CHAPTER 6

HIGH-WATER PROBLEMS ON THE DANISH NORTH SEA COAST

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With reference to the use of high-water frequency curves, which have been suggested by Wemelsfelder as an aid to fix the maximum flooding level, an attempt will be made in the following to estimate how far certain special geographical and meteorological conditions may be expected to influence the shape of the frequency curves for different localities. The investigation concerns a particular point on the Danish North Sea coast compared with the Dutch coast, but its principles may possibly be of interest in a wider sense.

INTRODUCTION

THE NORTH SEA.

The North Sea forms a kind of bay of the Atlantic, being at its north-western end connected with the great depths of that ocean, while its other connection with the Atlantic, through the English Channel, is so narrow and shoal that its influence on the water level is small. It is a very shallow sea (see the map, Fig.1,which also shows the main features of the bottom topography) particularly its southern part, which is just where adjoining territories in England, Germany and Denmark as well as - and predominantly - in Holland comprise very low-lying tracts. Many inundation catastrophes have, therefore, hit these regions through the ages, and dikes have been built at many places to safeguard against floods.

FREQUENCY CURVES

For the purpose of planning dikes and certain other maritime constructions, a determining maximum flooding level for each individual place must be fixed, and the establishment of this level was formerly based upon the knowledge of "the highest possible flood" gained by experience from inundations actually occurred during historical times, possibly with a certain safety margin added.Such experience may, however, be rather doubtful, and usually covers only a comparatively short span of years.

In order to provide a better survey of this problem P.J. Wemelsfelder (see [1] in "References") in 1939 suggested the application of a "frequency curve" produced by plotting in a system of co-ordinates the values of high water against the frequencies

(i.e. the average annual number of times according to available statistical material) with which a water level equal to or higher than the value under consideration has occurred at the place in question. When a semi-logarithmic system was used (the frequencies being represented in the logarithmic scale) the curve proved to be very nearly rectilinear (see Fig. 2, in which however, the lower curve is drawn on the basis of gales under special meteorological conditions only), and extrapolation of the curve gives an impression of the frequency with which specified extraordinarily high water levels may be expected to occur, or rather the probability of their occurring.

ASTRONOMICAL AND METEOROLOGICAL TIDES

That part of the change of level which is due to astronomical causes, the tides, is fairly exactly known in the case of the North Sea [2] . It consists of standing oscillations, maintained by the oceanic oscillations of the Atlantic in the north, but superimposed on these main longitudinal oscillations are smaller transverse oscillations due to the earth's rotation, the aggregate result being a circling tidal surge travelling southwards along the coast of Great Britain and - with greatly decreasing amplitude - northwards along the west coast of the Danish peninsula of Jutland. As to the influence of meteorological conditions on the water level much greater uncertainty reigns, and these are, therefore, the only ones which are considered when recording frequency curves, the known values of the astronomical tide being deducted in advance.

The influence of meteorological conditions on the water level has been studied in detail in various countries where flood warning services for threatened areas have been set up, and diverse methods of preparing these warnings on the basis of theoretical investigations combined with the utilization of statistics have been developed, for instance in Great Britain by R.H. Corkan [3] , in Holland by W.F. Schalkwijk [4] , in Germany by G.Tomczak [5], and in Denmark (where so far no warning service has been established) by J. Egedal [6] .

EXTRAPOLATION OF FREQUENCY CURVES

Generally. After the great inundation catastrophe that hit England and Holland i 1953, and during which the water level considerably exceeded heights previously recorded within historical times, the application of frequency curves has particularly come to the fore. It must be admitted that the utilization of a frequency curve embodying and arranging, almost automatically, all the existing actual observations, seems more attractive than relying only on the highest known water level within an arbitrary, pretty short, period, but the difficulty appears when the curve is to be extrapolated. Its upper part, being provided by very few observations, must be highly unreliable, and it also appears to be a fact that in Holland, where observations for more than 50 years are available, curves recorded separately for the individual decades

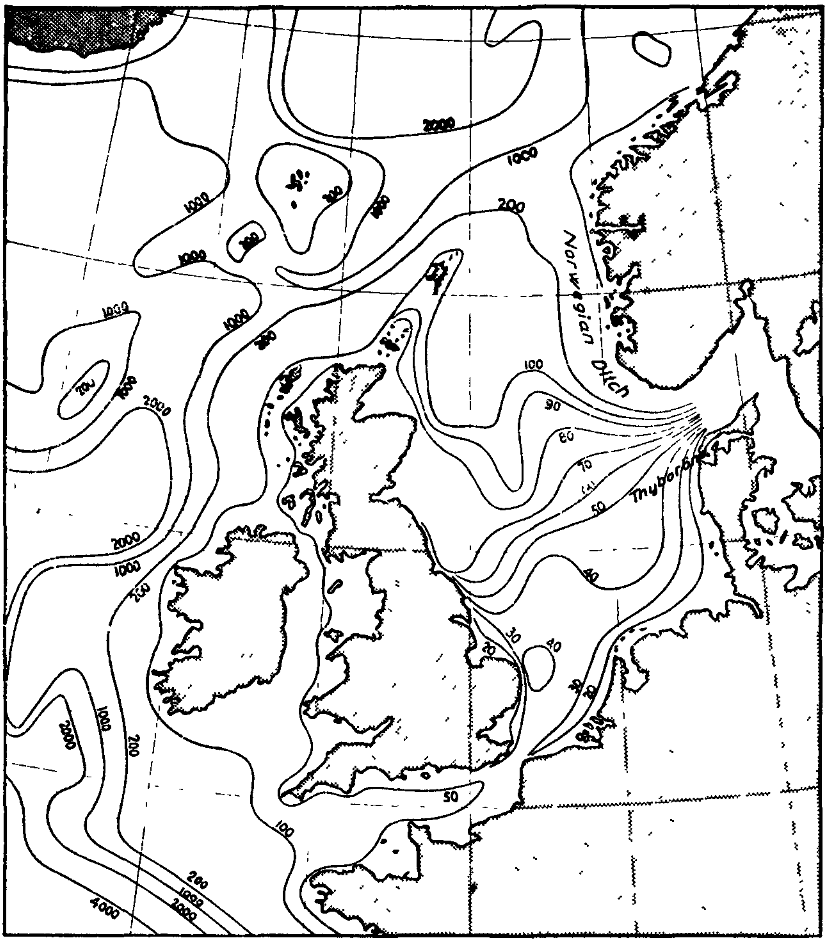


Fig. 1 Depths of the North Sea (in meters)
(After Schalkwijk)

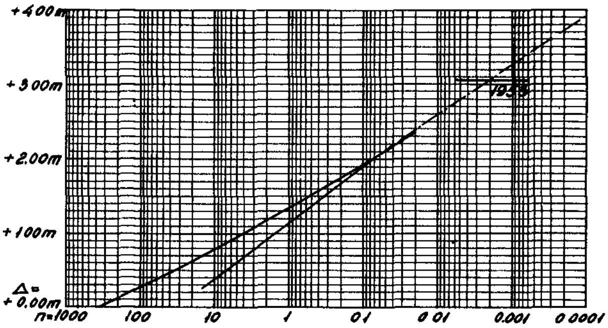
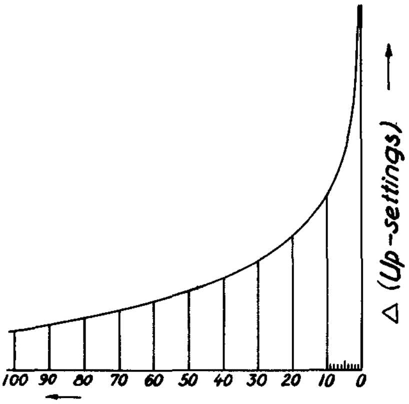


Fig. 2 Frequency curves
for Hook of Holland



Frequency of upsettings ≥ Δ
Fig. 3

differ greatly at their upper ends [7] . Further, it must be borne in mind that a rectilinear extension of the curve in the semi-logarithmic system has been chosen arbitrarily among many possible ext polations, and that this straight line, when transferred to a non-logarithmic system, gives a curve asymptotically approaching the y-axis (see Fig.3), thus involving the inherently unreasonable result that the height of the wind-effects tends to ∞ when the frequency approaches nil. This conforms badly to the common and "natural" conception that the water level must be approaching a ce tain limit when the frequency tends to nil, and after all it is th minute topmost fraction of the curve, where it grows asymptotic (and consequently improbable) which is "enlarged" by the logarithmic system and utilized. Already when advancing the method, Wemelsfelder was, indeed, aware of this, but he adduced that a minor extrapolation must be justifiable, as the limit of what is physica ly possible would probably not thereby be exceeded, and that even appreciable extrapolation does not lead to quite absurd figures (for the frequency 10^{-6}, i.e. once per one million years, he mentions a wind-effect of 5.9 m at Hook of Holland).

In Holland - To be sure, much discussion and deliberation ha taken place in Holland as to how the curve should be extrapolated [7] , but agreement has gradually been reached there on a rectilinear extrapolation, which seems to yield probable results in the case of Holland within that section of the curve which it is found reasonable to deal with, and it is thus assumed that a maximum flo level off Holland must at any rate be very high.

In Germany - Also in Germany rectilinear extrapolations of the frequency curves have been used when contemplating the height dikes in the marshlands [8] , but here it is only a matter of a small extrapolation (up to 10^{-2}), as - unlike in the case of Holland - the tracts to be protected are agricultural areas and not important, densely populated industrial ones.

CONDITIONS AT THE DANISH NORTH SEA COAST

In Denmark there are in the southern part of Jutland marshlands with conditions much like those in the adjoining regions of Germany. However, the question of maximum high water is also of importance for certain contemplated constructions at Thyborön in the northern part of Jutland (see Fig. 1), but here water level observations are only available for a comparatively short period, and some uncertainty exists as to how the frequency curve should be extrapolated at this place, where conditions are very different from those prevailing off Holland and Germany. While the mean rang of the tide varies between 1.3 and 3.7 m off Holland and is about 1.5 m at the Danish-German boundary, it is only 0.4 m at Thyborön, which is situated almost off the transition between the particularly shallow southern part of the North Sea and its somewhat deeper northern part.

HIGH-WATER PROBLEMS ON THE DANISH NORTH SEA COAST

SCOPE AND PRESUPPOSITIONS

In the following an attempt has been made to realize to what extent various geographical and meteorological conditions may influence the course of the frequency curves off Holland and at Thyborön respectively. Only a qualitative investigation in broad outline has been undertaken for the purpose of establishing the probable mutual relation between the two curves, but a lucid exposition of the problem has been aimed at. Moreover, the investigation has been confined to dealing with the stationary state directly generated by homogeneous fields of wind over the entire North Sea (here called the "wind-effect"), disregarding barometric effect, phenomena of inertia, additional quite local effects, seiches, etc., as well as disturbances generated outside the North Sea. As to these last mentioned "external effects", to which great weight is attached in Britain, it must be justifiable to presume that their amplitude - just as that of the tide - will have decreased much when they reach Thyborón.

METHODS

Schalkwijk concerning the North Sea - In his treatise [4] Schalkwijk surveys how the problem of wind-effect has been treated previously, and uses the formula:

$$\Delta\zeta = \frac{a\,V^2\,L\cos\psi}{H} \tag{1}$$

in which $\Delta\zeta$ is the height of the wind-effect in cm over a stretch of L km with a depth of H m and a velocity of wind of V m/sec., a is a constant which Schalkwijk fixes at 0.032, and ψ is the angle between the direction of the wind and the direction of a line connecting the two points between which the difference in water level is sought.

The introduction of cos ψ is due to the fact that the formula was originally established for a canal, and in his investigations concerning the Dutch North Sea coast Schalkwijk only applies it as follows: He seeks out that direction of wind (about 15° west of the longitudinal axis of the North Sea, which is about NNW-SSE) which causes the highest wind-effect at the point under consideration, and thereafter, as far as certain secondary elements are concerned, he calculates the effect of winds from other directions by means of the cosine of the angular deviation, while for the main element he uses an empirical function of the angular difference, the effect proving to be not quite symmetrical about the direction which causes maximum. A special section of the treatise deals with the connection with the Atlantic.

As an introduction Schalkwijk had considered the comparatively simple case of the wind blowing across an enclosed sea, and he finds (as previously Ekman [9]) that in this case an inclination of the surface arises which - in spite of the effect of the earth's rotation - very closely corresponds to the direction of the wind (i.e. is directed against it). This result holds good when the state has become stationary, while - during its development - the contour lines of equal water level of the surface are turned somewhat to the right.

Hellström concerning the Baltic Sea - The influence of the wind on an enclosed sea may thus be treated fairly simply, and this has for instance been done by B.Hellström in an investigation into the wind- effects in the Baltic Sea [10] , the comparatively narrow outlets to the North Sea through the Danish straits being disregarded. Hellström uses a formula corresponding to the one mentioned before, but in a slightly different notation, viz.:

$$\frac{dz_0}{dx} = \frac{\varkappa\, k}{\gamma(z_0 - z_1)} \qquad (2)$$

where $(z_0 - z_1)$ = the depth of water. x = the longitudinal coordinate, k = the tangential pressure of the wind, γ = the density of the water, and $\varkappa$ is a dimension-less coefficient, which is fixed at 1.5. If the ratio k/V^2 is assumed to be constantly 0.000213, while it is supposed by Hellström to be slightly varying according to the velocity of the wind and γ is assumed to be 1000 kg/m^3, we obtain:

$$\frac{dz_0}{dx} = \frac{3.2\times10^{-4}\, V^2}{1000\,(z_0 - z_1)} \qquad (3)$$

i.e. exactly the same as (1) when the inclination is taken to be dimensionless, and this form will be used in the following estimatory calculations.

Hellström proceeds as follows: For each direction of wind the mean depth for a number of cross-sections at right angles to the direction of the wind is calculated, which results in a mean longitudinal profile in the direction of the wind, and by applying the formula the inclinations of the surface corresponding to a number of points in the longitudinal profile are found. The mut al positions of the longitudinal section of the surface with incl nations varying according to the depth at each point and the calm water surface are now fixed so as to comply with the requirement that the aggregate amount of water must remain constant, and the contour lines of the surface are then drawn as straight lines at right angles to the direction of the wind and with the longitudin section as directrix, quite irrespective of the very irregular shape of the sea with islands, bays, etc. It is evident that a gr number of equalizing currents must arise before the surface can adjust itself in this position, but apparently they come to pass approximately within the same time as it takes for the inclinatio to develop. Also minor corrections are computed in order to take into account local bottom topography, but all things considered t results correspond pretty well with actual observations. It shoul however, be remembered that the depths of water in the Baltic Sea are comparatively small, averaging about 60 m, and that the great depths (maximum 460 m) are confined within few areas of negligibl extent.

COMPARISON BETWEEN CONDITIONS OFF HOLLAND AND DENMARK

ENCLOSED SEA

In order to get an impression of the importance of the uneven depths of water in the North Sea, let us first consider an enclosed sea, shaped as a square 600 x 600 km (see Fig. 4 a), one half of which is 40 m deep, while the other half is 80 m, as indicated by the cross-section shown in Fig. 4 b. For the sake of simplification the "sea" is provisionally supposed to be oriented due north-south, but actually it is intended to represent the southern two-thirds of the North Sea, highly simplified, and the point A would thus correspond to a point on the Dutch coast and B to Thyborön. A velocity of wind of 29 m/sec. (i.e. on the lower side of force 12 by Beaufort's scale), would give an inclination of the surface, according to (3) of

$$\frac{dz_0}{dx} = \frac{3.2\times10^{-7}\times29^2}{40} = 0.67\times10^{-5} \text{ or } 200 \text{ cm in } 300 \text{ km}$$

For the northern part half that figure, viz. 100 cm in 300 km will be found. If the two halves were separated, a northerly wind would cause the water level to take up the position shown by dotted lines in Fig. 4 b (the differences of level being much exaggerated) and indicated in Fig. 4 a by contour lines in connection with shading of high-water areas, but when they are inter-connected the water surface will follow the full-drawn oblique line in Fig. 4 b, as also indicated in Fig. 4 c, and in order to bring about this result there must, besides other currents, pass a current from the northern to the southern half as indicated by arrows in Fig. 4 d. A westerly wind would cause different inclinations in the two halves if they were separated (see Fig. 5 a), and Fig. 5 b shows a section along the "partition wall" with both inclinations represented by dotted lines, but when no such separation exists, the water must adjust itself by the mean depth, i.e. with an inclination of

$$\frac{dz_0}{dx} = \frac{3.2\times10^{-7}\times29^2}{60} = 0.45\times10^{-5} \text{ or } 135 \text{ cm in } 300 \text{ km}$$

as indicated in Figs. 5 b and 5 c, and to make the water assume this inclination, a circling current, as indicated in Fig. 5 d, is required.

Figs. 6 a , b,c and d give a corresponding representation of the effect of a north-westerly wind; Fig. 6 e shows a longitudinal section in the direction of the wind (along the diagonal) in which, besides the actual depths, also the mean depths of cross sections at right angles to the direction of wind are shown (as a shaded line). Accordingly inclinations of the surface would arise varying by these mean depths, as indicated in Figs. 6 e and 6 c, and this requires both an inflow from the north and a circling current as shown in Fig. 6 d (both currents, however, somewhat weaker than in the above cases); the two kinds of currents may also be added and will then give the result shown in Fig. 6 f. (This result will also be borne out when Fig. 6 b is considered).

South-westerly winds will give quite analogous conditions w
a circling current in the same direction as for NW,but now combin
with a northward outflow, as shown in Figs. 7 a - f.

All the Figures 4 -7 apply equally to winds in the respecti
opposite directions, when high and low waters are interchanged in
Figs. a, b, c and e (the zero line remaining fixed), and the current
arrows are inverted in Figs. d and f. On the basis of 4 c,5
6 c and 7 c curves have been drawn in Fig . 8, which for this par
cular velocity of wind show variations in the water level at poin
A and B when the wind veers round the entire compass. (If the
basin were supposed to represent the North Sea, it would only nee
to be turned $22\frac{1}{2}^{\circ}$ counter-clockwise, i.e. the compass points shou
be shifted in relation to the curves as shown for N in brackets
under the figure, but until further the orientation due north-sou
will be retained in these reflections).

OPEN SEA

If we now try to infer what conditions would be like, when
is no longer a question of an enclosed sea, it is evident that th
results will be far less exact, and that much depends on an estim
te.

So, let us suppose that the northern third of the North Sea
id added, in which the depth of water is again considerably great
averaging perhaps about 16o m, i.e. near the limit of the depth t
which the influence of strong winds will penetrate, and this basi
further is supposed to be connected at its northern end with the
lantic, the depth of which (at least 1ooo m) in this connection m
be regarded as being infinite, so that the wind cannot here produ
inclinations (although certainly currents) of any importance.On t
southern, shallow areas the wind will try to create an inclinatio
corresponding to the depth of water there, while at the northern
edge the water level must nearly remain constant. So Figs. 9,1o,
and 12 have been drawn in such a way that the course of the conto
lines in the southern third is retained as in the case of an encl
sed sea, while in the middle third they are modified slightly, so
as to pass through the northmost part, which acts as an intermediate
link, into the almost unchangeable water level at the nor
ern end.

In case of northerly wind (Fig.9) water must thus flow in
from the north until the entire water level has been raised as in
cated in Fig. 9 a, and in case of westerly wind (Fig.1o) - in ord
to maintain the inclination of the surface in the southern part -
circling current must flow in the same manner as in the enclosed
sea, in this case without any raising of the water level as a who
In case of north-westerly wind (Fig. 11) both effects of current
will arise, but in a somewhat lesser degree and consequently with
a somewhat slighter raising of the entire water level. In the cas
of southerly, easterly and south-easterly winds corresponding opp
site effects will prevail, and finally, Fig. 12 shows the situati
during south-westerly (and north-easterly) winds.Under the condi

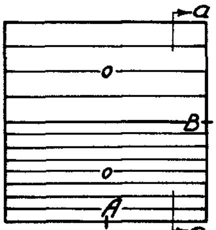


Fig. 4a

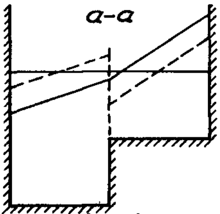


Fig. 4b

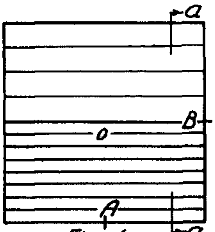


Fig. 4c

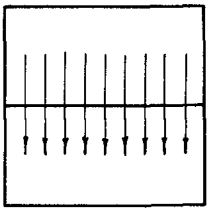


Fig. 4d

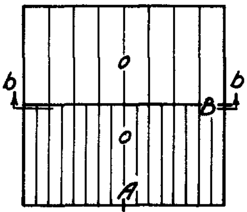


Fig. 5a

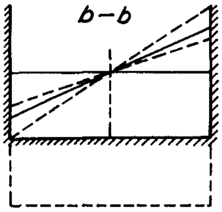


Fig. 5b

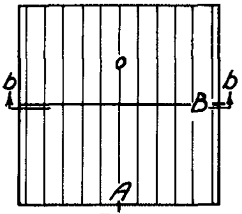


Fig. 5c

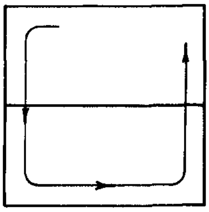


Fig. 5d

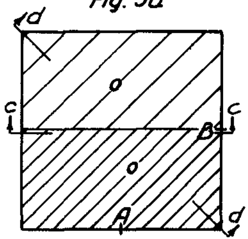


Fig. 6a

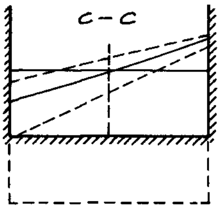


Fig 6b

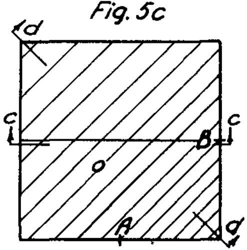


Fig 6c

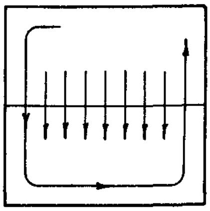


Fig 6d

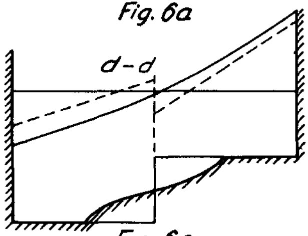


Fig. 6e

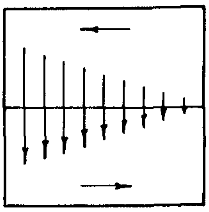


Fig 6f

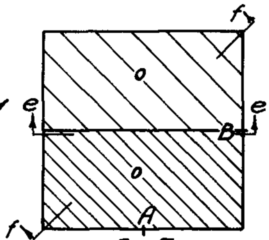


Fig. 7a

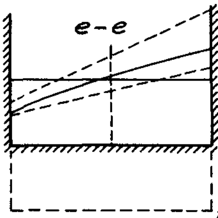


Fig 7b

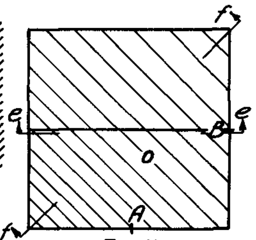


Fig. 7c

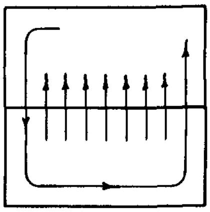


Fig. 7d

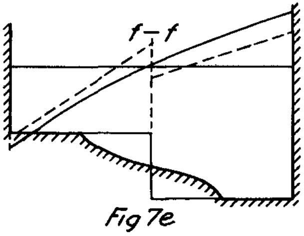


Fig 7e

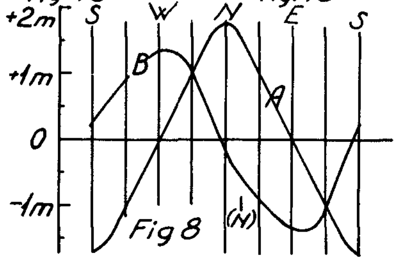


Fig 8

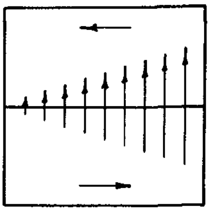


Fig 7f

tions of an open sea the same effects of current as in the case of the enclosed sea will assert themselves, but whereas the southward (and the corresponding northward) flow only take place while the situation is developing, the circling current must continue as lon as the situation persists. The water levels at points A and B migh now be read from Figures 9-12, but the same result will be obtaine by adding to the curves from Fig. 8, which have been traced in thi lines in Fig. 13 oriented by the compass points written under the figure, the dotted curve I, which shows the raising or lowering of the entire water level in the southern part, which movements - according to what is said above - are zero for west and east and maximum (1.25 m , corresponding to the figures calculated above) for north and south. The result is the two curves A_1 and B_1 in heavy lines in Fig. 13.

The earth's rotation - When regard is to be paid to the effects of the earth's rotation one might reason that as its influence on the surface inclinations in the case of an enclosed sea is minimal, it should be sufficient to include a calculation of the a ditional effects of the Coriolis-forces on the currents shown in Figs. 4 d- 7 d. For the circling currents we would thereby get a curve shaped as the dotted curve II in Fig. 13, the currents circling counter-clockwise (i.e. those caused by winds from westerly directions) raising the water level along the shore, and clockwise currents lowering it, and curve II would have to be added both to the A_1- and the B_1-curve. The currents flowing north-south would similarly give an additional curve as III, which only was to be used on the B_1-curve; as mentioned above, the latter current only flows while the situation is developing. Even if an estimate may well be formed as to the force of the said currents, there is nevertheless uncertainty in estimating their effects on the water levels, and further these effects depend on the depths at the respective places. In connection with the previously-mentioned turning of the whole system by $22\frac{1}{2}^{\circ}$ in order to make it correspond to the orientation of the North Sea, we will therefore now instead of adding the curves II and III merely turn the system by a further 15°, as this will give almost the same effect, including that the maximum effect off Holland is caused by a direction of wind of 15° west of NNW as stated by Schalkwijk. In Fig. 13 these turnings have been made by shifting the compass points to the positions noted above the figure, which positions when related to the he vy curves A_1 and B_1 should thus give an approximate picture of the combined effects off Holland and at Thyborön (The B_1-curve will be seen to be unmistakably lower than the A_1-curve, while its position does not quite agree with experiences from Thyborön, but this - which is of no great importance for the deliberations that follow below - is probably due to the very summary regard paid to the earth's rotation. Incidentally, in a later section this question will be given a little more consideration).

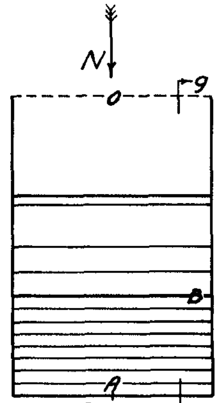


Fig. 9

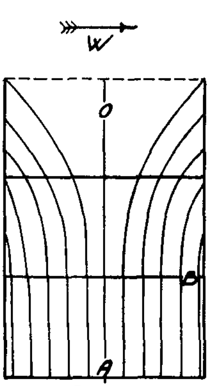


Fig 10

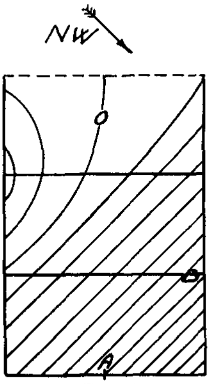


Fig. 11

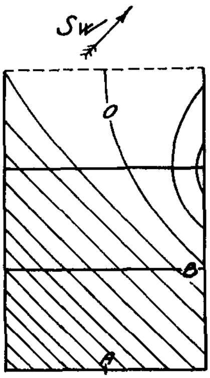


Fig. 12

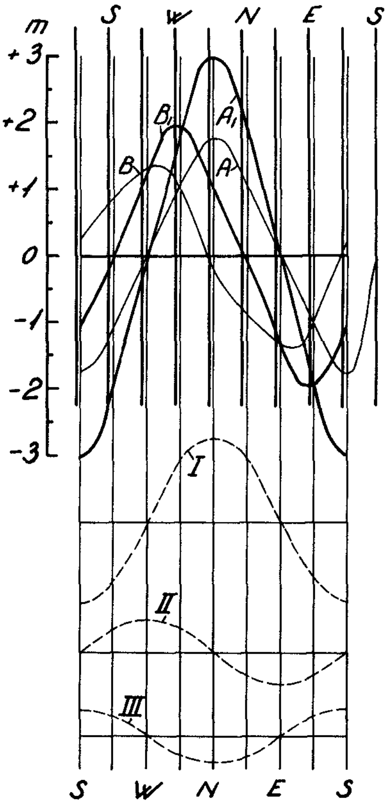


Fig. 13

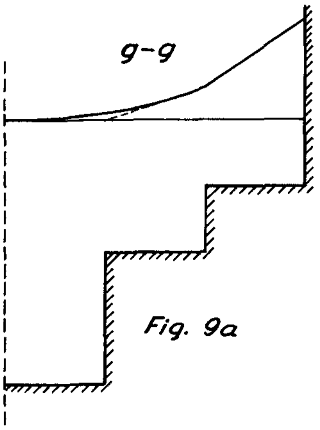


Fig. 9a

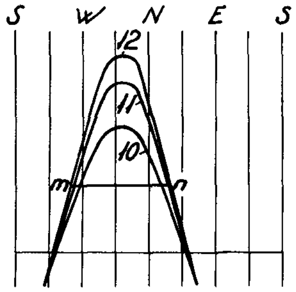


Fig. 14a

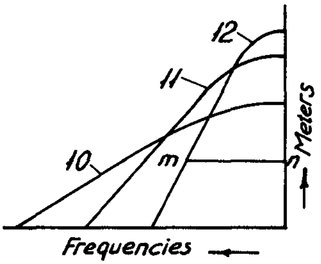


Fig 14b

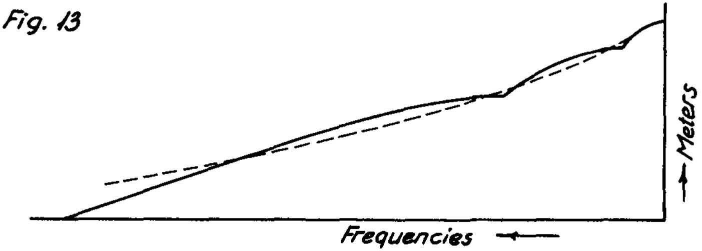


Fig. 14c

INFLUENCE OF BOTTOM TOPOGRAPHY ON THE FREQUENCY CURVE

As mentioned before, the curves have been traced for a definite velocity of wind (approx.Beaufort 12), but the corresponding curves for other velocities will be found from (3) by simply reducing it in the proportion$(V_{11}/V_{12})^2$, i.e. for force 11 in the proportion $(27/29)^2 = 0.87$, for force 10 in the proportion $(23/29)^2 = 0.63$, and in Fig. 14 a the high water section of the A_1-curve has accordingly been traced for these three velocities of wind.

If, until further, we now look at the 12- curve only, and imagine that all directions of wind are equally frequent, then the line segment, m - n, cut off by the 12-curve from a horizontal lin representing a certain height of water will be proportional to (and consequently constitute a measure for) the frequency with which this particular or still greater heights of water occur, and by inserting this segment as in Fig. 14 b we get a frequency curve for wind force 12 only, subject to the assumptions mentioned. Similarly, in Fig. 14 b frequency curves for other velocities of wind might be sketched in, but here with the use of different scales corresponding to the greater frequency of these velocities (in Fig. 14 b only a slightly larger scale has been used, althoug the 11-curve should, in fact, have been drawn with abscissas 10 times and the 10-curve with abscissas 100 times as big), and by adding up the abscissas for all velocities of wind the aggregate frequency curve would be obtained; in Fig. 14 c such an addition is shown for the three curves traced, and its wavy shape, which is du to the discontinuous division of velocities of wind, has been smoothed out by the dotted curve. Had a similar plotting of the B_1 - curve been made, it is apparent that we should have got a frequency curve starting from the same point on the x-axis, but lying lower throughout than the A_1-curve.

INFLUENCE OF WIND FREQUENCIES ON THE FREQUENCY CURVE

However, the various directions of wind do not occur with equal frequency, and the distribution of frequency on the directions of wind also varies according to the velocities of wind. Thi will be found (on the basis of Danish statistics published in [1 for wind force 3 the relative distribution shown in Fig. 15-a of the frequency for various directions of wind on the North Sea, while Fig. 15 c shows the distribution at wind force 10 (a scale 10 times as large as in Fig. 15 a having been used in Fig. 15 c). Th the two curves selected are, in fact, representative of the very powerful winds and the weaker(but very frequently occurring) win will be seen from Fig. 16, in which corresponding curves for all the wind forces 2 -12 have been traced together in a semi-logarithmic system (with the frequencies plotted logarithmically as ordi tes against the respective directions of wind), and it will be se that south-westerly and westerly winds are the most frequent ones but that north-westerly winds more frequently occur with very gre velocity.

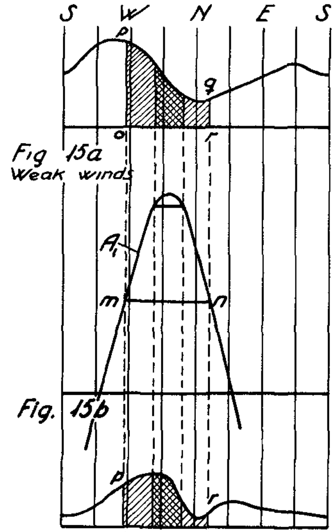


Fig 15a
Weak winds

Fig. 15b

Fig. 15c
Strong winds

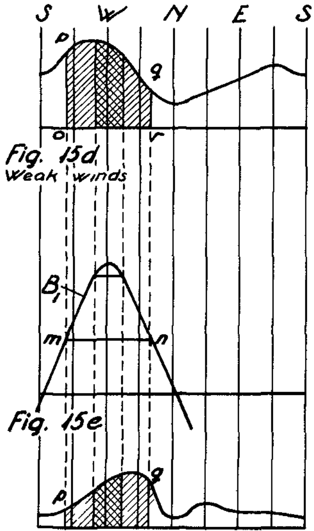


Fig. 15d
Weak winds

Fig. 15e

Fig. 15f
Strong winds

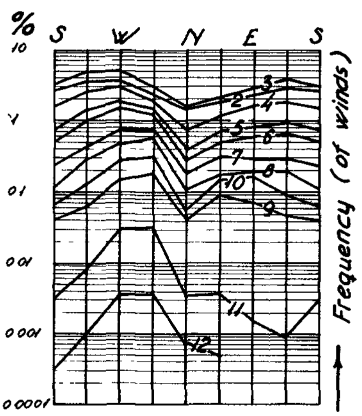


Fig. 16

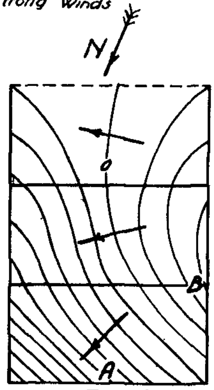


Fig 17

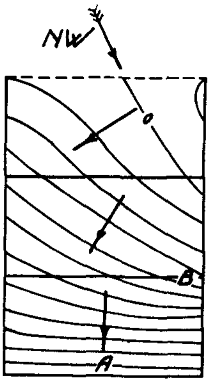


Fig. 18

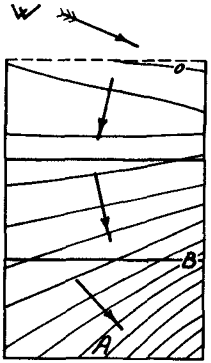


Fig. 19

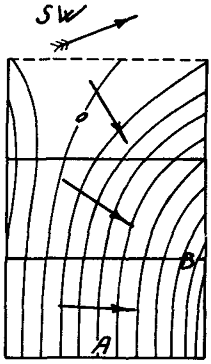


Fig. 20

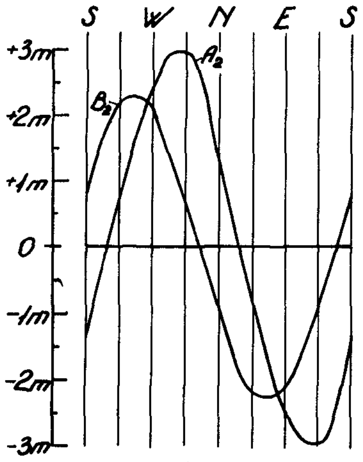


Fig. 21

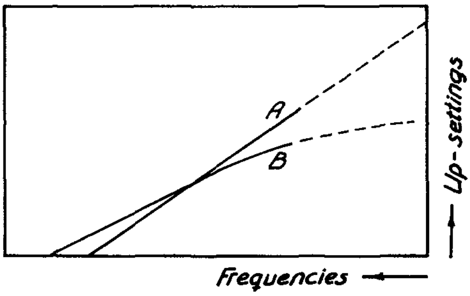


Fig. 22

The water level curves A_1 and B_1 previously found for Holland and Thyborön respectively, have been plotted separately in Figs. 15 b and 15 e, but now they are not supposed to apply to wind force 12, but alternately - using different scales - to the wind forces 3 and 10. While the segment (m-n) cut off by the water-level curve was used above as a measure for the frequency of a water level ≧ the one under consideration, this frequency may now be regarded as being represented by the shaded area o-p-q-r cut off on the frequency distribution curve for winds (see e.g.Fig. 15 a) off the said segment m-n. It appears that for weak winds greater high-water frequency is clearly found at Thyborön than off Holland,while for strong winds the difference is only negligible (and, if anything, rather opposite). When the high-water frequency curves for the individual velocities of wind are again supposed to be added up into a single curve it will be seen directly that the Thyborön curve must begin with greater frequencies for low water levels than th Dutch one, and as it should be less steep, taken as a whole, than the latter, they must intersect. It will also be seen that by plotting the wind frequency distribution curves semi -logarithmically a in Fig. 16, a high-water frequency curve of the same character as actually used will be obtained.

INFLUENCE OF THE EARTH'S ROTATION ACCORDING TO EKMAN'S THEORY

As already mentioned, the earth's rotation has only been considered very summarily above, but there may be reason to mention a few effects of this phenomenon, which seems to approximate the whole representation closer to actual facts.

V. Walfrid Ekman, who has developed the fundamental theory on the influence of the earth's rotation on ocean-currents caused by wind-effects [9] , shows in a later work [12] that currents caused by pressure gradients (i.e. generated, for instance, by an inclination of the surface and reaching right down to the bottom) in addition to the usual deflection owing to Coriolis-force will be further deflected when flowing across areas with varying depths of water, this deflection being cum sole (that is to the right on th northern, and to the left on the southern hemisphere) when shallower water is encountered, and contra solem when it enters deeper water. In consideration of the above-mentioned circling currents this phenomenon would, if anything, during westerly winds tend to reduce up- settings at Thyborön, while it would increase them at t northern part of the English coast. During the gale in February, 1953, the maximum of up-settings at the English coast was, as a matter of fact, according to [13] , reached at "The Wash", where i is quite possible that the water may have been pressed up owing to the sea growing shallower.

According to Ekman's theory a wind-generated current will at the surface be directed 45° cum sole from the direction of the win when the depth is ∞ . The angle of deflection increases regularl with the depth, while at the same time the velocity decreases.

Supposing the current-velocities at various depths are represented by vectors, and the end points of these vectors are projected on a horizontal plane, a logarithmic spiral will be obtained, and the resultant of all these vectors (i.e. the average velocity of the total flow) is directed 9o° cum sole from the direction of the wind. The influence of the wind ceases, practically speaking, at a certain depth, D, Ekman's "depth of frictional influence", depending on the velocity of the wind and representing the layer of water stirred up by the wind, and according to [4] Palmén fixes the value of D as:

$$D = 35 + 5.4\ V \qquad (4)$$

At depths smaller than D the deviation of the total flow from the direction of the wind will decrease, thus being (according to Ekman):

about 7o° when the depth d = o.5 D
 - 3o° - - - d = o.25 D
 - 1o° - - - d = o.1 D

If on this background we examine how the wind will act on our tripartite model of the North Sea, the value of D for V= 29m/sec. being 35 + 5.4 × 29 ~ 19o m, the depths of the three different sections of the model should correspond to about o.2o D, o.4o D and o.85 D respectively, and consequently for this velocity of wind the current-directions shown by the arrows in Figs. 17-2o are obtained.

However, it must be remembered that these currents generated directly by the wind, are only one factor among many determining the inclinations of the surface, these inclinations being the result of interaction between the said wind-currents, gradient-currents (also influenced by the earth's rotation), the course of the coast lines, etc., but merely by considering the directions of the wind-currents - which are, after all, the very root of the matter - we obtain an impression of how SW (and perhaps in an even higher degree SSW) must give the highest water level at Thyborön, as is also shown by experience. Based on an estimate, contour lines have been drawn in Figs. 17 - 2o in a similar manner as in Figs. 9-12, but now with regard paid to the various directions of wind-currents. It must,however, be admitted that the result according to the above is bound to be rather arbitrary, which is the reason why these figures have not been used as a basis for the foregoing investigations concerning the frequency curves. From the Figs. 17-2o water level curves for points A and B have been drawn in Fig. 21, and they seem to correspond quite well to actual conditions. For lower velocities of wind a rather more pronounced deflection of the directions of currents might be expected as in these cases the value of D decreases.

It may be added that Ekman's theories are not altogether undisputed. They simplify matters by assuming a constant " eddy viscosity" from surface to bottom, and theories have been advanced which take into consideration that this is hardly true, but H.U. Sverdrup writes in 1946 in [14] that "Ekman's classical theory appears to give satisfactory approximation, especially because no observations are as yet available by means of which the results of a refined theory can be tested".

INFLUENCE OF THE NORWEGIAN DITCH

Above has only been discussed how the up-settings arise, and it will have been seen that they reach the highest levels in the southern part of the North Sea. If we now assume that the wind actions cease (or diminish) after great quantities of water have bee pressed up in the south, this water will seek back towards the nort and on its way it will be deflected sum sole by the earth's rotation and consequently preferably seek towards the west coast of Jutland (the deflection, however, being counteracted to some extent by the increasing depth of water). That this actually does happen is illustrated by a series of curves (reproduced from J.R. Rossiter in [15]) depicting the variation in up-settings at various places during the gale in 1953. The highest up-setting was reached at Harlingen, Holland, (about 3.4 m), while at Hanstholm, some 50 km north of Thyboròn, which was not directly affected by the gale, a high-water accurred about 9 hours later which, to be sure, was only about 1 m, but which in return was of longer duration.

Moreover, the up-setting will fall most quickly where the water, on account of a large sectional area of the current (i.e. great depth of water), can flow away quickly, and it will therefore seek towards the deep ditch running along the southern and western coast of Norway right up to the Atlantic. This Norwegian Ditch ("Norske Rende") is deepest off the southern point of Norway, where it reaches a depth of more than 500 m with more than 50 km between the 100 m contour lines; further north its depth decreases while in return its width increases. A calculation shows that with a head loss in water level of 1 m along the 600 km stretch from the southern point of Norway to the deep water of the Atlantic, this ditch can carry a quantity of water in the magnitude of 14×10^{10} m^3 per hour, and even if the upper layers (here estimated at 150 m), which are subject to influence by the wind, are left out of the calculation, the same head loss in water level will give a rate of flow of about 4×10^{10} m^3 per hour. In the latter case the velocity will at its highest (and only for a relatively short distance) be about 1.5 m /sec. ~ about 3 knots, i.e. no in any way improbable, and in consideration of the fact that the total excess of water in the North Sea during the gale in 1953 has been calculated by Rossiter (as quoted in [13]) to be about 43×10^{10} m^3, it will be seen that the outlet through the Norwegian Ditch must exercise a very great influence on the water-level conditions. Irrespective of influences of the wind on the surface, th ditch will be capable of carrying back to the Atlantic large quant ties of water pressed into the North Sea, and in doing so offset all very great fluctuations of the water level in its vicinity, thus also at Thyborön. It may be added that owing to the earth's rotation the surface in the ditch will endeavour to develop a transverse inclination, the water level being raised on the right and lowered in the left looking in the direction of the current, and this transverse inclination, which - according to Ekman - is more pronounced for great depths of water than for shallower water, will likewise contribute to offsetting both high and low waters off the coasts of northern Jutland. The fact that high water in the North Sea finds a certain outlet round the north of Jutland to replenish the Danish home waters, will have a similar effect. However, the case is far from being simple, the current in the Norwegian Ditch also being affected by many other circumstances, such as outflow from the Baltic Sea, variations in the temperature and salinity of the water, etc., but it must be justifiable to expect that the proximity of the ditch must cause a downward bend of the upper part of the frequency curve for Thyborön and an increased number of moderate high waters.

SUMMARY

The results found in the foregoing may be summarized as follows:

I. The main features of the bottom topography of the North Sea being so that Thyborön is situated almost off the transition between the particularly shallow southern and the somewhat deeper northern part, cause the frequency curve throughout to be less steep for Thyborön than for the sea off Holland.

II. The fact that south-westerly and westerly winds as a whole occur most frequently, whereas the north-westerly winds are those which most frequently occur with great force, involves that the frequency curve for Thyborön starts with greater frequencies than does the Dutch curve.

III. The presence of the deep Norwegian Ditch, which provides an outlet for all great accumulations of water in the southern part of the North Sea, causes the same effect as in II, viz. an increased number of moderate high waters at Thyborön, while the very proximity of this deep ditch counteracts the formation of extraordinarily high floods at Thyborön and thus causes a downward bend of the upper part of the frequency curve.

———— 0 ————

In view of this one would expect the mutual relation between the frequency curves for Holland and Thyborön roughly to be like that of the curves A and B in Fig. 22.

CLOSING REMARKS

As already mentioned, only the direct influences of wind hav been dealt with above, while many secondary circumstances have bee disregarded, including the familiar fact that the astronomical and the meteorological high water cannot directly be superimposed on each other, as the changes in the height of water will cause mutual influences between them. Further the above-mentioned circling currents may be expected to cause some loss of energy, thereby diminishing the up-settings, and another point is that the formula used for the wind-effect should possibly be modified when D is exceeded. It will thus be understood that the results found can only represent certain main features concerning the frequency curves.

Finally, it must be pointed out that the "derived" type of frequency curve with a maximum value corresponding to a wind-velocity of 29 m/sec. does not, of course, correspond to actual conditions, as the wind may be much stronger (cf. the fact that Beaufort 12 just designates wind- velocities higher than 29 m/sec. even if, as a rule, the strongest winds may probably be supposed only to prevail over a limited area. However, as van Veen has said [7] , a gale can blow "harder than hard and longer than long", and the very purpose of the frequency curve is by its extrapolation to provide a well-founded estimate concerning extreme cases, but - especially where the period of observations is short - there will be every possible reason to supplement direct observations by a closer study of geographical and meteorological conditions, thereby widening our knowledge of actual circumstances and improving our understanding of the phenomena which occur.

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