the space of time we have to take into account.

2. DESCRIPTION OF A FREQUENCY CURVE OF HIGHWATER

Let us suppose that tide gauge readings of highwater are available for a reasonable space of time. The first thing to do is to count the number of highwaters, surpassing every dm interval of the gauge.
If we plot these numbers as abscissa against the heights as ordinates we obtain the distribution curve of excess, which henceforth for the sake of convenience we will call the frequency curve.
Fig. 1 shows such a curve for the highwaters at the gauge of Hook of Holland. The vertical axis corresponds with the gauge heights. The Netherlands datum level NAP is practically equal to mean sea level; mean highwater equals NAP + 90 cm; a heavy stormflood reaches up to NAP + 280 à 320 cm and the disastrous stormflood of 1953 piled up to NAP + 385 cm at this gauge. In particular the higher floods will be the subject of our present study.
The abscis gives the number N of the times each level has been exceeded, reduced to the number per year. For practical reasons the scale of the abscissa is logarithmic.
It is important to note, that this procedure leads to a fairly straight curve in particular if not all the values of highwater are counted, but only those in the winter season.
As we are mostly interested in the higher and very high floods, the question arises how the curve should be extrapolated for higher levels. This is only a minor question in relation to the main subject of this paper. But for better understanding of what follows a short discussion of the higher part of the frequency curve may be useful.

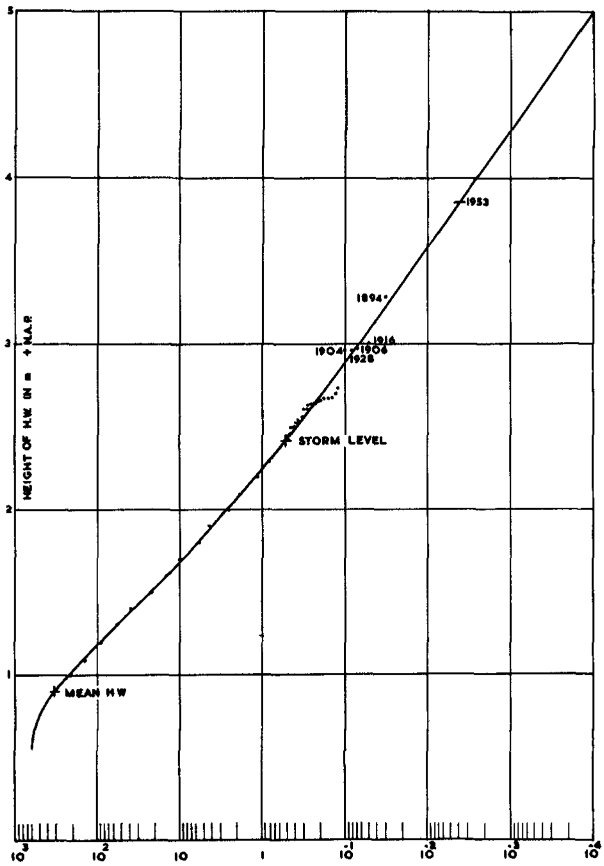

Fig. 1. Frequency curve of highwater at Hook of Holland.

Obviously the frequency curve can not end abruptly at the highest observed highwater. The curve will continue beyond this point.
From calculations we know that in Hook of Holland stormfloods up to NAP + 6 to 6,5 m may not be regarded as impossible from a physical point of view and there is no valid reason to assume that even such extremely high levels should never be exceeded.
This consideration leads of necessity to an extrapolation of more or less straight character, at least for the levels, which will be of interest for the present investigation. Such an extrapolation is presented in fig. 1. And if perhaps the frequency curve in still higher regions will tend to deflect to some asymptotic value this does not interest us greatly. For this is in any case far beyond the levels considered in the scope of the present study.

Owing to the general character of frequency curves, of which fig. 1 is only a sample, we are faced with three important aspects:

1. nature confronts us with very high levels, liable to be exceeded;
2. possibly there is no limit given by nature. So man is forced to consider a reasonable limit which is convenient to his purposes;
3. the probability of the very high levels being exceeded is extremely small.

Thus if we have chosen a definite height as a design level, we know in advance, that there always remains the chance of it being exceeded. A discussion of the real content of the term exceeding and the real meaning of the term chance is therefore necessary.

3. A "STANDARD" FREQUENCY CURVE

The exceeding curve of the gauge of Hook of Holland has been used only as a sample. Another gauge may have a somewhat different curve, with differences in general shape, steepness and gauge values. In order to simplify the explanation, in fig. 2 a "standard" frequency curve is introduced, being an exactly straight curve F .

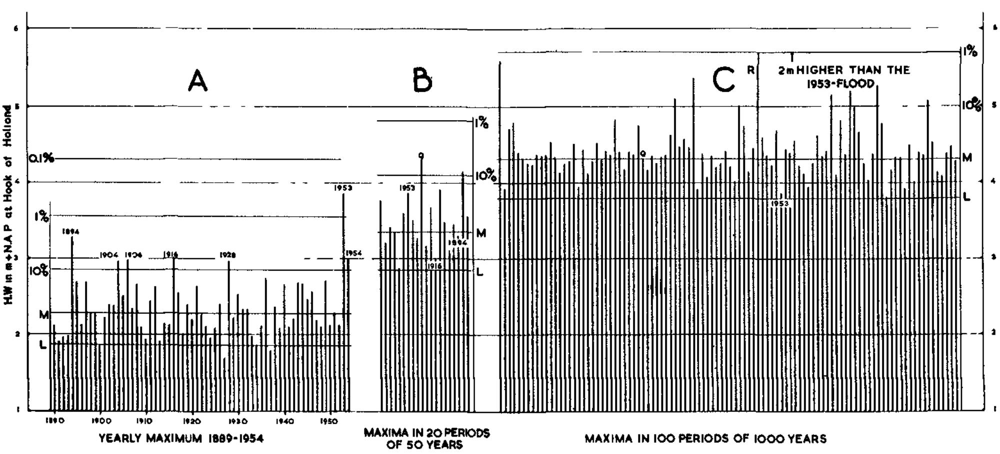

Fig. 2. Standard frequency curve F and curve of "maximum values" G .

The abscis shows on a logarithmic scale the exceeding value m. The ordinate shows h as an auxiliary height of an arbitrary character. In this diagram every value of m is directly related to a value of h by the straight frequency curve.
The frequency curve of highwater at a specific gauge such as e.g. fig. 1 provides the relation between the same value of m and the corresponding level at that gauge. From this results a well defined relation between any gauge reading H and the auxiliary height h.
So we may introduce the straight line F of fig. 2 as a standard frequency curve, valid for all gauges in the world as an exact representation, the ordinate being a nonlinear transformation of any gauge value into the uniform parameter h.
The abscis represents the exceeding value (or frequency) m, appearing in a period of T years. If we put N to be the number of cases of exceeding per year we have the relation:

$$m = T \cdot N \tag{1}$$

For the straight standard frequency curve the equation applies:

$$h - h_1 = -s \log m \tag{2}$$

if h_1 is the height corresponding to the value $m=1$, which value is marked in the diagram by the central point M.
The coefficient s represents the steepness of the curve, so:

$$s = -\frac{h-h_1}{\log m} \tag{3}$$

If h_1 corresponds to $m=1$; $h_{0,1}$ to $m=0,1$; $h_{0,01}$ to $m=0,01$ etc., then:

$$s = h_{0,01} - h_{0,1} = h_{0,001} - h_{0,01} \text{ etc} \tag{4}$$

This means that s represents the height Δh, which decimates the frequency m.

As the standard frequency curve is a straight line, the value of s is a constant. This implifies the further investigations considerably. Yet this is not a simplification of the general problem. For the frequency curve of a special gauge may deviate considerably from a straight curve and the decimating value may vary for different levels. The nonlinear transformation of H into h takes this fully into account.
From (1) follows:

$$m = e^{-\alpha \frac{h-h_1}{s}} \tag{5}$$

with $\alpha = \ln 10 = 2,3$.

4. THE MAXIMUM VALUE IN A GIVEN PERIOD

If we ask for the probability k that in a given period of T years r facts occur, the mean value of these occurrencies being m, Poisson's law states:

$$k = \frac{m^r}{r!} e^{-m} \qquad (e = 2{,}72\,..) \tag{6}$$

The chance of a given level h, corresponding to the exceeding value m, being not exceeded is given by the value of k for $r = 0$. So the chance of not being exceeded in a period of T years is:

$$k = e^{-m} \tag{7}$$

The chance q of being exceeded is the complementary value:

$$q = 1 - e^{-m} \tag{8}$$

Starting from the standard frequency curve F of fig. 2 it is a simple matter to calculate the values of q once for all. The result of this calculation is presented in fig. 2 curve G. The ordinates of this curve correspond to the same values of h as already discussed.
The abscis in this case gives the probability of exceeding q, ranging from 100% to 0%. The formula of this curve G can easily be derived from (8), resulting in:

$$q = 1 - e^{-e^{-\alpha \frac{h - h_1}{s}}} \tag{9}$$

This mathematical form is of little use for the present purpose, because formula (8) enables to calculate the curve in a much simpler way.
Gumbel uses this formula in general form as a starting point of his theory of maximum values. He does not use the whole universe but only the maxima. Our present work is based upon the use of the whole universe of observations and we come to final conclusions without any speculations about laws or coefficients.

4[a]. DISCUSSION OF THE FREQUENCY CURVE G

The curve G represents the probability q that a parameter height h will be exceeded in a period of T years. The central point of this curve is once more the mode M with the characteristic value $m = 1$ and the corresponding height $h = h_1$. For this point M the value of q is equal to:

$$q = 1 - e^{-1} = 0{,}63 = 63\% \tag{10}$$

If we have a period of T years and the height $h = h_1$ with the exceeding value $m = 1$, then the period T is exactly what in Anglo-Saxon scientific litterature is called "return period". Thus there is in a given period, which equals the length of the "return period", a probability

$$k = e^{-1} = 37\%$$

that the maximum value in that period will be lower than the corresponding height h (or the corresponding gauge height H), and a probability

$$q = 1 - e^{-1} = 63\%$$

that the maximum value will be higher.
If we take for m the value 5 the chance of not being exceeded is equal to:

$$k = e^{-5} = 0{,}7\%$$

and the probability of being exceeded:

$$q = 1 - e^{-5} = 99{,}3\%$$

We may conclude from this, that the height h_5, related to $m=5$ can practically be regarded as the lowest possible maximum height for a period of T years. Nearly always the maximum height in T years will be higher. Though in theory there is no limit in downward direction, for practical purposes the height h_5 has to some extent the character of such a limit. For if we take h_7 or h_{10} these heights will be found to be very close to h_5, but their probability of not being exceeded is only one hundredth of that of h_5. So it is nearly "impossible" to have lower maxima.
The highest values of the maxima are not limited in this sense. If m is small, e.g. less than $0{,}1$, we have:

$$q = 1 - e^{-m} = m \tag{11}$$

So for all values of m smaller than $0{,}1$ the chance of being exceeded is equal to the exceeding value itself.
The curve G corresponds to the mathematical form (9) and is represented here in the ogee-form. The Gumbel's diagram offers a possibility to draw the line G as a straight line. For our present purpose there is no need to make use of this possibility.

5. A SUBDIVISION OF THE RANGE OF POSSIBILITIES

From the preceding paragraphs we know, that the maximum values may range from h_5 (with $m=5$) up to every value of h without any limit. In order to discuss this wide range of possibilities it seems useful to introduce a division in classes, adapted to the needs of practical use. In order to attain this we divide the probability scale into classes.
Five characteristic values of the exceeding value m that may serve our intention, can be chosen namely:

$$m = 5 \quad 1 \quad 0{,}1 \quad 0{,}01 \quad 0{,}001 \tag{12}$$

The value 5 has been discussed already. The value $m=1$ represents the central value of the mode M and we have chosen the associated values

0,1 , 0,01 and 0,001 because we are living under the rule of the decimal system.
These values of m divide the range of possibilities into the following classes:

from $m = 5$	to $m = 1$	the class of	LOW maxima
from $m = 1$	to $m = 0,1$	the class of	NORMAL maxima
from $m = 0,1$	to $m = 0,01$	the class of	REMARKABLE maxima
from $m = 0,01$	to $m = 0,001$	the class of	EXCEPTIONAL maxima
from $m = 0,001$	to $m = 0,000$	the class of	EXTREME maxima

The five mentioned values of m correspond to the five heights of the auxiliary scale h_5 h_1 $h_{0,1}$ $h_{0,01}$ $h_{0,001}$ as shown in diagram 2. Due to this relation we may connect the five classes immediately to the vertical scale, as is done in the right hand part of fig. 2. Moreover the five classes are written along the line F .

A short discussion about these classes may be useful. There is no class below h_5 , for nearly never there will be a period of T years with a maximum value below h_5 .
If the maximum is found between h_5 and h_1 it is justified to call such a maximum LOW. It remains below the central height M . If we could observe a great number of periods of T years length, in 37% the maximum should be found to be below M , so belonging to the class of low maxima.
Maxima between h_1 and $h_{0,1}$ have been named NORMAL, thus stressing the fact, that it is quite normal that the maximum value in a period of T years presents itself in this range. The percentage of maxima, falling in this class, is 63% - 10% = 53%. So roughly speaking half of all maxima are normal.
After this definition it is quite normal, that in a given space of time of T years a maximum height of a stormflood $h_{0,1}$ occurs. This means a height with an exceeding value $m = 0,1$. Or, still in other words, it is quite normal to meet in a period of T years a stormflood which has 10 x T as its "return period".
The class next to the normal stormfloods has been named REMARKABLE maxima, which name seems to be fitting to the purpose. Of course just beyond the upper limit of normality we will have to distinguish a range of floods, being not quite normal at one hand, but being not really extreme in the usual sense of the word. So from $h_{0,1}$ up to $h_{0,01}$ we may meet "remarkable" floods. So we may say that we have had a "remarkable" flood if we observed in a period of T years a stormflood of a height with a returnperiod between 10 x T and 100 x T years. 10% - 1% = 9% of all maxima belong to this class.
Above the class of the remarkable stormfloods we distinguish the class of EXCEPTIONAL maxima. This class ranges from $m = 0,01$ up to $m = 0,001$. While a phenomenon, occurring at a rate of 1 in 10 can rightly be called remarkable, for a phenomenon presenting itself at a rate of 1 in 100 only, the term "exceptional" may be considered as justified. The total number of maxima, belonging to this class, is 1% - 0,1% = 0,9%. The small quantity of about 1% is in fair agreement with the current meaning of the word "exceptional".
From $h_{0,001}$ up to any possible height a stormflood may be called "extreme". The word "extreme" is used here in another sense than Gumbel does in his theory of extreme values. Gumbel's "extreme values"

in the present paper are called "maxima". This is only a matter of using words. But nevertheless it is my intention to discuss here the necessity to distinguish low maxima well from high maxima. For this purpose a more refined distinction is needed which leads to reserve the word extreme for those maxima beyond the class of "exceptional" maxima. That means that the word "extreme" encompasses all those occurrencies, lying beyond the normal, the remarkable and even beyond the exceptional occurrencies.
This classification will prove to be very useful for an understanding of the true nature of the variability of maximum stormfloods in a limited or even unlimited space of time.

6. AN ANALYSIS OF THE PERIOD TO BE TAKEN INTO ACCOUNT

We shall now discuss the character of the period of time of years. For this we can choose an arbitrary number, adapted to the situation we want to consider. As an illustration we take into view three distinct values, viz:

T = 1 year, representing interests of only short duration (merchandise on wharves for some weeks or months, execution of coastal engineering works for a few months or years etc.).
Although to the intellect one year is quite a short period in relation to a life time or seen as a part of history, in the daily walk of life, psychologically, we do not look beyond it as a rule.

T = 50 years, representing a "life time". With a fifty years period we take in view a whole life time of interests of rather restricted and individual character (factories, harbour works, buildings and also human life in the personal sense of the word). A period of fifty years has a definite significance, although it is not constantly before our mind.

T = 1000 years. With this third period the scope is widened to a time interval during which works of public character as an entity have to function in order to secure safety of life and existence of the community as a whole. Though the individual hydraulic constructions may have a life time of not more than 50 to 150 years, their collective aggregate forms a continuous entity, exposed to a constantly threatening force of nature.
From this "social" point of view we have to consider the life time of a whole community.

The three periods of 1, 50 and 1000 years are of course an arbitrary choice. They are meant to represent certain fields of interests for each of which a somewhat different figure could equally well be argued. The fields of interest themselves, however, we do consider as significant and their discussion may be useful as a guidance.

7. THE MAXIMUM STORMFLOOD IN EACH OF THE THREE PERIODS

It has been argued in the preceding paragraphs, that the "maximum height" is not a single value. Fig. 2 has shown that the maximum in a given period of T years may take any value between about h_5 and $h_{0,0}$ or infinitely high. Now attention must be paid to the fact, that the length of the period T plays an important role.
In order to translate the frequency or exceedingvalue N/yr, as given by the abscis in fig. 1, into the exceedingvalue m, to be read at the abscis in fig. 2, a period T has to be defined. We will now see, what the maximum values will be for each of the three periods arbitrarily chosen in par. 6.

Let us suppose we want to know the distribution of the yearly maxima of a 66 year time interval. Curve G of fig. 2 gives "all" possibilities. We divide the abscis of curve G into 66 equal parts. Each part corresponds on curve G with a value of h. Each value of h corresponds on line F with a value of m. Each of these values m can now be divided by the value of T, being 1 in this case. In this way every value of m leads to a corresponding value of N. Each value of N gives on the exceeding curve of fig. 1 a corresponding value of H, being the height of a stormflood at the gauge at Hook of Holland.
The result of this calculation can easily be compared with the observations of 66 years. This has been done in an earlier publication (see 1). A perfect correspondance was found. In connection to this for the present investigation the calculated heights have been replaced by the observed heights. Fig. 3 part A presents the sequence of the observed yearly maxima of the period 1889-1954. The higher values are marked by a date.

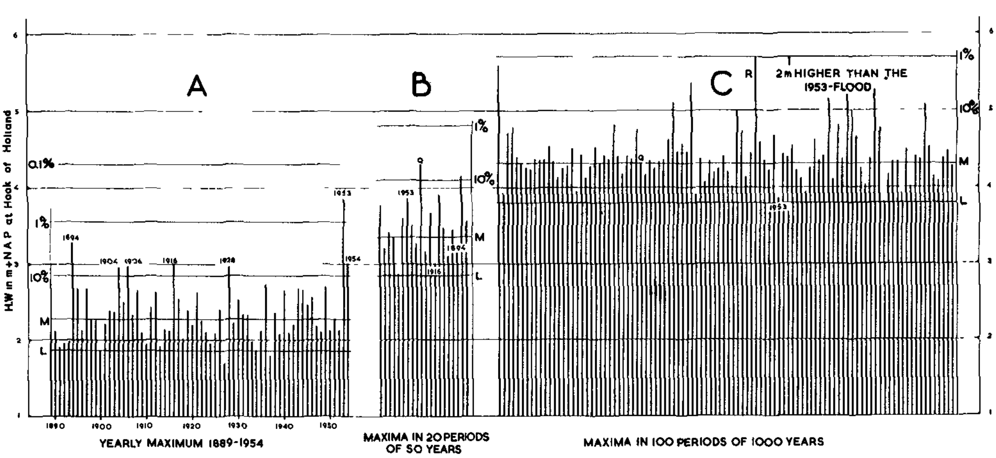

Fig. 3. The distribution of the maxima in periods of different lengths.

For the 50 years period we suppose that we want to know the most probable maxima of 20 periods. Dividing the abscis of curve G into 20 parts we can read on curve G the corresponding twenty parameter heights h and via curve F the corresponding values of m. After dividing each of the twenty values of m by 50 ($T=50$) we obtain twenty values of N. These values of N correspond in fig. 1 with 20 heights H. These heights are drawn in fig. 3 part B in an arbitrary order.
For the period of $T=$ 1000 years we find after an identical procedure part C of the diagram.
The diagram as a whole demonstrates clearly the distribution of the maxima. Such a distribution is always present, in the yearly maxima as well as in the maximum values in 50 year periods or in 1000 year periods.
This diagram illustrates the fact that a single maximum value is of little importance, which means also that the maximum stormflood, known by observation, is of little importance. It may be just a quite arbitrary choice by nature out of the whole range of possibilities. If we adjudge any importance to such an "observed maximum stormflood" we probably are misleading ourselves and others.
For what is presenting itself to us as an absolute maximum, being the highest level we ever observed, may, after diagram 3, possibly be only quite a low maximum.

This important discussion can be supported by pointing to fig. 3 B. This part of the diagram presents the most probable maximum height of 20 periods of each 50 years length. From observations we know 3 maxima of 50 years period, viz:

period 1850-1900 the 1894 flood is the highest one.
period 1900-1950 the 1936 flood is the highest one.
period 1950-2000 the 1953 flood will probably prove to be the highest one.

We have placed these three dates at the top of the three heights which are approximately the same as the three corresponding heights in fig. 3 A. From this we see, that the stormflood of 1936, being indeed a "very high flood" (in the opinion of observers of those days) and the maximum of a fifty years period, in reality has been only a low maximum for a period of that length. Even the disastrous flood of 1953, being in the one-year class an exceptional flood, proves to be in the 50 years group only a NORMAL maximum.
Turning over now to part C of fig. 3, we see the height of 1953 as number three from the bottom. In a period of 1000 years there is 97% probability, that the highest value will be higher than the 1953 flood Thus part A shows the stormflood 1953 as a Gulliver among the dwarfs, but part C shows the same 1953 as a Gulliver among the giants. This demonstrates the importance of the length of the period T.

8. APPLICATION OF THE CLASSIFICATION, PROPOSED IN PARAGRAPH 5

From fig. 1 can be taken immediately the heights of L, M, 10%, 1% and 0,1% for 1, 50 and 1000 years periods. These figures are presented in table 1.

height	in the proper period	period of 1 year (A)	period of 50 years (B)	period of 1000 years (C)
L	nearly lowest maximum (m=5)	+ 185	+ 290	+ 380
M	most probable maximum (m=1)	+ 225	+ 335	+ 430
10%	upper limit normal maxima	+ 290	+ 405	+ 500
1%	upper limit remarkable maxima	+ 355	+ 480	+ 570
0,1%	upper limit exceptional maxima beginning of extreme maxima	+ 430	+ 550	+ 640

Table 1. Characteristic heights of the periods A, B and C.

These heights have been marked in fig. 3. The practical value of the proposed classification can now easily be seen.
First the height L , computed with the exceeding value m=5. It is clearly shown that this height L indeed represents practically the lowest maximum height, to be expected in any given period. This applies as well to 1 year as to 50 or 1000 year periods.
As to M , the modus, characterized by the value m=1, fig. 3 shows, that this height is found not very far above L . The exact definition of M is that this height will be surpassed once (as an average!) in a given period. From fig. 3 however we see, that this value is of little importance when we are looking for a design flood. Quite many floods (63%) are higher than M.
This unimportance of M may be stressed once more. In scientific litterature often expressions are used like "a hundred years flood" or "a thousand years flood". With such expressions is meant the height of a flood exceeded in that period once as an average. This is exactly the height M. The expression "a thousand year flood", however, gives the impression of an extremely high flood, not to be exceeded in 1000 years. This is misleading. There is 63% chance that the maximum height in 1000 year will be higher, possibly even to a large amount, as clearly shown in fig. 3.

We now consider the 10% height. This means 10% chance of exceeding in a given period. From fig. 3 part A we used 66 observations. 10% of these values or about 7 will be higher than the 10% height. As such we see the maxima of the years:

1894 1904 1906 1916 1928 1953 1954 .

These 7 gales are well known in our country as "big gales". Nearly all of them caused more or less serious damage. The stormfloods 1894, 1906, 1916, 1928, 1954 are known to the public and 1953 has a worldwide reputation.
It is important to point out, that none of these stormfloods of importance is below the 10% limit. All the storms below the 10% limit have aroused no great interest, are "normal" storms. This agrees with the philosophy of pragraph 5, where the class between m=1 and m=0,1 has been called the class of normal stormfloods.
From the 7 floods mentioned above 6 are comprised between the 10% and the 1% limit. So all these floods belong to the class of "remarkable floods". This is in fair agreement with common parlance. All these floods are well known. The lower floods are unknown, they have not been remarkable.

From 1% to 0,1% we distinguished the zone of "exceptional floods". So in this nomenclature the disastrous flood of 1953 is an exceptional flood for the one-year scope.
Floods above the 0,1% height have not been recorded. Perhaps they have occurred in earlier centuries before the characteristic heights were registered.

This short discussion may show that the proposed classification is in fair agreement with common parlance. It shows moreover that the 10%, the 1% and the 0,1% limits are directly related to physical realities, to facts.
It has to be borne in mind, that up till now we have been discussing part A of the diagram. That is the series of annual maxima. It means, that all floods between M and the 10% height are to be called "normal" only in their quality as a n n u a l maxima. And the floods of 1894, 1904, 1906 etc. are to be called "remarkable floods" only in their quality as a n n u a l maxima. The big 1953 flood is an "exceptional flood" only in the sense of a maximum of one year.
From this we see, that the common nomenclature is closely related to a one-year period. Human awareness of natural processes such as stormfloods may be called a one-year embracing awareness. We appreciate the violence of a stormflood only in relation to the very moment we are living in.
If we had to our immediate disposal an organ to embrace more than only the few days of our present living our scale of appreciation would be another one. Fig. 3 part B shows what we should experience. In this part B the unit of time is 50 years.

The first important fact to be noticed is that the maxima of diagram B as a whole are much higher as those of diagram A. And the heights of L , M , 10% and 1% are higher just as well. (The 0,1% height has been omitted) The lowest maximum height L in graph B is exactly equal to the 10% for the one-year period, graph A. The three floods 1916, 1894 and 1953, being marked in diagram B, have already been discussed in paragraph 7 as being of less importance, in relation to 50 years periods.
In the class of remarkable floods (from 10% up to 1%) there is only one height present in B. It is marked Q and represents a stormflood 45 cm higher than 1953, which is an exceptional flood in the one-year period. Relatively the flood Q corresponds with 1916, 1928 and 1954 in the one-year period.
The community as a whole is interested in a much longer period. This may be different from case to case, but for the convenience we introduced a period of 1000 years. Fig. 3 part C gives the answer to the question what may be the maximum height in the course of any 1000 years period. The zone between L and M shows the "lower" maxima for a 1000 years period. Up to + 500 (the 10% height) we find the "normal" maxima. Above this height there are another 10 "remarkable" maxima. The stormflood Q, being in diagram B a remarkable maximum in relation to a 50 year period, is in diagram C in relation to a 1000 year period a rather unimportant level, just equal to the mode M.
This discussion may have illustrated that a classification, based upon the exceeding value m, applies to periods of every chosen length. The classification can be applied to any specific gauge.

It is, however, immediately related to a given period. So one has to bear in mind the necessity to determine first of all from case to case the length of the period that has to be taken into account.

9. PERIOD AND RISK

It is quite usual to regard the frequency of stormfloods as a one dimensional quantity. The relation between level and frequency is very simple and direct. Only one frequency curve, as e.g. given in fig. 1, is sufficient to translate a height at a given gauge into an exceeding value vice versa.
In the preceding paragraphs, however, we have argued, that this simplicity is misleading. In reality the question of the highest values is a matter of t w o dimensions, i.e. p e r i o d a n d r i s k.
In order to explain this the one-dimensional fig. 1 has been transformed into a two-dimensional diagram: fig. 4.

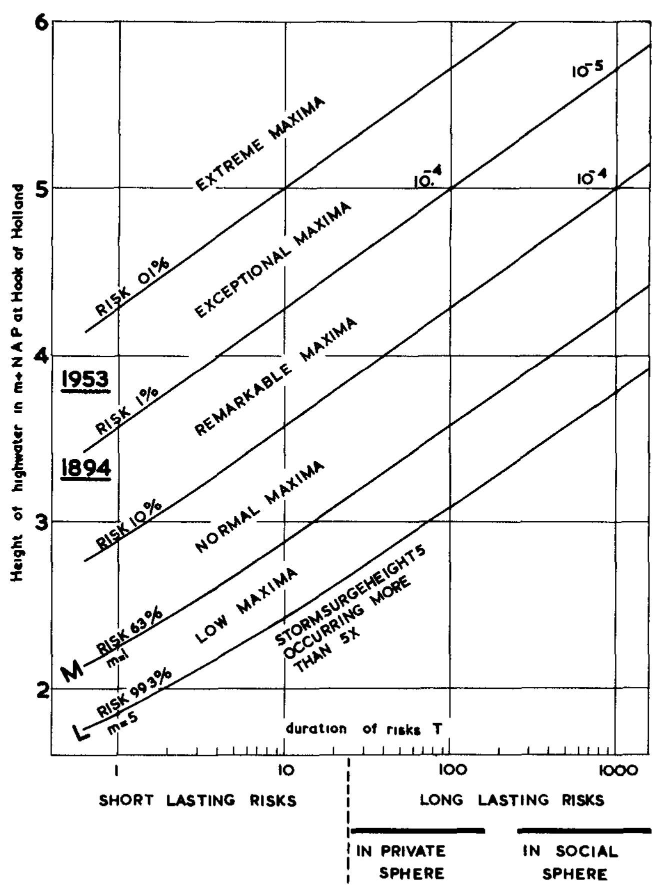

Fig. 4. Probability as a function of period and risk.

This diagram gives exactly the same as fig. 1. Yet the general impression differs considerably. The ordinate in fig. 4 gives the levels of highwater at the gauge at Hook of Holland, just as the ordinate in fig. 1.
The abscis gives on a logarithmic scale the length of the period T in years. This period T has to be regarded as the length of the duration of any risk. From 1 year or less up to 10 years or 25 years we may speak of "short lasting risks". From 50 years upward we could speak of "long lasting risks". These long lasting risks are divided into a "personal sphere" and a "social sphere". The longer periods are related to the social sphere.
The diagram shows 5 curves, respectively for $m=5$ (curve L), for $m=1$ (curve M), $m=0,1$, $m=0,01$ and $m=0,001$. Each height, given by these five curves can immediately be derived from fig. 1 by application of formula (1).
For curve M applies $m=1$. So $N=1/T$ and since the scale of N in fig. 1 is identical to the scale of the inverse value of T in fig. 4, the curve M in fig. 4 is identical with the curve in fig. 1.
The curve L represents the "lowest possible maximum" for any period, given by the abscis. This curve is rising, as all the curves are, with increasing length of the period. This means that with increasing length of the period the lowest possible maximum height grows higher and higher.
Between the curves we find the classes, mentioned in paragraph 5. The heights, belonging to each of these classes, move upward as the period increases.
Proceeding horizontally from left to right we see, that a given level of highwater may be called "exceptionally high" for the abscis value 1 (one-year period). This applies to the stormflood 1953, marked in the diagram. The same level however is only "remarkable" for a 10 year period, only "normal" for a 100 year period and even "low" related to a 1000 year period.
This graph shows that when time passes on every high flood is loosing its importance more and more. Going through the diagram along a line of constant height, (it may be some important stormflood) from left to right, there will come a moment, that we cross the curve L . About that time we may be sure, that our initial height will be exceeded. If we cross the curve of 1% there is already 1% chance of being exceeded. If we cross the curve of 10% the chance of being surpassed by a higher flood is increased to 10% etc.
From this investigation it is clear that the design level depends upon two factors:

a) acceptable risk (m)
b) duration of the risk (T)

And though m and T are connected together by formula (1) to

$$N = \frac{m}{T}$$

and N is connected only to one definite height, to establish a suitable design flood diagram fig. 4 should be preferred above fig. 1.
This may be emphasized once more in other words. To indicate a design flood as a flood, occurring once in its returnperiod, is misleading in a fourfold sense.

Firstly a very high flood does not return as such as shown in the diagrams of fig. 3. Secondly it is not a question of occurring of this particular height, but of exceeding it. Thirdly it is not exceeded "once" in the period T, but "as an average" it is exceeded once in that period. The main objection, however, is this. In relation to a design flood the so called returnperiod has no practical meaning.
The height h_1, corresponding to the point M and the value $m=1$, which is being exceeded just once in the period T, is such a low maximum, that it has no use as a design level.
As a design level only $h_{0,1}$, $h_{0,01}$ or $h_{0,001}$ can be taken into consideration.
If we take, e.g.: $h_{0,01}$ as design level, we accept 1% risk of it being exceeded in a period of T years. This height $h_{0,01}$ corresponds with a value of N given by:

$$N = \frac{m}{T} = \frac{0,01}{T} = \frac{1}{100\,T}$$

So the inverse value of N, being traditionally named "returnperiod", is in our example a hundred times the period T.
Let T in a special case be 200 years. If we accept a risk of the design level being exceeded of 1%, then we have to take from the frequency curve a height with an exceeding value $N = 0,5 \times 10^{-4}$. This value has no relation with a "returnperiod" of 20000 years. A period of 20000 years does not really enter into the argument. So the use of the term "returnperiod" in this sense should be avoided.
In principle the seemingly one-dimensional exceeding value has to be translated into the product of the two-dimensional value of acceptable risk with the inverse value of the duration of the risk.
Therefore, if a design level has been established at a height, determined by $N = 10^{-4}$, one has to translate this into 1% risk in a 100 years period, (or 10% risk in a 1000 years period), but never as 100% risk (which means certainty) in 10000 years.

10. ON THE ESTABLISHMENT OF THE DESIGN LEVEL

The preceding investigation provides a basis to establish a design level for each particular case. What we have to do is:

1) establishing a frequency curve for the gauge in question, including extrapolation (par. 2 and fig. 1);
2) determining the period T, during which the risk is present continuously for the interests, taken into account (par. 6);
3) choosing an acceptable value for the total risk on serious damage during the period T (par. 5). The total risk should never exceed 10%; for life and well-being of thousands a total risk of 1% or even 0,1% has to be taken into consideration.

After having established in this way a provisional design level one may come to the conclusion, that the costs, necessary to realise the safety aimed at, are not in right proportion to the economic and human values to be protected. Here a second question may arise viz:

what càn we realise with the technical and economic means at our disposal in a special case.

Another important point may be kept in mind. If we have erecte a hydraulic construction with the design level arrived at and safety is fully guaranteed against stormfloods up to this level, this does not mean that we have to expect a total loss if the stormflood is only 1 cm higher. There is a margin between the first unimportant damag and the stormflood level which leads to total loss of the proteoted interests. Moreover there is in several cases, as for instanoe embank ments an extra freeboard against wave runup which includes a consider able reserve.

The Netherlands Delta Commission has taken this into account. This commission established $m = 10^{-4}$ as a basis for the design levels. But in fact safety is considered to be guaranteed up to a stormflood leve corresponding to $m = 10^{-5}$. This indeed corresponds with a risk on "total loss" of 1% in a 1000 years period.

For some islands of no great economic value and a not very dense popu lation the design level is lowered to about $m = 2$ to 5×10^{-4}.

Litt. 1)
P.J.Wemelsfelder. Wetmatigheden in het optreden van stormvloeden.
De Ingenieur (Holl.), 1939, nr. 9.