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PROBABILISTIC DETERMINATION OF DESIGN WATERLEVELS IN THE EASTERN SCHELDT

by Niek Praagman(*) and Ary Roos(+)

Abstract: A probabilistic computation method for the determination of the design-waterlevel of a dam or dyke is presented. Results of the application of the method in the Eastern Scheldt estuary are shown.

1. INTRODUCTION

The design waterlevel is associated with the astronomical tide and storm surges. In determining the crestlevel of a dyke or dam the wave run-up and some "extra-height" should be added to the design waterlevel. The "extra-height" accounts for the relative rising of the sea level and shrinking of the dyke body.
Along the coast of the South Western part of the Netherlands the design waterlevel is defined as the waterlevel with an excess-frequency of 2.5*10(-4) times per year.
Normally this waterlevel is obtained from excess-frequency curves which are determined utilizing historical observations. This method is described in chapter 2 and will be referred to as the "Classical Method".
For locations in the Eastern Scheldt estuary (see figure 1) this method is not applicable since in the mouth of the estuary a stormsurge barrier has been constructed. This barrier is part of the so called "Delta Plan",initiated after the flood disaster of 1953. The barrier will be open under normal conditions, so that the tidal movement - important for the ecology of the estuary - will remain. Only when severe storms are expected the barrier will be closed.
To separate the inland shipping route between Antwerp and Rotterdam from the tidal estuary and to create a fresh water lake two compartment dams are built. These are called the Philipsdam and the Oesterdam (see figure 1).
The design waterlevels of those dams cannot be obtained from existing frequency curves because the waterlevels in the Eastern Scheldt will change due to the barrier and the dams themselves. The barrier influences the waterlevels in two ways : the aperture in the mouth of the estuary will be reduced and during severe storms the barrier will be closed.
In this paper a method for the determination of design waterlevels in the modified Eastern Scheldt is described. The method will be referred to as the "New Method". The excess frequencies are computed using a combination of historical observations at the mouth of the estuary and a mathemathical tidal model that includes wind effects.
Although the proposed method can be applied generally, up to now it has only been calibrated to and used for the Eastern Scheldt area.

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2. THE CLASSICAL METHOD

At various locations along the Dutch coast water level observations are available for a period of almost 100 years. In the classical method an excess-frequency curve is made using the observed data. For each location points are plotted in a diagram in which the waterlevels are on the y-axis and the logarithm of the number of exceedences of a waterlevel per year on the x-axis. The plot shows a more or less straight curve.

Because of the limited period of observations no estimates for water levels with an excess-frequency less than 0.01 times per year are directly available from the diagram. The extrapolation of the curve has been the subject of extensive statistical research. (van Dantzig & Hemelrijk, 1960). They showed that the observed waterlevels can be described as observations drawn from a distribution, having in the logarithmic scale an asymptote towards higher water levels. Figure 2 shows observed data and the extrapolated curve for the location Hook of Holland. (Wemelsfelder, 1960).

3. THE "NEW METHOD"

In an estuary waterlevels are mainly determined by the astronomical tide, the wind set-up at the mouth and the internal wind effect. In total eight parameters can be distinguished.
For the internal windeffect three parameters :

- Winddirection
- Windduration
- Windvelocity

The wind set-up can be described by two parameters :

- Wind set-up duration
- Wind set-up level

Further one parameter for :

- Astronomical tide

Finally, due to phase differences, two more parameters have to be considered :

- Phase difference between wind and wind set-up
- Phase difference between wind set-up and astronomical tide

Historical observations show that these eight parameters are not independent. In the following a description of the dependencies is given.
Considering observations it turns out that winddirection and windvelocity give rise to a two-dimensional matrix of probabilities. Insection 3.1 more information concerning the relation of these two parameters can be found. There exists also a relation between windvelocity and windduration. For several locations in the Netherlands a statistical investigation of storms has been made to obtain a quantitative relation for these two parameters. The formula

$$(1) \qquad k = 28.8 \left(\frac{V_{max}}{V_k} - 1 \right)^{0.84}$$

with (see figure 3)

k : Number of hours during which the one hour average wind velocity V exceeds the velocity Vk without interruption
Vmax : Maximum one hour average windvelocity over the total period of the storm

applies for the historical data of the Eastern Scheldt area. (Rijkoort, 1960) Once the maximum velocity Vmax is given the time history of the wind velocity and so the windduration are fixed.

Considering the historical data for wind set-up duration and windset-up level it has been shown that the expression

$$(2) \qquad s(t) = sm * \cos \left(\frac{\pi t}{D} \right)$$

holds for the Eastern Scheldt area.(Vrijling & Bruinsma , 1980).

The meaning of the parameters is :

s(t)	:	wind set-up at at time t
sm	:	maximum wind set-up
D	:	wind set-up duration

Especially the symmetric behaviour in time of the set-up s(t) with respect to the duration D is not found in general. In many applications form and coefficients of both formulas (1) and (2) may differ considerably.

For the determination of sm an empirical formula

$$sm = C(R) * \frac{V9 * V9}{g} \qquad (3)$$

has been used. (Weenink , 1958)

Here C(R) : Empirical coefficient which expresses the relation between the maximum wind set-up and the windvelocity that is exceeded for 9 hours : V9. The R shows that this coefficient is direction dependent. For our application it has been assumed that the wind is uniform over the whole Eastern Scheldt area. This assumption is realistic in most situations, but especially during storm conditions which is due to the fact that the Eastern Scheldt area has rather small dimensions compared to the dimensions of the windfield.

g : The acceleration of gravity.

Finally it has been noticed that the phase difference between the maximum windvelocity and the maximum wind set-up is always approximately six hours for the mouth of the Eastern Scheldt. In other words : the maximum wind set-up sm is found to appear six hours later than the maximum windvelocity Vmax. In formula :

$$t_{sm} = t_{Vmax} + 6 \qquad (4)$$

Considering the relations described so far the number of determining parameters is decreased to the following five :

Winddirection	:	R
Windvelocity	:	V
Wind set-up duration	:	D
Astronomical tide	:	H
Phase difference between wind set-up and astronomical tide	:	F

In order to make a discrete probabilistic model, the continuous range of values of the parameters is divided in a number of discrete classes. For each class the probability of occurrence of a special tidal cycle as a result of the combination of the five parameters R, V, D, H and F may be obtained by multiplication of the probabilities of each. Since one year contains approximately 706 high-tides the final result has to be multiplied by 706 in order to determine the probability of occurrence of the computed high waterlevel per year. In formula

$$p(ijklm) = 706 * p(Ri,Vj) * p(Dk) * p(Hl) * p(Fm)$$

In chapter 4 numerical values for the probabilities p are given for the mouth of the Eastern Scheldt estuary. For each combination of R, V, D, H and F high waterlevels in the Eastern Scheldt area have to be computed. To that purpose a numerical one-dimensional tidal model, called IMPLIC, is used. ((Stroband & Wijngaarden , 1977) and (Voogt & Roos, 1980)). The IMPLIC model has been calibrated and verified extensively. The model integrates the continuity equation and the momentum equation by a finite difference technique. In IMPLIC wind is included as an external driving force in the momentum equation. The estuary is schematized in a network of branches and nodal points (see figure 4). To each branch the finite difference equivalent of the continuity and the momentum equation holds. Because the high waterlevels have to be computed for the situation with compartment dams and storm surge barrier, those elements are included in the schematization.
The high waterlevels in the estuary depend on the closing strategy of the barrier. Several closing strategies for the storm surge barrier have been considered. (Roos e.a., 1980). For the design waterlevel of the compartment dams the strategy that the barrier is closed in one hour as soon as the seaside waterlevel exceeds mean sea level +3.25 meter, being the strategy which leads to the highest waterlevels in the estuary, has been adopted.
For each computation with the IMPLIC model a boundary condition at the mouth of the Eastern Scheldt and a windfield applying to the interior of the basin have to be made available. The windfield is defined by the values of the parameters R, V and D. The waterlevel at the seaside is obtained combining the astronomical tide at that location and the wind set up according to equation (2).
High waterlevels together with their probability of occurrence are computed for several locations in the estuary. From these data excess frequency curves are obtained adding for each waterlevel the probabilities of occurrence of all higher waterlevels. The discrete curve obtained in this way is transformed to a continuous one using standard continuation processes.

4. PROBABILITY DISTRIBUTIONS FOR THE EASTERN SCHELDT

In the design of the classes with probabilities of occurrence an optimum has been strived for. On the one hand the classes should not be too small in order to restrict the number of combinations possible and hence the number of computations with the IMPLIC model to be made. On the other hand, small classes are desirable in order to have, especially in the region of interest, enough separating power. In the following classes and probabilities are listed together with a short justification. Also values for the coefficient C(R) of formula (3) are specified.

4.1 WINDDIRECTION R and WINDVELOCITY Vmax

For the winddirection the compass has been divided in twelve classes, each class a sector of 30 degrees. Only the classes SW, WS, W, WN and NW (see figure 5) are important in the case of the Eastern Scheldt. Observations show that the distribution of the windvelocity Vmax is dependent on the direction R. Therefore table 1 has been constructed in which for each combination (Ri,Vj) a probability of occurrence is given.
For the velocity ten classes V1, V2, ... , V10 have been created. The range of each class is defined by

$$V_j = (5 *(j-1),\ 5 * j \ ) \ m/s, \quad j=1,2,\ldots,10$$

Since only five directions are important the table has fifty entries. The table has been constructed by combining data of the lightvessel "Goeree", during the period 1951 - 1960. (Dorrestein, 1967)

4.2 WIND SET-UP DURATION D

For the Eastern Scheldt the probability density of the wind set-up duration is a log-normal function. (Vrijling & Bruinsma, 1980). In formula :

$$(5) \qquad p(D) = \frac{1}{D\,(\ln 1.4)\,\sqrt{2\pi}} \exp\left[-0.5*\left(\frac{\ln D - \ln 51.3}{\ln 1.4} \right)^2 \right]$$

The historical data show that this probability density is independent of the direction R for the five directions considered. (Vrijling & Bruinsma, 1980).
In order to keep enough detail the set-up duration has been divided in twenty intervals Dk with :

$$D_k = \langle (k-1) * 10,\ k * 10 \rangle \text{ hrs},\ k = 1, 2, \ldots, 20$$

Since the probability of occurrence p(D) is not uniform over each interval, as follows from (5), a weighted duration <Dk> has been computed for each class using the formula :

$$(6) \qquad \langle D_k \rangle = \frac{\sum_{D=(k-1)*10+1}^{k*10} D * p(D)}{\sum_{D=(k-1)*10+1}^{k*10} p(D)}$$

Results are given in Table 2.

4.3 THE ASTRONOMICAL TIDE H.

Along the Dutch coast the tide is semi-diurnal. It is almost symmetric and can be approximated by a sinus-curve. For the mouth of the Eastern Scheldt the formula

$$(7) \qquad H(t) = a * \sin\left(\frac{2 \pi t}{T} + F \right) + b$$

applies with :

- a : tidal amplitude
- T : tidal period
- b : mean water level related to mean sea level

A division in three classes, each with a probability of occurrence of $p(H)=1/3$ has been used. The classes coincide approximately with the average spring tide, the average mean tide and the average neap tide. The values for a and b are given in Table 3.
The value of b differs from zero for mean tide and for spring tide. This is due to the difference between the observed curve and the approximating sinus-curve.

4.4 THE PHASE DIFFERENCE F.

The phase differences of wind set-up and astronomical tide cover the interval of 0 hours to 12 hours and 25 minutes. Since both are totally independent a strictly mathematical division in six classes, each having a length of 2 hours, 4 minutes and 10 seconds has been used. For each class the probability of occurrence is $p(F_i)=1/6$ and in the computations per class a mean value for the phase F is used.

4.5 THE PARAMETER C(R).

From the observations of 54 historical storms an estimate has been made for the value of C(R) in equation (3). For the mouth of the Eastern Scheldt the following values have been found :

C(SW) = 0.0150 C(WS) = 0.0175 C(W) = 0.0225
C(WN) = 0.0250 C(NW) = 0.0300

5. COMPUTATIONAL RESULTS FOR THE EASTERN SCHELDT ESTUARY.

In order to show the potential power and the reliability of the used formulae in the new method, the method has been applied to the mouth of the Eastern Scheldt for the original situation. Furthermore the method has been used to compute the excess frequency curves for the compartment dams in the Eastern Scheldt for the new situation. Results of both computations are given in this chapter.

5.1 EXCESS FREQUENCY CURVE AT THE MOUTH OF THE EASTERN SCHELDT

For the application of the method for a location at the mouth of the Eastern Scheldt waterlevels had to be made available for all the combinations of the parameters R, V, D, H and F. No IMPLIC computations were needed. Computation of the waterlevels and adding their probabilities of occurrence delivers the excess frequency curve as shown in figure 6. The curve can be compared with the excess frequency curve obtained by the classical method. The two curves show a good agreement which justifies the calibration of the formulae and the division in discrete classes of the five parameters as used.

5.2 EXCESS FREQUENCY CURVES FOR THE COMPARTMENT DAMS.

Because tidal amplification and internal wind effects do play an important role in the Eastern Scheldt estuary, computations with the IMPLIC model had to be made for all the combinations of the parameters R, V, D, H and F for the new situation. The computation of the waterlevels with their probabilities of occurrence resulted in the curves as shown in figure 7 for the Philipsdam and figure 8 for the Oesterdam. To show the effect of the barrier and the compartment dams also curves for the original situation, obtained with the classical method, are included in the figures. The large effect of the changes on the waterlevels is clearly illustrated.
From the curves as shown in the figures 7 and 8 the design waterlevels have been derived at the excess frequency of 2.5 * 10(-4) times per year. Those waterlevels have been used in the design of the compartment dams.

6. DISCUSSION

A method to compute excess frequency curves on a probabilistic basis has been proposed. Although the method can be used for general application whenever sufficient data are available, up to now it has been applied and calibrated to the Eastern Scheldt area only. Formulae and parameters of this paper are restricted to this estuary.

For a location along the coast the method can be used as an alternative to the classical method. The new method is not "better", because also in the new method extrapolation, in this case of the wind, is needed. However if a new or modified geometry is created, as in the presented example, only the new method is applicable.

APPENDIX I. - REFERENCES

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Appendix II. - Notation

The following symbols are used in this paper :

- a = Tidal amplitude
- b = Mean water level, related to mean sea level
- C = Empirical coefficient for set-up
- D = Wind set-up duration
- F = Phase difference between wind set-up and astronomical tide
- g = Acceleration of gravity
- H = Astronomical tide
- p = Probability
- R = Wind direction
- s = Wind set-up
- t = Time
- T = Tidal period
- V = Wind velocity

WINDVELOCITY V IN M/S	WINDDIRECTION R				
	SW	WS	W	WN	NW
0.0 - 5.0	3.76666667	4.70000000	3.23333333	2.40000000	2.53333333
5.0 - 10.0	3.01333333	3.76000000	2.58666667	1.92000000	2.02666667
10.0 - 15.0	3.31466667	4.13600000	2.84533333	2.11200000	2.22933333
15.0 - 20.0	1.04713333	1.30660000	0.89886667	0.96720000	0.40426667
20.0 - 25.0	0.11177600	0.19560800	0.30738400	0.25149600	0.13972000
25.0 - 30.0	0.01094171	0.01094171	0.02188342	0.04376684	0.03282513
30.0 - 35.0	0.00040112	0.00040112	0.00040112	0.00320895	0.00080224
35.0 - 40.0	0.00002186	0.00002186	0.00002186	0.00034978	0.00004372
40.0 - 45.0	0.00000174	0.00000174	0.00000174	0.00002788	0.00000349
45.0 - 50.0	0.00000016	0.00000016	0.00000016	0.00000253	0.00000032

Table 1: Probability of occurrence of the combination windvelocity - winddrection (R_i, V_j) in percents.

Class	Class boundaries (hrs)	$\{D_k\}$ (hrs)	p (D_k)
1	1 - 10	9.74	1.1 e-6
2	11 - 20	18.56	3.2 e-3
3	21 - 30	27.08	5.8 e-2
4	31 - 40	36.02	1.8 e-1
5	41 - 50	45.52	2.4 e-1
6	51 - 60	55.25	2.1 e-1
7	61 - 70	65.11	1.4 e-1
8	71 - 80	75.02	8.2 e-2
9	81 - 90	84.97	4.4 e-2
10	91 - 100	94.94	2.3 e-2
11	101 - 110	104.93	1.2 e-2
12	111 - 120	114.92	5.7 e-3
13	121 - 130	124.92	2.8 e-3
14	131 - 140	134.92	1.4 e-3
15	141 - 150	144.93	6.8 e-4
16	151 - 160	154.93	3.4 e-4
17	161 - 170	164.94	1.7 e-4
18	171 - 180	174.95	8.6 e-5
19	181 - 190	184.95	4.4 e-5
20	191 - 200	194.96	2.3 e-5

Table 2: Probability of occurrence of the wind set-up duration D_k.

Class	a (m)	b (m)
1	1.55	0.08
2	1.41	0.05
3	1.23	0.00

Table 3: The tidal amplitude a and the mean water level b for the three astronomical tide-classes at the mouth of the Eastern Scheldt.

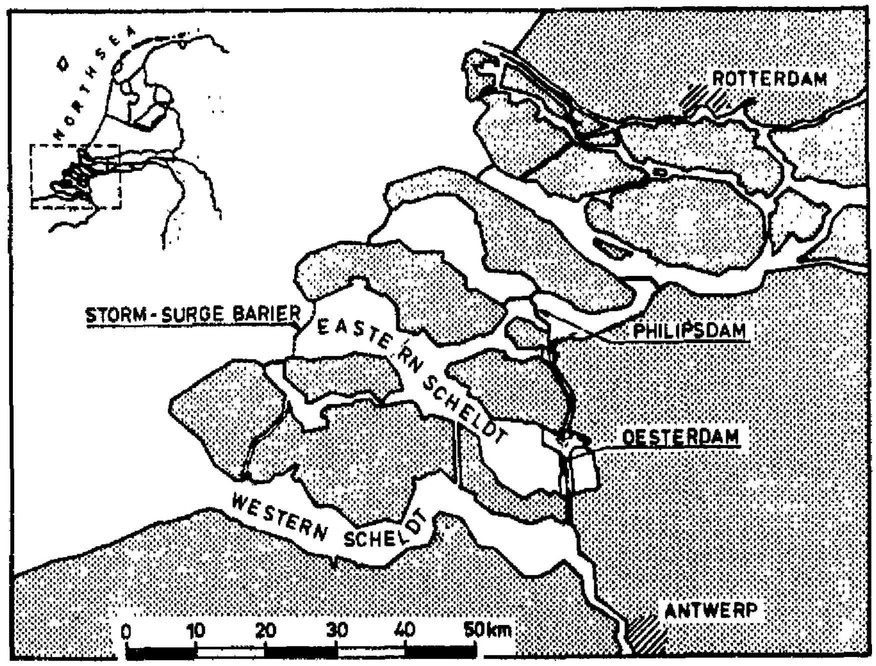

Fig. 1: The South-Western part of the Netherlands.

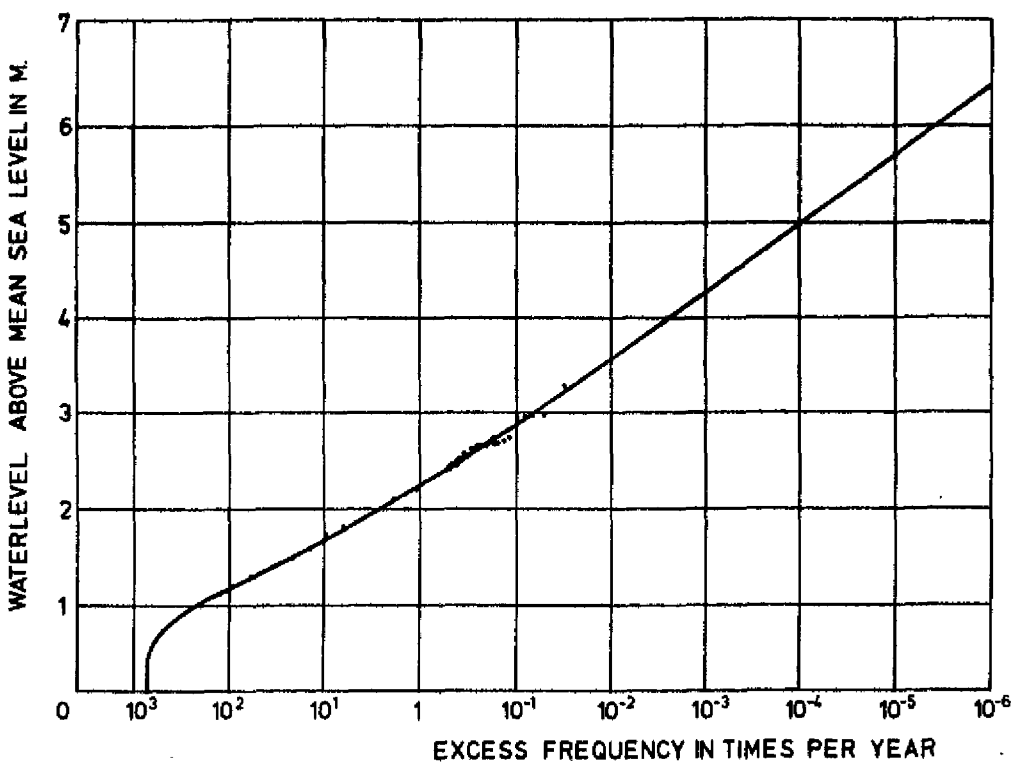

Fig. 2: Excess frequency curve for Hook of Holland.

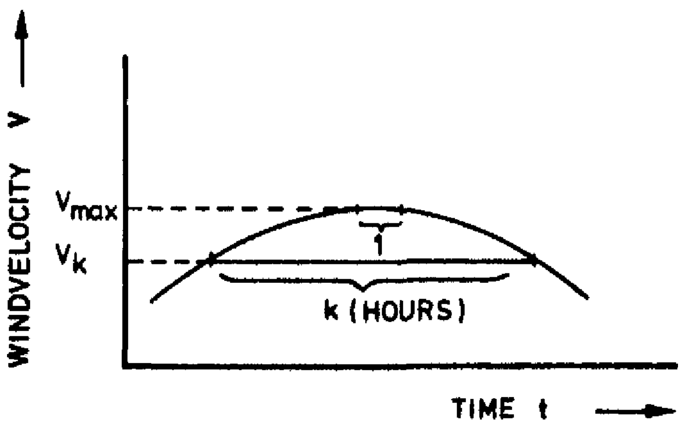

Fig. 3: Definition sketch of the time history for the windvelocity.

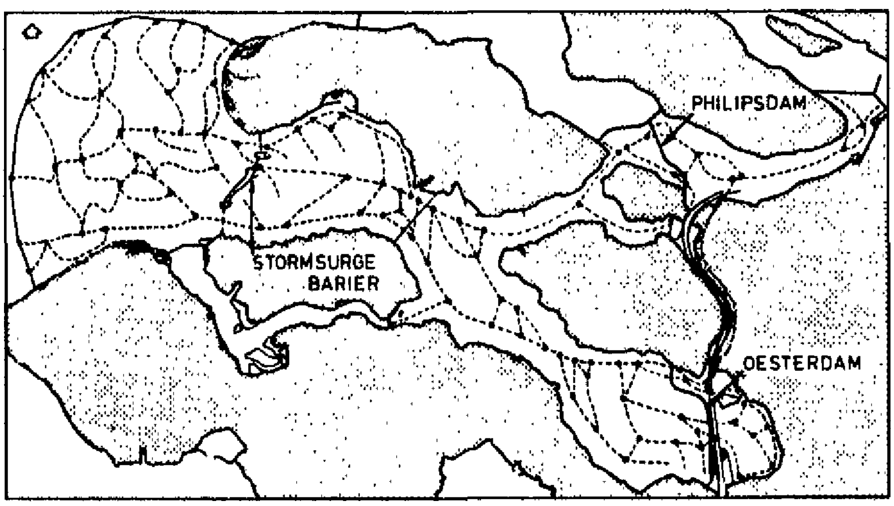

Fig. 4: Network of the Eastern Scheldt model.

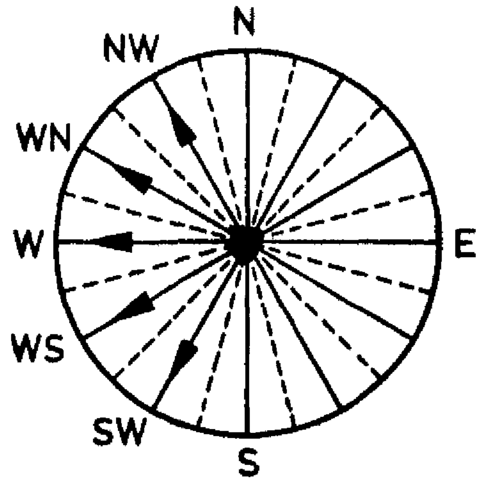

Fig. 5: Compass-card for winddirections.

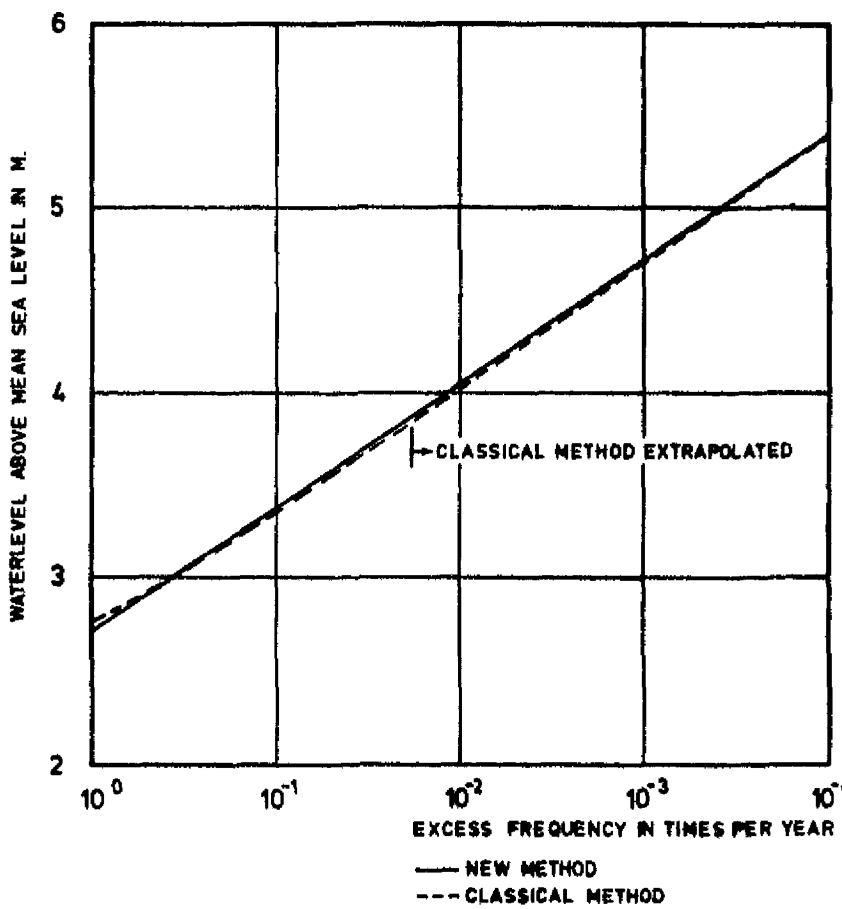

Fig. 6: Comparison of the excess frequency curves obtained bij the new method and the classical method at the mouth of the Eastern Scheldt for the original situation.

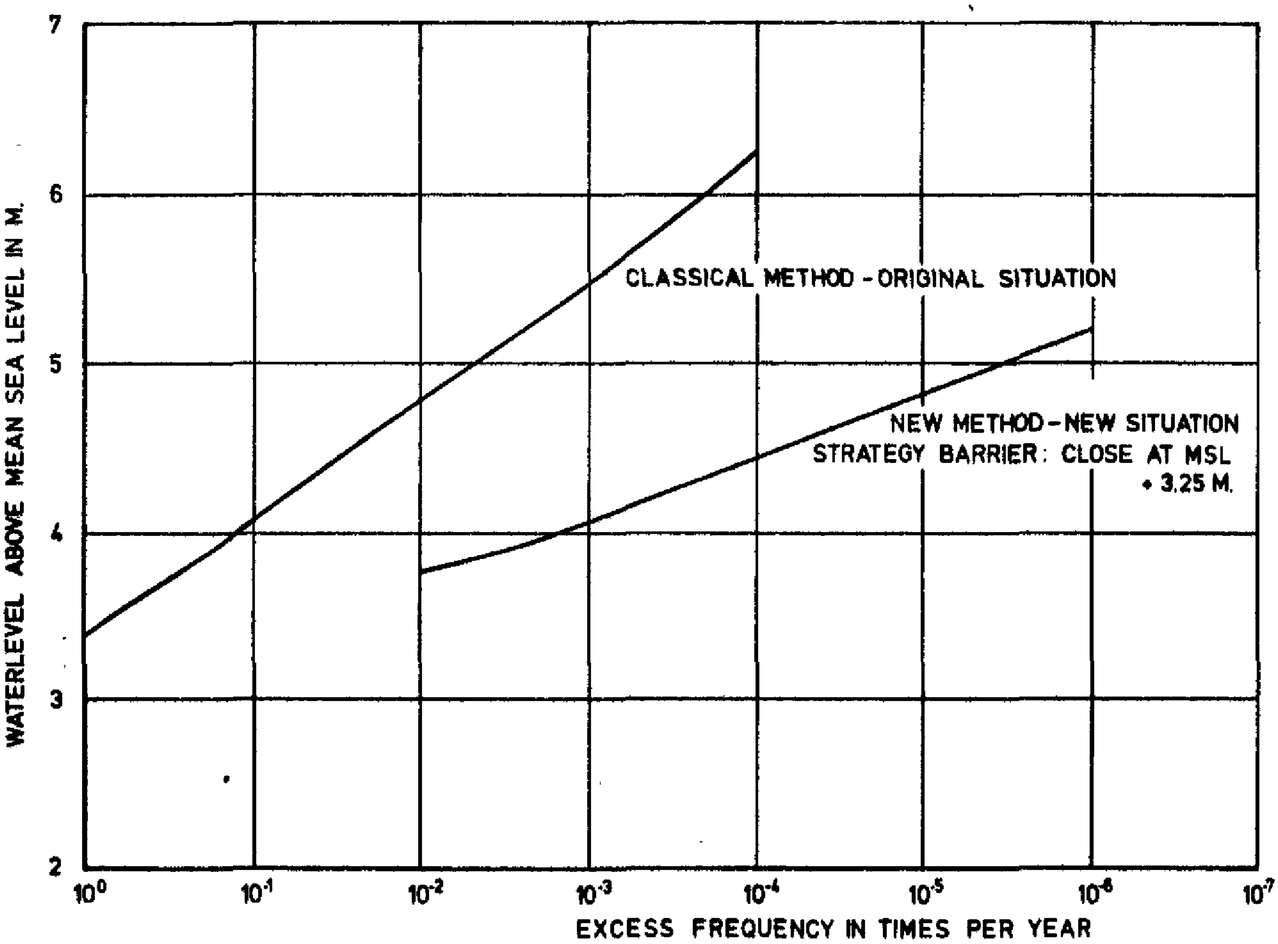

Fig. 7: Excess frequency curves for the Philipsdam.

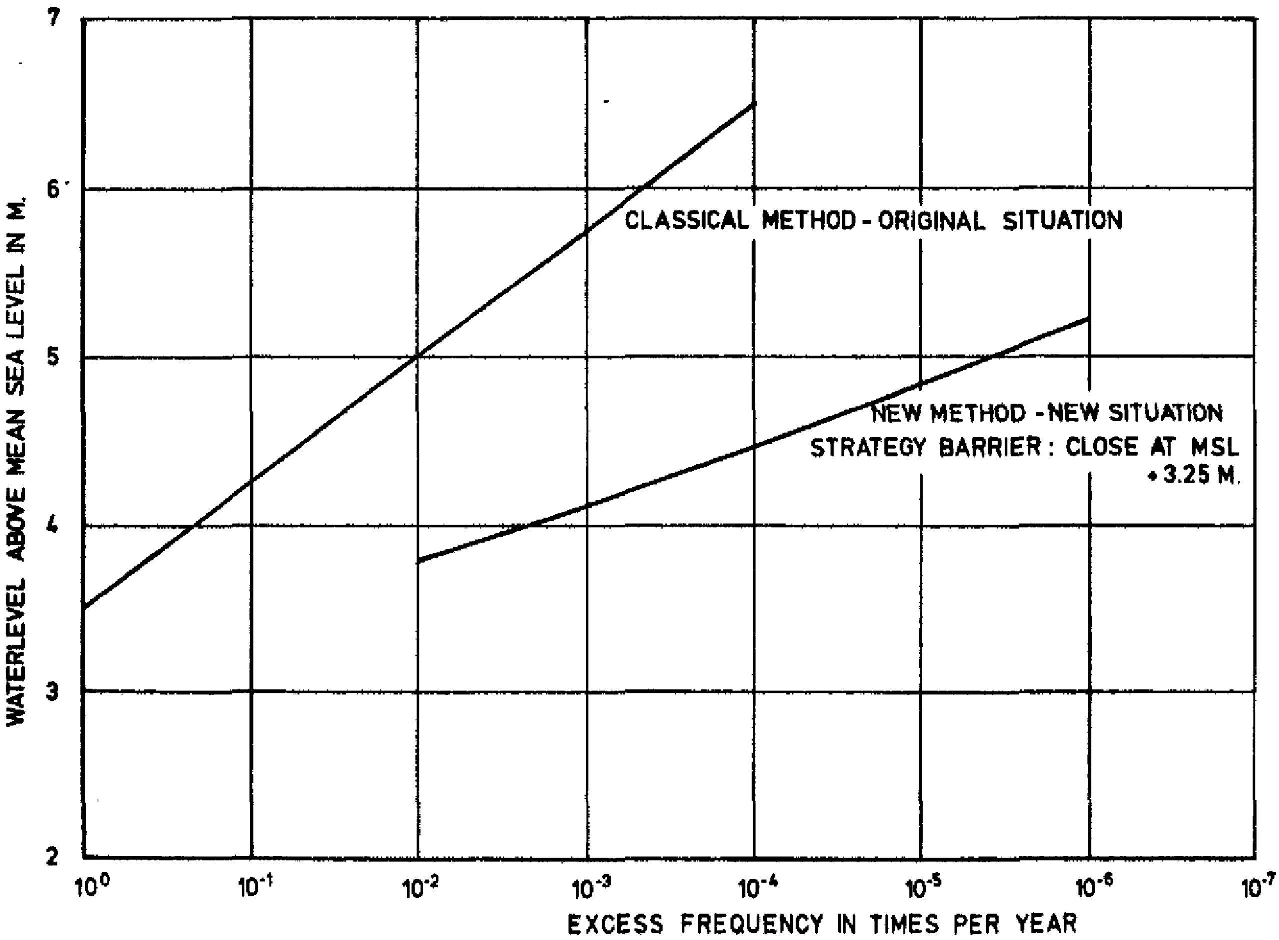

Fig. 8: Excess frequency curves for the Oesterdam.