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by currents and waves; measurements with the aid
of radioactive tracers in The Netherlands.

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J. J. ARLMAN, P. SANTEMA and J. N. SVAŠEK.

Progressreport, June 1957

Issued by Deltadienst, Rijkswaterstaat,

Ministry of Transport and Waterstaat, The Netherlands.

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(Sedimentbeweging)

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List of symbols used

Appendix A

Appendix B

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MOVEMENT OF BOTTOM SEDIMENT IN COASTAL WATERS BY CURRENTS AND WAVES; MEASUREMENTS WITH THE HELP OF RADIOACTIVE TRACERS IN THE NETHERLANDS.

by

J. J. Arlman,¹⁾ P. Santema²⁾ and J. N. Svašek³⁾

1.0.0. INTRODUCTION AND JUSTIFICATION.

1.1.0. A large part of The Netherlands lies below the normal high-water levels in the adjacent part of the North Sea. (Fig. 1). In so far as dunes do not form a natural protection, this low country must be protected from floods by means of dikes. In proportion to their surface The Netherlands have a long coast-line, 280 km protected by dunes and 1700 km by dikes.*) The necessity of protecting such a great part of the coast-line by dikes is chiefly due to the numerous estuaries in the south-west, which penetrate deep into the country, and to the Waddensea in the north.

Because of these tidal waters stormtides make themselves felt deep into the country, the dikes having to stem high waters over a great length. This situation has many times given rise to flood disasters. During the great catastrophe of February 1st 1953 as many as 150,000 hectares of land were flooded, and about 1800 people were drowned; the damage amounted to about Dfls 2,000,000,000 (Fig. 1). This disaster has greatly stimulated the projecting of the so-called Deltaplan. This Plan, which is now being carried out, comprises i.a. the building of dams in the mouths of the estuaries in the south-western part of The Netherlands, with the exception of the West Scheldt and the Rotterdam Waterway; thus the length of the coast which is subject to the influence of the tides will be decreased by about 350 km, while moreover the height of the storm-tide levels will be greatly decreased over a much greater length. Though the primary object of the Plan is to improve the protection of the low country against storm-tides, there is moreover the important advantage of a possible improvement of the hydrological conditions through the establishment of large reservoirs of fresh water, in consequence of which agricultural production may be increased in extensive areas.

1.2.0. As a result of the Deltaplan the existing hydrographic situation in the coastal area of the south-western part of The Netherlands will be drastically changed. At the moment there is a large-scale exchange of water between the estuaries and the adjacent coastal area, which makes itself felt even at a great distance from the coast, the currents being directed perpendicular to or from the coast during a great part of the tide. The so-called submarine delta is to a high degree coherent with the currents which are directed perpendicular to the coast. This submarine delta is an extensive, rather shallow area, situated between the estuaries and the actual deeper area of the sea, in which the gullies coming from the estuaries proceed or end more or less fan-shaped. In the actual deeper area of the sea the currents are mainly directed parallel to the coast. (Fig. 2).

When the estuaries are dammed up, the currents which are directed perpendicular to the coast will decrease considerably or disappear altogether so that mainly currents parallel to the coast will be left. These factors will greatly affect the submarine delta in the sense that the sediment movement and the depth relations in the coastal area will be changed. Moreover, the existing exchange of

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*) This length relates to the dikes along all waters affected by the tides.

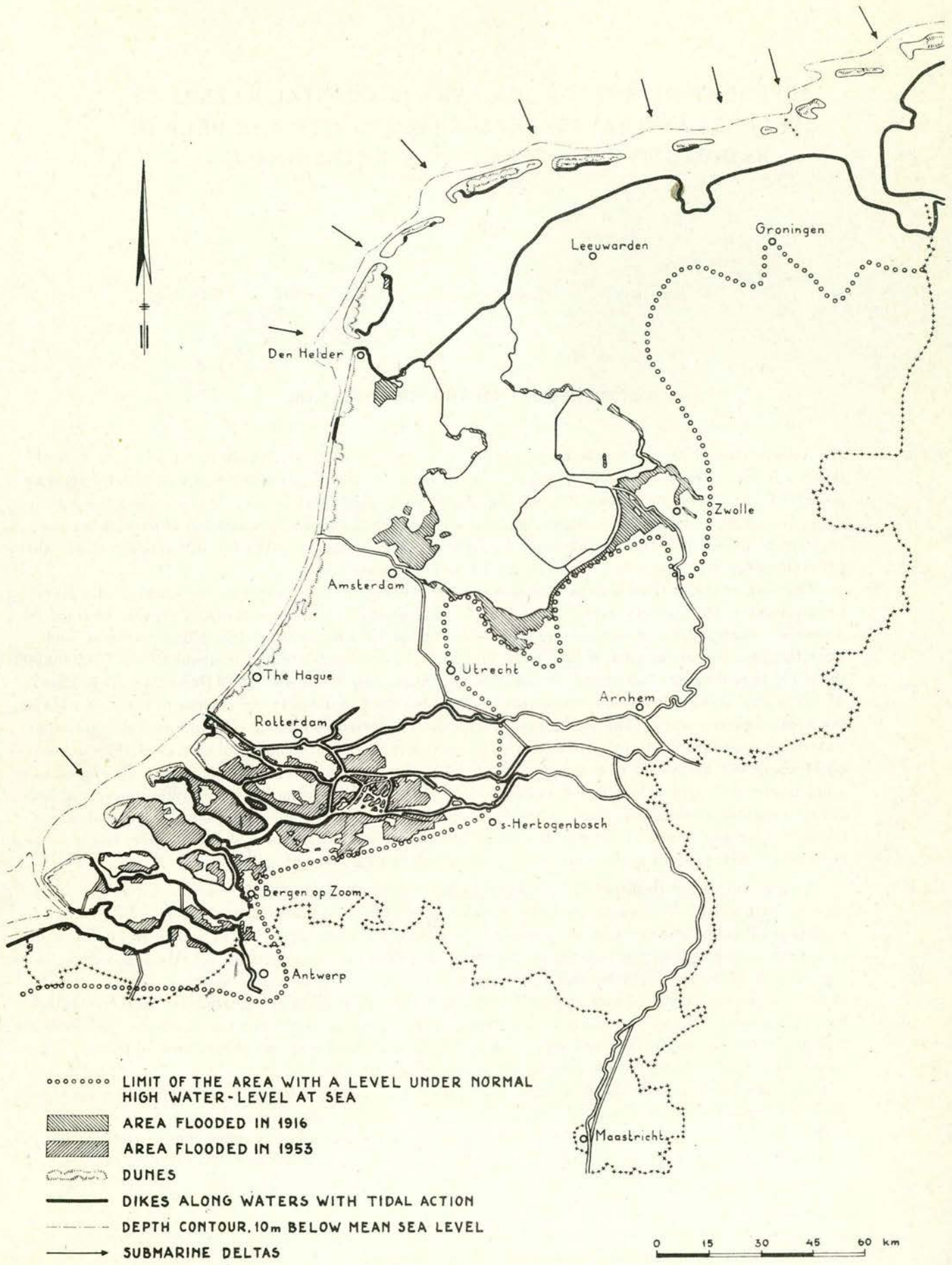


Fig. 1

sediment between the estuaries and the coastal area will be eliminated. In consequence of the changing depth relations the current picture will be changed further, and especially the wave picture will be altered too.

The ultimate changes, as to the sediment movement and the depth relations in the coastal area, which will be the result of the damming of the estuaries in the south-western part of The Netherlands, cannot be predicted precisely. The interests dependent on it are, however, very great. In connection with the protection of the low part of the country against the sea a deterioration of the coastline must be considered to be intolerable. If this risk should be run, very expensive works would be required to avoid the danger. Furthermore the maintenance of entrance channels of sufficient dimensions to the principal seaports is a matter of the greatest importance. Though the expectations concerning the consequences which the Deltaplan will have for the coast, are not unfavourable at the moment, it is most desirable to increase the knowledge about the sediment movement in the coastal waters. In the relevant investigations to be made in the field, radioactive tracers will shortly play an important role.

1.3.0.

In what follows there will be discussed:

the currents and waves prevailing in the coastal area of the south-western Netherlands; the present state of the knowledge about the movement of sediment by currents and waves will be discussed too;

the methods of measuring sediment transport used hitherto in the coastal region in The Netherlands. In this discussion the reasons will be given why measurements of this kind are not very effective;

a group of methods of measuring which could indeed be applied in the coastal waters, i.e. the methods in which use is made of tracer materials; in this discussion it will be shown that preference should be given to radioactive tracers;

the factors playing a role in the choice of the kind, the radioactivity and the quantity of radioactive tracer to be used; the instruments and methods of measuring to be used will be discussed too;

a pilot-experiment made with respect to the measuring of sediment transport in a hydraulic model by means of radioactive tracers;

Finally an outlook will be given on the planned further investigations in The Netherlands with regard to the movement of sediment by currents and waves.

*
* *

2.0.0. MOVEMENT OF SEDIMENT BY CURRENTS AND WAVES IN THE COASTAL REGION.

2.1.0. CURRENTS.

Generally one may distinguish several causes of the currents in coastal regions. In the coastal area of The Netherlands they are: tides, discharges of rivers, density differences in the water, wind and waves.

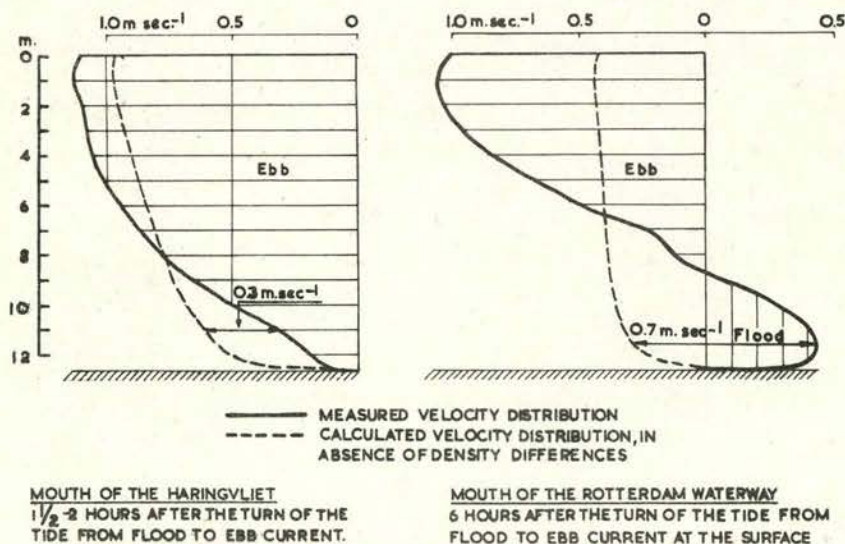
2.1.1. As to the currents caused by tides and river discharges the results of many measurements are available. These results give a picture of the currents as a function of the phase and range of the tide and of the magnitude of the river discharges. Fig. 2 gives an impression of the prevailing currents in the coastal waters of the south-western Netherlands.

However, the measurements only show the present situation. If we also want to know the currents in future, greatly changed conditions – e.g. after an estuary will have been dammed up – we are dependent on tidal computations or model tests. In the case of tidal computations the current picture in the new situation can be determined starting from a number of known boundary conditions and a number of physical constants, which can be determined by checking the present measured situation by means of the tidal computation methods. As regards the last mentioned methods the relevant literature may be referred to *).

It may be remarked that shortly it will be possible to accelerate the present time-consuming tidal computation procedure considerably by means of electronic computers and analogs.

With the hydraulic models used hitherto difficulties are met with in the introduction of the force of Coriolis, which cannot be neglected in coastal regions with a pronounced three-dimensional movement of water; for this reason the models have sometimes to be placed on turning tables.

2.1.2. As to the influence of the density differences in the water on the currents, the following can be remarked. In The Netherlands these differences are of less importance as regards their influence on the general movement of the water than as regards their influence on the velocity distribution in a vertical sense. This last mentioned influence is very strong in the mouth of the Rotterdam Waterway, and is also very well observable in the Haringvliet (situation in figure 2e). During certain phases of the tide there can e.g. be a strong flood current on the bottom in the mouth of the Rotterdam Waterway, whereas there is a strong ebb current at the surface. A frequently occurring value of the current velocity near the bottom, resulting from density differences (maximum during a tidal periode), is 0.70 m/sec; for the mouth of the Haringvliet this value is 0.30 m/sec (Fig. 3). It will be clear that this



**INFLUENCE OF DENSITY DIFFERENCES OF THE WATER
ON THE VELOCITY DISTRIBUTION IN A VERTICAL.**

Fig. 3.

*) J. J. Dronkers, J. C. Schönfeld,
Tidal computations in shallow water, Proc. Am. Soc. Civ. Eng., V. 81, 1955.
(+ references mentioned therein).

phenomenon is of great influence on the transport of sediment; not only the magnitude and the direction of the current velocity near the bottom play a role here, but also the vertical velocity gradient.

One may try to find out the changes in the current picture in the coastal waters caused by changes in the present situation, at the presence of density differences, tidal currents and river discharges, with the help of computations or investigations on hydraulic models. Up to now the computations have met with great difficulties. At the moment measurements are being prepared in which in a great number of places along the Rotterdam Waterway the profile dimensions, the waterlevels, the current velocities and the density differences will be measured; if required this will be done continuously. After one thus has been able to check the theories against the results of these measurements, and one has got a better knowledge of the mechanism of the relevant phenomena for the two-dimensional case of a long and relatively narrow channel, the application of similar computations for the three-dimensional case of the coastal waters can be considered.

With model tests we not only meet with the difficulty mentioned in 2.1.1., but we are also faced with the trouble that the mechanism of the phenomenon is not yet sufficiently known, though approximations are very helpful.

2.1.3. About the currents which may be caused by windstress in the Netherlands coastal waters, relatively little has become known through direct measurements. Regular observations made on board 3 lightvessels, at a 10 - 15 km distance from the coast, have supplied some data in this respect. From these it appears that current velocities caused by wind are rather frequent up to 0.20 m/sec in the place where these lightvessels are situated. For a more general picture of the present situation, more measurements would have to be made; as regards future changed circumstances we are dependent on complicated computations in this respect.

After the flood disaster of February 1st 1953 much work has been done in The Netherlands with regard to the further development of the methods of computation meant, within the scope of the studies concerning possible high storm-tide levels and the prediction of suchlike waterlevels.

2.1.4. The forward transport of water caused by the wave movement results in several kinds of currents in the neighbourhood of the coast, which in many cases can be so strong that they exceed the currents resulting from the previously mentioned causes (Fig. 4). In view of the great influence exercised by the currents meant on the movement of the sediment, these phenomena will be elucidated by means of some formulae. It must be emphasized that the following considerations are mainly of a qualitative character. In the first instance one must think of a long straight coast with parallel depth lines and a wave movement which is equally strong over the whole length.

According to Wiegel and Johnson *) the average forward velocity of the current, caused by the wave movement, in the direction of the propagation of the waves, amounts to:

$$V_1 = \frac{0.3 \times \sqrt{g} \times H^2}{h \times \sqrt{L \times \operatorname{tgh} \frac{2 \times \pi \times h}{L}}} \quad \text{-----} \quad (1a)$$

In this formula, which holds seaward from the breaker zone:

V_1 = the average forward current velocity in the direction of the wave propagation.

H = the wave height.

L = the wave length.

h = the depth of the water.

g = the acceleration due to gravity.

Note: the index $_b$ indicates quantities in the breaker zone; the index $_o$ indicates quantities in deep water.

For the conditions near the breaker zone the formula can be written:

$$V_1 = 0.065 \times \sqrt{g \times H_b} \quad \text{-----} \quad (1b)$$

In consequence of the component of the forward transport of water perpendicular to the coast the water is pushed up somewhat against the coast, which results in return currents. Part of the return flow is distributed more or less equally over the length of the coast, the velocity distribution being strongly affected in a vertical sense. According to various investigators the current velocity on the bottom, in consequence of the transport of water perpendicular to the coast and the even return current, is directed landward. However, according to other investigators the resulting current is said to

*) R. L. Wiegel, J. W. Johnson,
Elements of wave theory,
Proc., 1st Conf. Coastal Eng., 1950.

CURRENTS AND SEDIMENT TRANSPORT IN THE NEARSHORE ZONE, CAUSED BY WAVES

N.B.) ALL CURRENTS WHICH HAVE BEEN INDICATED ARE ASSOCIATED WITH SEDIMENT TRANSPORT

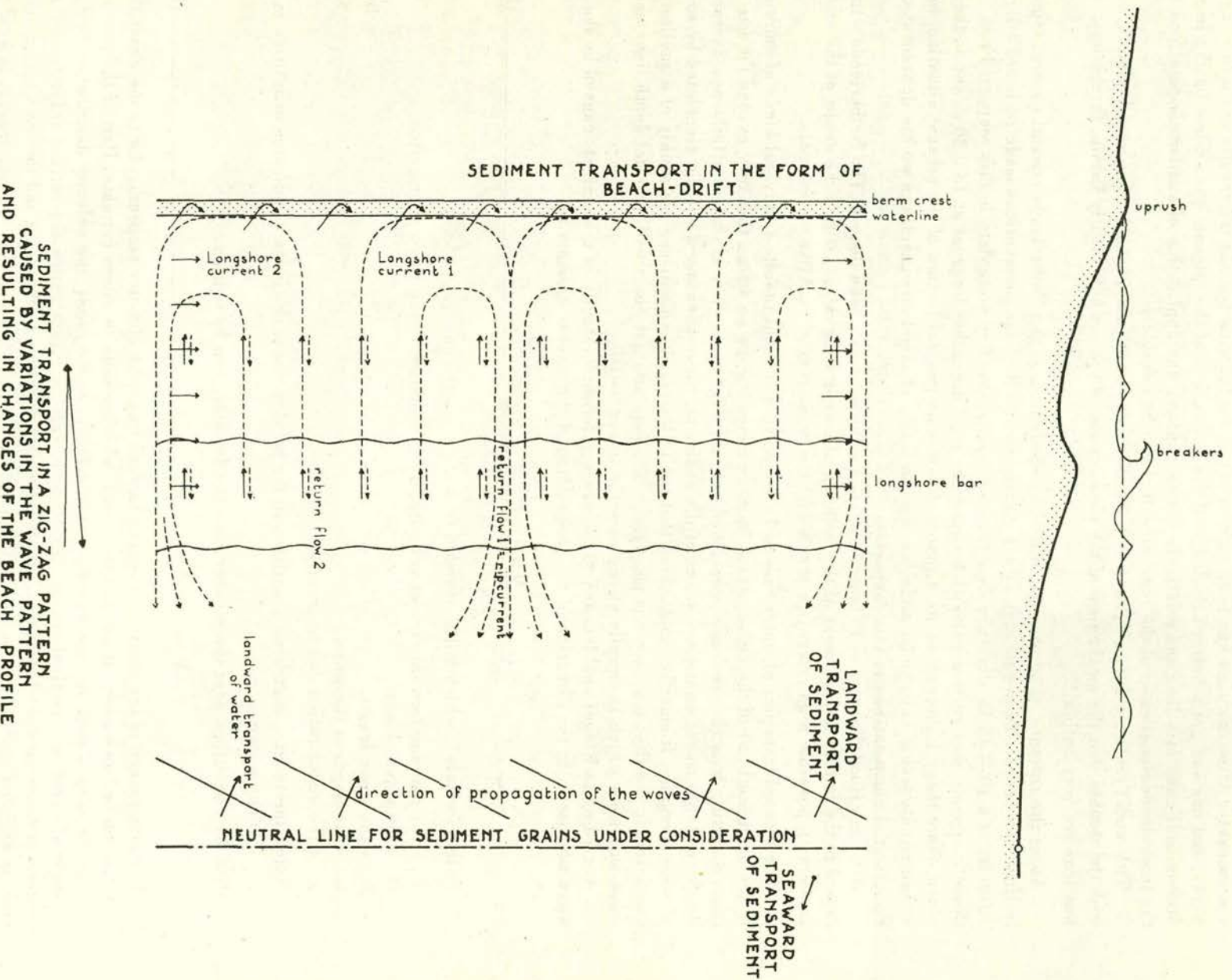


Fig. 4

be directed seaward on the bottom. It may be remarked that the return current has the tendency to leave the bottom at some distance from the coast, so that at least there the resulting current on the bottom is directed landward.

The other part of the previously mentioned return flow takes the form of rip-currents. The water that is transported to the coast, flows off sideways in the form of longshore-currents, and finds its way back to the sea, more or less concentrated in the form of so-called rip-currents. Often these rip-currents have a pulsating character; they are strong during the periodic occurrence of groups of low waves, and decrease in force or even change their direction during the periodic occurrence of groups of high waves. Consequently there are small variations of the water level along the coast with a period equal to the period of the occurring of groups of higher and groups of lower waves. About the relations between the longshore-currents and the rip-currents meant here on one hand, and the other currents, the wave movement, the sediment, etc., on the other hand, little is known as yet; the distance between the rip-currents seems to be greatest when there are regular, long waves.

When the waves approach the coast obliquely, the component parallel to the coast of the forward transport of water will bring about a second longshore-current. The average current velocity parallel to the coast, landward of the breaker zone was computed by Putnam, Munk and Taylor*) to be:

$$V_2 = \frac{1,3 \times I_b \times C_c^2 \times H_b \times \cos \phi_w}{g \times T} \left[-1 + \sqrt{1 + \frac{2,3 \times g \times T}{I_b \times C_c^2 \times \cos \phi_w} \times \sqrt{\frac{g}{H_b}}} \right] \quad (2)$$

In this formula:

V_2 = the average velocity of the longshore-current caused by the waves approaching the coast obliquely, within the breaker zone.

T = the wave period.

ϕ_w = the angle between the wave crests and the coast.

I_b = the slope of the bottom, landward of the breakers.

C_c = the coefficient of Chézy for the region landward of the breaker zone.

As known the topography of the bottom of the relevant part of the coast, and the resulting refraction and diffraction phenomena exercise a great influence on the wave movement and on the resulting currents. The possible differences herein from place to place can result in other compensating currents. From the foregoing it will be clear that in parts of the coast with a less simple bottom topography a complicated current picture can originate, merely as a result of the wave movement.

With regard to the changes which will be brought about in the wave movement and in the currents coherent with this movement, in the coastal region after the inlets will have been dammed up, we refer to 2.3.0.

2.2.0. MOVEMENT OF SEDIMENT BY CURRENTS.

2.2.1. The sediment transport caused by currents can be distinguished as bed-load and suspended-load. With bed-load the grains are transported rolling, sliding or with little jumps in the so-called bed-layer, so there is always more or less contact between the grains and the bed. With the suspended-load the grains are transported quasi in suspension by the current.

In a straight, wide channel with the same permanent flow conditions and the same sediment transport in each cross section, which channel is thus in an equilibrium state, there exists a definite relation between the bed-load and the suspended-load. In such a case the differential equation expressing the concentration of suspended sediment is:

$$\frac{dN_y}{dy} - \frac{w}{R \times I_e \times g} \times \frac{h}{h-y} \times \frac{dv_y}{dy} \times N_y = 0 \quad \text{----- (3) } ^{1)}$$

In this formula:

N_y = the concentration of sediment at a height y above the fixed bed.

w = the settling velocity of the relevant grains of the sediment in water.

*) J. A. Putnam, W. H. Munk, M. A. Taylor,
A prediction of longshore-currents,
Trans. Am. Geoph. Union, V.30, 1949.

1) See i.a.: H. A. Einstein,
Bed-load function for sediment transportation in open channel flows,
Soil Cons. Serv., Techn. Bull. Nr. 1026, 1950.

v_y = the average current velocity at a distance y above the fixed bed.

I_e = the slope of the energy line.

R = the hydraulic radius.

From the afore-mentioned equation it appears that the concentration of the suspended material is i.a. influenced by the value of $\frac{dv_y}{dy}$; from this it follows that density differences in the water, which affect the vertical velocity gradient, can be of great influence on the sediment transport, even if they would not change the average current velocity in that vertical.

Starting from a normal logarithmic velocity distribution in a vertical sense, based on Von Kármán's similarity theorem, with the constants proposed by Keulegan *), the following expression can be formulated for the transport of suspended material, in the supposed channel in a state of equilibrium:

$$q \text{ susp.} = 11.6 \times \sqrt{R \times I_e \times g} \times N_y \times y \times \{ \Delta \times I_1 + I_2 \} \text{ --- (4) **)}$$

In this formula:

$q \text{ susp.}$ = the transport of sediment in suspension in the waterlayers from the surface to a height y above the bottom, per unit of width.

N_y = the concentration of sediment in suspension, at a height y above the firm bed.

Δ = a known function of $\frac{D_{65}}{\delta}$ and $\frac{D_{65}}{d}$, D_{65} representing the grain diameter of which 65 percent (by weight) is δ finer;
 δ is the thickness of the boundary layer.

I_1 } = known functions of $\frac{y}{d}$ and $\frac{w}{\sqrt{R \times I_e \times g}}$.
 I_2 }

In the case of the supposed channel in a state of equilibrium, the suspended load can be calculated by means of the above formula, if the flow conditions, the sediment concentration at one specific height above the bed, and the composition of the bed material are known.

Equalization of the sediment concentration in the bed-layer that is connected with the bed-load on the one hand, and the sediment concentration at the upper boundary of the bedlayer that is connected with the suspended-load on the other hand, yields the following equation, given by Einstein **):

$$q_{\text{tot}} = q_{\text{bed}} \times (\Delta \times I_1 + I_2 + 1) \text{ --- (5)}$$

With respect to the bed-load q_{bed} many formulae have been put forward describing this transport as a function of the flow conditions and the composition of the bed material. The results obtained by the various investigators do not show much agreement, however. Of the more recent formulae which have been applied to a certain degree in The Netherlands, those of Einstein **), Kalinske ***) and Meyer-Peter/Müller ****) may be mentioned. For a more exhaustive treatment of the bed-load formulae the literature may be referred to.

It should be remarked that in the above considerations one specific grain diameter in the moving sediment has been started from; if the sediment of the bed is of a varied granular composition, the transport of each of the various fractions must be fixed separately.

Einstein, i.a., paid much attention to the division of the total flow resistance of a channel into resistance of the walls and resistance of the bottom; the latter can again be divided into bottom resistance and resistance as a result of ripples and bars. This so-called shape resistance, consisting of over- and under-pressures effected by the bars and ripples, is only converted into turbulence at a relatively great distance from the bed, so it does not affect the sediment transport directly. Especially for coastal waters, where, also as a result of the wave motion, well developed ripples and bars are often found, this difference seems to be of significance.

Regarding the forming and the distortion of ripples, bars, etc. by currents, and also regarding the sorting of sediment which takes place thereby, relatively many tests have been made. The results obtained by the various investigators do not always show agreement.

*) G. H. Keulegan,
Laws of turbulent flow in open channels,
Nat. Bureau of Standards, Journ. Res. 21, 1938.

**) H. A. Einstein,
Bed-load function for sediment-transportation in open channel flows,
Soil Cons. Serv., Techn. Bull. nr. 1026, 1950.

***) A. A. Kalinske,
Movement of sediment as bed-load in rivers,
Trans. Am. Geoph. Union, V. 28, nr. 4, 1947.

****) E. Meyer-Peter, R. Müller,
Formulas for bed-load transport,
Proc. 2nd Meeting. I.A.H.R., 1948.

In the above considerations a permanent current has been supposed. In the coastal waters the current varies from moment to moment. As a result of this the sediment transport is no longer directly related to the flow conditions at that moment and in that place.

In the coastal waters in The Netherlands, where as a rule rather a fine sediment is found - D_{50} mostly varies between 100 and 300 μ -, and a very great part of the total sediment transport takes place in the form of suspended-load, the circumstances mentioned greatly influence the sediment movement. Until now it has not yet appeared to be possible to express the influence of a non-permanent flow condition on the sediment transport in practically usable formulae.

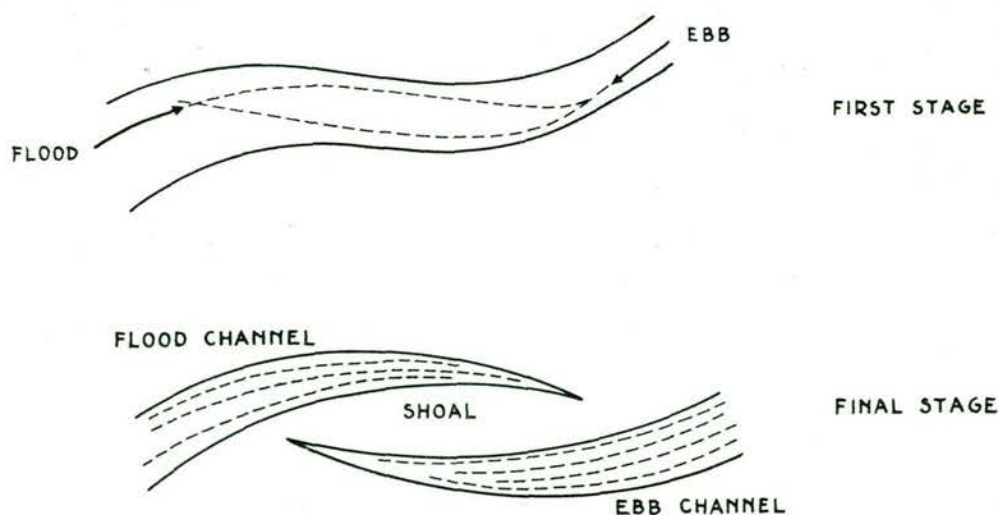
Moreover, in the above considerations a two-dimensional character of the sediment transport has been assumed, whereas in the coastal waters the latter is clearly of a three-dimensional character. This will be elucidated in the following.

When somewhere in a wide channel, which is rectangular in cross section, an occasional deepening arises, the current and the sediment transport are apt to concentrate there. The differences in transverse direction in sediment concentration in the water will result, together with the turbulence of the water, into the sediment transport in transverse direction, and that from the deeper part of the channel to the shallower parts.

Assuming that the amount of sediment in movement in all places in the channel was already in agreement with the transport capacity existing there, the transverse transport will cause a silting up in the shallower parts, whereas it will have a scouring effect in the deeper parts. Under the influence of the slope of the bottom which comes into existence, there will be in the end a compensating transport of the sediment from the shallower to the deeper part of the channel. The shape and dimensions of the channel, which at last are reached in the state of equilibrium, depend i.a. on the flow conditions, the sediment transport, and on the composition of the sediment.

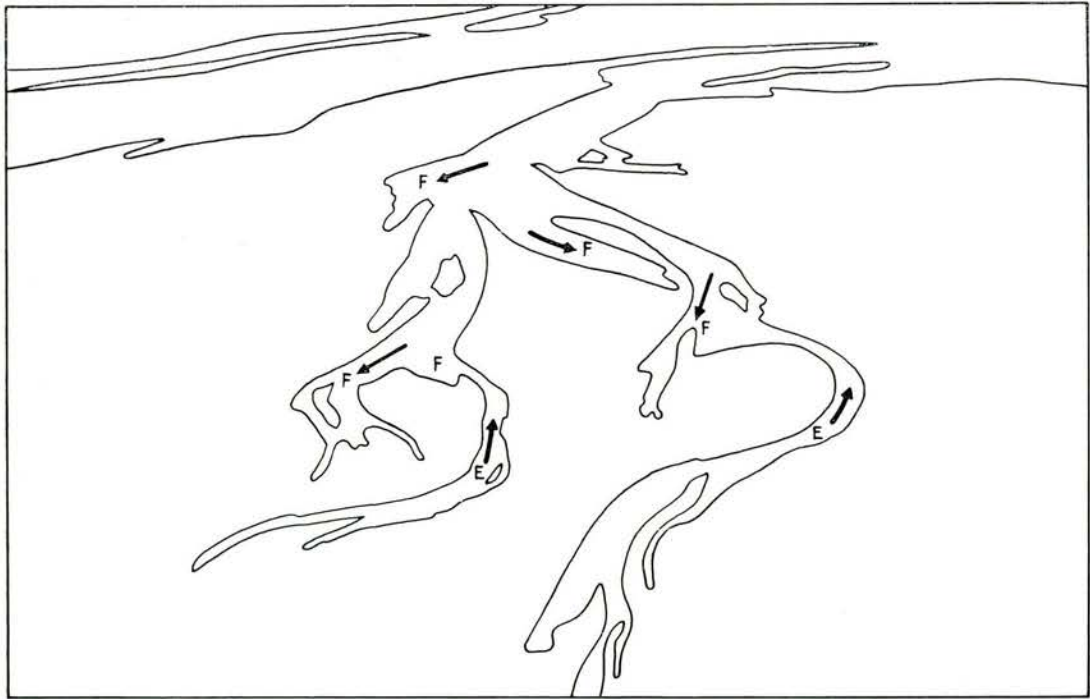
When the current passes through bends, the three-dimensional character of the sediment transport manifests itself even stronger. As a result of the then active centrifugal force there is near the bottom a cross-current directed towards the inner bend. The force of Coriolis, which as a matter of fact is always present, causes also a cross-current, which on the northern hemisphere, with respect to the main direction of the current near the bottom, is directed to the left. These cross-currents also influence the slopes the bottom shows in the end.

From the above it will be clear that the currents in the coastal waters greatly contribute to the moulding of the bottom, thus forming certain patterns of gullies and shoals. In the mouths of the estuaries ebb channels, flood channels, and continuous gullies can be distinguished. An ebb channel is a channel that is mainly open to ebb current, and has a bar on the sea side; a flood channel is mainly open to the flood and has a bar on the land side. Under certain circumstances the ebb channels in an estuary can form one continuous channel. The so-called meander effect is an important factor in the forming of ebb and flood channels. (Fig. 5). In the ebb channel a resulting sediment transport is usually found in the direction of the ebb current, in the flood channel, on the other hand, it is found in the direction of the flood. The afore-mentioned bar is then located at the meeting-point; sometimes one or more connecting gullies are found in the bar which usually are very mobile. Fig. 6.



MEANDER ACTION IN TIDAL CHANNEL

Fig. 5

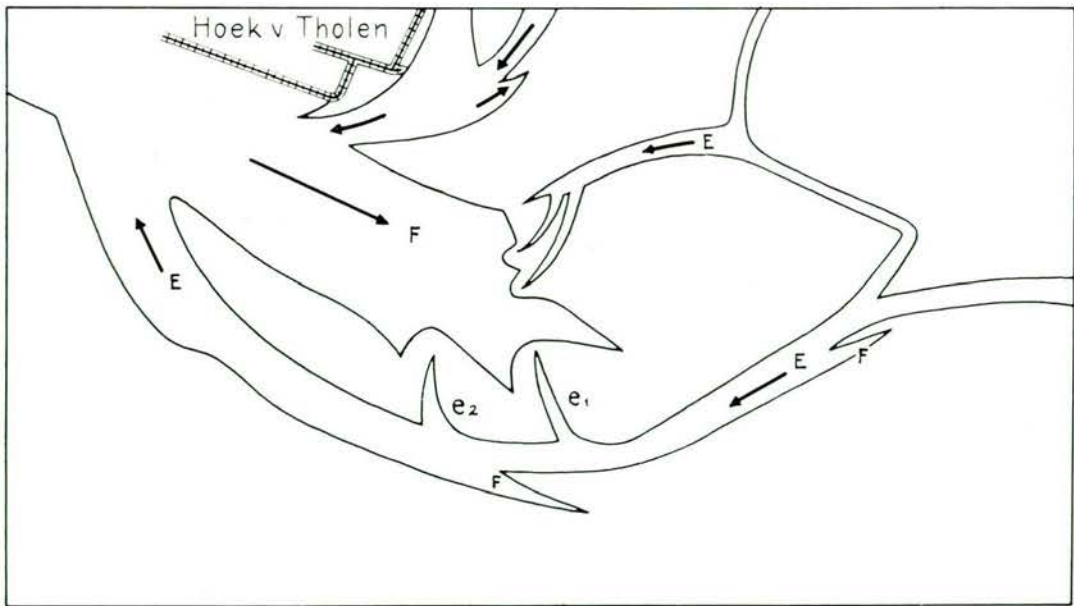
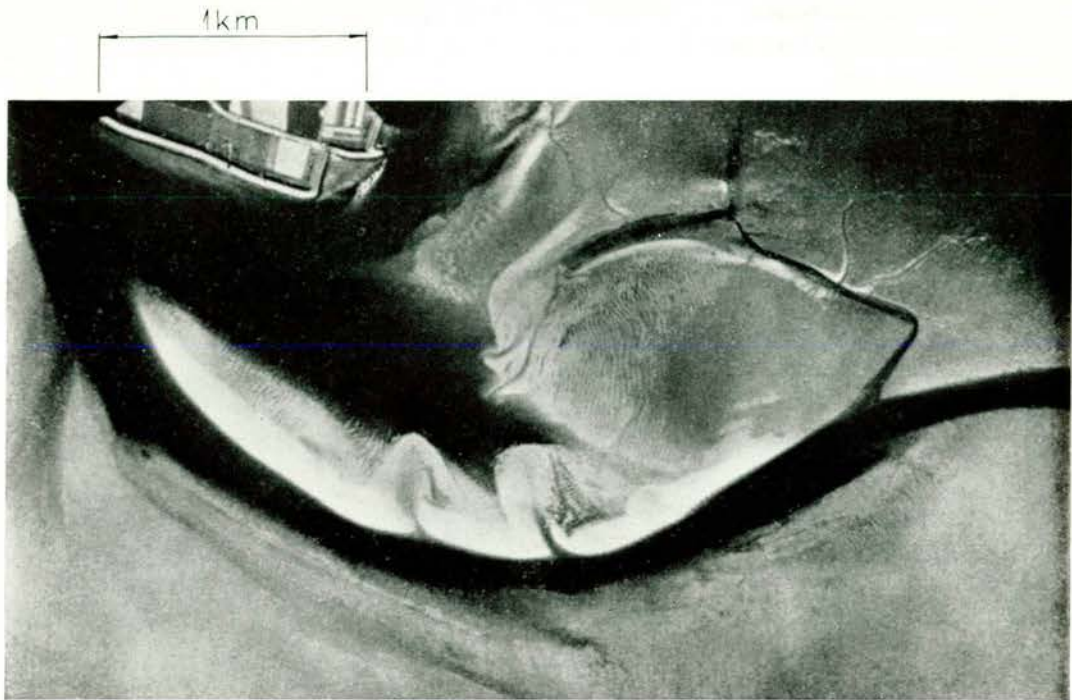


E = EBB CHANNEL

F = FLOOD CHANNEL

Fig. 6^A

EBB AND FLOOD CHANNEL SYSTEM IN THE DUTCH COASTAL REGION; WADDENSEA. THE PHOTO SUGGESTS CLEARLY THE DIFFICULTIES WHICH ARISE IF ONE WANTS TO MEASURE THE SEDIMENT TRANSPORT IN THIS AREA WITH THE CLASSIC METHODS MENTIONED IN 3.1.0.



E = EBB CHANNEL

F = FLOOD CHANNEL

Fig. 6^B

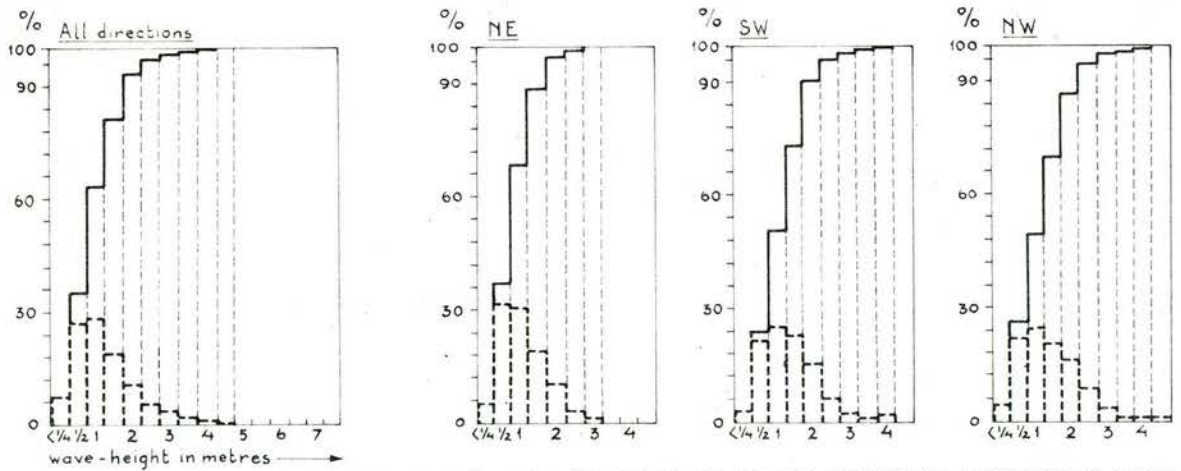
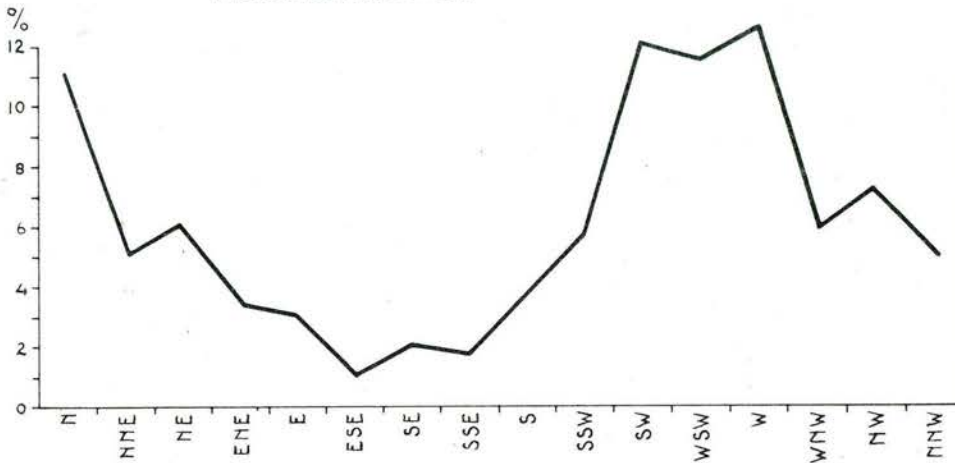
EBB AND FLOOD CHANNEL SYSTEM IN THE DUTCH COASTAL REGION; EAST SCHELDT.
 SECONDARY EBB CHANNELS e1-e2 RUN FROM THE EBB CHANNEL TO THE FLOOD CHANNEL THROUGH THE SEPARATING SAND BAR, MAKING LITTLE DELTAS IN THIS FLOOD CHANNEL.

2.3.0. WAVES.

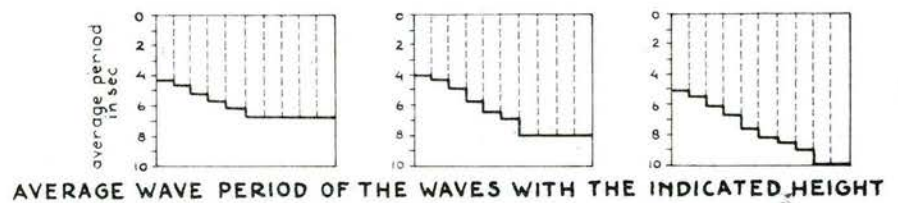
Until recently relatively few quantitative data were known regarding the wave movement in the Netherlands coastal waters. Especially since 1953 much work has been done to collect these data; as a matter of fact it was in that year that the plans to dam up the estuaries in the south-west took a more definite form.

2.3.1. Some idea of the wave movement in the coastal searegion, outside the submarine delta in the south-western part of The Netherlands, is given by the visual wave observations on board the light-vessel "Goeree". Since 1949 the height, period, and direction of the waves have been estimated here, the velocity and direction of the wind also being determined. (Fig. 7). There are many drawbacks as

PERCENTAGE OF TIME WAVES ARE COMING FROM THE INDICATED DIRECTION



PERCENTAGE OF TIME WAVES FROM THE INDICATED DIRECTIONS HAVE THE INDICATED HEIGHT (OR LESS)



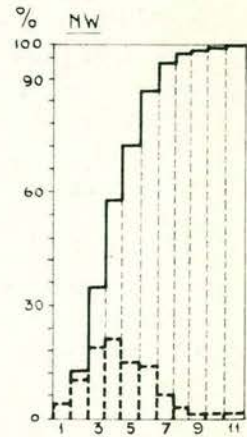
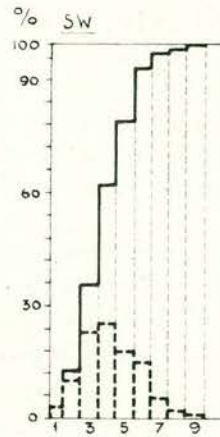
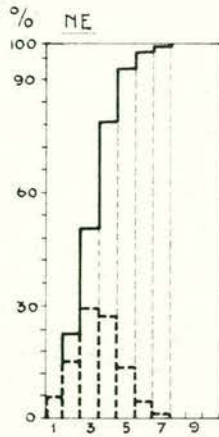
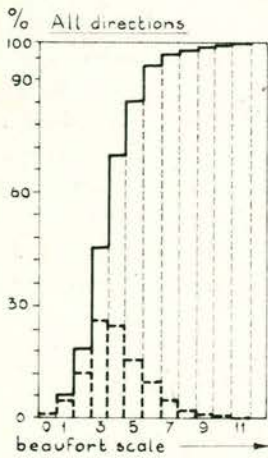
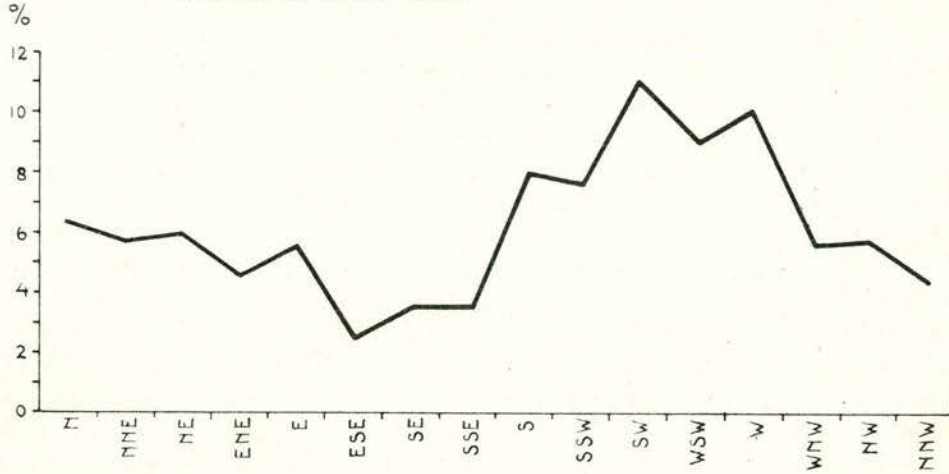
AVERAGE WAVE PERIOD OF THE WAVES WITH THE INDICATED HEIGHT

Fig. 7^a

WAVES OBSERVED ON BOARD THE LIGHTVESSEL „GOEREE”

PERIOD 1949 - 1954

PERCENTAGE OF TIME WIND BLOWS FROM THE INDICATED DIRECTIONS



PERCENTAGE OF TIME WIND FROM THE INDICATED DIRECTIONS HAS THE INDICATED STRENGTH OR LESS)

Fig. 7^b

WIND OBSERVED ON BOARD THE LIGHTVESSEL „GOEREE”

PERIOD 1949 - 1954

to the visual wave estimations, both with regard to the exactness and to the place which the estimated value occupies in the spectral diversity of the phenomenon in question. These drawbacks can only be eliminated by means of wave recorders.

2.3.2. With respect to the wave movement in the area of the submarine delta, no quantitative data are available at all. It is known from experience that here the wave picture is extremely complicated, because mostly complex cross patterns occur. In this rather shallow region the dimensions of the waves coming from the North Sea are greatly influenced. The depth of the water, and the wave length – and in this connection also the refraction –, together with the currents, play an important role here; moreover, with a strong wave movement the submarine delta soon forms one large zone of breakers.

2.3.3. Up to 1953 no quantitative data regarding the wave movement in the mouths of the estuaries were known either. Since that time, however, more systematic observations have been made in an increasing number of places. Initially these observations were exclusively made visually, the results being read from fixed wave gauges or from floating wave measuring poles with damping plates, which poles are moved from place to place by survey boats. By thus using a reading scale, data regarding the wave height spectrum can also be obtained by means of visual observations.

In 1954 fixed wave measuring stations were erected in the mouths of the estuaries at distances up to many kilometers off shore, which stations were provided with wave recorders; afterwards the number of stations was further increased. Fig. 8.

From the collected observation material the following was apparent. The wave movement in the mouths of the estuaries may be conceived as a composition of the residue of wave movement coming from the North Sea that has passed the „screen” of the submarine delta, and of the wave movement generated locally. Which part of the wave movement coming from the North Sea can enter the mouths of the estuaries depends i.a. on the height, length, and direction of the waves in the North Sea, the water level, and the magnitude and direction of the currents. The influence of the water level is very important; for the mouth of the Haringvliet this may e.g. be read from figure 9. The resulting wave movement in the mouths of the estuaries strongly differs from place to place, as e.g. appears from figure 10, which also refers to the mouths of the Haringvliet.

As was remarked already in the introduction the wave movement in the coastal waters of the south-western Netherlands will change as a result of the changes in the conditions which will arise after the damming up of the estuaries. It may be attempted to determine, by means of refraction calculations, the changes in the wave movement as a result of the changes in the current picture, and in the depth relations. The experience gained in this country in this respect is less favourable. In the first place, too little is known regarding the energy losses caused by the breaking of the waves on the shoals, or, as a result of too great a concentration of wave energy, by refraction. In the second place it has appeared that the period spectrum of the waves is not independent of the ratio between the depth of the water and the wave length; apart from the fact that too little is known yet regarding this phenomenon, this makes the drawing of refraction patterns an uncertain undertaking.

A second manner to learn something about changes in the wave movement as a result of the changed conditions after the damming up of the estuaries, is the use of hydraulic models. In view of the extensive regions generally concerned, and in view of the scales to be used, these investigations require usually the construction of large models.

2.4.0. MOVEMENT OF SEDIMENT BY WAVES.

Waves can transport sediment as a result of the special character of the orbital movement of the water particles in shallow water, and also as a result of the currents originated by the waves. The simultaneous occurrence of the orbital water movement and the more or less continuous currents, make the transport of sediment by waves a complicated phenomenon.

By means of measurements in nature and by means of investigations on hydraulic models, attempts have been made to study parts of the problem separately. Certain phenomena have been analysed successfully in this way, but also many questions have remained unanswered.

2.4.1. It should be remarked that many of the following considerations are based on the results of model tests. Strictly speaking, the results of model tests with regard to the sediment transport by waves and by the currents caused by waves, cannot be applied to natural conditions. The model law of Froude does not apply e.g. to waves distorted by bottom friction, and no more does it hold in the breaker zone; till now little has become known regarding the properties of the water-air mixture in the breakerzone. Moreover most of these model tests have the drawback that wave

PLACES IN THE SOUTH WESTERN PART OF THE NETHERLANDS
WHERE WAVE MEASUREMENTS ARE MADE

Fig.8

- WAVE MEASURING STATIONS WITH RECORDING INSTRUMENTS
- x WAVE GAUGE, VISUALLY OBSERVED
- PLACES WHERE MEASUREMENTS ARE MADE WITH THE HELP OF THE FLOATING WAVE MEASURING POLE

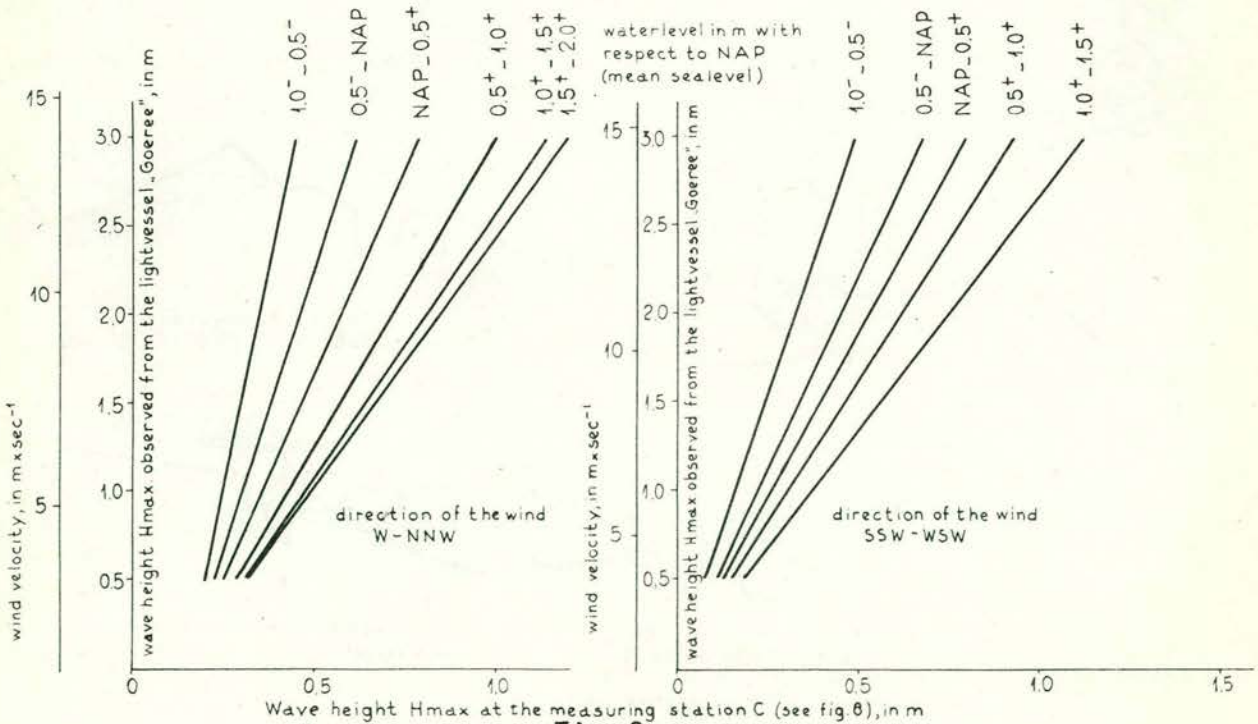
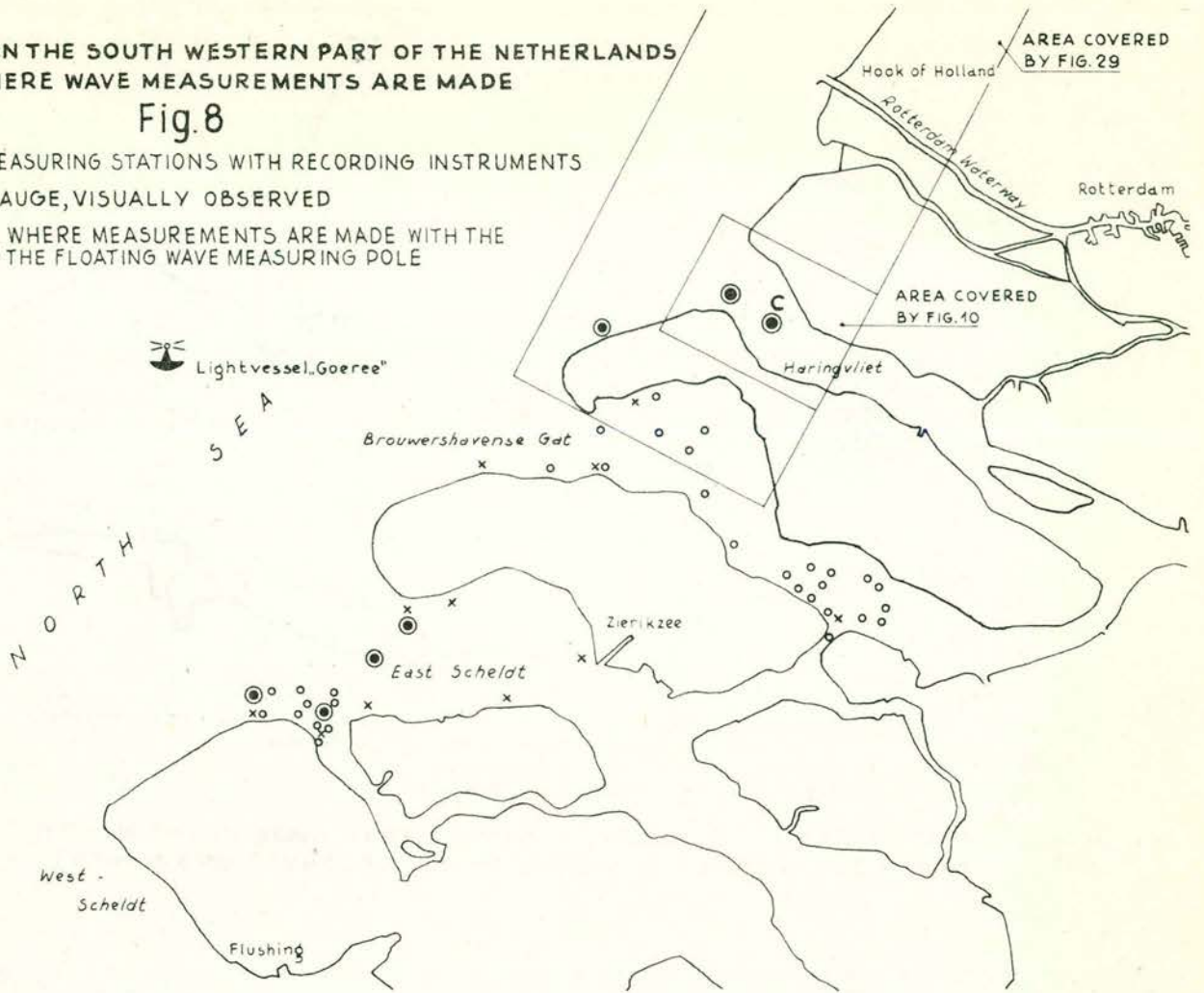
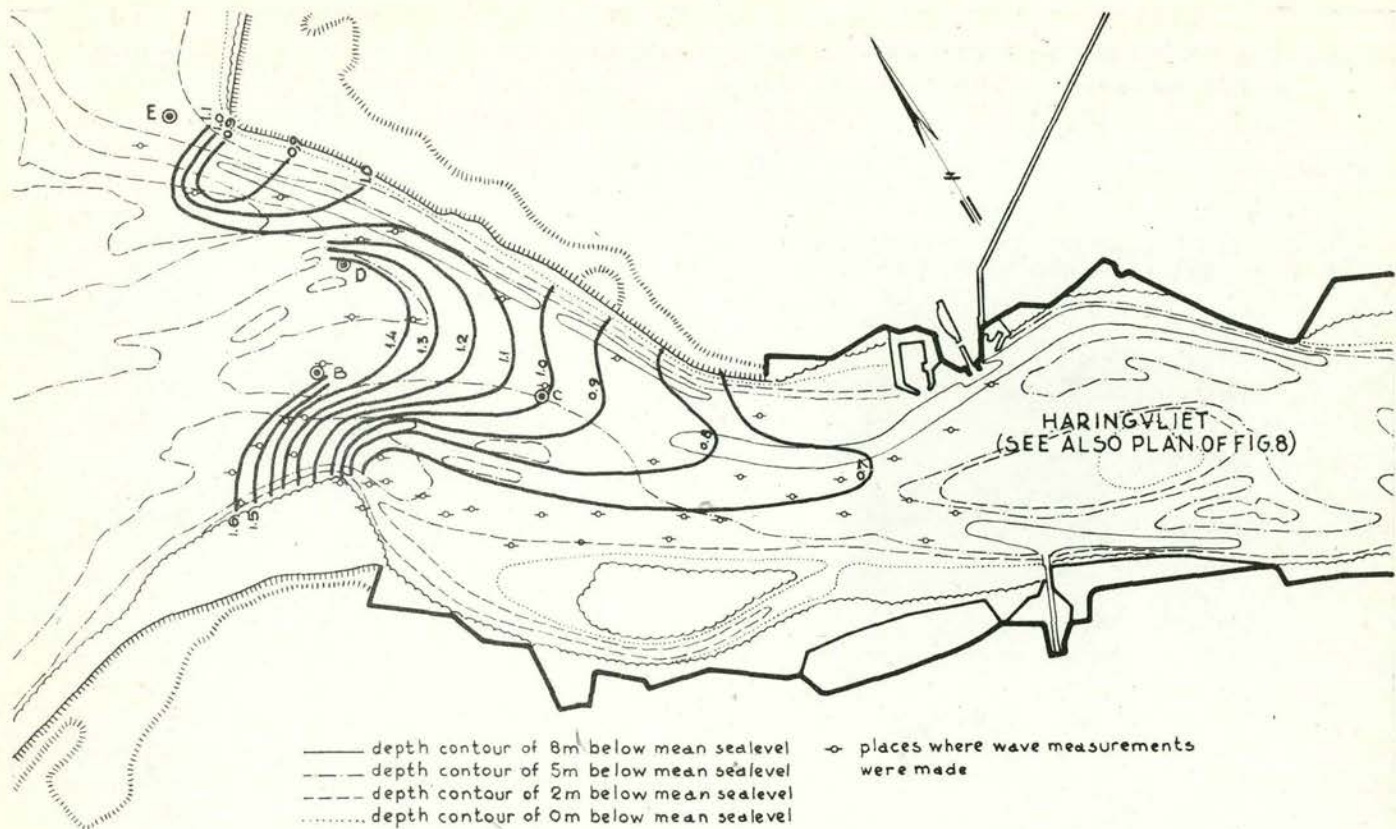


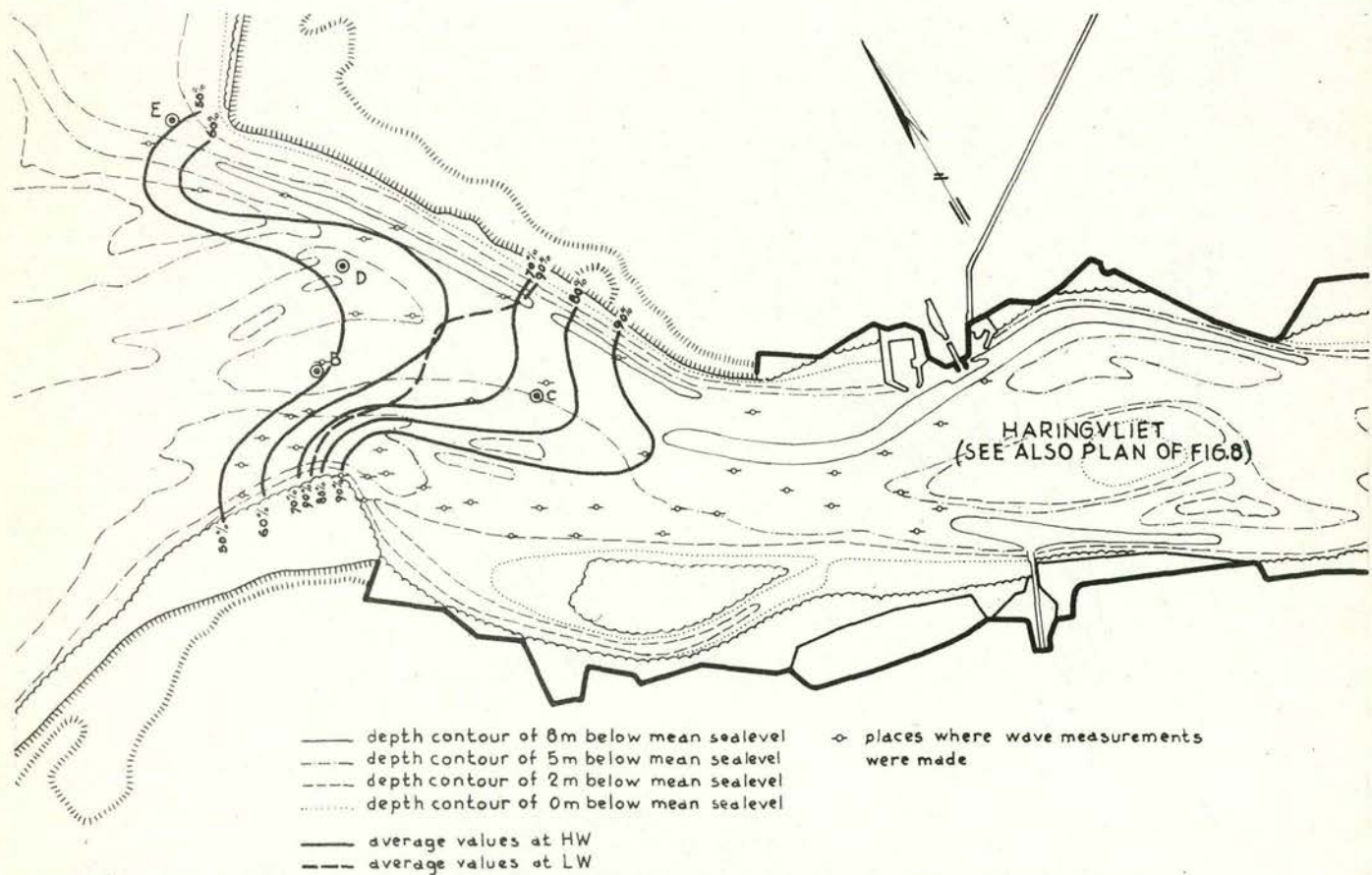
Fig.9

EMPIRICAL RELATIONSHIP BETWEEN THE WIND VELOCITY (RESPECTIVELY THE WAVE HEIGHT IN THE NORTH SEA AREA), THE DIRECTION OF THE WIND, THE WAVE HEIGHT IN THE MOUTH OF THE HARINGVLIET AT THE MEASURING STATION C (FIG.8), AND THE HEIGHT OF THE WATERLEVEL



LINES OF EQUALLY RELATIVE WAVE HEIGHT H_{max} IN THE MOUTH OF THE HARINGVLIET (AVERAGE OF ALL OBSERVATIONS IN 1955)

Fig.10^a



LINES OF EQUAL PERCENTAGES OF TIME DURING WHICH THE WAVE HEIGHT H_{max} IS SMALLER THAN 0,5m (REVISED GRAPH; AVERAGE OF ALL OBSERVATIONS IN 1955)

Fig.10^b

pictures have been used in which the spectral diversity, as regards the wave height and the wave period as they are nearly always observed in nature, does not manifest itself; observations in nature and also certain model tests indicate, however, that the movement of the sediment and the shore profiles which may result from the latter, are influenced by the variations in the wave picture. On the other hand the investigation of shore processes is especially stimulated by the relevant model tests. Special mention must be made of the many investigations made under the auspices of the Beach-Erosion Board. During this research – seen in the light of the above, surprising – agreement has appeared to exist between model and nature many times. Nevertheless the following considerations have a qualitative character more than a quantitative one.

2.4.2. When the shore has been exposed to the influence of waves of certain dimensions for a certain time, a certain equilibrium profile relating to these waves sets in.

In this respect we can especially distinguish between the so-called summer and winter profiles. The steepness of the waves H/L would be chiefly the determining factor in this case. With a steepness in deep water of $H_0/L_0 = 0.025$ to 0.030 the winter profile is usually found, with erosion phenomena on the shore and well developed longshore bars; with a steepness of $H_0/L_0 = 0.015$ to 0.020 , however, the summer profile occurs, with an accretion of the shore, slightly developed longshore bars and a steep foreshore *). Figure 11.

It must be remarked that especially eroding shores without defence works and shores with just enough supply of sand, assume the equilibrium profile belonging to the relevant wave picture; the shoreline then may be shifting landward or be stable. Overfed shores often show irregularities.

In general the slope of the foreshore would increase or decrease with the decrease or increase respectively, of the steepness of the waves and of the wave period; the opposite holds for the grain size of the sediment. As for the offshore, the opposite would hold in this respect. Several formulae have been published regarding the equilibrium profiles, which describe these profiles as being a function of the determining quantities; for brevity's sake, the literature may be referred to here.

The so-called longshore and offshore bars form one of the most striking characteristics of shore profiles. The dimensions of these bars, and the depths at which they occur are dependent on the dimensions of the waves and apparently especially on the wave height. The forming of the bars is suppressed the more as the tidal range is greater; the bars are best developed during neap tides and otherwise similar circumstances. Apart from the beach width the tide difference is of little influence on the coastal profile.

Besides the system of large bars and troughs, one or more ripple systems can mostly be distinguished too. As regards the forming of these ripples, in cases of oscillating water movement the following stages may be distinguished. With steadily increasing velocity of the water particles near the bottom, first some grains of the bottom material get into movement, after that a more general movement sets in, and next the forming of ripples starts. If the velocity of the water particles is increased even more, the ripples at a certain moment reach their maximum height and velocity of propagation; after this the ripple height decreases, whereas the ripple length increases further. Ultimately the ripples disappear completely, in which stage a layer of more or less suspended sediment moves along the bottom. With respect to the beginning of these stages various criteria have been published which, however, do not agree with each other.

Though it has appeared that there are certain relations between the intensity of the sediment transport and the dimensions, form, and velocity of propagation of the ripples, the sediment transport cannot be calculated by multiplying the ripple content by the ripple velocity; the distance over which the grains are removed plays a part here.

2.4.3. With respect to the sediment transport a distinction may be made between the offshore, the area in and near the breaker zone, and the foreshore. In the following considerations the general case of waves approaching the coast at an oblique angle, is started from.

Apart from the influence of the return currents, the sediment transport on the offshore mainly takes place in the form of bed-load. Here a so-called zero point can be distinguished for the various sizes of the grains. Grains that are landward of their zero position, are transported into the breaker zone, where under unchanging circumstances they remain in oscillating motion, grains, however, which are seaward of their zero point are transported seaward into the area where the orbital velocities near the bottom are too small for further transportation.

According to Ippen and Eagleson **) the zero position is characterized by

$$\left(\frac{H}{h}\right)^2 \times \frac{L}{H} \times \frac{c}{w} = f(I_b) \text{ ----- (6)}$$

*) Th. Scott,
Sandmovement by waves,
Beach Erosion Board, Techn. Mem. nr. 48 1954.

**) A. T. Ippen, P. S. Eagleson,
A study of sediment sorting by waves shoaling on a plane beach,
Beach Erosion Board, Techn. Mem. nr. 63, 1955.

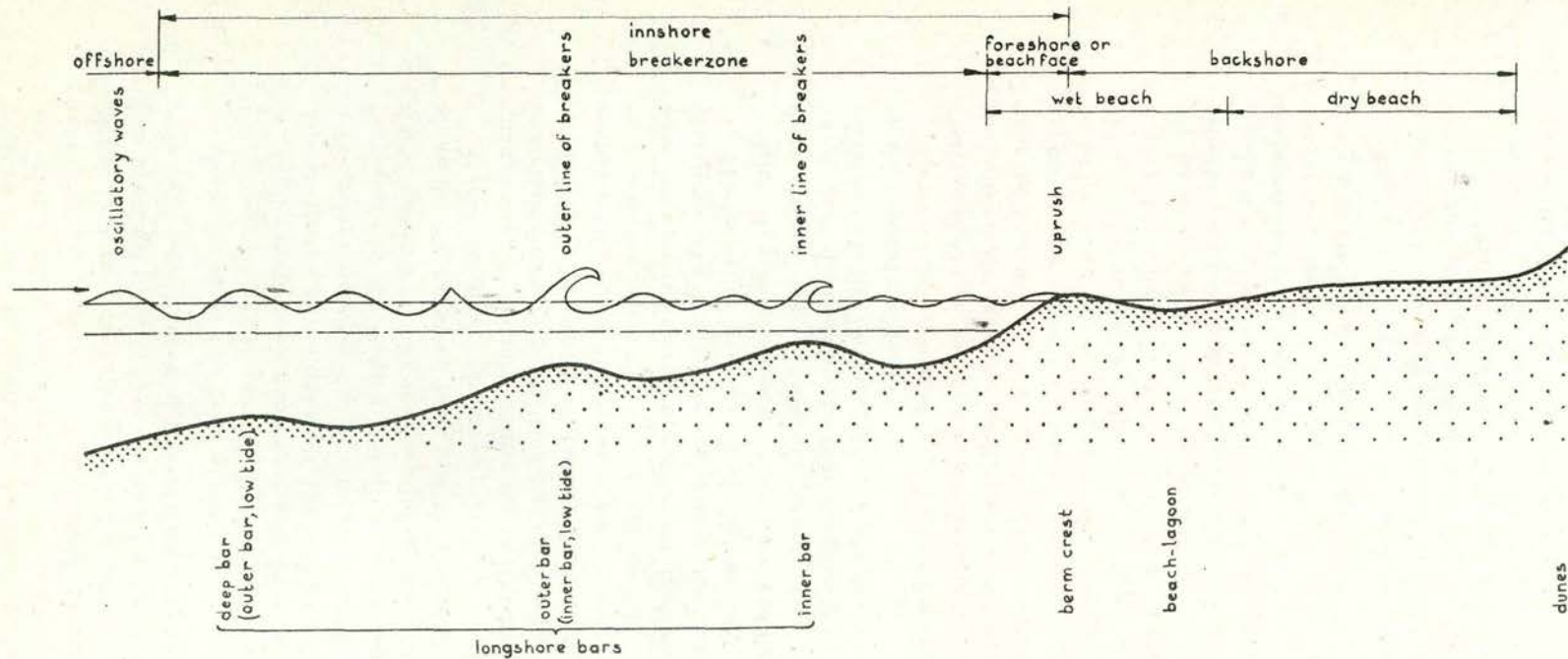


Fig. 11^a BEACH PROFILE -RELATED TERMS

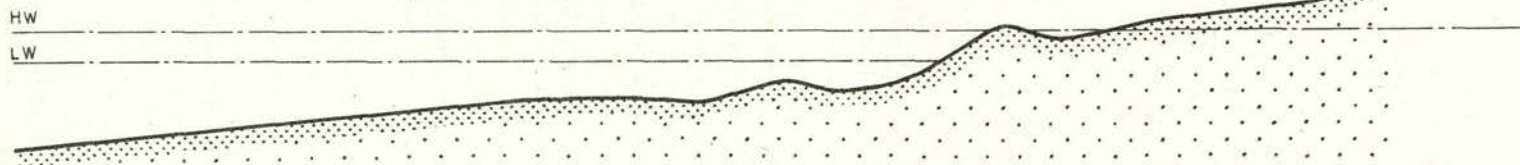


Fig. 11^b SUMMER PROFILE OF BEACH

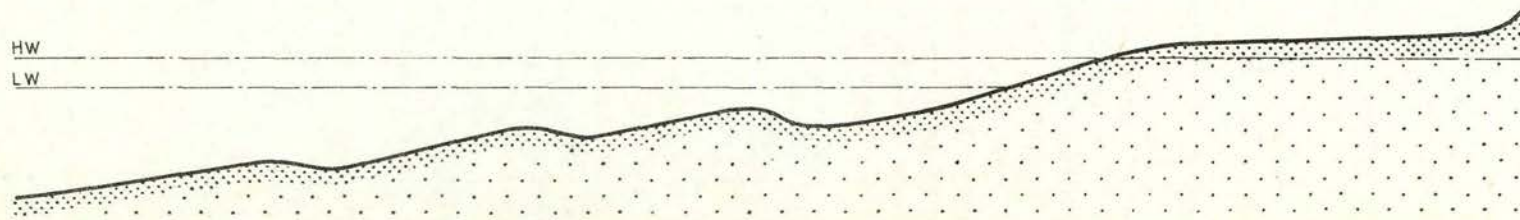


Fig. 11^c STORM OR WINTER PROFILE OF BEACH

In this formula:

c = the velocity of propagation of the waves.

I_b = the slope of the offshore.

The phenomenon described here is also the cause of the sorting of the sediment in lanes parallel to the coast which will be discussed hereafter.

At one certain wave movement there will be an equilibrium profile after a short time, possibly with certain fluctuations in consequence of the tide. The sediment which at this equilibrium profile is transported seaward by the return currents — e.g. the rip-currents —, takes part in the aforementioned process on the offshore, whereupon it again is transported mainly landward, and so on; the resulting zig-zag movement causes a certain transport of sediment parallel to the coast (Fig. 4). The sequence of various wave movements occurring in nature, and the accompanying profile adaptation will bring about a second, slow zig-zag movement (Fig. 4). Little is known about the size of the transport of sediment parallel to the coast, which is the consequence of the latter phenomenon.

2.4.4. The sediment transport in the breaker zone is effected mainly in the form of suspended-load; the sediment which is brought in suspension by the breakers is displaced parallel to the coast by the longshore-currents (Fig. 4).

The sediment transport on the foreshore is effected mainly in the form of bed-load. When the waves approach the coast obliquely there will be a zig-zag movement, the ultimate result being a transport parallel to the coast, the so-called beach-drift (Fig. 4).

For the greater part the transport of sediment parallel to the coast takes place in and near the breaker zone and landward of it. Beach-drift is preponderant at summer profiles and suspended-load at winter profiles, the transition taking place at a steepness of the waves $H_o/L_o = 0.020$ to 0.030 . The transport of sediment parallel to the coast would reach a maximum at a steepness of the waves $H_o/L_o = 0.015$ to 0.025 , i.e. at the presence of summer profiles; so then the maximum transport is mainly beach-drift. For the rest the transport increases in proportion as the wave energy increases (Fig. 12)*). The sediment transport parallel to the coast also depends on the angle formed by the directions of the wave crests and the coast. This can be expressed roughly by:

$$Q_{//} = C_t \times \sin 2 \phi_{wb} \text{ ----- (7)}$$

In this formula:

$Q_{//}$ = transport of sediment parallel to the coast,

C_t = a constant,

ϕ_{wb} = angle formed by the directions of the wave crests at the breaker zone and the coast line.

Observations have shown that the littoral transport reaches a maximum at an angle between the direction of the wave crests and the direction of the coast line, in deep water usually between 20° — 50° . With curved coasts the relations are little different in consequence of the compensating currents which may be caused by refraction. **)

2.4.5. As has already been mentioned in the afore-going, sediment is sorted on the offshore in consequence of the nature of the transport. This sorting is, however, not restricted to the offshore. The coarsest material in a coastal profile usually is found in the breaker zone. Furthermore the sediment on the tops of the bars is mostly coarser than the sediment in the troughs. So the sorting takes place in lanes parallel to the coast; this phenomenon is hardly affected by the rip currents (Fig. 13).

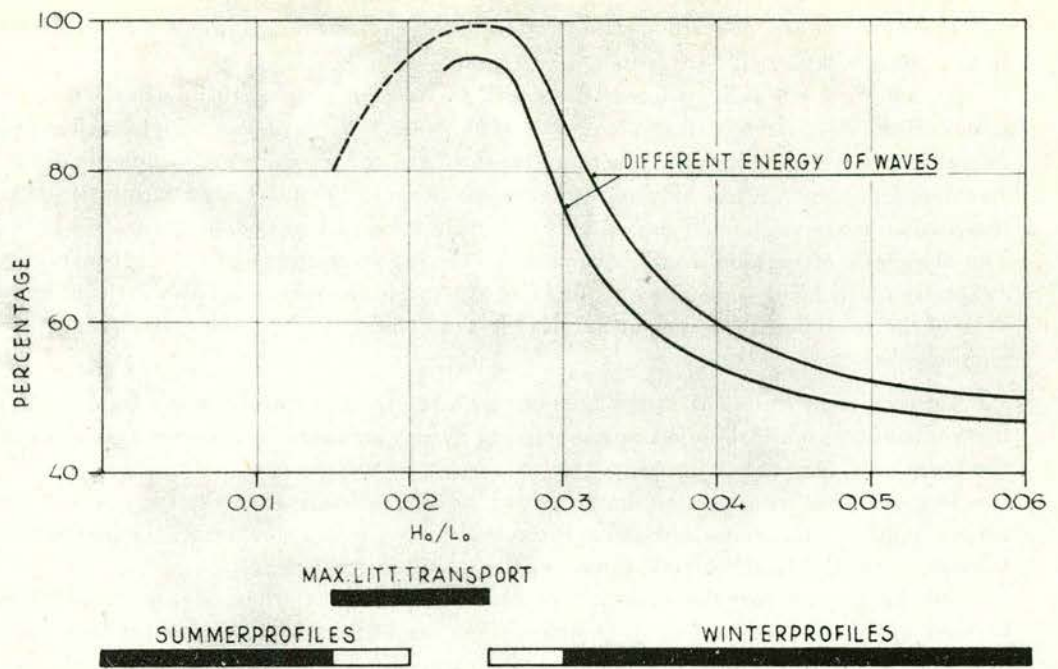
Also from a mineralogical point of view there is a certain sorting. The quantity of heavy minerals is mostly largest on either side of the breaker zone, whereas it is often small in the breaker zone itself. Fragments of shells are often found concentrated in the breaker zone.

2.4.6. The littoral sediment transport sometimes gives rise to the forming of waves in a straight coast line. Off the coast of Jutland for instance suchlike waves have been observed, the length being 200 — 2000 m and the height 50 — 90 m; the speed at which these sand waves moved varied from 0 — 1000 m a year.

For the sake of brevity we shall not deal here with the littoral sediment transport along coasts with special features, such as e.g. travelling forelands, etc., or coasts provided with groynes, breakwaters, piers, etc.; for this purpose we refer to the literature.

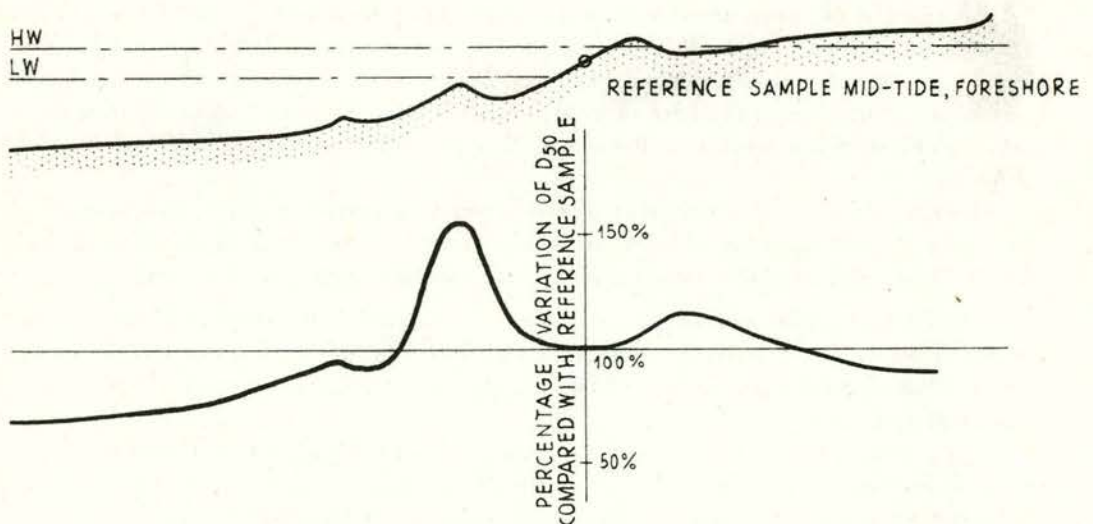
*) Th. Saville,
Model study of sand transport along an infinitely long straight beach,
Trans. Am. Geoph. Union, nr. 4, 1950.

**) P. Bruun,
Forms of equilibrium of coasts with a littoral drift,
Univ. Calif., Inst. Eng. Res., series 3, issue 347, 1953.



TREND OF THE PERCENTAGE OF TOTAL LITTORAL SEDIMENT TRANSPORT MOVING AS BED-LOAD, RELATED TO WAVE STEEPNESS

Fig.12



EXAMPLE OF THE VARIATION OF THE GRAIN SIZE ACROSS A BEACH

Fig.13

3.0.0. EVALUATION OF THE TRANSPORT OF SEDIMENT BY CURRENTS AND WAVES.

As is apparent from the previous chapter the transport of sediment in the coastal waters is of an extremely complicated character. At the moment the situation is by no means such as to enable the computation of the sediment transport from the data concerning bottom topography, currents, waves, and composition of sediment, supposing these data were available to a sufficient degree. Therefore it is necessary to fix the sediment transport directly by means of measurements in nature. In planning the relevant programme of measurements use can be made of the theoretical knowledge acquired so far, whereas on the other hand it may be expected that the results of the measurements will give us a better understanding of the mechanism of the relevant phenomena.

3.1.0. MEASUREMENTS WITH BED-LOAD AND SUSPENDED-LOAD METERS.

To fix the sediment transport in the coastal waters use is made in The Netherlands of the „Sfinx” meter for the bed-load and of the „Delft-bottle” meter for the suspended-load; some older types of measuring instruments are still being applied, but will be replaced by the newer types within a short time.

3.1.1. The principle of the „Sfinx” is mainly as follows. *) Figure 14.

A rectangular tube, with a cross section of $1.0 \times 5.0 \text{ cm}^2$, is placed on the bottom, in such a manner that the current in front of, and in the surroundings of the mouth is not disturbed. The instrument is dimensioned in such a manner that the water flows into the tube with a velocity which is about equal to the velocity in the undisturbed stream. Via the tube the water-sediment mixture reaches a kind of spiral case, in which the sediment settles, while the water leaves the instrument at the back again. A small part of the sediment that has entered the spiral case, disappears together with the water, dependent on the fineness of the sediment and on the current velocity; the measured values of the bed-load have to be corrected accordingly.

The actual bed-load meter is suspended in a frame by means of plate springs; a rudder keeps the whole device in the direction of the current. As the bed-load reacts immediately to the placing of an object on the bottom, the frame is lowered in such a manner that first the rudder touches the bottom, next the front part of the frame and finally the bed-load meter itself. The plate springs provide for the mouth being kept on the bottom with a small, constant force.

The transport meters are lowered and raised quickly, in order to reduce the quantity of sediment, which is caught during the lowering and raising, to a minimum. Near the bottom all operations are carried out very carefully.

3.1.2. The principle of the „Delft-bottle” is mainly as follows. **) Figure 15. The water together with the suspended sediment flows into the instrument through a nozzle and then enters a relatively large room where the sediment settles. Ultimately the water leaves the instrument again through holes at the back. The sediment caught can be removed via another hole at the back. The afore-mentioned nozzle has such a length that the opening is outside the area where the current is affected by the instrument itself. Further the suspended-load meter is dimensioned in such a manner that the current velocity in the nozzle is nearly always equal to the velocity in the undisturbed stream. A small part of the sediment leaves the instrument again, dependent on the fineness of the sediment and on the current velocity; the measured values of the suspended-load have to be corrected accordingly. In order to be able to adapt the suspended-load meter somewhat to the prevailing conditions, it has been provided with two different nozzles, having cross sections of 2.0 and 3.8 cm^2 ; these nozzles can be used at smaller, respectively larger velocities and smaller, respectively larger concentrations of suspended sediment.

The instrument can be suspended direct on a cable or placed adjustable in a frame, which can be lowered to the bottom by means of a cable. In the latter case the suspended-load meter can be placed in the frame in a slanting position, so that the area close to the bottom can be reached by means of a somewhat curved nozzle.

*) J. B. Beckering Vinckers, E. W. Bijker, J. B. Schijf,
Bed-load transportmeter for fine sand „Sphinx”,
Minnesota Int. Hydr. Conv., 1953.

**) Hydraulics Laboratory, Delft,
Sample of sand in suspension;
and in:
Measurement and analysis of sediment loads in streams,
Chapter X, sect. 84, Iowa, 1940.

3.1.3.

A difficulty in measuring the bed-load is that the results are greatly dependent on the accidental position of the mouth of the instrument when placed on the bottom, with regard to the tops and troughs of the bars and ripples. When e.g. during a measurement a ripple higher than the height of the mouth of the instrument is passing, an incorrect value of the bed-load will be measured. Generally speaking the time, during which the instrument remains on the bottom, will influence the value of the result obtained. During measurements in the Dutch big rivers outside the tidal region, made by means of an instrument similar to the „Sphinx“, it appeared that under permanent flow conditions the bed-load at one and the same point showed considerable variations; supposing the average of 10 measurements of 2 minutes each to be 100, the minimum and maximum of these 10 values amounted to 20 and 350 respectively. Einstein also found considerable variations in the bed-load by measurements in the Upper Rhine *).

In view of the distribution of the suspended-load in a vertical sense, measurements have to be made at several points in a vertical. The best thing would be to measure all points in a vertical simultaneously, but in practice the instruments available, davits, the space on board, and the personnel available, are mostly insufficient for that purpose. The various points or groups of points in a vertical have therefore to be measured one after the other, which often leads to difficulties with regard to the interpretation of the results obtained; the instruments have to remain from 2 to 20 minutes at one and the same point to give a comparatively representative result or measurable quantities of sediments, and the various points are thus measured during different phases of the tide with different current velocities, concentration of sediment, etc. The time during which an instrument remains at one and the same height is important; during measurements in the Dutch big rivers outside the tidal area it appeared that under permanent flow conditions the sediment transport through one and the same point in a vertical showed considerable variations; supposing the average of 10 measurements of 10 minutes each to be 100, the minimum and maximum of these 10 values amounted to 30 and 250 respectively.

3.1.4.

The two instruments described in the afore going are only suitable for measuring a transport of a sediment resulting from more or less continuous currents, and not for the transport caused by waves. In places where the current greatly predominates the movement of water caused by waves, these instruments produce good results; in view of the above it is no wonder, however, that the collection of reliable data through this method costs a great amount of time and trouble. When the instruments are used on board a ship, which is the only practicable method for the hydrographical exploration of a coastal area, measurements are not possible in periods of rough weather; just in these periods large quantities of sediment, brought into suspension also by the waves, are being removed by the currents in the coastal area.

The above difficulties inherent to the methods hitherto in use have been the reason that other means had to be found for measuring the transport of sediment in coastal waters.

3.2.0.

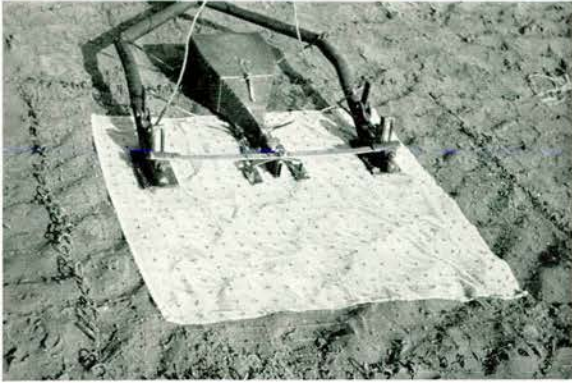
MEASUREMENTS WITH TRACERS.

Generally speaking the methods based upon the marking of the bottom sediment by tracers seem to be more suitable for the determination of the sediment transport in coastal waters than the methods described before. For this marking a quantity of well identifiable material is added to the bottom sediment – in separate points or along sight lines – and after some time the place and concentration of this tracer in the bottom sediment in the area in question is determined; by means of these data the sediment transport can be evaluated. This method is suitable for measuring the transport of sediments by currents as well as by waves; the influence of the period of rough weather can be ascertained by determining – immediately after such a period – the place and concentration of the tracers dumped before.

3.2.1.

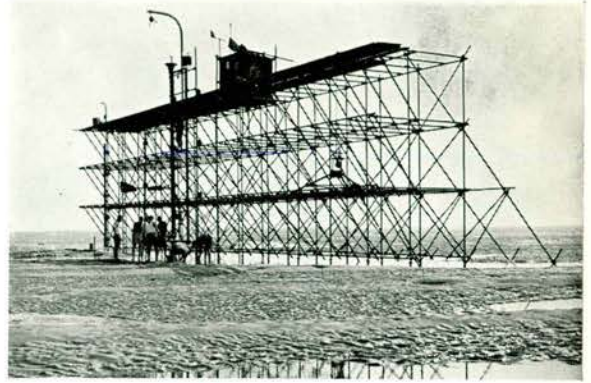
The tracer should have certain qualities that can be specified as follows. The tracer material must have the same transport qualities as the sediment in question and should not – neither by currents nor by the wave movement – be sifted out; this means that it has to fulfill the following conditions: the specific weight, the grain size distribution, the nature of the surface of the grains, and their shape must be equivalent to those of the sediment, while the degree of hardness must not be much lower than that of the sediment, in connection with the scouring effect of this sediment during the transport. Moreover the tracer material must be chemically stable, its distribution must be determinable in a simple way by concentration measurements, its properties may not conflict with health requirements and must be of such a nature that repeated measurements in the same area will be possible.

*) H. A. Einstein,
Die Internationale Rheinregulierung von der Illmündung bis zum Bodensee,
IV Die Eichung der im Rhein verwendeten Geschiebefänger, Schweiz. Bauzeitg., 110, nr. 13, 1937.



a

"SPHINX" PUT ON A NYLON NET FOR RESEARCH PURPOSES

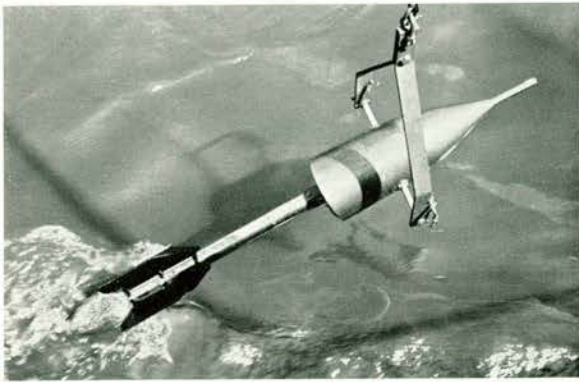


b

SCAFFOLDING ON A SANDBANK IN THE WEST-SCHELDT FOR TESTING I.A. SEVERAL KINDS OF TRANSPORT METERS (SAND BANK 2.0 M ABOVE NORMAL LOW WATER; TIDAL RANGE ABOUT 4.0 METERS)

BED-LOAD METER "SPHINX"

Fig. 14



a

DIRECTLY SUSPENDED INSTRUMENT



b

INSTRUMENT WITH A BENDED NOZZLE SUSPENBED IN A FRAME

SUSPENDED-LOAD METER "DELFT BOTTLE"

Fig. 15

3.2.2. As tracers by which the sediment can be marked in principle, the following materials can be mentioned:

a. **Tracer material of specific mineralogical composition;**

e.g. a homogeneous sediment of glass or of a certain mineral that does not or only rarely occur in the measured area. A disadvantage of this tracer is that the distribution can be determined only by means of repeated sampling, whereby for each sample a mineralogical analysis should be carried out, which is a time-consuming and expensive affair. Moreover the ultimate limit of the concentration that can be ascertained, is very high, large quantities of material being required to check the distribution in an area of some extension; this also accounts for the high cost of this method.

b. **Sand of natural colour.**

The difficulties are mainly the same, although the mineralogical analysis consists in a simpler microscopic examination.

c. **Sand of an artificial colour.**

The difficulties are the same as mentioned above; it is also difficult to attach a scour-proof layer around the grains without changing the transport qualities.

d. **Tracer materials which have entirely different chemical qualities,** and whose presence can therefore be proved chemically or by means of a spectro-analytical examination; e.g. aluminium, manganese-aluminium, etc. There too the difficulties are that a great number of samples are required and that the analytical examination is expensive. Moreover the erosion in sea water is great, especially in scouring environments; the consequence will be a loss of marking materials and change of the transport qualities.

e. **Tracer materials which have fluorescing qualities,** and whose presence can be proved photographically. As for the measuring technique this method takes much time; presumably long exposures are required and the samples require careful treatment. In this case too, a great number of samples are required.

f. **Radioactive tracers.**

Measurements with these tracers are being applied in a constantly growing field. Especially the accurate and comparatively simple measurement of radioactivity makes this method attractive. Another advantage is the fact that after a lapse of some time a former measurement — at a suitable chosen half-life of the tracer — will no more interfere with a second measurement. Radioactive tracers will be dealt with in more detail in the following chapter.

*
* *

4.0.0. EVALUATION OF SEDIMENT TRANSPORT BY CURRENTS AND WAVES, BY MEANS OF RADIOACTIVE TRACERS.

4.1.0. RADIOACTIVE TRACERS.

With regard to the preparation of radioactive tracers, suitable for measuring sediment transport, the following possibilities can be distinguished.

4.1.1. **Radioactivation of natural sand in a reactor** is possible if the variety of sand to be used is of such a chemical composition that by irradiation a simple appropriate kind of radioactivity will be formed. Inman and Goldberg *) irradiated some varieties of sand in a reactor and found that St. Peter sandstone had obtained a radioactivity that was identical with the 1.7 MeV β -radiation of P^{32} , Si^{31} , which originates from irradiating SiO_2 , unfortunately has a half-life of only about 3 hours; moreover it is a pure β -emitter with β 's to a maximum of 1.8 MeV.

The disadvantages of this method are the following. In connection with the desired statistical distribution of the tracer in the sediment a great number of grains of the tracer material have to be irradiated. The large quantities of material to be irradiated cannot be put at the same time into the limited space within the reactor, while moreover an even intensity of irradiation cannot be achieved. A difficulty is also the inhomogeneity with respect to the chemical composition of the varieties of natural sand.

4.1.2. Another method consists in the **dissolution of an element in a carrier material**, e.g. glass or plastic, which element is transformed into a suitable radioactive isotope by irradiation in a reactor. Before the irradiation the carrier of this element would already have to possess the transport qualities of the bottom sediment. An advantage as compared with the previous method is that a better chemical homogeneity of the material is attainable; for the rest the difficulties are the same.

4.1.3. The method of **making an element radioactive and incorporating it afterwards into glass, plastic or another carrier material**, has already repeatedly been applied. ¹⁻⁴⁾ This method has the advantage that, starting from a comparatively small quantity of material, the radioactive isotope can be made with a high specific activity in a reactor or cyclotron. In case the element in question is scarce and very expensive, it is of great importance, in view of the cost, to have the possibility of incorporating the total activity desired in a small quantity of the element; this material has then to be irradiated in a high flux. As in the case of small scale tests a cyclotron can also be used for this method there will be a greater choice of radio isotopes in practice. An objection is that the transformation of the produced amount of radioactive carrier material into the final grain-shaped tracer requires special precautions for the protection of the workers and the prevention of radioactive contamination in the factory or the laboratory.

4.1.4. A method which has also been applied consists **depositing of a radioactive isotope on the surface of the grains of the bottom sediment**. In the Laboratorio Nacional de Engenharia Civil in Portugal radioactive sand was made by depositing radioactive silver (Ag^{110}) from silvernitrate on sand grains ⁵⁾. The tests proved that 30% of the silver originally attached to the sand grains, were

*) E. D. Goldberg, D. L. Inman,
Neutron-irradiated quartz as a tracer of sand movements,
Scripps Inst. Oceanogr., new series nr. 761, 1955.

- 1) J. L. Putnam, D. B. Smith, R. M. Welles, F. Allen, G. Rowan,
Thames siltation investigation-preliminary experiment on the use of radioactive tracers for indicating mud movements,
Atomic Energy Res. Establ., Harwell; Hydr. Res. Stat., D.S.I.R., Wallingford; 1954.
- 2) R. Hours, W. D. Nesteroff, V. Romanovsky, P. Pruvost,
Utilisation d'un traceur radioactif dans l'étude de l'évolution d'une plage,
Ac. Sc., 1955.
- 3) Shizuo Inose, Naofumi Shiraishi,
Measurements of littoral drift by radio isotopes,
Nat. Hokkaido Development Bur., Japan, 1956.
- 4) R. Hours, W. D. Nesteroff, V. Romanovsky,
Méthode d'étude de l'évolution des plages par traceurs radioactifs,
Trav. Centre Rech. Etudes Océanogr., V. 1, 1955.
- 5) A. Gibert,
Essai sur la possibilité d'employer Ag^{110} dans l'étude du transport du sable par la mer,
Lab. Nac. de Engenharia Civil, Lissabon, 1954.

released under the washing influence of the seawater and the scouring effect of the sand itself. Especially the latter effect by which during long extended tests the tracer will entirely lose its characteristic qualities, is a great disadvantage of the method applied. This method may possibly be improved by burning the sand grains at a temperature approaching the sinter temperature, after the radioactive isotope has been deposited chemically on the grains, diffusion enabling the radioactive material to penetrate into the sand grains.

4.1.5. Another method to be shortly applied in The Netherlands consists in incorporating a radioactive isotope in an ion exchanger, e.g. a zeolite. The zeolites are natural and synthetic aluminium silicates, which in their crystal-lattice comprise univalent (Na^+) or bivalent (Ca^{++}) ions; however, these ions can be replaced by trivalent or multivalent ions.

It is possible to build a radio isotope, of which an ion of higher value exists, into a zeolite which meets the transport requirements mentioned in 3.2.1, as well as possible. Besides the fact that a radioactive material with a high specific activity can be used, the possibility of applying radioactive isotopes of rare earths and fission products also offers advantages; as a rule these fission products belong to the cheapest radioactive materials.

Most of the ion exchangers used at present in the chemical industry are synthetic resins with a low specific weight and are unsuitable as tracers for measuring sand transport. Of the inorganic zeolites only greensand, known in the market as Ionac C 50, has a specific weight (2.75 to 2.78) which approaches the specific weight of the bottom sediment (2.65 to 2.68) in the coastal waters of The Netherlands to a sufficient degree.

A disadvantage of greensand, however, is its low degree of hardness which is far below that of sand. Scouring tests with a mixture of greensand and ordinary quartz sand in water, showed that very small particles of greensand had already been formed after a few minutes, while at longer extended tests a shift of the grain size distribution curve of the mixture towards the finer sizes took place. A considerable increase of the hardness of greensand was obtained by burning this material at about 900°C ; the ion-exchange velocity, however, was reduced by this. In view of the endeavours to attach to the grains a small quantity of radioactive material with a high specific activity and in the second place because of the desirability to restrict the activity of the single grains as a protective measure, this does not, however, offer any difficulties. Hardness tests with burned greensand proved that there was no noticeable abrasion even after a considerable time. Figure 16. To ascertain the abrasion which corresponds to a long stay in the coastal area, hardness tests of a longer duration should be carried out.

Greensand was tested for its absorption capacity and absorption velocity for Sc^{46} from an Sc_2O_3 -solution. Here it was proved that unburned greensand already absorbed the required amount of Sc^{46} within three minutes, while the absorption capacity was still considerably higher. The burned greensand absorbs the same quantity of Sc^{46} only in about two hours. Furthermore, it was investigated to what degree Sc^{46} is washed out by seawater. At this test no trace of radioactivity could be found in the seawater after 48 hours of stirring.

4.1.6. The choice of the radioactive isotope to be applied is determined by various factors which will be dealt with in the following. First the nature of radioactive radiation, can be mentioned.

If one wishes to carry out the measurements of sediment transport directly on the bottom of the coastal area in question, and not be restricted exclusively to taking samples of the bottom, which have to be examined in the laboratory, one has, when choosing the radioactive isotope, to reckon with a comparatively great absorption of the radiation in the seawater and in the bottom sediment itself. Therefore α - and β -emitters are practically unsuitable for this purpose and even soft γ -emitters had better not be chosen. Hard γ -radiation is advantageous as compared with the previous forms of radiation, because of its lesser sensibility to the variations in the thickness of the layer of water which will undoubtedly occur under the detector for measuring the radioactivity, owing to the unevenness of the bottom. Moreover, for the same quantity of tracer grains and the same requirements regarding the statistical aspect of the counting, the area to be covered will be larger, in proportion as the γ -radiation is harder.

If Geiger-Müller counters are used in the measuring equipment, the efficiency for hard radiation is greater than for soft γ -radiation. If a scintillation crystal is used the absorption in the crystal for soft γ -radiation is greater than for hard radiation. The absorption for hard γ -radiation, however, can be sufficiently increased by increasing the thickness of the crystals (4.2.2.).

4.1.7. For practical reasons a half-life of the isotope in question of at least one week will have to be required in connection with a margin for the date of the measurements, which is necessary with a view to the weather conditions, because they will not always allow a measurement on the fixed date.

On the other hand a half-life of a year is too long because later measurements could be interfered with by previous ones; moreover, a shorter half-life will be preferable in order not to endanger the beaches by contamination. An advantage of a shorter half-life is also that as a rule isotopes with a shorter half-life can be quickly produced in large quantities and show a great energy transport per disintegration, so that the chance that these isotopes have a hard γ -radiation to a sufficient degree is great.

For measuring the sediment transport in the coastal region a half-life of about one to three months seems indeed suitable.

4.1.8. The technique described under 4.1.2., 4.1.3., 4.1.4. and 4.1.5. imposes certain conditions regarding the **chemical qualities** of the radio isotope. On the basis of the explanations under 4.1.6., 4.1.7. and 4.1.8. the choice will practically be restricted to a few radio isotopes.

4.1.9. In connection with the **availability** of the isotope, only reactor isotopes or fission products can practically be considered for measurements on a large scale. In view of the number of facilities in Europe and North America where radiations can be carried out, the supply of sufficient radioactivity is no problem. For tests on a laboratory scale the required small amount of radioactivity may be supplied by a cyclotron.

4.1.10. It is important to reduce the **radiation danger** to a minimum. Previous computations can be made of the radiation danger to which the persons who are concerned with the tests will be exposed when a certain working method is applied.

Beforehand the whole experiment has to be exercised in detail without radioactivity. When such a dummy experiment is made we shall not seldom be faced with a situation which would be most undesirable if the material were strongly radioactive. Thus the dummy experiment will enable us to avoid such dangerous situations when the actual test with radioactivity is made. Time studies can give us an idea of the doses which may be received by the research workers. It should be investigated whether during or after the experiment the maximal permissible concentration in air and water is exceeded in places where people may be present.

The safety on bathing beaches in the neighbourhood must be guaranteed. In general the dilution will be such that the bathers would have to eat some kilogrammes of sand before the maximum body burden would be reached. Concentration of radioactive material must be avoided; this requirement corresponds with the one for the transport properties of the tracer.

In table I (appendix I) a survey has been given of a number of radioactive isotopes, which entirely or partly fulfill the requirements stated. In table II (appendix II) the requirements with regard to the maximum permissible doses to be received by the research workers are stated.

4.2.0. INSTRUMENTS; RADIOACTIVITY AND QUANTITY OF TRACER GRAINS TO BE USED.

4.2.1. In considering the equipment for the measuring of the sediment transport by means of radioactive tracers we shall start from the supposition that it must be possible to follow the tracer over a distance of at least 1000 m, from the point where the tracer was deposited when starting the measurement; the tracer is assumed to be spread evenly over a circular surface having a 2000 m diameter, i.e. a surface of more than $3 \times 10^6 \text{ m}^2$. Furthermore it should be borne in mind that the tracer will not stick exclusively to the surface of the bottom during the transport but that it will be distributed over a layer with a certain thickness. Data concerning this distribution in a vertical sense are to be obtained by taking samples.

To be able to carry out the measurements at such a dilution of the radioactivity the following conditions must be fulfilled:

- a. the number of grains of which the detector observes the radioactivity must be sufficiently large to keep the statistical deviations of this number under a certain percentage, e.g. 10%;
- b. the statistical deviations of the number of quanta recorded during the time of measurement must not exceed a certain percentage either, e.g. 10%.

In connection with the desired small statistical deviations in the distribution of tracer grains it is desirable to work with as many grains as possible. For practical reasons this quantity, however, can not be unlimited. In practice it is objectionable to deposit e.g. 1000 kilogrammes of tracer grains on the bottom of the sea. Also with respect to the total amount of radioactivity there are limits in practice, in view of the health requirements and the practical difficulties in handling too large quantities of radioactive material.

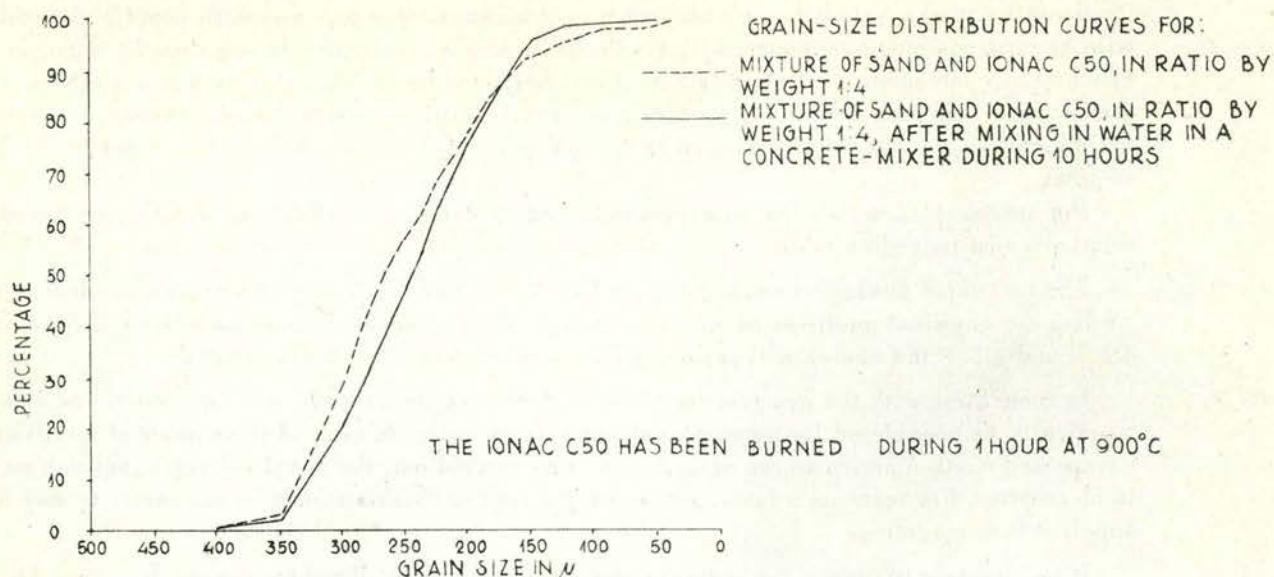


Fig.16 INFLUENCE OF SCOURING BY SAND ON THE GRAIN SIZE DISTRIBUTION CURVE OF IONAC C50

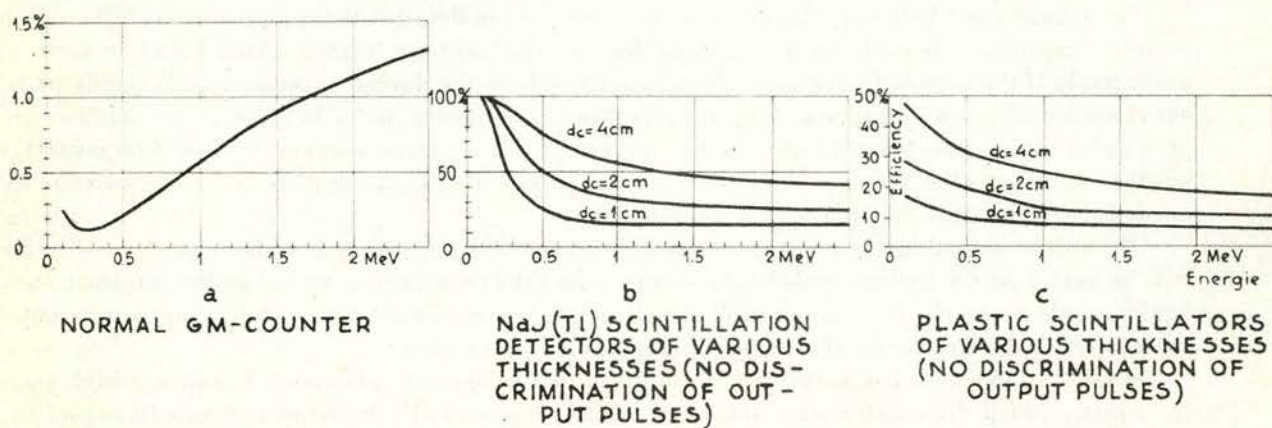


Fig.17 EFFICIENCY FOR γ -RADIATION OF SEVERAL COUNTERS

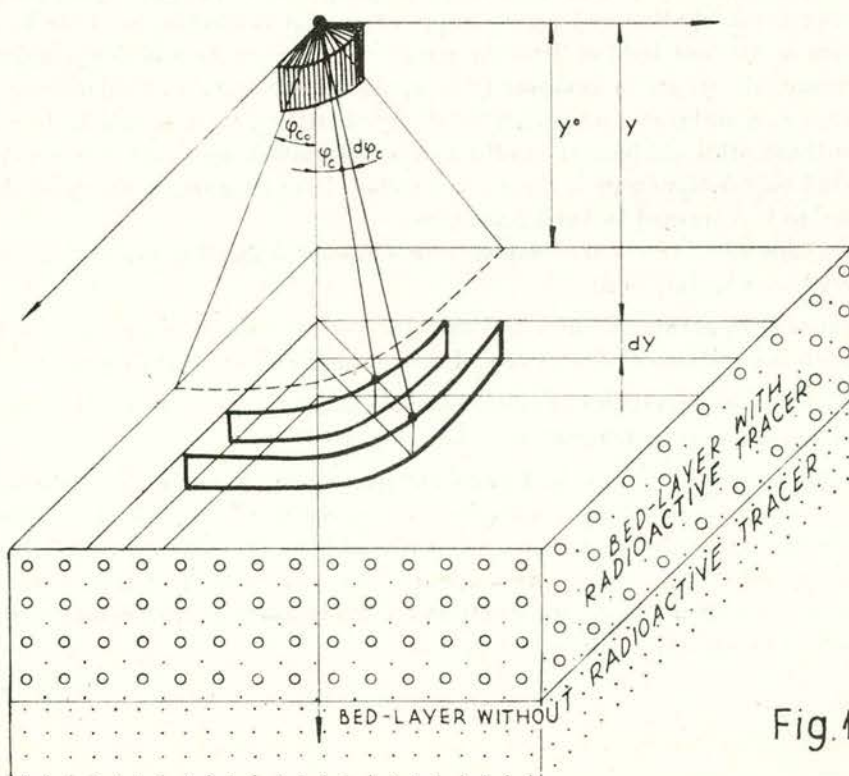


Fig.18

From the afore-going it appears that the detector besides the general requirement of reliability, must meet the following conditions:

- a. great efficiency for the hard γ -quanta emitted by the radioactive tracer (see 4.1.6.);
- b. the volume from which quanta contribute to the counting rate must be as large as possible (see 4.2.4.);
- c. in order to facilitate the determination of the most desirable places for the taking of samples, there must be supplied as much information as possible on the distribution of the activity in a vertical sense (see 4.2.7. and 4.2.8.).

In order to be able to compare the various equipments with each other, one radio isotope, viz. Sc^{46} , will be started from. Sc^{46} has a half-life of 85 days, and per desintegration there are two γ 's, of 0.89 MeV (100%) and 1.12 MeV (100%) respectively; for the rest this radio isotope also meets the requirements stated in 4.1.6. - 4.1.10. reasonably well.

4.2.2. The hard γ -radiation can be measured by means of:

- a. Geiger-Müller (GM) counters;
- b. Scintillation (sc) plastics or scintillation fluids;
- c. Scintillation (sc) crystals (NaI).

The efficiency of GM-counters for 1 MeV γ -radiation is between 0.5 and 2%. The efficiency of NaI-crystals and sc-plastics depends on their thickness, but is much greater. Figure 17.

An advantage of the GM-counter is that it is a simple instrument. Due to the very low efficiency for γ -radiation the use of GM-counters, especially for scanning of the bottom, is not very attractive. Moreover, it is not possible to discriminate the impulses by means of these counters.

The advantage of sc-plastics and fluids is that elements of large dimensions can be manufactured. Sc-crystals of NaI with a diameter of 12.5 cm and a height of 10 cm exist, but these dimensions are about the maximum. On the other hand, with the normal sc-plastics and fluids it is not possible to discriminate between the 0.89 MeV and the 1.12 MeV γ -radiation, whereas this can be realised without any objection for NaI crystals (see also 4.2.7.). In order to make the discrimination also possible for sc-plastics and fluids, they would have to be loaded with e.g. Pb-atoms. At the moment there are, however, few data known about these loaded scintillators.

4.2.3. As to the hydraulic aspects of the sc-counter to be used under water, it may be remarked that the detector has to be built in such a device that the distance between the bottom and the detector remains constant at a towing velocity of 0.5 - 1.0 m/sec and a current velocity of maximum 1.5 m/sec at 0.5 m above the bottom.

4.2.4. It is of importance to find out from what part of the bed a detector absorbs the main part of the totally received radiation. For this purpose the following simplified assumptions are started from. The tracer grains and the radioactivity are distributed homogeneously over a layer of a certain thickness. Figure 18. So in this layer the number of tracer grains per cm^3 is constant. We can also say that the number of desintegrations in the bed material is constant per minute, per cm^3 . The detector moves at a distance y_0 above the bottom, air being present between the detector and the bottom. Only radiation emitted by tracer grains within the cone with a half vertex angle ϕ_{c0} , can reach the detector, assuming that the material outside this cone has an infinitely large absorption capacity.

Now a tracer grain is considered which is situated at a depth y and on a line which makes an angle ϕ_c with the axis of the afore-said cone. The fraction of the radiation emitted by this grain, which passes the detector with the base A, is proportional to

$$\frac{A \times \cos^3 \phi_c}{4 \times \pi \times y^2}, \text{ i.e. if the absorption in the bed is neglected.}$$

Integration over the volume, with a thickness $y - y_0$, situated within the aforesaid cone with a half vertex angle ϕ_{c0} , shows that the

$$\text{counting rate is } \therefore \frac{A}{2} \times (y - y_0) \times (1 - \cos \phi_{c0}) \text{ ----- (8)}$$

(without absorption).

So the counting rate increases linearly with the thickness of the layer in which the tracer grains are present, the absorption being neglected.

If the absorption in the bed is taken into account the expression (8) passes into:

$$\text{counting rate is } \therefore \frac{A}{2} \times \int_{y_0}^y dy \times \int_0^{\phi_{c0}} \sin \phi_c \times e^{-0.693 \times \frac{y - y_0}{d \times \cos \phi_c}} \times d\phi_c \text{ ----- (9)}$$

(with absorption in the bed)

in which d = the half-thickness for wet sediment (for wet sand for 1 MeV γ -radiation this is about 9 cm).

In the tables III and IV the expressions (8) and (9) have been indicated as a function of the thickness of the layer with radioactive grains (expressed in the half-thickness d for the wet bed material) and of the half vertex angle ϕ_{CO} ; moreover there has been indicated the relative contribution to the total counting rate of the layers with radioactive tracer grains, situated at various depths.

TABEL III

Values of the expression (8); without absorption in the bed				
Active layer from y_0 to y	Total counting rate			
	$\phi_{CO} = 90^\circ$		$\phi_{CO} = 45^\circ$	
	Proportional to:	Percentage %	Proportional to:	Percentage %
$y_0 - y_0 + \frac{d}{2}$	$\frac{A \times d}{2}$ 0.5	25	$\frac{A \times d}{2}$ 0.147	25
$y_0 - y_0 + d$	$\frac{A \times d}{2}$ 1.0	50	$\frac{A \times d}{2}$ 0.294	50
$y_0 - y_0 + 2d$	$\frac{A \times d}{2}$ 2.0	100	$\frac{A \times d}{2}$ 0.588	100

TABEL IV

Values of the expression (9); with absorption in the bed								
Active layer from y_0 to y	Total counting rate							
	$\phi_{CO} = 90^\circ$		$\phi_{CO} = 45^\circ$		$\phi_{CO} = 30^\circ$		$\phi_{CO} = 6^\circ$	
	Prop. to:	Perc. %	Prop. to:	Perc. %	Prop. to:	Perc. %	Prop. to:	Perc. %
$y_0 - y_0 + \frac{d}{2}$	$\frac{A \times d}{2}$ 0.319	51	$\frac{A \times d}{2}$ 0.120	41	$\frac{A \times d}{2}$ 0.056	40	$\frac{A \times d}{2}$ 0.0023	39
$y_0 - y_0 + d$	$\frac{A \times d}{2}$ 0.480	77	$\frac{A \times d}{2}$ 0.200	69	$\frac{A \times d}{2}$ 0.094	68	$\frac{A \times d}{2}$ 0.0039	67
$y_0 - y_0 + 2d$	$\frac{A \times d}{2}$ 0.626	100	$\frac{A \times d}{2}$ 0.289	100	$\frac{A \times d}{2}$ 0.139	100	$\frac{A \times d}{2}$ 0.0059	100
Infinitely thick layer	$\frac{A \times d}{2}$ 0.722	115	$\frac{A \times d}{2}$ 0.361	125	$\frac{A \times d}{2}$ 0.180	130	$\frac{A \times d}{2}$ 0.0079	133

From the tables it appears that the application of a cone-shaped limitation makes the arrangement relatively more sensitive to the depth at which the radioactivity is present. However, as the said percentages for $\phi_{CO} = 45^\circ$ differ not yet too much from those for $\phi_{CO} = 6^\circ$, the counting rate profit, which is attained through the application of a large vertex angle, will be decisive and lead up to the choosing of a large vertex angle.

Furthermore it appears from the computations that, if y_0 is sufficiently large with respect to the dimensions of the surface A , the counting rate is independent of y_0 .

4.2.5.

When the detector consists of a small sc-crystal of NaI-diameter 2.5 cm, height 2.0 cm – placed 20 cm above the bottom, the surface seen by the detector at $\phi_{CO} = 45^\circ$ has a diameter of at least 40 cm. If per cm^3 of bed material, in a layer of the thickness d under the surface of the bottom, there are n_1 tracer grains, each with n_2 microCurie, the counting rate for Sc^{46} , at an efficiency η of

the crystal will be: $3.7 \times 10^4 \times 60 \times 2 \times n_1 \times n_2 \times \eta \times \frac{A \times d}{2} \times 0.200$; with $\eta = 0.35$, $A = 5 \text{ cm}^2$, and $d = 9 \text{ cm}$ this will be $7.0 \times 10^6 \times n_1 \times n_2$ counts per minute (cpm). The background of this sc-counter amounts to about 300 cpm. For a short-time measurement in one certain place the counting rate must be at least 50% more than this background, so that $7.0 \times 10^6 \times n_1 \times n_2 \geq 150$, in other words $n_1 \times n_2 \geq 2.15 \times 10^{-5} \mu \text{ C per cm}^3$ of bed material. For a volume of sand in the area under consideration, with a surface of at least $3 \times 10^6 \text{ m}^2$ (see 4.2.1.) and a thickness equalling $d = 9 \text{ cm}$, there follows from this a totally required radioactivity of about 6.1 Curie. If the activity would be distributed homogeneously over a depth of $10 \times d = 90 \text{ cm}$, 37 Curie would be required to record the same counting rate. It should be borne in mind that in the latter case the tracer grains in the upper layer which has a thickness d are responsible for about 60% of the counting rate.

To avoid the trouble caused by great statistical deviations in the number of grains which irradiate the detector from the influential upper active layer of the bed, there must be a sufficient number of tracer grains, e.g. about 100, in the volume which is viewed by the detector, i.e. $\frac{\pi \times 40^2}{4} \times 9 \text{ cm}^3$. Thus the total number of tracer grains for the surface of $3 \times 10^6 \text{ m}^2$ and a thickness of 9 cm, can be computed to be 2.4×10^9 . If we suppose grains with $D = 200 \mu$, with a weight per grain of 10^{-5} grammes, then a total amount of 2.4×10^4 grammes or 24 kilogrammes of radioactive tracer are required. With a homogeneous distribution over $10 \times d = 90 \text{ cm}$ this quantity would be about 150 kilogrammes.

For the scanning of the bottom a counting rate of 5 times the background can be assumed, i.e. the scanning is possible as long as the radioactivity has not spread further than over 0.1 part of the afore-mentioned $3 \times 10^6 \text{ m}^2$. In this case, at a 10 sec effective integration time of the counting rate meter, the number of impulses entering during these 10 sec is such that the recorder indication will not be affected too much by statistical deviations. When the detector is moved slowly over the bottom, e.g. at a rate of 1 m/sec (3.6 km/hour) the displacement during this measuring time is 10 m, that is small with respect to the diameter of at least 600 m of the said limited area. If the counting rate is higher in the early part of the measurement in an area which is closer to the point where the radioactive material is dumped, the integration time can be reduced; so at a smaller distance from that point the displacement during the measuring time also remains small with respect to that distance.

By making use of a large sc-crystal of NaI – diameter 12.5 instead of 2.5 cm, height 10 instead of 2 cm – in an arrangement analogous to the one of the small sc-crystal of NaI, the required quantity of radioactivity can be reduced by a factor of about 30, or the measurement can be made in an area with an 11000 m diameter, the activity remaining the same. In the latter case the number of tracer grains will have to be 30 times as large, i.e. at a homogeneous distribution of these tracer grains over a layer of 9 cm of bed material, a total quantity of 720 kilogrammes of tracer material would have to be placed. However, the manufacturing and handling of such quantities of radioactive material meets with objections in practice.

The afore-said factor 30 follows from the ratio of the volumes of the bed which contribute to the counting rate, of the efficiency of the detectors, and of the estimated geometrical factors for arrangements with a large crystal or a small one.

In figure 19 the geometrical factors for point sources have been indicated for some arrangements, the distance between the undersurface of the crystal and the bottom being 20 cm. The geometrical factors for point sources cannot simply be used for the comparison between these arrangements; due to the extent of the source a correction must be applied *). The thus modified geometrical factors for the sc-material mentioned are respectively 0.0009, 0.006 and 0.032.

By making use of a large sc-plastic – diameter 40 cm, height 10 cm – in an arrangement analogous to the one of the small sc-crystal of NaI, the quantity of radioactivity can be decreased by a factor of about 100 (figure 19), and the quantity of tracer grains by a factor 4, or the measurement can be made in an area with a diameter of 20.000 m, the activity remaining the same. In the latter case the number of tracer grains will have to be 25 times as large, i.e. with a homogeneous distribution of the tracer grains over a layer of 9 cm of bed material, a total quantity of 600 kilogrammes of tracer material would have to be placed. However, in practice the manufacturing and handling of such quantities of radioactive material meets with objections.

If GM-counters are used, the low efficiency of these instruments for γ -radiation can be compensated by choosing a larger effective surface of the counter. Taking the same value of $\eta \times A$, as of the small sc-crystal of NaI, i.e. 1.75 cm^2 , an active counting-tube-cross-section of 175 cm^2 is required at an

*) G. B. Cook, J. F. Duncan, H. A. Hewitt,
Geometrical efficiency of end-windows GM-counters,
Nucleonics 8, nr. 1, 1951.

efficiency of 1% for 1 MeV γ -radiation. This value of 175 cm^2 can be attained by composing a small number of large counting tubes or a large number of smaller ones. Thirty counting tubes of the Philips'-type-18503 can e.g. be mounted on a surface of $20 \times 20 \text{ cm}^2$, to which the truncated cone with half vertex angle $\phi_{\text{co}} = 45^\circ$ and a height of 20 cm can correspond. In this case the counting rate will be about twice the one which holds when the small sc-crystal is used. The required quantity of tracer grains can be about twice as small. By means of a more scattered arrangement of the GM-counters a further saving of tracer material may be obtained; for practical reasons the dimensions of the detector are limited, however.

4.2.6.

The afore-mentioned figures for the required radioactivity and the quantity of tracer grains have been computed for an experiment in which the total quantity of radioactive material of which the distribution is to be followed, is deposited in one place. One can imagine that the detector is moved in a circle around the place where the material has been deposited and that the radioactivity is recorded along the circle. From the distribution of the radioactivity along the circle, at various moments, the polar diagrams of the transport velocity are found. When the greater part of the radioactive material has passed, so that the counting rate has decreased strongly, the measuring is continued in the same manner on a circle with a larger diameter, etc.

At a given moment this diameter has become so large that the presence of radioactivity can no longer be ascertained with sufficient accuracy. Some insight into the sediment movement has then been obtained already. To follow this sediment movement further, a new equal quantity of radioactive tracer can now be placed on a point of the last explored circle. For certain reasons a particular point may be chosen for this purpose, e.g. the point where the transport velocity is greatest.

In figure 20 the principle of the repeated dumpings of radioactive tracer material has been further elaborated. The scanning takes place in the sequential order:

a	b	c	d	---	l
a'	b'	c'	d'	---	l'
a''	b''	c''	d''	---	l''

It is not necessary that the time intervals between the scanning of the various circles should be equal. In principle it is also possible that point 4 moves again to the left.

This method offers special advantages if the sediment transport is effected in a pronounced direction. If circle l has a diameter of 200 m, scanning with the said small sc-crystal of NaI is still possible, if the total activity is 3.7 Curie in a quantity of tracer grains of 15 kg, spread homogeneously over a layer of bed material having a thickness of 90 cm (see also 4.2.5.). In this manner a length of 300 m is covered by means of 2 dumpings having a total activity of 7.4 Curie; in case of one single dumping 37 Curie would be used to obtain the same effect. Another advantage is that not all the radioactive tracer material is put overboard in one dumping, but that during the experiment the dumpings can be adjusted to the sediment transport that has already been observed; this probably means a considerable saving of the radioactive tracer material. Whether the method discussed here can actually be applied in practice is i.a. dependent on the transport velocity, and on the time passing between two successive measurements dependent i.a. on the weather conditions.

4.2.7.

To obtain a picture of the distribution in vertical direction of the tracer grains, sampling is necessary. The question is to what extent the above discussed measurement of the radioactivity can help in determining the place of the sampling. In principle it is possible to make use of the difference in hardness of the γ -radiation emitted by Sc^{46} - 0.89 and 1.12 MeV -, to obtain information regarding the depth where the radioactive tracer material is situated. It is namely possible to measure the two γ 's separately by applying a channel discriminator. For a superficially thick layer of bed material in which the radioactivity is distributed homogeneously, the ratio between these two measurements is $r = d^s/d''$; d^s and d'' are the half-thicknesses of the bed material for 0.89 and 1.12 MeV γ -radiation respectively. Figure 21. If the radioactivity is a distance y_u below the surface the ratio between the measurements r will not be d^s/d'' , but it will be influenced by the thickness of the layer without radioactive tracer material. Therefore it is possible to distinguish in this manner between low radioactivity at the surface and high radioactivity deep below the surface and vice versa; for the sampling this distinction is of great value.

4.2.8.

The distribution of the tracer grains in a vertical sense can be determined more accurately by means of investigations on unstirred samples.

An apparatus for taking unstirred bottom samples below the groundwater-table has been developed by the Soil Mechanics Laboratory, Delft *); the Mineral Technological Institute, Delft, has developed this instrument further for sampling in deep open waters.

*) R. v. d. Beld,
Method of sampling sandy layers below the groundwater-table.
Proc. 3rd Int. Conf. Soil Mech. and Found. Eng., Zürich, 1953.

With the latter apparatus bottom samples have been taken in the Haringvliet at a depth of 14 metres (figure 22); the greatest length of such a sample was 2.0 metres so far. The samples are contained in plastic tubes which may be investigated with the help of a detector in such a way that a distribution curve for the activity in vertical sense can be recorded directly.

Due to the relatively small content of the sampling tubes and the requirement of keeping the statistical deviations of the recorded quantities sufficiently low, the area which can be investigated by the sampling method is smaller than the area which can be investigated by measurements with the sc-counter over the bottom. By the sampling method, however, for this limited area valuable data can be obtained with respect to the relations between the ripples and bars and the sediment transport, and also with respect to the absorption of the activity in the bottom; to some extent these data may be extrapolated to a greater area.

4.2.9. The equipment for placing the radioactive tracer on the bottom of a water, used by Shizuo Inose and Naofumi Shiraishi *), has especially interesting features. In the light of quantitative measurements of sediment transport, the question whether the tracer material may be placed on the bottom, or must be placed in the bottom in order to avoid boundary disturbances, needs further study.

4.2.10 The following conclusions may be drawn from the above:

- a. the use of a sc-crystal with discriminator, is advisable for measurements in the neighbourhood of the dumping place;
- b. for measurements at a great distance from the dumping place the use of sc-plastics or fluids has advantages;
- c. the method of scanning along circles around the dumping place, combined with repeated dumpings, reduces the amount of radioactivity and of tracer material needed in case of sediment transport in a pronounced direction;
- d. the taking of bottom samples in deep open waters can be effected with the equipment which has already been developed for this purpose.

*) Shizuo Inose, Naofumi Shiraishi,
Measurements of littoral drift by radio-isotopes,
Nat. Hokkaido Developm. Bur., Japan, 1956.

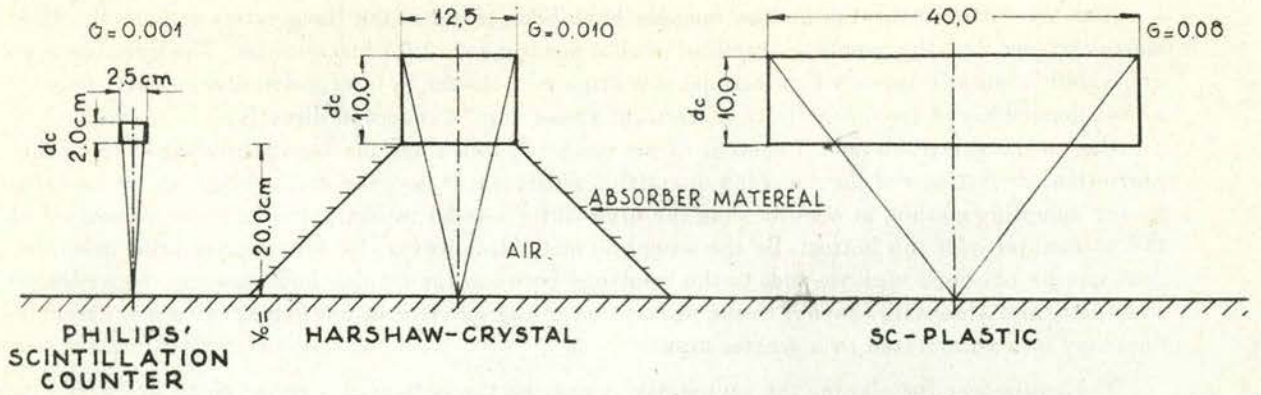
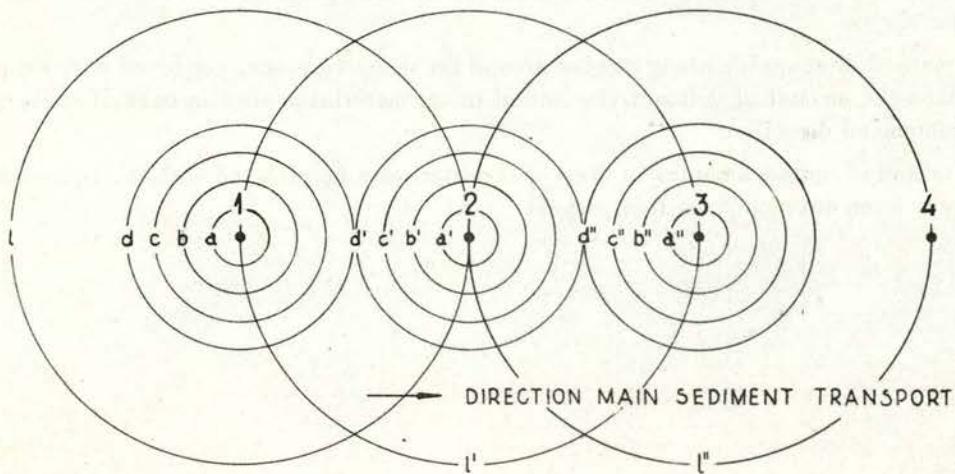


Fig. 19
 GEOMETRICAL FACTORS G FOR POINT SOURCES
 AND SEVERAL
 SCINTILLATION MATERIALS



PRINCIPLE OF MEASUREMENT WITH REPEATED DEPOSITS OF RADIOACTIVE TRACER MATERIAL 1,2,3,4, etc.

Fig. 20

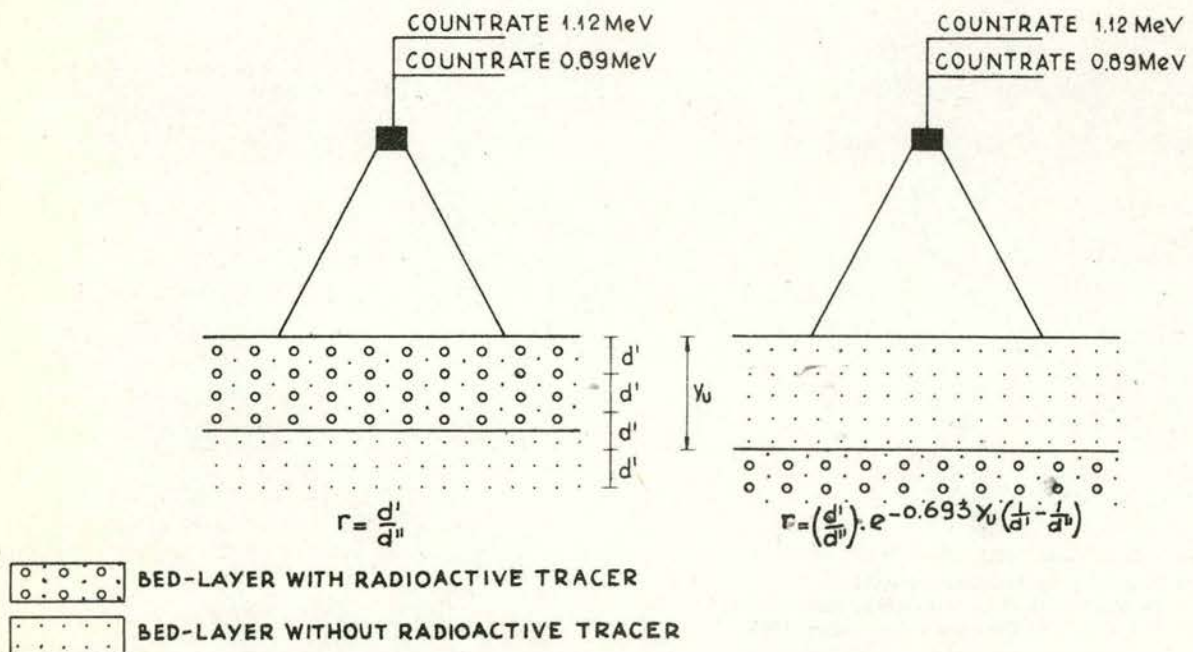
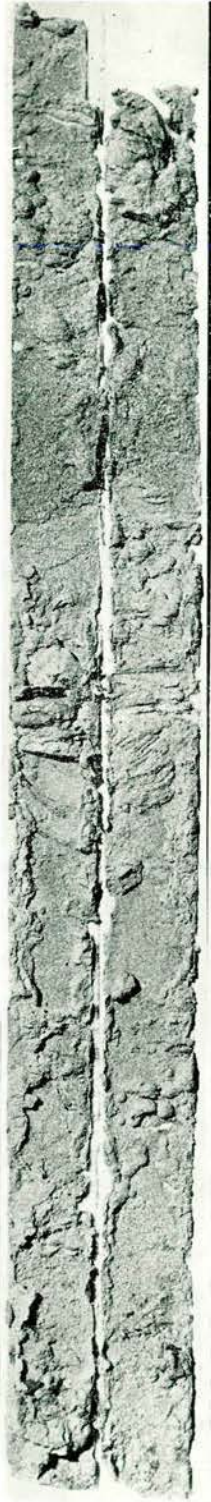


Fig. 21



TWO HALFS OF UNSTIRRED BOTTOM SAMPLE,
TAKEN IN WATER OF 14m DEEP; LENGTH OF SAMPLE 1m.

Fig. 22

NOTE LAYERS OF FINE AND COARSE SAND, THIN SILT LAYERS AND SHELL FRAGMENTS

5.0.0. PILOT-EXPERIMENT.

5.1.0. During the preliminary investigations with respect to the possibilities of measuring sediment transport by means of radioactive tracers it appeared to be desirable to make a test on a laboratory scale under absolutely controllable conditions.

The purposes of the test were:

the obtaining of experience with the two principal types of instruments for measuring radioactivity, viz. the GM-counters and the sc-counters, in order to be able to choose the right type of instrument for measurements in nature (see also 4.2.0.);

a further precision of the requirements with respect to the transport properties of the radioactive tracer material (see also 3.2.0.);

the gaining of a clearer insight into the interpretation of the figures obtained from the measurements of radioactivity (see also 5.8.0.);

the gaining of experience in handling radioactive materials, especially in view of the safety measures required.

5.2.0. After the Isotope Committee of the Royal Netherlands Academy of Sciences had been informed of the planned experiment and this committee had raised no objections to it, the Isotope Laboratory of Philips-Roxane Ltd. was requested to supply the radioactive tracer materials, to provide for the measuring equipment, and to control the safety of the relevant staff. The experiment was made in the Hydraulic Laboratory „De Voorst“.

In order to obtain reliable results it was decided to make a test arrangement which could be interpreted very simply from a hydraulic point of view. That is why the test was made in a straight flume of constant width at permanent flow conditions. This permanence involves that the water discharge and the transport of bottom material are constant at an equilibrium state of the bed. The permanence of the transport of bottom material was maintained by regularly supplying a mixture of sediment and radioactive tracer at the beginning of the bed (the so-called deposit area), in this procedure boundary disturbances could, however, not be avoided.

In the deposit area 160 l of ordinary sand were replaced for the test by sand mixed with the radioactive tracer in the volume ratio of about 1 : 1300. The further supplies (about 80 l per 4 hours) were mixed according to the same ratio.

5.3.0. During the test the following quantities were measured:

the radioactivity in the axis of the flume by means of a sc-counter, from a measuring bridge, the distribution of the radioactivity over the thickness of the bed by investigating samples of sand in a GM-counter;

the decrease of the activity of radioactive standard samples as a function of the time;

the hydraulic conditions during the test (sounding the bottom and the surface of the water from the middle of the measuring bridge, sounding transverse sections, measuring the slopes of the water surface and measuring discharges).

5.4.0. After the test was started it appeared that the supplied mixture was not carried off sufficiently from the deposit area in consequence of a very dense packing originating from the mixing. Thus the equilibrium of the bottom was disturbed, and deeper and shallower parts were formed. It appeared to be possible to determine the velocity of propagation of these irregularities by means of soundings from the measuring bridge, which proved to be a matter of importance when the results of the test were elaborated.

As it appeared to be possible to make measurements after all tracer material had been put in the flume, it was decided to continue the test, without replenishment of the deposit area and with decreasing transport of bed material.

The experiment lasted for six days in total, the test flume having flowed for about 100 hours.

5.5.0. As mentioned in the afore-going the displacement of the radioactive particles was followed from the measuring bridge by means of a sc-counter, Philips' type PW-4111; the measuring bridge could be moved in the longitudinal direction of the flume, the sc-counter being fixed in the middle of the measuring bridge. (Figures 23 and 26). The crystal of the counter had been built in a leaden diaphragm under the bridge, so that it could only "see" a surface of $30 \times 10 \text{ cm}^2$ of the bottom; the intensity of the γ -rays, originating from other parts of the bed near the surface viewed directly, was considerably decreased by the lead-screening.

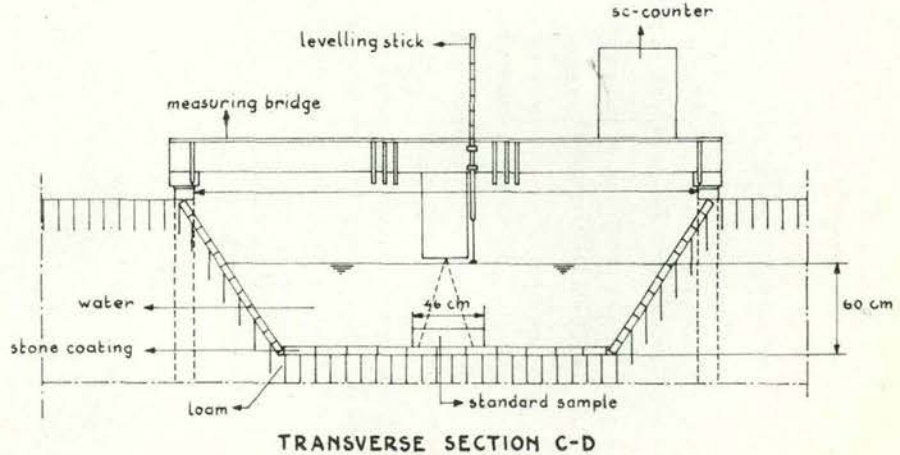
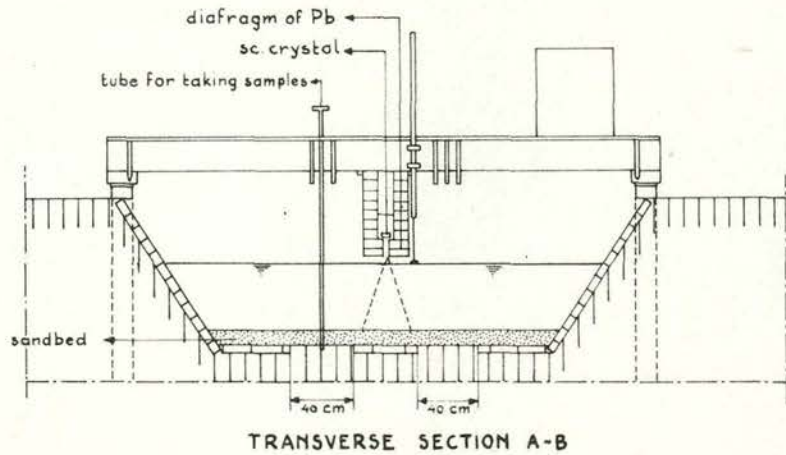
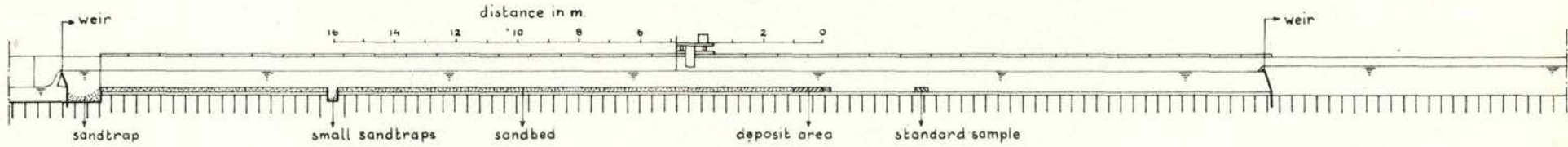
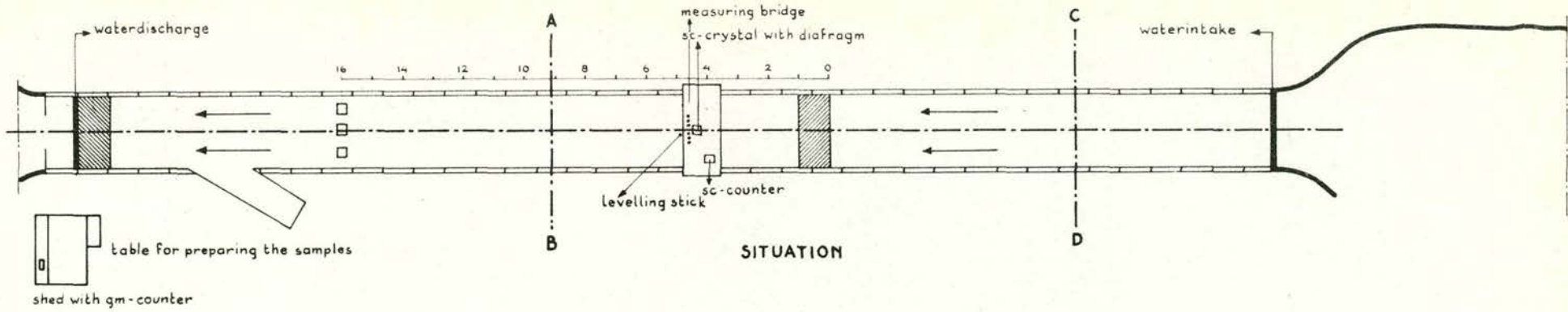
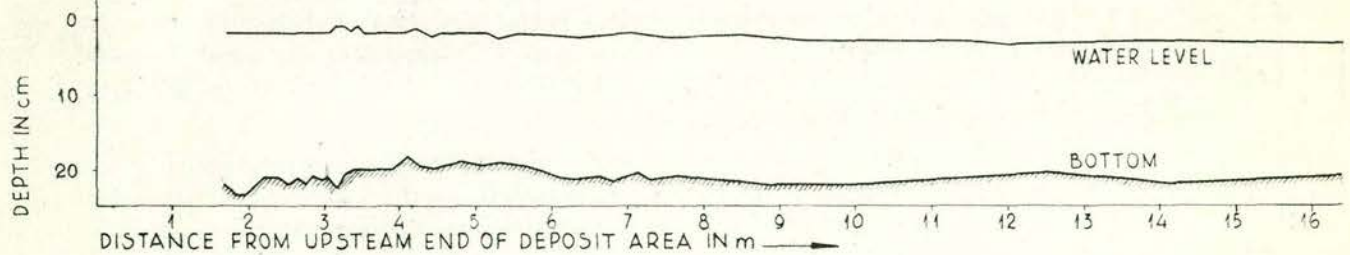
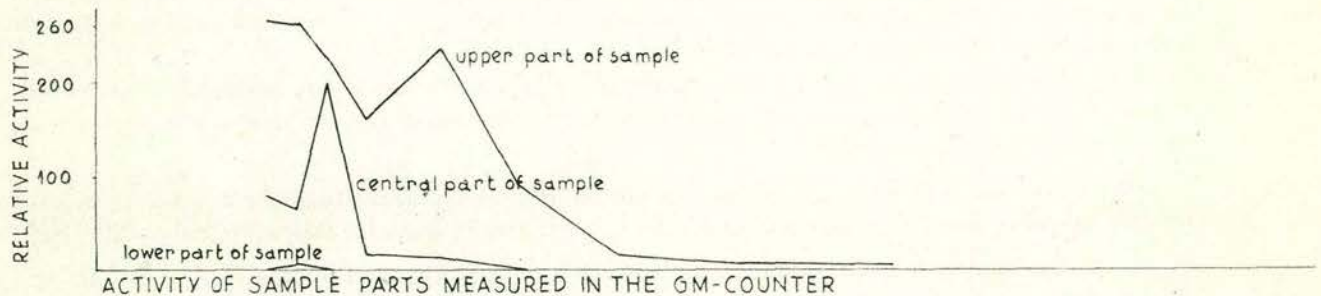
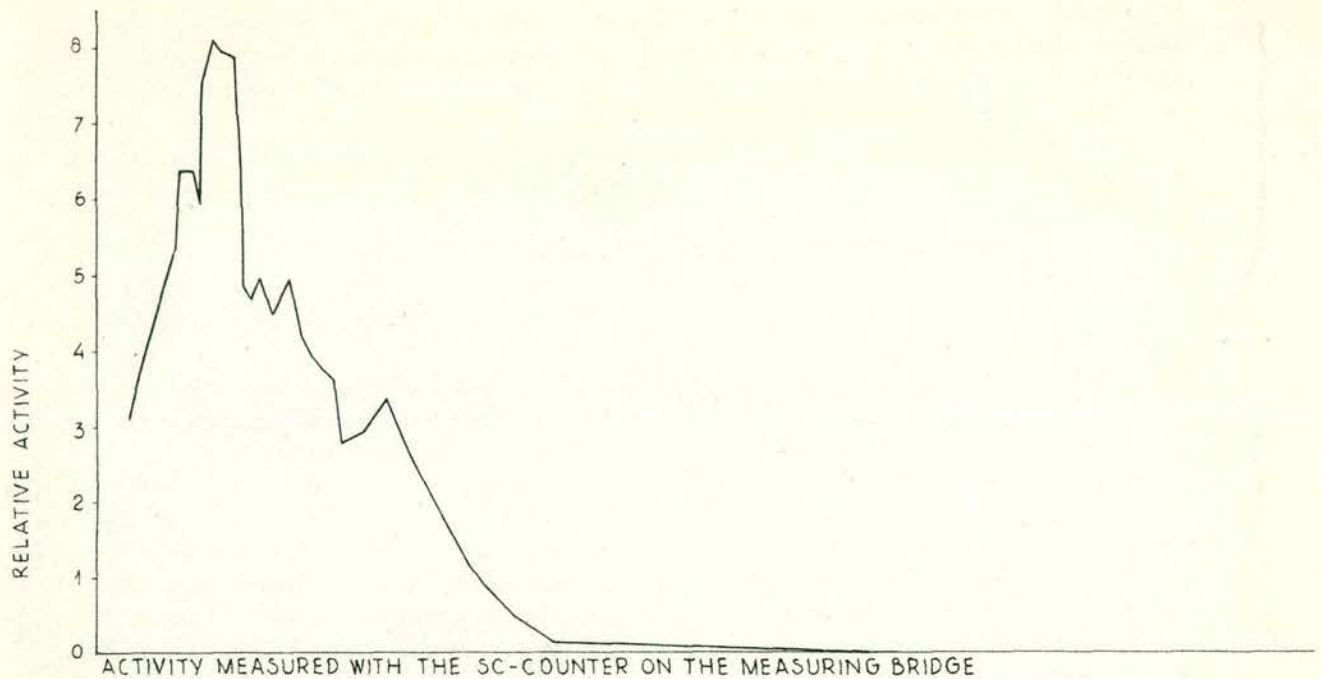


Fig.23
EXPERIMENTAL FLUME, HYDRAULIC LABORATORY "DE VOORST"



EXAMPLE OF RESULTS OF A TEST-RUN

Fig.24

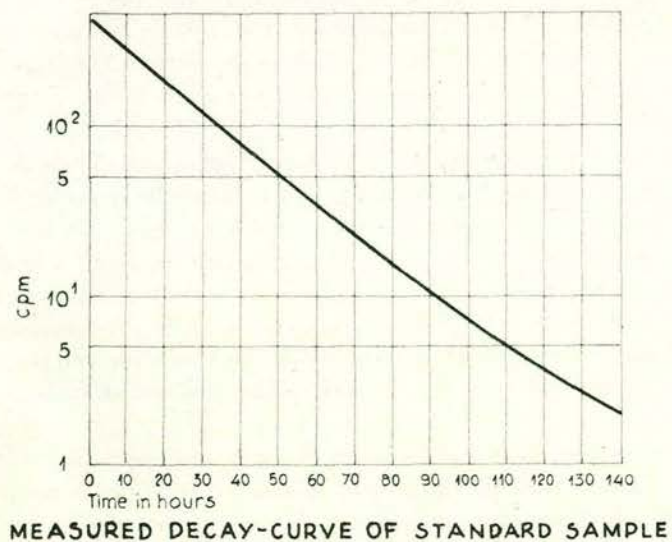


Fig.25

To check the influence of the surroundings on the measured activity, the radiation background was measured upstream of the deposit area. Already at a 1.5 m distance from the beginning of the bed the influence of the accumulation of the radioactivity in the deposit area could not be shown any more.

To calibrate the sc-meter and to measure the decay-curve of the tracer material a standard sample was placed in the upstream part of the model. The activity of the standard sample was measured regularly. (Figures 23 and 25.)

So the sc-counter recorded only impulses originating from a 30 cm wide bottom strip of which the axis practically coincided with the axis of the flume. The distribution of the radioactive particles over the other parts of the flume was determined by measuring the activity of unstirred samples of sand of the bed. (Figure 24).

For this purpose sample tubes were stuck from the measuring bridge through the bed into the loam of the original bottom so that the lower part of the tubes was closed by a 1 cm lump of loam. On the spot where the sample was taken the stone-coating of the flume had been removed already before the test was started. (Figure 23). The material caught was pressed from the sample tubes and divided into three parts; from these parts equal quantities were ultimately removed into test tubes. The activity of this material was measured in a liquid-counter, a Philips design of the GM-counter.

As the upper, the middle, and the lower part of each sample was investigated as to activity, it was possible to ascertain the distribution of the radioactive particles in a vertical sense. (Fig. 24).

It has become apparent that the sc-counter, e.g. of the normal Philips design, is extremely suitable for sand transport measurements on a laboratory scale. In the early part of the test the smallest quantities of radioactivity measured corresponded with 2×10^{-3} l of labelled sand or with about 100 particles of radioactive material per 1 l of bed sand.

It has become apparent that the GM-counter of the type used is not very suitable for measuring the radioactivity of the samples; the required initial preparation of the samples was too complicated and gave rise to inaccuracies.

5.6.0.

Of the several methods for producing radioactive tracers the irradiating of glass pearls in a reactor has been chosen for this test (see also 4.1.2.). The reasons for this were:

the test corresponds to the measurements of silt and sand transport by means of radioactive tracers made in other countries;

it was possible to dispose immediately of glass pearls of a suitable chemical constitution, which, after having been irradiated in a nuclear reactor, derive their radioactivity mainly from Na^{24} . The isotope of Na has a half-life of 14.2 hours and emits very hard γ -rays (1.38 and 2.76 MeV), which have a very great penetrating power;

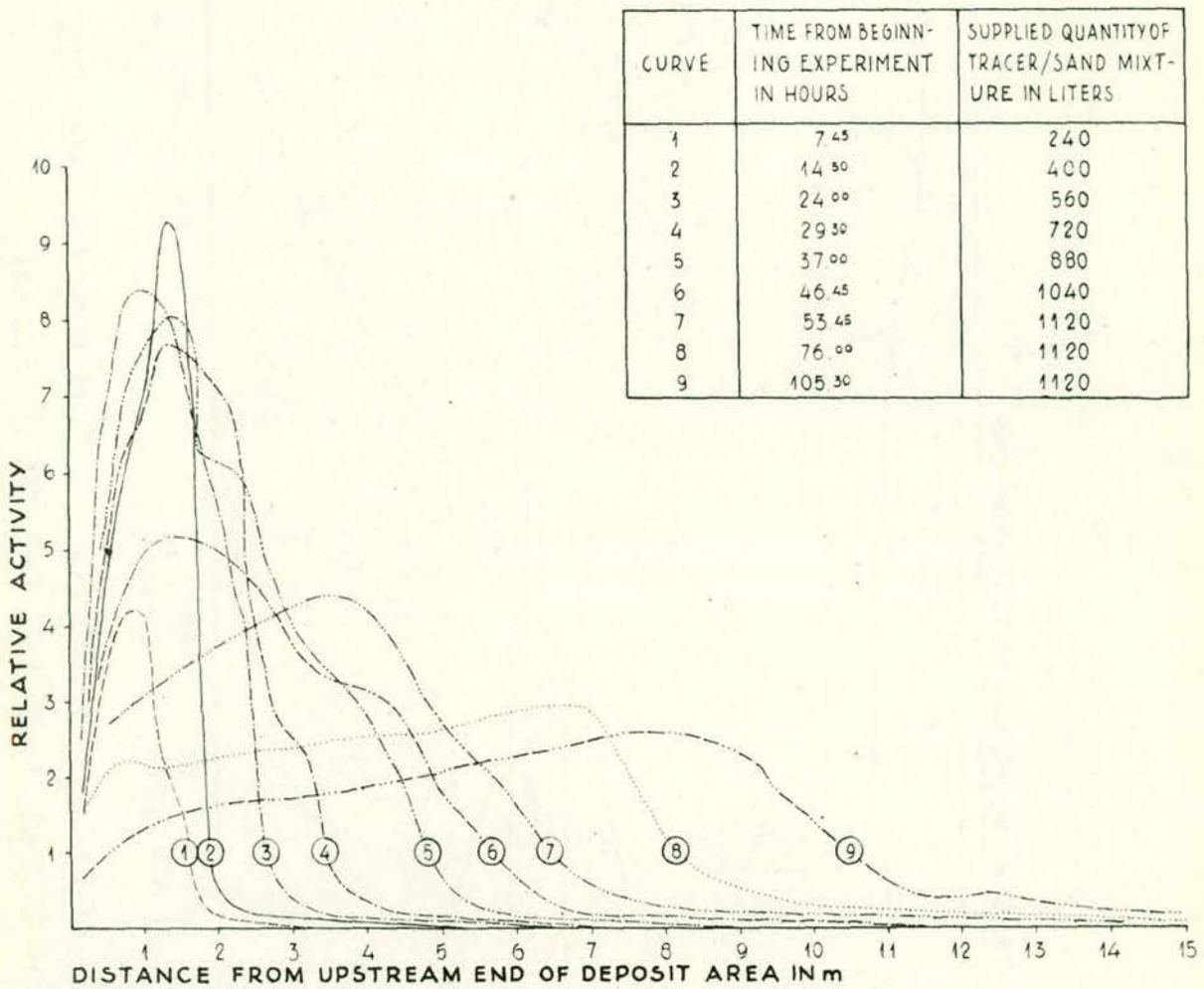
the investigation with respect to the unsableness of greensand had not progressed far enough for such a test; the other methods of producing radioactive tracers were not recommendable either, because of the time required for the preparations and the inherent cost.

For these reasons material was used which did not sufficiently meet the requirements with respect to the transport properties.

The glass pearls were rather big and the quantity available was insufficient for the composition of a large quantity with the right particle-size distribution. The lower limit of D_{50} , which could be attained by the recombination of the sifted fractions, was 270 μ . The sand used in the test had a $D_{50} = 160 \mu$. Moreover the specific weight of the glass pearls was high (2.95) with respect to the specific weight of the sand used in the test (2.65). It should be borne in mind that the sand transport caused by currents is i.a. a function of the quantity $\frac{\rho_s - \rho_f}{\rho_f} \times D_{50}$ (in which ρ_s = the density of the sediment and ρ_f = the density of the liquid); the ratio of the values of this factor for the glass pearls and the sand respectively, was not less than 2.1. So it was to be expected that the glass pearls would be transported considerably slower than the sand grains.

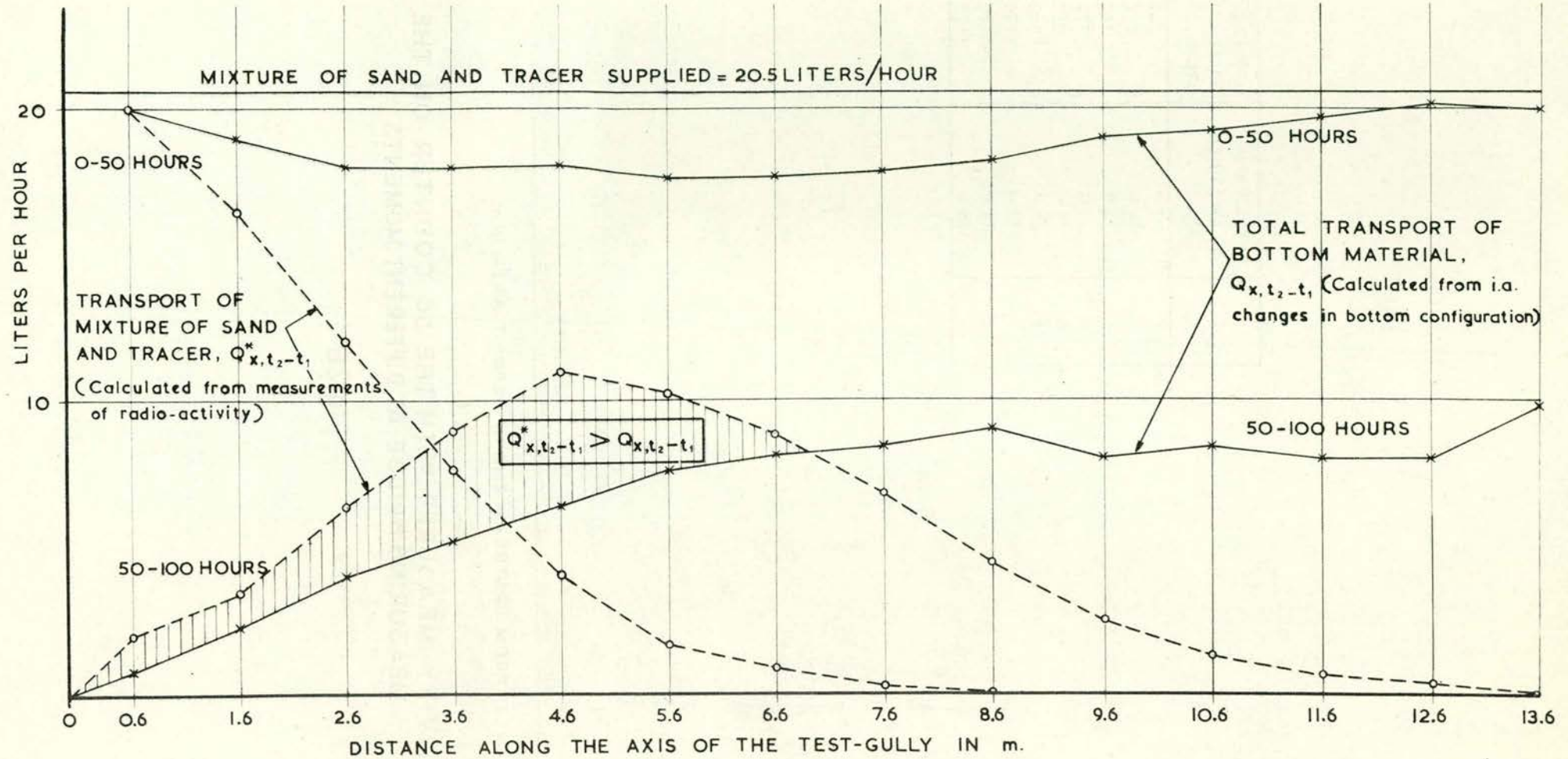
The glass pearls, which had been put into 15 aluminium boxes, each containing 128 grammes, were irradiated in the nuclear reactor at Kjeller, Norway; after the radiation a total activity of about 20 Curie was measured. To screen off this very high activity during transport, 700 kilogrammes of lead were used; the transport was done by lorry. When the boxes arrived in the hydraulic laboratory at „De Voorst”, an activity of about 100 milliCurie was measured at each of them; so in all about 1.5 Curie.

The boxes were opened by means of very simple tools and emptied in a concrete mixer on measured quantities of sand. After the glass pearls and the sand had been mixed long enough to justify the supposition of a homogeneous mixture, the latter was transported to the test flume and put into the deposit area.



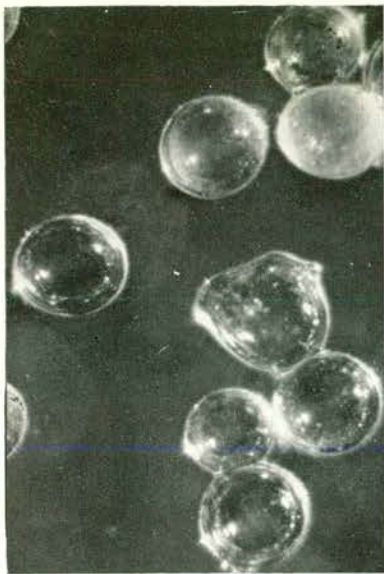
ACTIVITY MEASURED WITH THE SC-COUNTER ON THE MEASURING BRIDGE, AT DIFFERENT MOMENTS

Fig.26



AVERAGE TRANSPORT OF BOTTOM MATERIAL AS A FUNCTION OF THE DISTANCE
ALONG THE AXIS OF THE TEST FLUME

Fig. 27



a
RADIOACTIVE GLASS PEARLS



b
GLASS PEARL IN THE MIDST
OF SAND GRAINS



c
GRAINS IONAC C 50



d
DETECTOR ABOVE STANDARD SAMPLE



e
DUMPING THE MIXTURE OF TRACER AND SAND
IN THE DEPOSIT AREA



f
CONTROL LEVEL OF RADIOACTIVITY
BY MEANS OF HANDMONITOR



g
LEVELLING OF WATERSURFACE
AND BOTTOM



h
SAMPLING BED CORES

Fig. 28
MEASUREMENT OF SEDIMENT TRANSPORT BY MEANS OF RADIOACTIVE
TRACERS IN TEST FLUME, HYDRAULIC LABORATORY "DE VOORST"

5.7.0. In connection with the test many safety measures were taken. Before the experiment was started all the persons concerned were informed by the leader of the Philips-Roxane Ltd. team on the dangerous aspects and on the precautionary measures to be taken. Furthermore their safety was constantly checked throughout the test. This control consisted of:

5.7.1. Control of the level of radioactivity by means of a hand-monitor. After the test had been started the level of radioactivity was measured for all operations. Then for each of these operations the time limit, which was not to be exceeded by the relevant people, was fixed. As the activity in the deposit area increased with each quantity of sand with the radioactive tracer that was added, the level had to be checked regularly. In other places the activity decreased in consequence of the natural decay, so that there one measurement in the early stage of the test was sufficient.

5.7.2. Dose control by means of pocket dosimeters. The pocket dosimeters record at any time the total amount of radiation absorbed by the bearer. This check was made on persons charged with work in areas with high activity.

5.7.3. Dose control by means of photometric blackening meters, which was exercised on all persons co-operating in the experiment. After the test had been finished, this check showed what radiation dose was received by the bearer of the control film during the test. It has appeared that the largest dose received by one person during the test amounted to 160 milliröntgen. This was the case with those who were present at the test for three days, and 8 hours a day. The admissible dose is 100 milliröntgen a day, or 300 milliröntgen a week.

The entrances to the area where the measurements were made, had been marked by warning notices, and admittance was refused to people not concerned with the test.

5.8.0. With regard to the results of the test the following can be remarked. The measurements of the radioactivity of the bottom samples did not make it possible to draw conclusions about the absorption of the radioactive radiation in the bottom. The distribution of the glass pearls over the thickness of the bed was very irregular, and for a statistical elaboration of the data the number of samples taken was insufficient.

The extent to which the glass pearls stay behind with respect to the actual bed material (see also 5.6.0.) can be determined by comparing the results of the bottom soundings with the activity measurements in the axis of the test flume, as will be shown below.

The total sand transport $Q_x, t_2 - t_1$ in the period $t_2 - t_1$, in a cross section at x in the test flume, is:

$$Q_{o,t_2-t_1} = \frac{\sum_x (y_{b,x,t_2} - y_{b,x,t_1}) \times \Delta x}{t_2 - t_1} \quad \text{----- (10)}$$

In this formula is:

Q_{o,t_2-t_1} = the transport supplied at the beginning of the flume, in the period $t_2 - t_1$;

$y_{b,x,t}$ = the height of the bottom at x , at time t , above an assumed zero level.

In figure 27 the function Q_{x,t_2-t_1} is drawn for $t_2 = 50$ hours, $t_1 = 0$ hours and for $t_2 = 100$ hours, $t_1 = 50$ hours.

In the first period of 0-50 hours the transport at $x = 0$ is equal to the transport at $x = 13.6$ m, i.e. there is equilibrium at the boundaries. Within this area the maximum local deviations of the transport of Q_{o,t_2-t_1} are about 6%. In the second period of 50-100 hours no more sand was supplied at $x = 0$, but there was transport in the places $x \neq 0$, so that scouring occurred. At the end of the bed Q_{x,t_2-t_1} then approaches the value of 10 litres per hour; this value, which is low as compared with the relative value in the first period, is caused by the hydraulic conditions which meanwhile have changed.

The relative activity $a_{x,t} \times \Delta x$ of the part Δx of the bed in the flume, i.e. the measured activity, divided by the value of the activity of the standard sample, is proportional to the number of glass pearls present at x within the length Δx of the bed, a homogeneous vertical distribution of the glass pearls being assumed. If it is also assumed that the glass pearls have the same transport properties as the actual bed material, $a_{x,t} \times \Delta x$ is also proportional to the number of grains of sand that, mixed with the glass pearls, is added at $x = 0$ to the flume, so that:

$$Q_{x,t_2-t_1}^* = Q_{o,t_2-t_1}^* - \frac{C_t^* \times \sum_x (a_{x,t_2} - a_{x,t_1}) \times \Delta x}{t_2 - t_1} \quad \text{----- (11)}$$

In this formula is:

$Q_{x,t_2-t_1}^*$ = the transport of the added mixture of sand and radioactive tracer in the period t_2-t_1 in a cross section at x ;

$Q_{0,t_2-t_1}^*$ = the transport supplied at the beginning of the flume in the period t_2-t_1 ;

C_t^* = a constant that can be derived from:

$$C_t^* \times \sum_0^{\text{flume}} a_{x,t_2-t_0} \times \Delta x = Q_{0,t_2-t_1}^* \times (t_2 - t_0) \text{ ----- (12)}$$

The boundary condition for the test was:

$$Q_{0,t}^* = Q_{0,t} \text{ ----- (13)}$$

In figure 27 is drawn the function $Q_{x,t_2-t_1}^*$ for $t_2 = 50$ hours, $t_1 = 0$ hours and for $t_2 = 100$ hours, $t_1 = 50$ hours.

Based on the probability of the movement, $Q_{x,t_2-t_1}^* \leq Q_{x,t_2-t_1}$ may hold, but not $Q_{x,t_2-t_1}^* > Q_{x,t_2-t_1}$, if it is assumed that the glass pearls and the actual bed material have the same transport properties. As it has appeared that in the second period of 50-100 hours the said inequality has nevertheless occurred (see figure 27) the only possible conclusion is that in the first period of 0-50 hours the glass pearls have been left behind with respect to the grains of sand of the actual bed.

A closer examination of the average velocities of propagation of the glass pearls and of the actual bed material has shown that for the glass pearls this velocity was on an average 0.09 m/sec, whereas for the bed sand it was at least 0.16 m/sec. The latter velocity is the average velocity of propagation of the irregularities of the bed (see also 5.4.0.); the assumption was made that the individual sand grains moved with the same velocity or faster than these irregularities.

Figure 29 shows some pictures of the experimental procedure.

5.9.0.

The conclusions drawn from the test are:

the sediment transport caused by currents can be measured qualitatively and quantitatively by means of radioactive tracers;

the sc-counter is more satisfactory for measurements of the sediment transport than the GM-counter;

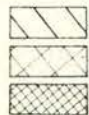
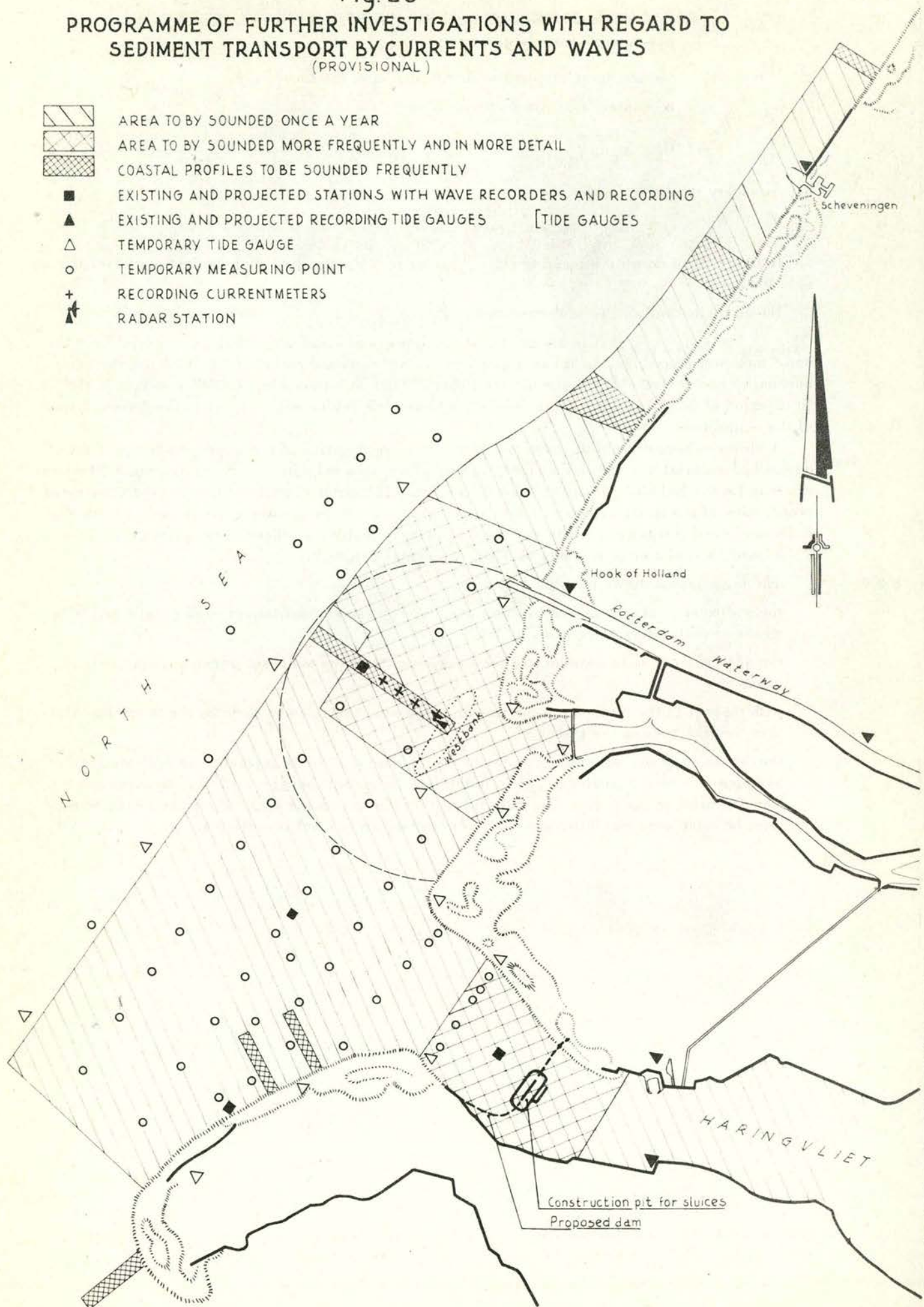
with respect to the transport properties higher demands have to be made on the tracer material than was the case in the test;

the operation of the measuring equipment can be entrusted to for instance the ordinary staff of hydrographic survey parties. Experts in the field of nuclear physics will have to supervise the manufacturing of the radioactive material and its placing on the spots where the measurements must be made very carefully; after which a brief safety control is sufficient.

*
* *

Fig. 29

PROGRAMME OF FURTHER INVESTIGATIONS WITH REGARD TO
SEDIMENT TRANSPORT BY CURRENTS AND WAVES
(PROVISIONAL)



- AREA TO BE SOUNDED ONCE A YEAR
- AREA TO BE SOUNDED MORE FREQUENTLY AND IN MORE DETAIL
- COASTAL PROFILES TO BE SOUNDED FREQUENTLY



- EXISTING AND PROJECTED STATIONS WITH WAVE RECORDERS AND RECORDING
- EXISTING AND PROJECTED RECORDING TIDE GAUGES [TIDE GAUGES
- TEMPORARY TIDE GAUGE
- TEMPORARY MEASURING POINT
- RECORDING CURRENTMETERS
- RADAR STATION

6.0.0. PROGRAMME OF FURTHER INVESTIGATIONS WITH REGARD TO SEDIMENT TRANSPORT BY CURRENTS AND WAVES, IN THE NETHERLANDS.

6.1.0. As is apparent from chapter 2.0.0. comparatively little is known regarding the sediment transport in the Netherlands coastal waters. Very little is known, too, of the factors which to a large degree determine this sediment transport, viz. the wave movement, and of all kinds of details of the current picture — details which nevertheless greatly influence the sediment transport. As has already been shown in the introduction of this paper, it is very desirable that the data regarding the sediment movement in the coastal waters should be supplemented soon, not only with respect to the present situation, but also with respect to the situation after the Deltaplan has been executed.

In what follows a broad outline will be given of the manner in which this problem will shortly be dealt with in this country. The coastal area comprising the mouths of the Haringvliet and the Rotterdam Waterway has been chosen as an example; this area will be the first part of the coastal region to be affected by the Deltaplan.

6.2.0. Since 1950 the whole area has been sounded once a year, in order to make it possible to follow the changes in the depth relations; it is intended to continue these soundings as much as possible with the same frequency. (Figure 29.)

6.3.0. As in the area concerned the differences in the current picture at various places are large, a dense network of measuring points is required to obtain complete data; for the time being about 60 measuring points are considered to be sufficient; the measurements will be made during a complete tidal period and will include current velocities, current directions, salinity, and possibly temperature and silt concentration, each time at several points and in a vertical sense. Figure 29. In view of the variations occurring from day to day in the tidal current, the wind drift, the current caused by density differences, the salinity, the temperature, the silt concentration, etc. as many points as possible have to be measured simultaneously. Then the various groups of simultaneous observations can be interrelated by means of the measurements at the so-called reference points; in this way data are obtained about the variations in the observed quantities which can appear in the course of time at these reference points.

Especially for the reference points recording instruments which can work independently for a long time are being considered; at the moment various types of recording instruments are in a developmental stage. Moreover, tests are being made to investigate the usability of an 8 mm radar equipment for the effectuation of current measurements with floats. Probably it will shortly be possible to determine the position of the survey boats by means of a special radiographic position-indicating survey system.

6.4.0. In order to get a better knowledge of the vertical tide it will be necessary to extend the number of recording gauge stations. Experiments are already being made with certain types of the apparatus required; for the stations situated at a larger distance from the coast, recording instruments which can work independently for a long time are required, while after some time it will probably be possible to transmit the data by radio to the shore.

During the current measurements mentioned in 6.3.0. it will be necessary to record the vertical tide even more in detail by means of a number of temporary extra observation posts along the coast; on sea recording pressure meters will be used for this purpose. Figure 29.

6.5.0. Data about the wave movement in the relevant area can be obtained through fixed measuring stations provided with recording instruments; the number of these stations in the coastal region will be extended shortly. Figure 29. These stations supply data concerning the height and the period of the waves; data about the wave pattern will be collected by means of aerial photographs, and with the aid of the radar equipment mentioned (see also 6.9.0.) and of model tests. A hydraulic model on a large scale, by means of which the wave movement in the mouth of the Haringvliet is studied, is at present in the Hydraulic Laboratory at Delft; preparations are being made for the construction of a larger model which also comprises the mouth of the Rotterdam Waterway.

Since 1953 the number of types of wave recorders has been extended considerably. Besides the several instruments requiring a cable connection with the shore, the so-called wave-amplitude recorder is an important instrument *); at the moment experiments are being made with a wave recorder which transmits the relevant data by radio to the shore. In the near future it will be possible to provide the lightvessel "Goeree", which lies at a 15 km distance from the coast, with a floating wave-meter, which is being developed by the Royal Netherlands Meteorological Institute.

*) H. A. Ferguson, P. J. Wemelsfelder, P. Santema,
Paper,
XIXth Intern. Nav. Congres, section II, comm. 3, 1957.

6.6.0. In order to get a detailed picture of the composition of the bottom a large number of bottom samples will be taken throughout the area. These samples will be investigated, i.a. with respect to the grain size, and partly as to their mineralogical composition. This procedure can be repeated in order to get an idea of the variations during a certain period.

A semi-automatic sedimentation balance by means of which grain size distribution diagrams can be quickly determined, is developed further; this is also the case with the apparatus required to take under water unstirred samples of sand over a length of several metres.

The knowledge of the geological structure of the coastal region can be increased by making borings. The material to make borings off shore is available.

6.7.0. By comparing the soundings made at different moments something can be learned about the consequences of the sediment movement in the coastal region. However, a clearer insight into the magnitude and the direction of the sediment transport, as a function of the factors which are of influence on it, can be gained only through measurements of the sediment transport made by means of radioactive tracers.

If necessary, these measurements made in nature can be supplemented by tests made on a model; in this connection the remarks made in chapter 2.0.0. with respect to model tests may be referred to.

6.8.0. In order to be able to study the development of coastal profiles under the influence of currents and waves, a number of coastal sections are levelled and sounded in detail and rather frequently, i.e. over a width of about 500 m and from the foot of the dunes as far as the depth contour of 10 m below mean sealevel. Moreover, bottom samples are taken in a number of sight lines, which samples are investigated as to grain size distribution and partly as to mineralogical structure. It is intended to make these surveys about 12 times a year in order to be able to study the variations in the course of time. The relevant sections are situated both on the unprotected coast and on the coast which is protected by groynes, and where the coastline is shifting seaward, landward, and where it shows an equilibrium state. At the moment this programme already covers 3 sections, and it will be extended in the near future. Figure 29.

Besides the coastal profiles, the coast in plan will be studied. For this purpose use will be made of the beach surveys which were already started in the 19th century and of old historical charts and writings. The forms of the coast will be studied in detail by means of aerial photographs, which are available in large numbers, while even more photographs will be taken in the future.

6.9.0. More extensive measurements will be started in one of the afore-said sections in order to be able to study the relation between the currents and waves on the one hand and the sediment movement on the spot on the other hand. For this purpose a fixed measuring station with recording instruments for measuring the wave height and the wave period can be established at some distance from the coast. A picture of the wave pattern can be obtained by means of an 8 mm radar apparatus. At the moment experiments are being made with such an installation, i.a. for this purpose.

The currents and the vertical tide can be measured with recording current and tide meters; the current meters will have to be arranged in such a manner that both the tidal currents and the currents caused by the waves can be determined. The sediment movement can be determined by means of radioactive tracers. Figure 29.

After all planned measurements have been made on one part of the coast, the station can be removed to another part where other conditions prevail.

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LIST OF SYMBOLS USED

A	= area of the under surface of the detector
a	= relative activity
C_c	= Chezy's coefficient of flow
C_t	= a transport constant
c	= velocity of propagation of the waves
D_{65}	= grain size of which is 65 % (by weight) finer
D_{50}	= grain size of which is 50 % (by weight) finer
d	= half-thickness of wet sand for 1 MeV γ -radiation
d'	= half-thickness of wet sand for 0.89 MeV γ -radiation
d''	= half-thickness of wet sand for 1.12 MeV γ -radiation
d_c	= thickness of sc-crystal
e	= base of natural logarithms
f(. .)	= function of quantities within the brackets
g	= acceleration due to gravity
H	= height of the waves from top to trough
h	= water depth
I_e	= slope of the energy line
I_b	= slope of the bottom
I_1	= integral value f' $\left(\frac{\Delta}{d}, \frac{w}{\sqrt{R \cdot I_e \cdot g}} \right)$
I_2	= integral value f'' $\left(\frac{\Delta}{d}, \frac{w}{\sqrt{R \cdot I_e \cdot g}} \right)$
L	= length of the waves
N	= concentration of sediment in the water
n	= number
Q	= total sediment transport per unit time
Q^*	= transport of sediment-tracer mixture per unit time
$Q//$	= littoral transport per unit time
q_{susp}	= suspended-load, per unit time, per unit width
q_{bed}	= bed-load, per unit time, per unit width
R	= hydraulic radius
T	= period of the waves
t	= time
V_1	= forward current velocity caused by the waves; average in a vertical
V_2	= velocity of the longshore current caused by the waves approaching the coast obliquely, inside the breaker zone; average in a vertical
v	= current velocity at a certain point above the bed
w	= settling velocity of the (sediment) grains in water
x	= distance in horizontal direction
y	= distance in vertical direction above datum
y_b	= distance in vertical direction of the surface of the bottom above datum
y_o	= distance between the detector and the bottom

- y_u = distance between the surface of the bottom and the surface of the layer with radioactive grains
 Δ = $f^m \left(\frac{D_{65}}{\delta}, \frac{D_{65}}{d} \right)$
 δ = thickness of the boundary layer
 η = efficiency of the counter
 ϕ_c = half vertex angle of a cone, the axis of which coincides with the axis of the detector
 ϕ_{co} = half vertex angle of a cone, the axis of which coincides with the axis of the detector, indicating the maximum view of the detector
 ϕ_w = angle between the direction of the wave crests and the straight coastline
 ρ_s = density of the sediment
 ρ_f = density of the water

INDICES.

- 0 = quantities in deep water
 b = quantities in the breaker zone.

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APPENDIX A.

TABEL I. RADIOACTIVE ISOTOPES EMITTING γ -RAYS WITH AN ENERGY OF MORE THAN 0.32 MeV AND A HALF-LIFE BETWEEN 5 AND 365 DAYS.

Element	Atomic weight	Energy (MeV)	%	Half-life (days)	Availability
Au	196	0.33 0.36 0.43	59 95 5	5.6	only in small quantities cyclotron produced
I	131	0.28 0.36 0.64 0.72 0.16	9* 80* 8* 2* 1*	8	big quantities pile produced by (n, γ) reaction on Te or fission product
Ag	106	0.51 0.72 1.04 1.54 and others) 17) all less) than) 5%	8.6	small quantities cyclotron produced
Nb	92	0.93 1.83	96.5 3.5	10	small quantities cyclotron produced
Nd	147	0.09 0.58	66* 32*	11 40	big quantities fission product
Ba	140	0.16 0.31 0.54	together 40	13	big quantities fission product
Cs	136	0.9 1.2 ?		13	not available
I	126	0.39 0.67	100** 100**	13.3	small quantities cyclotron produced
Eu	156	25 different γ -s of 0-2 MeV		14	not available
As	74	0.596 0.635	63 16	17.5	small quantities cyclotron produced
Rb	86	1.08	10	19	big quantities pile produced by (n, γ)
Cr	51	0.32	10	28	big quantities, pile produced by (n, γ) reaction
Nb	95	0.23 0.75	100 100	35	big quantities fission product
Ru	103	0.50	90-99	42	big quantities fission product
Cd	115 m	0.485 0.935 1.30	10** 74** 31**	43	moderate quantities pile produced by (n, γ) reaction
Fe	59	1.10 1.29	54+ 46	45	moderate quantities pile produced by (n, γ) reaction
Hf	181	0.133 0.136 0.345 0.482 0.615	7** 1** 2.3** 14**	46	big quantities pile produced by (n, γ) reaction
Sb	124	0.600 1.700 and others	100 45 very small	54	big quantities, pile produced by (n, γ) reaction
Zr	95	0.235 0.722 0.754	3 43 54	65	moderate quantities pile produced by (n, γ) reaction big quantities as fission product
Ir	192	many of 0.137-0.615		70	big quantities, pile produced by (n, γ) reaction
Co	58	0.805	100	72	small quantities pile produced by (n, p) reaction
Tb	160	0.09 0.20 0.29 0.89 0.96 1.18 1.27	12** 5** 14** 34** 34** 25** 11**	73	big quantities pile produced by (n, γ) reaction
Sc	46	0.89 1.12	100 100	85	big quantities, pile produced by (n, γ) reaction
Y	88	0.91 1.85 2.76	99 99 1	105	small quantities cyclotron produced
Ta	182	1.13 1.22 1.24 and others	100** 100** 100**	111	big quantities, pile produced by (n, γ) reaction
Se	75	many max. 0.405	14	127	moderate quantities pile produced by (n, γ) reaction
Zn	65	1.11	45.5	245	moderate quantities pile produced by (n, γ) reaction
Mn	54	0.84	100	290	small quantities cyclotron produced

N.B. 4e column 74** does not mean 74% of the desintegrations but gives only a relative value.

APPENDIX B.
TABLE II

Isotope	Body burden μC	MPC _w $\mu\text{C}/\text{cm}^3$	MPC _a $\mu\text{C}/\text{cm}^3$	MPI (0.3 rem in a week) μC	MPI (15.7 rem in a year) μC	MPI (150 rem in 70 years) μC	MPI (0.3 rem in a week) μC	MPI (15.7 rem in a year) μC	MPI (150 rem in 70 years) μC	MPI (0.3 rem in a week) μC	MPI (15.7 rem in a year) μC	MPI (150 rem in 70 years) μC	MPI (0.3 rem in a week) μC	MPI (15.7 rem in a year) μC	MPI (150 rem in 70 years) μC	MPI (stomach) μC	MPI (small intestine) μC	MPI (upper large intestine) μC	MPI (lower large intestine) μC
	1	2	3	4a	4b	4c	5a	5b	5c	6a	6b	6c	7a	7b	7c	8a	8b	8c	8d
Sc ⁴⁶	6	0.3 0.4	5×10^{-8} 7×10^{-8}	40 29	6.7×10^2 470	6300 4300	10 57	160 92	1600 880	6.3×10^{-6}	2.9×10^{-5}	2.9×10^{-4}	5.7	26	250	220	95	19	<u>9.2</u>
Cr ⁵¹	600	0.7 0.02	10^{-5} 4×10^{-6}	10^4	10^5	10^6	2.8×10^3	2.9×10^4	2.8×10^5	4.6×10^{-4}	4.4×10^{-3}	4.4×10^{-2}	670	6700	63000	14000	11000	1000	<u>500</u>
Fe ⁵⁹	13	3×10^{-3} 10^{-4}	5×10^{-7} 2×10^{-8}	14	120	1200	9.1	79	750	7.5×10^{-6}	5.1×10^{-5}	5.1×10^{-4}	9	63	600	270	150	140	<u>68</u>
Zn ⁶⁵	400	0.002 0.06	2×10^{-6} 4×10^{-7}	1500	16000	16000	450	4800	46000	6.6×10^{-5}	2.0×10^{-4}	1.9×10^{-3}	21	67	600	750	370	99	<u>49</u>
Rb ⁸⁶	64	0.003	4×10^{-7}	140	3300	32000	100	2500	24000	1.6×10^{-6}	2.0×10^{-5}	2.0×10^{-4}	11	140	1300	170	170	250	<u>130</u>
Zr ⁹⁵ +Nb ⁹⁵	10	0.4 6×10^{-4}	8×10^{-8} 10^{-7}	110	530	5300	27	140	1300	4.9×10^{-6}	2.7×10^{-5}	2.7×10^{-4}	7.3	43	400	350	220	33	<u>16</u>
Nb ⁹⁵	44	0.002	2×10^{-7} 3×10^{-7}	170	1800	17000	79	860	8200	1.9×10^{-5}	1.6×10^{-4}	1.6×10^{-3}	14	120	1200	450	240	93	<u>46</u>
I ¹³¹	0.6	6×10^{-5}	6×10^{-9}	0.70	17	170	0.52	13	120	6.3×10^{-6}	1.5×10^{-4}	1.5×10^{-3}	22	530	5000	380	<u>290</u>	700	350
Ba ¹⁴⁰ +La ¹⁴⁰	1	3×10^{-4} 5×10^{-4}	2×10^{-8} 6×10^{-8}	8.7	150	1400	2.4	41	390	1.3×10^{-6}	2.1×10^{-5}	2.1×10^{-4}	4.3	77	730	330	260	19	<u>7</u>
Ta ¹⁸²	6	0.1 5×10^{-4}	2×10^{-8} 9×10^{-8}	47	180	1700	11	46	430	5.1×10^{-6}	2.1×10^{-5}	2.1×10^{-4}	8.7	7	330	260	150	25	<u>12</u>
Ir ¹⁹²	3	5×10^{-4} 9×10^{-4} 6×10^{-3}	3×10^{-8} 5×10^{-8} 9×10^{-8}	31 47	400 250	2300	12 3.6	150 18	1500 180	4.0×10^{-6}	2.0×10^{-5}	2.0×10^{-4}	7.3	7	370	200	130	24	<u>12</u>

APPENDIX B.

TABLE II; EXPLANATION.

- Column 1*) Maximum permissible body burden in μC .
- 2*) Maximum permissible concentration in water, MPC_w , in $\mu\text{C cm}^{-3}$.
- 3*) Maximum permissible concentration in air, MPC_a , in $\mu\text{C cm}^{-3}$.
- 4 - 8**) Tables for incidental irradiations. Maximum permissible quantity of radioactivity inhaled (tables 4, 7 and 8) or absorbed via punctured wounds or injections (tables 5 and 6).
4. Inhalation of soluble radioactive matter, computed for the case that the critical organs are not the gastro intestinal tract or the lungs. The table shows the maximum permissible intake, MPI, the number of μC which is present in a volume of air inhaled in 8 hours.
- 4a. MPI gives an effect equalling the effect of 0.3 rem in 1 week.
- 4b. MPI gives an effect equalling the effect of 15.7 rem in 1 year.
- 4c. MPI gives an effect equalling the effect of 150 rem in 70 years.
5. Injections or infection of punctured wounds with soluble radioactive matter. The table gives the MPI in μC 's administered.
- 5a. MPI gives an effect equalling the effect of 0.3 rem in 1 week.
- 5b. MPI gives an effect equalling the effect of 15.7 rem in 1 year.
- 5c. MPI gives an effect equalling the effect of 150 rem in 70 years.
6. Injections or infection of punctured wounds with insoluble radioactive matter. The table gives the MPI in μC 's administered.
- 6a. MPI gives an effect equalling the effect of 0.3 rem in 1 week.
- 6b. MPI gives an effect equalling the effect of 15.7 rem in 1 year.
- 6c. MPI gives an effect equalling the effect of 150 rem in 70 years.
7. Inhalation of insoluble radioactive matter computed for the case that the lungs are the critical organs.
- 7a. MPI gives an effect equalling the effect of 0.3 rem in 1 week.
- 7b. MPI gives an effect equalling the effect of 15.7 rem in 1 year.
- 7c. MPI gives an effect equalling the effect of 150 rem in 70 years.
8. Inhalation of insoluble radioactive matter computed for the case that the gastro intestinal tract is the critical organ. The table gives the MPI, the number of μC present in a volume of air inhaled in 8 hours, which will deliver a dose of 0.3 rem during the following week to:
- 8a. the stomach
- 8b. the small intestine
- 8c. the upper large intestine
- 8d. the lower large intestine.

*) Recommendations Int. Comm. on Radiological Protection, British J. Radiol., suppl. no. 6, 1955.

**) Morgan and others, Maximum permissible concentration of radio isotopes in air and water for short period exposure. Proc. Int. Conf. Peaceful Uses At. Energy, U.N.O., V. 13, 1956.

