PREPRINT

CONTRIBUTION TO THE STUDY OF THE SALINITY DISTRIBUTION AND CIRCULATION IN THE WESTERN SCHELDT ESTUARY.

by

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This paper not be cited without reference to the author

I. INTRODUCTION

In recent years, several ecological, sedimentological and hydrological research programs have been undertaken in this economically important estuary (cfr. a. o. BASTIN, 1964; DE PAUW, 1971; PETERS, 1966; 1972; WOLLAST, 1967; WARTEL, 1972; CIPS, 1972; WOLFF, 1973).
In estuarine systems, knowledge of the salinity-distribution as one of the most important properties characterizing the water masses is a primary necessity for a good understanding and interpretation of the other often related phenomenous : self purification mechanisms, sediment transport, dispersion of plankton organisms, mixing processes, etc.
The scope of this publication is to supply additional basic information on the salinity distribution in the Scheldt estuary which could be used for further ecological and hydrodynamical studies. Our results should, of course, be seen in connection with, and as addition to former investigations undertaken by several authorities. Among the most important contributors we mention : CODDE (1951, 1958), DEN HARTOG (1963) and PEELEN (1967). The information contained in an unpublished report of the Rijkswaterstaat (1934) also was of great value to the authors.
We are aware of the fact that much other inside information exists which was not at our disposition.

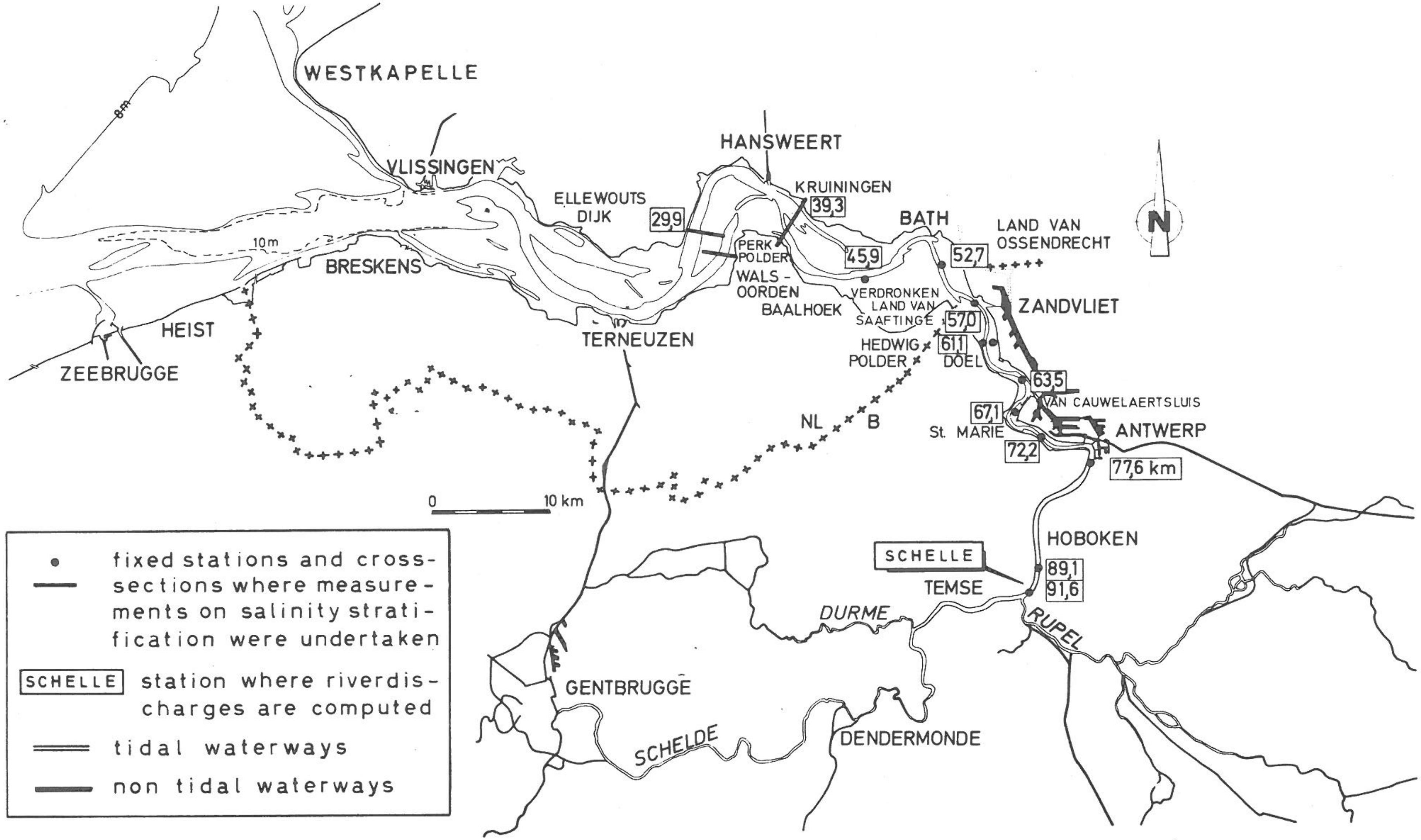

FIG. 1 - THE SCHELDT ESTUARY

Information on river-discharges and tides in Belgium was provided by the Antwerpse Zeediensten while information on tides in the Netherlands was made available by the Rijkswaterstaat at Vlissingen. In this paper, special attention has been given to :

- the longitudinal salinity-distribution and the possible shifts of the isohalines under the influence of the changing river-discharge;
- the magnitude of the salinity variations due to tidal motion during a tidal cycle;
- the vertical salinity gradients or stratifications, the vertical circulation and mixing of the water masses;
- the existence of lateral salinity differences.

2. DESCRIPTION OF THE AREA

2. 1. General.

According to the classification of PRITCHARD (1967), the Western Scheldt may be considered as a typical example of a coastal plain estuary.

The Western Scheldt , leading to the port of Antwerp, is geographically situated in the southern part of the Delta region, flowing partly in the Netherlands, partly in Belgium (cfr. Fig. I). It has a lenght of approximately 160 km counted from the month of the estuary up to the locks in Ghent, the artificial border of the estuary. Descriptive data on the Scheldt estuary may be found in the publications of CODDE (1951, 1958), VALCKE et al.(1966), PEELEN (1967) and STERLING AND PETERS (1973).

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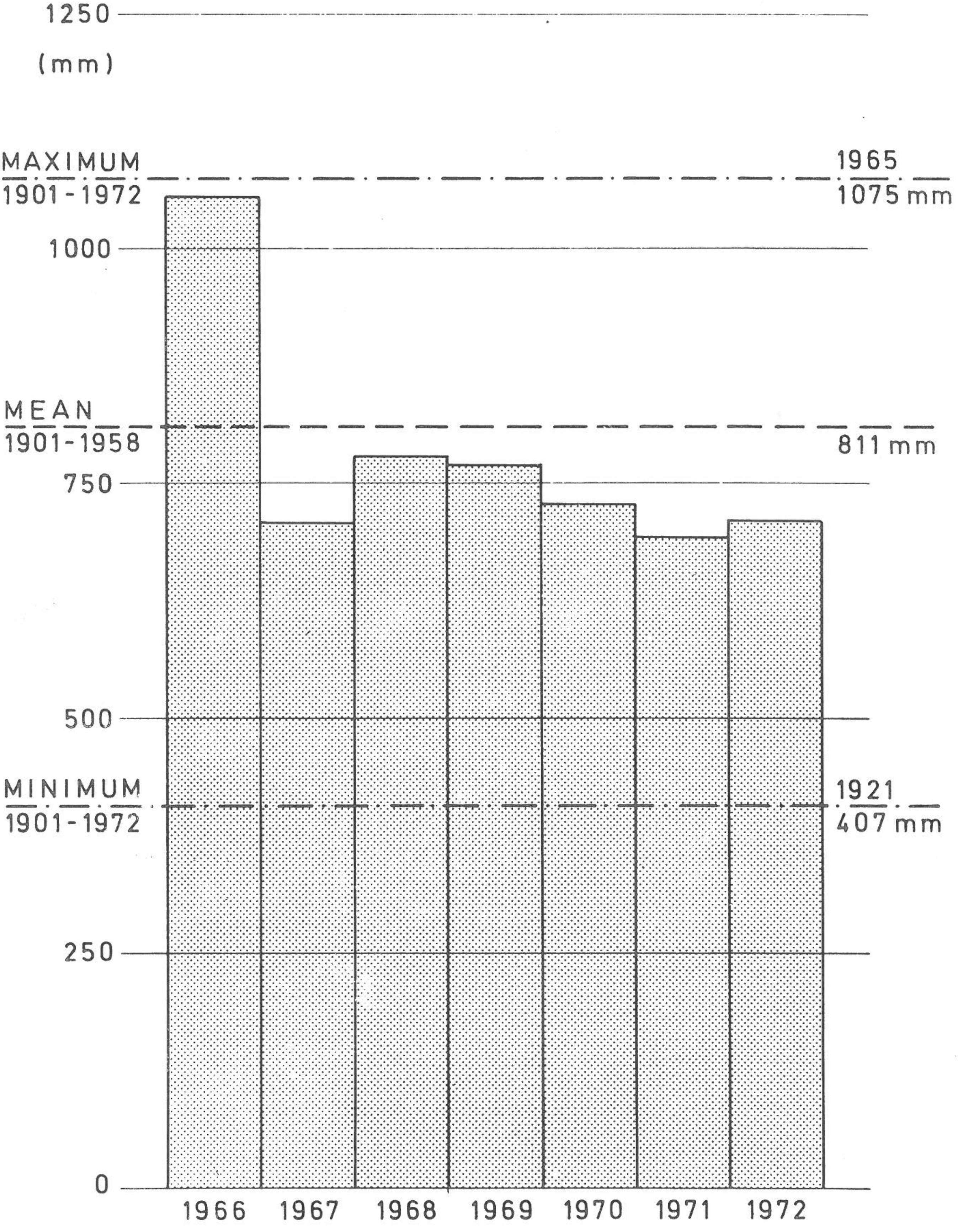

FIG. 2 - AVERAGE YEARLY RAINFALL FOR THE OBSERVATION PERIOD

2.2. Climatological characteristics.

The estuary is lying in the moderate climatic zone. Water temperatures usually fluctuate between 0 and 25°C , increasing from January-February to July-August when the maximum is reached. Going seaward from Ghentbrugge to Vlissingen, a decreasing water temperature gradient nearly always existed (DE PAUW, 1973). During the last ten years ice has never been observed in the estuary. The most frequent directions of the winds are SW-NW. Dominance of eastern winds are rather exceptional. The wind force varies between 0 and 12 Beaufort, but is usually between 2 and 6 Beaufort (cfr. Bull. Roy. Inst. Meteorol) Strong and long during winds in one or another direction may influence the water levels (cfr. VALCKE et al. , 1966).

The average precipitation in the area of Ukkel (which is characteristic for the hydrographical basin) was 811 mm for the period 1901-1958. The precipitation generally does not exceed 900mm a year, and is distributed regularly throughout the year. However, summer months are usually dryer than winter months.

During the last 6 years (1966-1972), the precipitation varied between 545 and 967 mm a year (cfr. Fig. 2). In comparison to the average of 811mm ,1966 was exceptionally wet, 1967, 1971 and 1972 were rather dry. Since January 1973 precipitation was normal, low , or exceptionally low especially in August 1973.

2.3. Hydrological characteristics.

The folowing data are mainly compiled from CODDE (1951, 1958) and VALCKE et al., 1966).

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a) Tidal movements.

The Western Scheldt estuary has a free connection with the sea. The tidal wave entering from the sea is mainly the semi-lunar(M2) wave with a period of 12 h. 25min. The tidal wave is penetrating very deeply into the estuary. In Ghentbrugge which is the artifical limit, lying 160 km land inwards, the energy of the tidal wave is far from being exhausted : the mean tidal amplitude still being 1. 96 m which is 52% of the initial tidal range. Near the river mouth at Vlissingen the mean amplitude is 3. 80 m.

Further characteristics may be found in the recent studies of VALCKE et al. (1966), THEUNS and COEN (1973), and STERLING and PETERS (1973).

b) River-discharge.

Like the Elbe, the Scheldt may be considered as a true rain river (PEELEN, 1967). The estuary drains off the water of a streambasin of about 19, 000 km2 . the most important constituents are : (cfr. VALCKE et al., 1966).

	surface in km2	
1) Scheldt + Leie River	10, 505)	12, 686
Dender	1, 381)	
Durme	325)	
Scheldt : Ghent -Rupel mouth	475)	
2) Zenne	1, 160)	6, 455
Dijle	3, 420)	
Kl. Nete	766)	
Gr. Nete	719)	
Beneden Nete	120)	
Rupel	270)	

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All these components are responsable for a part of the total freshwater discharge in the Scheldt estuary. The average freshwater discharge for the period 1949-1958 among these components is distributed as follows :

River	m3/sec	%
Dijle	19.90	24
Zenne	9.40	11
Kl. +Gr. Nete	13.90	17
Rupel	46.60	54
Scheldt (upstream Rupelmouth)	42.10	46
Dender	8.28	9
Scheldt (Ghentbrugge)	28.50	30

The total average river-discharge downstream the Rupelmouth was 46.60 m3/sec+42.10 m3/sec = 88.70 m3/sec. The daily river discharge during the same period varied between a few and about 600 m3/sec and the yearly average between 42 and 145 m3/sec. Interesting to note is that the total freshwater discharge upstream from the Rupelmouth is of the same order of magnitude as the freshwater discharge coming from the Rupelbasin, and this in spite of the fact that the hydrographical basin of the Scheldt is 1.96 times larger. The explanation must be looked for in the feeding of different canals with Scheldt water. Furthermore, during the period April-December , the Leie water is not deviated into the Scheldt but in the canal leading to Heyst, located at the belgian coast.

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The total freshwater inflow, compared to the flood volume is small. At Antwerp, located 83 km from the mouth, the normal inflow never exceeds more than 10% of the flood volume, which at that site is estimated, to be 62 million m3.

The river discharges cited in this contribution were provided by the Antwerpse Zeediensten . The values are estimates of the river discharge. The definitive values will be published in a report later on (COEN and THEUNS, pers. comm.).

3. MATERIAL AND METHODS

3. 1. Material.

This contribution is based on two types of salinity-measurements: first, longitudinal profiles along the axis of the estuary, second, salinity variations at fixed stations during complete or half tidal cycles.

Since 1966, about 15,000 salinity determinations were made, about 2000 titrimetrically on collected samples and about 13,000 in situ measurements with a conductometer.

These measurements were carried out mainly in the following institutions : the Laboratory of General Biology (State University Center Antwerp), the Delta-Institute for Hydrobiological Research, Yerseke (The Netherlands), the laboratory of Hydraulic Research (Borgerhout) and the Laboratory for Industrial Chemistry (Free University Brussels).

Also incorporated in this paper are some results of the salinity determinations on samples taken in the area of Antwerp-Zandvliet at slack high water during the period 1967-1970 by the Provincial Institute for Hygiene in Antwerp.

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Longitudinal profiles were determined during more than 50 cruises along the axis of the stream, covering the area between Ghentbrugge and Vlissingen. For practical reasons, the estuary was devided in three parts : Vlissingen-Zandvliet, Bath-Antwerp and Antwerp-Ghent because sampling on one day was difficult to realise.

At 53 occasions , salinity determinations during tidal cycles at fixed stations were carried out. The stations were located between Temse and Vlissingen. During the period 1967-1969, measurements took place monthly in the whole estuary, mainly along the longitudinal axis but also during several tidal cycles at fixed stations. Special attention was given to the relations between salinity and tides as well as river-discharges.

Since 1969, emphasis was put on stratification. In 1972 and 1973 several samplings along the whole lenght of the estuary or at fixed stations were devoted to stratification.

3.2. Methods.

Salinity-chlorinity-determinations.

Part of the salinities were determined titrimetrically following the method of MOHR-KNUDSEN (STANDARD METHODS, 1965 and STRICKLAND and PARSONS , 1965). Depending on the salinity range covered, two different AgNO3-solutions of different normality were used.

The great majority of the salinities were measured directly in situ with a 4 electrode temperature-compensated conductometer (ECR-P4EN).

All salinities were expressed as chlorinities in gCl/l(‰), because the latter quantity, namely chloride , is primarily determined by titration and also read from the tables converting conductivity to chlorinity.

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Chlorinity can easily be converted to salinity with the KNUDSEN-formula $S\,^{\circ}/_{\circ\circ} = 1805\ \mathrm{Cl}\ ^{\circ}/_{\circ\circ} + 0.03$.

However, in estuarine waters, it is not certain that the relationship will hold completely since the composition of the diluting freshwater is dependent on its origin and the hydrographical basin. Moreover, the composition can be altered under the influence of man-made activities, for example the discharge of all kinds of waste waters.

Sampling technique.

Surface samples for salinity determinations were in most cases taken with a plastic bucket; depth samples with a VAN DORN-sampler or with centrifuge pumps. Direct in situ salinity measurements were made with the conductometer on a vertical profile.

Presentation of results.

In the graphs was often referred to the so called "Venice system" (1959), a classification-system for brackish waters commonly in use among hydrobiologists, and created to situate the biological phenomenons observed. The classification is based on chlorinity as the chloride-ion is a non-metabolic ion (PEELEN, 1967).

The different classes are:

- Euhalinicum	from 22	to 16.5 $^{\circ}/_{\circ\circ}$ Cl'
- Polyhalinicum	16.5	10
- Mesohalinicum	10	3
a-meso	10	5.5
b-meso	5.5	3
- Oligohalinicum	3	0.3
- Freshwater(Limneticum)	< 0.3	

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In most cases no recalculations have been made with regard to the tidal phases encountered while sampling. The tidal amplitude in function of moon periodicity has neither been taken into account. In the area of Vlissingen-Zandvliet, the observed chlorinities in situ for 1967 were tentatively compared to those converted to the high water moment at Vlissingen by shifting the observation point over some distance along the channel-axis (DORRESTEIN , 1960). For these conversions it was necessary to know the evolution of the current velocities in the different stations (Stroomkaart, Westerschelde, 1964), in order to calculate the distance covered by a water particle between the time of sampling and the time of H. W. at Vlissingen.

4. RESULTS.

4. 1. Longitudinal salinity distribution.

4. 1. 1. Description of the general trend.

Fig. 3 represents the extreme surface-chlorinity values observed since 1966.

At Vlissingen-Breskens, considered as the mouth of the estuary, chlorinity never exceeded 18.5 Cl°/₀₀ at slack H. W. This corresponds to a mixture of 95% seawater and 5% freshwater. The lowest value in that area was about 13 g Cl °/₀₀ (dilution 67%).

Going upstream the chlorinity decreases progressively, slowly to Hansweert or Baelhoek, then more rapidly till it reaches approximately 1 °/₀₀ Cl (dilution 5%). This may occur in Bath at slack LW when river-discharges are high, inversely in St-Amands at slack HW when river-discharges are low. The distance between Bath and St-Amands is 55 km.

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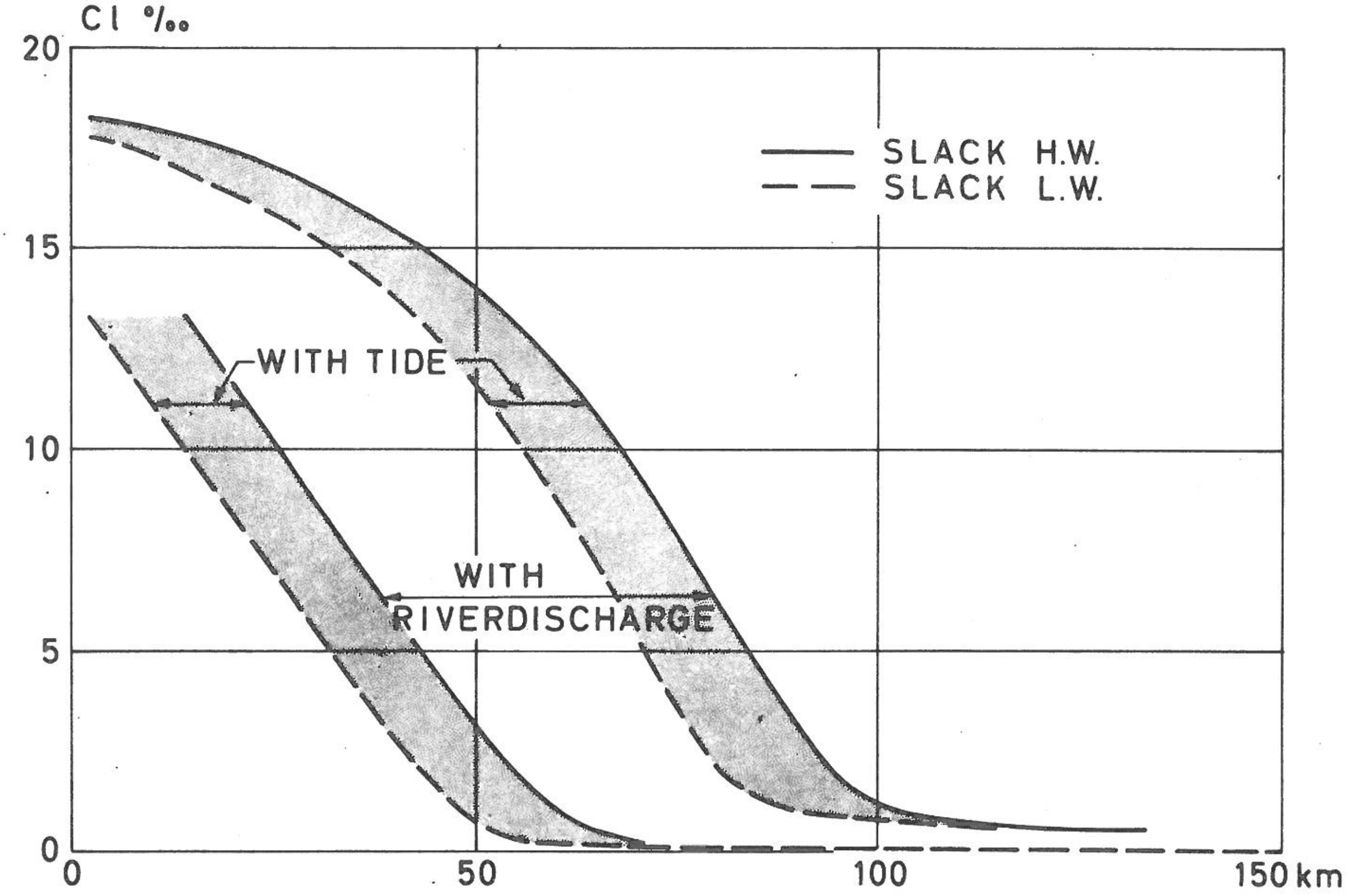

FIG. 3 - POSSIBLE VARIATION OF SALINITY - PERIOD 1967-1973
(DEDUCED FROM THE CHLORINITIES OBSERVED DURING THE PERIOD 1967-1973)

The longitudinal chlorinity gradient is highest near Bath. Even under extreme conditions the shape of the curves remains fairly constant.

4. 1. 2. Salinity of the components of the estuarine water.

Estuarine water is a mixture of salt-and freshwater. The salinity is thus dependent on the salinity of the mixing components, namely fresh, brackish and seawater.

The different components are:
a) from the landside.
Most of the inland waters, which are indirectly in connection with the Scheldt estuary and not staying under tidal influences, may be considered as limnetic, i. e. having a chlorinity below 0. 300 g Cl °/₀₀. In most cases, the chlorinity does not exceed 0. 100 g Cl °/₀₀ , which is conform to the formerly considered upper limit of freswater (REDEKE, 1922). In some localities, chlorinity exceeded 0. 100 g Cl °/₀₀. This may be due to the discharge of domestic waste waters containing much chloride ions, or is the result of the feeding of certain inland waters (such as the Oude Schelde at Temse) with Scheldt water having a slightly higher chlorinity.

Along the estuary various inland, slightly brackish waters, are also located. For a survey of the chlorinity of these waters we refer to DE RIDDER (1954, 1956). As far as we know, no information is available on the quantities of brackish water discharged into the estuary. We believe however, that these quantities are neglectable compared to the freshwater inflow in the estuarine basin.

Near the sluices of Ghenbrugge, the chlorinity was sometimes slightly higher than in the downstream stations of Wetteren and

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Schoonaarde, and even exceeded 0.300 g Cl°/oo, which is considered to be the upper limit of freshwater. This was the case for exemple in December 1968 and from July to December 1969. The chlorinity content reached maximally 0.452 g Cl °/oo. According to the Venice system we should call it oligohaline water. Moreover were the average values calculated for Ghentbrugge always higher than in localities more downstream. For example in Wetteren lying 15 km more seaward, the average chlorinity in 1969 was 0.098 g Cl °/oo compared to 0.186 g Cl°/oo, in Ghentbrugge. Discharge of large quantities of waste water originary from the domestic pollution of Ghent and from the rivers Leie and Scheldt are probably responsible for this phenomenon.

Domestic waste waters contain chloride ions and may increase the chlorinity in the freshwater zone (cfr. also DORRESTEIN, 1960; CASPERS, 1959).

Large quantities of waste waters are discharged into the Scheldt estuary in other localities (via the Rupel and the Dender, at Antwerp, through the Schijn, at Terneuzen etc...).

WOLLAST (1967) mentioned several anomalies in the ionic composition of water samples taken in the estuary between the Rupel and Zandvliet.

b) <u>from the seaside</u>.
Between the section Vlissingen-Breskens and the section Ostend-Westkapelle, the coastal waters belong to the mixo-euhaline categorie (Venice system), i.e. having a chlorinity of more than 16.5 g Cl °/oo (> 30 °/oo S).
In the Channel, between Calais and Dover, the salinity slightly varied around 19.5 g Cl °/oo during September 1973 (cfr. Fig. 15).

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During the period 1967-1969 TIJSSEN (1968-70) recorded salinities of 32-33 °/oo S(± 18 g Cl ‰ in the areas adjacents to the mouth of the estuary(head of Walcheren-Zeebrugge). Near the Westhinder the chlorinities varied between 17. 56 and 19. 55 g Cl °/oo (period 1951-1955) (VAN MEEL, 1972). At the Grote Bank, 30 km offshore, the chlorinities in June 1967 ranged from 17. 78 to 18. 87 g Cl °/oo (DE PAUW, 1973).

4. 1. 3. Tidal variation in salinity.

The vertical tides in seas and estuaries correspond with horizontal water movements. Since the mixing of fresh-and seawater produces a longitudinal salinity gradient (cfr. 4. 1) downstream from the limnetic reach of the estuary, a periodic variation will be observed at a fixed station. It is logic to relate this variation to the horizontal tide, i. e. with the currents.

The vertical tide is a periodic movement of the water level between high and low water.

The horizontal tide is a periodic movement of the watermasses between slack high water and slack low water.

In the Scheldt estuary slack high water and slack low water occur 1/2 to 1 1/2 hour after respectively high water and low water. These differences in time, change with the station and with the tidal amplitude.

The tidal salinity variation at fixed stations depends on site tidal amplitude, river flow, wind action, etc..

En example of tidal salinity variation related to the vertical and horizontal tide is given in Fig. 4.

An order to study these tidal salinity variations along the axis of the estuary more closely, several sampling were undertaken during complete or half tidal cycles.

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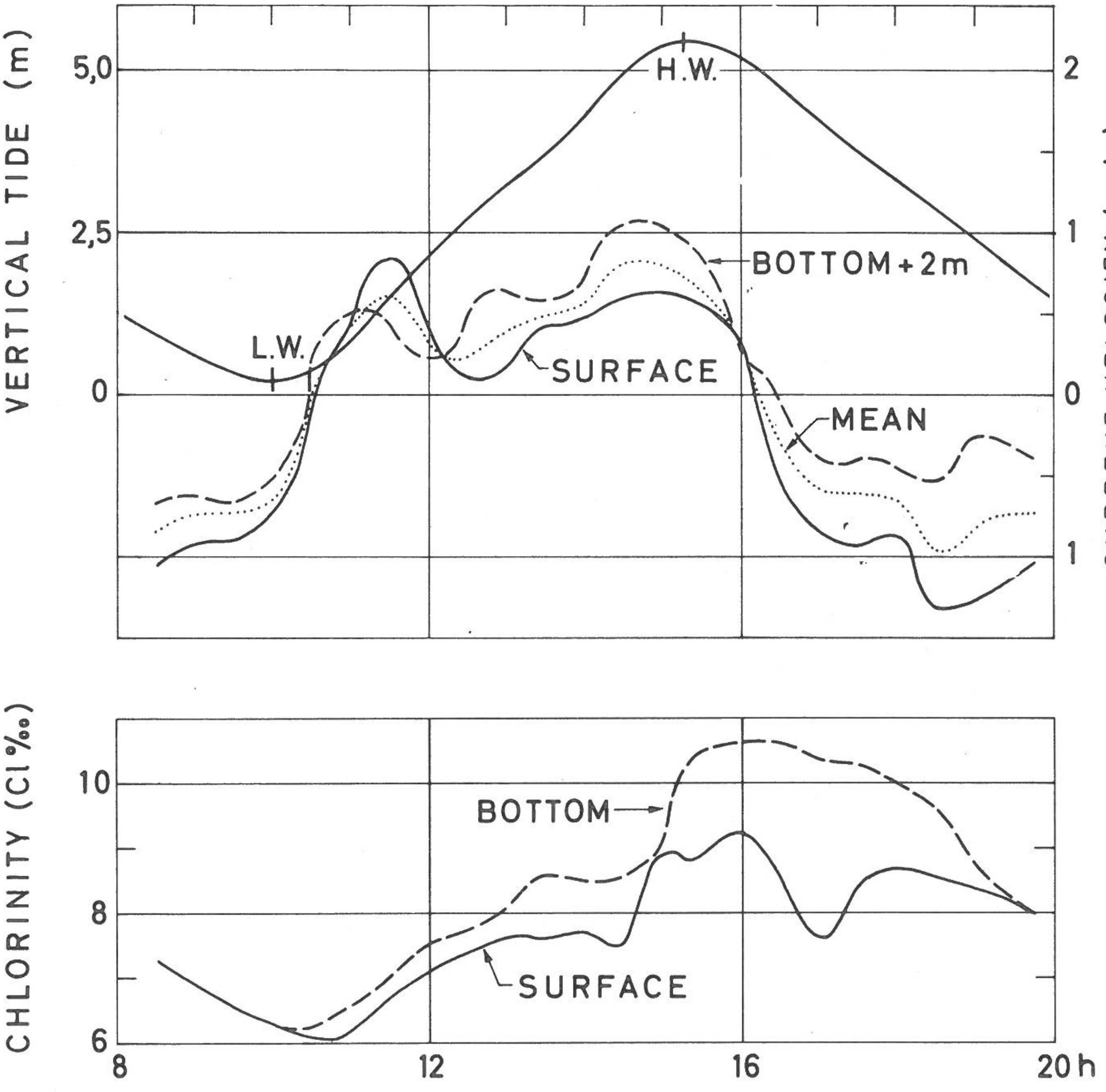

FIG. 4 - TIDAL VARIATIONS OF WATER LEVEL, CURRENT VELOCITY, AND SALINITY

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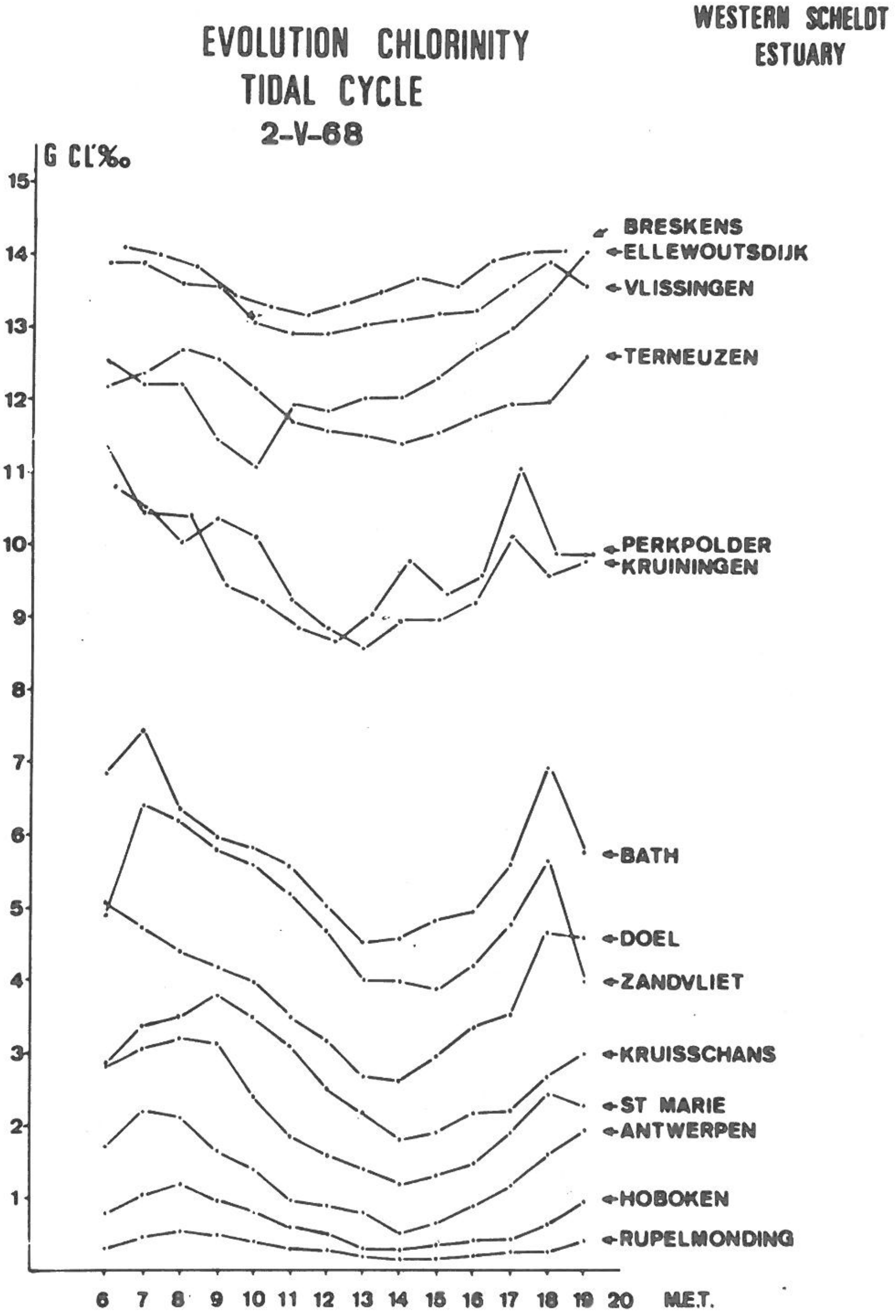

FIG. 5 - EVOLUTION CHLORINITY - TIDAL CYCLE 2-V-1968

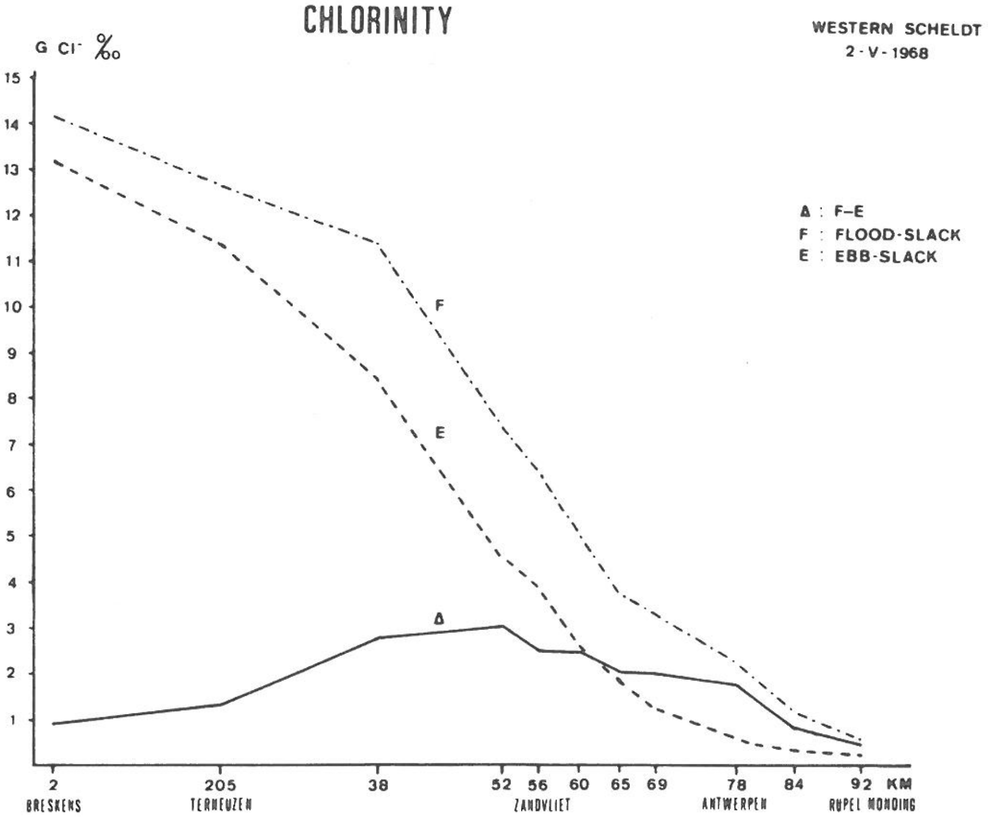

FIG. 6 - CHLORINITY — 2-V-1968

In collaboration with the Delta-Institute (Yerseke, NL) simultaneous samples were taken during a complete tidal cycle at 14 stations located along the axis of the estuary between Vlissingen and the Rupelmouth on 2 May 1968.

During sampling the environmental conditions may be considered as normal : a river-discharge of 65 m3/sec. and a tidal amplitude of 4.81-4.73 m in Antwerp (Loodswezen). Furthermore, no discharge of polder water occurred on that day, neither dredgings. The wind force varied between 2 and 4 Beaufort . The samples were taken from landingsites and from the ferries Breskens-Vlissingen, Terneuzen-Ellewoutsdijk and Kruiningen-Perkpolder. The results of our observations, represented in Fig. 5 and 6 , may thus be considered as characteristic for an average tidal cycle in the Scheldt.

Fig. 5 is showing the regular trend of the curves, lying one above another, going from the Rupelmouth to the mouth of Western Scheldt. Moreover, with the exception of Ellewoutsdijk, the curves for other stations are rather symmetrically.

Aberrations of the sinusoïdal trend may be caused by the existence of horizontal circulation currents around the tidal flats. The trend is more regular in the betterlined-off and smaller channel of the belgian part of the Scheldt.

With the same sampling data, the longitudinal salinity gradient can be drawn, plotting the maximum and minimum values along the axis of the estuary (cfr. Fig. 6) . On 2 May 1968, the amplitude of the tidal chlorinity variation, increases from approximately zero in the open sea, to 3 g Cl °/oo in the area Perkpolder-Bath, decreasing again upstream to approximately zero in the freshwater zone.

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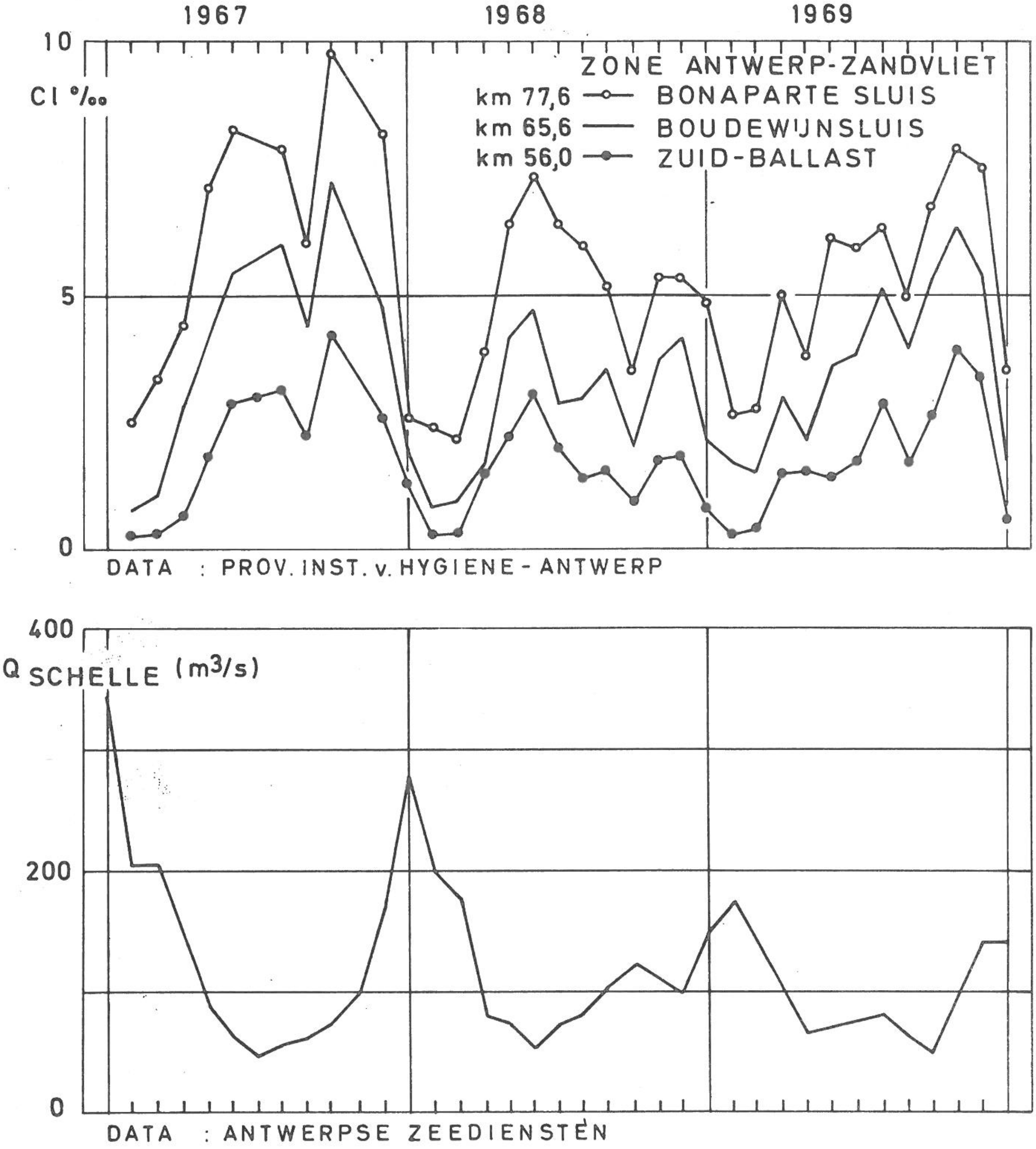

DATA : PROV. INST. v. HYGIENE - ANTWERP

DATA : ANTWERPSE ZEEDIENSTEN

FIG. 7 - VARIATION OF CHLORINITY AT SLACK HIGH WATER WITH RIVERDISCHARGE

From this graph we may also derive the longitudinal displacement of the water masses which are due to the horizontal tide and can reach approximately 15 km in the observation area.

Many other chlorinity measurements were made during tidal cyles at fixed stations. The maximum chlorinity amplitude was always observed in the area of Bath and reached maximally 4.5 g Cl°/oo. The tidal chlorinity variation varies with the tidal amplitude. At spring tide the variation is maximal because of the longitudinal movement of the water masses and also because the longitudinal chlorinity gradient is maximum. The minimum value is observed at neap tide.

4.1.4. Influence of river-discharge on salinity.

The non-tidal variations of salinity are mainly due to changes in river-discharge. Investigations on the influence of these variations are very difficult because there is no reliable nor an accurate computation method for the river-discharge of the Scheldt.

We have already mentioned that an increase of riverflow results in a shift of the longitudinal salinity gradient while at fixed stations salinity will decrease . For example : Fig. 7 shows a seasonal variation of chlorinity in three stations located in the brackish water part of the estuary, namely Bonapartesluis(Antwerp) , Baudewijnsluis (Schijn) and Zuid-Ballast (Zandvliet) during 1967, 1968, 1969. All samples were taken at slack high water.

Plotting the computed discharges of the estuary and the chlorinities , an anticorrelation appears. CODDE (1958) used this anticorrelation to compute river-discharge from salinity measurements in Antwerp. This point will be discussed in 5.3.

The shift of longitudinal salinity gradients is illustrated in Fig. 8 and 9 . In Fig. 8, salinities measured between Vlissingen and Zandvliet during the period March 1967-January 1968, show a

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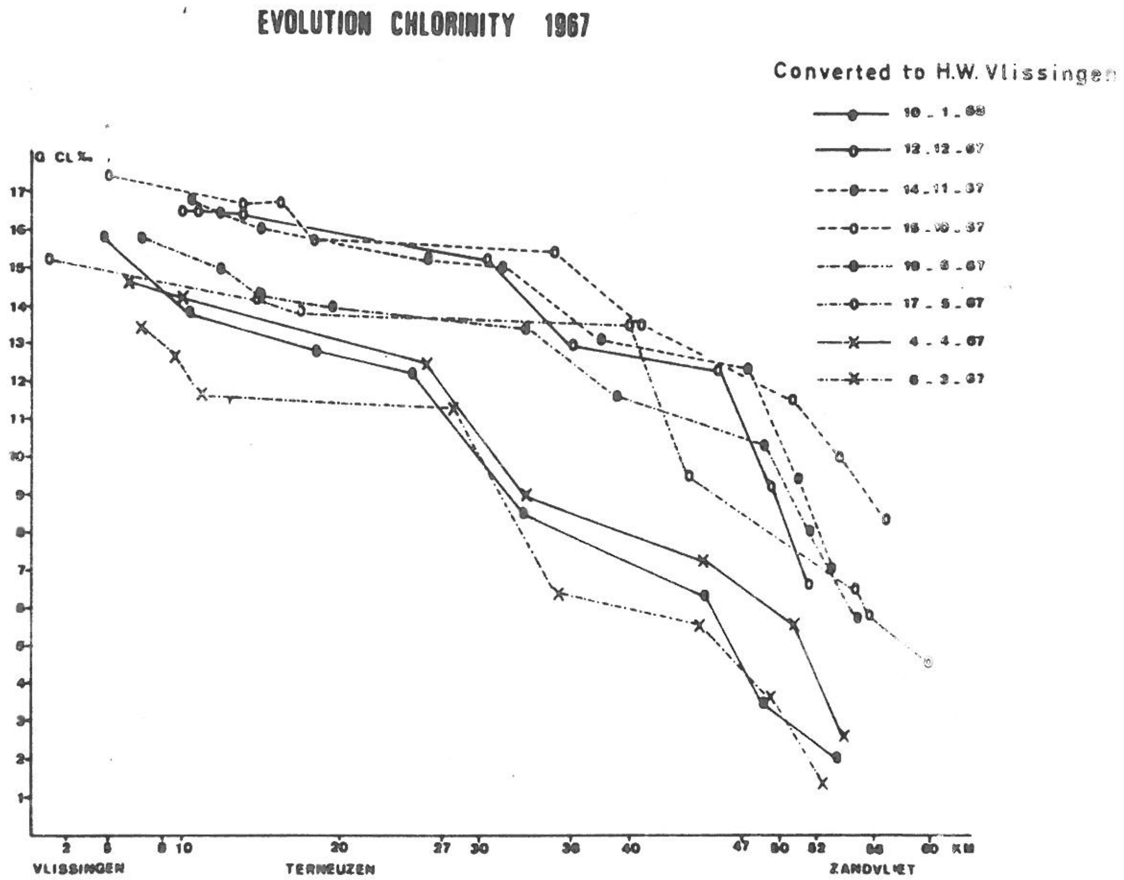

FIG. 8 - EVOLUTION CHLORINITY 1967

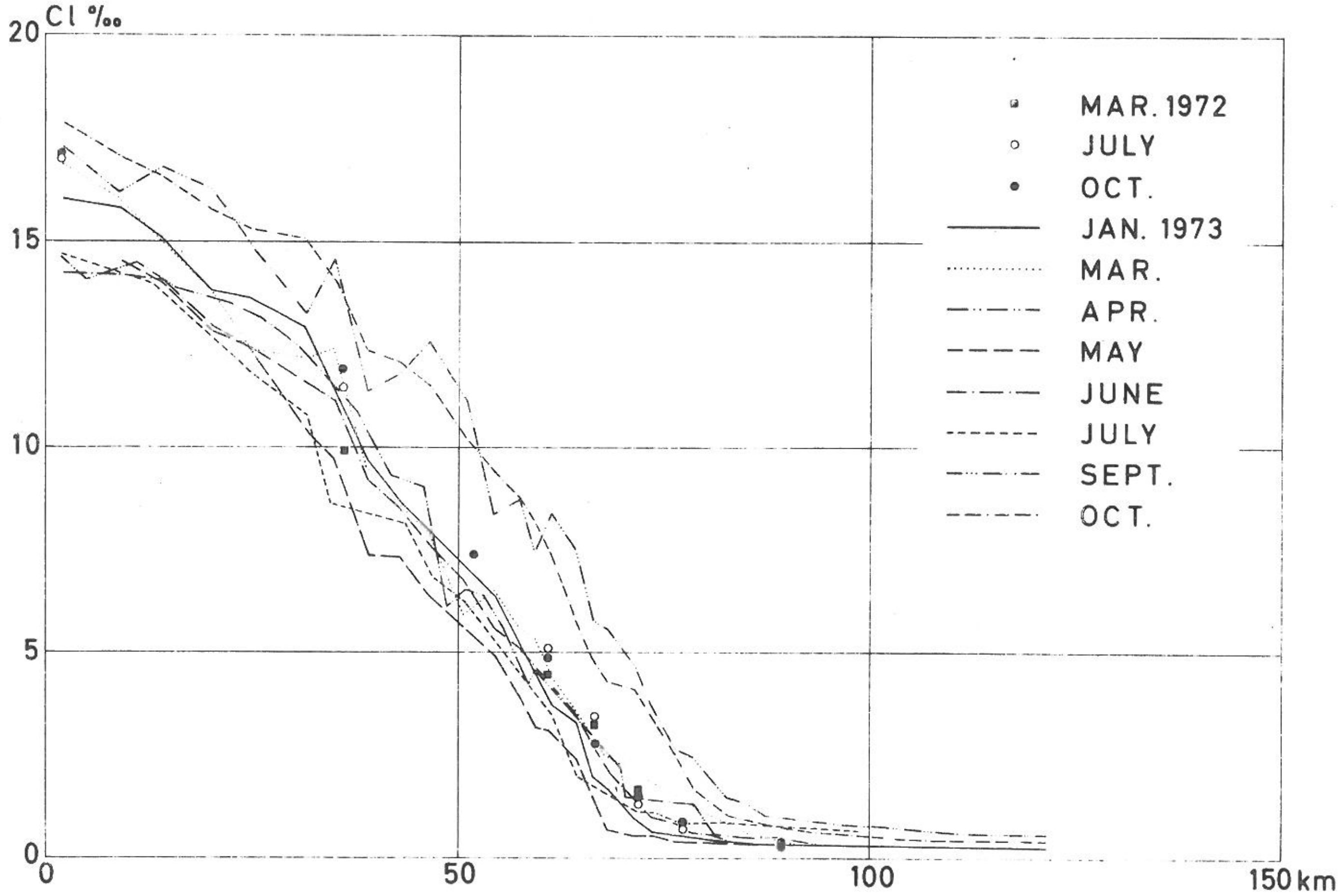

FIG. 9 - CHLORINITIES AT SLACK LOW WATER

horizontal shift upstream from March 1967 to October 1967, and a downstream one from October 1967 to January 1968. All data were converted to the moment of high water at Vlissingen.
The downstream or upstream movement of the salinity gradient gives respectively an increase or a decreases of the salinity in each fixed station as shown in Fig. 7 . The magnitude of these variations depends on the location of the station, and is maximal near Bath. In 1967, 1968 an 1969 the maximum differences observed near Bath were respectively 9.93 °/oo, 7.59 °/oo and 6.59 °/oo (g Cl/l).

Besides the foregoing, Fig. 9 represents some salinity profiles in 1972 and 1973. River-discharges were very low, ranging from 20 to 80 m3/sec. All data were measured at, or converted to slack low water. No important shifts could be observed, exception made for September-October 1973, following an unusually dry summer.

There is some delay between the change in river-discharge and the resulting change of chlorinity.

Chlorinity can decrease very quickly. Especially from autumn till winter the chlorinity drops were very significantly. Some examples are given in table I.

TABEL I (in g Cl °/oo)

Period	12. XII. '67 27. XII. '67	Dec. '69 Jan. '70	12. XII. '67 10. I. '68	10. I. '68 7. II. '68
Location	Zandvliet	Zandvliet	Breskens	Breskens
Time interval (in weeks)	2	3	4	4
Chlorinity at beginning	7.0	7.6	17.30	16.25
Chlorinity at end	2.9	3.5	16.25	13.69
Chlorinity drop (approximately)	4	4	I	2.5

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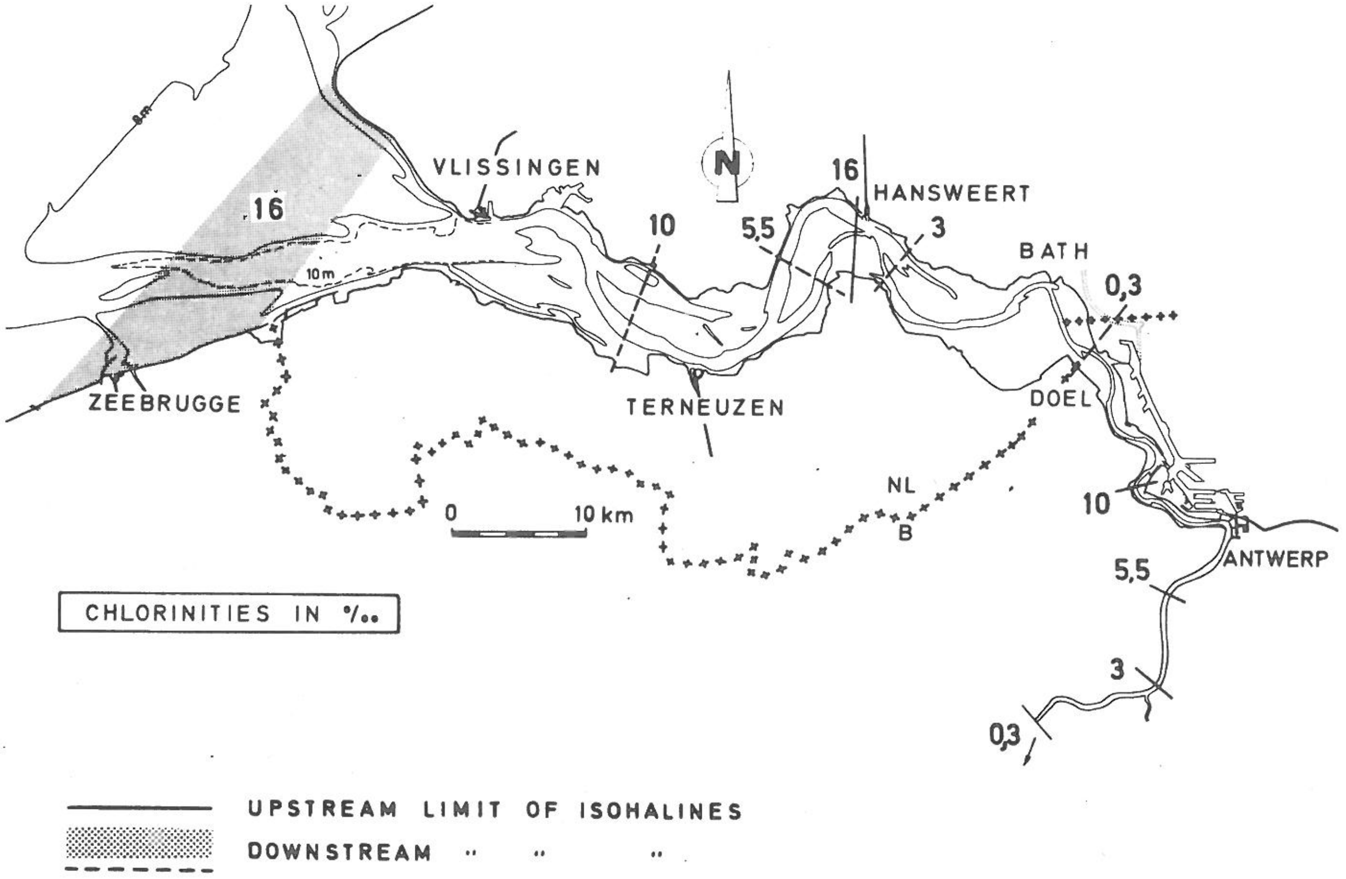

FIG. 10 - POSSIBLE SHIFTS OF ISOHALINES DURING PERIOD 1967-1973

The chlorinity drop is maximal near Bath where the salinity gradient in the steepest. In Breskens, on the contrary, the salinity gradient is rather smouth and the chlorinity drop rather small.

Near the mouth of the estuary, the salinity drops with a delay of several weeks after the increase of river-discharge, because of the residence time.

Fig. 10 shows the possible shifts of the isohalines since 1967. The extremes observed correspond with the extreme river-discharges,350 and ± 20 m3/sec. The values of the isohalines were chosen in function of the Venice system, namely 0. 3, 3. 0, 5. 5, 10. 0 and 16. 5 g Cl°/$_{oo}$. We could observe a longitudinal shift of the isohalines reaching 50 km. For example the 0. 3 °/$_{oo}$ Cl'-isohaline, considered to be the upper limit of freshwater (Venice resolution 1959), could be observed in Temse (± 100 km from Vlissingen) or in Zandvliet (± 54 km from Vlissingen). The mesohaline zone with chlorinities ranging from 3 to 10 g Cl°/$_{oo}$ could be located in the area Antwerpen-Zandvliet when the river-discharge was low, and in the area Baalhoek-Baarland when river-discharge was high. The latter horizontal shift reached about 30 km. In September and October 1973, all the isohalines shifted over more than 10 km upstream, compared to the upper limit observed for the period 1967-1969. The exact river-discharge was not yet known for these two months when this paper was written. The brackish water zone may shift and extend or reduce its length under the influence of the tide and riverflow. This has a serious impact on live in the stream (cfr. DE PAUW, 1971, 1973).

Below in table II , a survey is given of the geographical boundaries of the brackish water trajectories.

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Table II: Extreme chlorinities observed during the period 1967 – 1973

Locality	VLISSINGEN	SLOEHAVEN	BORSELE (Buoy 13)	TERNEUZEN	BAARLAND (Buoy MG-E)	HANSWEERT (Buoy 42)	BAALHOEK (Buoy 60)	BATH (Buoy 75-75A)	ZANDVLIET (Buoy 87)	DOEL	SCHIJN	FT. PAREL	ANTWERPEN (Loodswezen)	HOBOKEN	SCHELLE (Rupelmonde)	TEMSE	ST. AMANDS	DENDERMONDE	SCHOONAARDE	WETTEREN	GENT
km.	2	5	10	20	27	36	46	51	57	61	64	67	78	86	91	98	109	122	133	145	160
Salinities																					
Maximum (1) in m S	42.5	42.4	42.1	40.8	39.5	37.5	35.2	33.4	31.0	29.2	27.8	25.8	17.67	11.77	7.90	4.08	2.45	1.83	1.73		
(2) in $^{\circ}/_{\circ\circ}$ Cl$^-$	18.23	18.20	18.05	17.45	16.80	15.82	14.70	13.88	12.77	11.93	11.27	10.40	6.82	4.37	2.87	1.40	0.82	0.60	0.57		
Minimum (3) in $^{\circ}/_{\circ\circ}$ Cl$^-$	13.3	12.5	11.1	8.2	6.4	3.7	1.1	0.5	0.252		0.207	0.080	0.071	0.081	0.078	0.055	0.018	0.042	0.055	0.042	0.050
Corresponding Venice System Class																					
Maximum	e	e	e	e	e	p	p	p	p	p	p	p	α	β	o	o	o	o	o		
Minimum	p	p	p	α	α	β	o	o	L	L	L	L	L	L	L	L	L	L	L	L	L

Code :
euhaline	e :	> 16.5 Cl $^{\circ}/_{\circ\circ}$
polyhaline	p :	10 - 16.5
a-mesohaline	α :	5.5 - 10
b-mesohaline	β :	3 - 5.5
oligohaline	o :	0.3 - 3
Limnitic	L :	< 0.3

(1) salinities measured with conductometer-expressed in m S

(2) salinities converted from conductivities (m S) to chlorinities (g Cl/1 or $^{\circ}/_{\circ\circ}$)

(3) measured titrimetrically in chlorinities (g Cl/1 or $^{\circ}/_{\circ\circ}$)

4.2. Vertical salinity distribution.

An estuary can be easily classified by its vertical salinity distribution.

Chlorinity measurements on surface and bottom samples were made during 21 cruises between Vlissingen and Antwerp in 1967, 1968 and 1969.

In situ measurements on vertical profiles were made monthly since January 1973, between Vlissingen and Dendermonde. Besides these, measuring campaigns during tidal cycles were undertaken at fixed stations located between the Rupelmouth and the section Ossenisse-Baerland.

a) Observations along the axis during the cruises.
Generally, the salinity is higher near the bottom. The differences between surface and bottom are usually lower than 0.5 g Cl °/₀₀. The greatest differences were found in the area Bath-Zandvliet. These observations are not sufficient to define the degree of stratification because it varies during the tidal cycle.

b) Observations at fixed stations.
Several measurements were made in 1969, 1970, 1972 and 1973. The results show that the phenomenon is rather complex. For a long time, the Scheldt estuary was considered as a completely mixed estuary (cfr. CODDE , 1951, 1958). During our investigations and during those of the Rijkswaterstaat (1934) stratification was found to be present at least during a certain period of the tidal evolution. At different fixed stations, stratification could occur at different moments of the tide. Generally the differences between chlorinities of bottom and surface samples were highest during the slack periods especially at slack HW. A few examples are given in Fig. 11.

- Stratification and current velocities.
The influence of stratification on water movements in estuaries

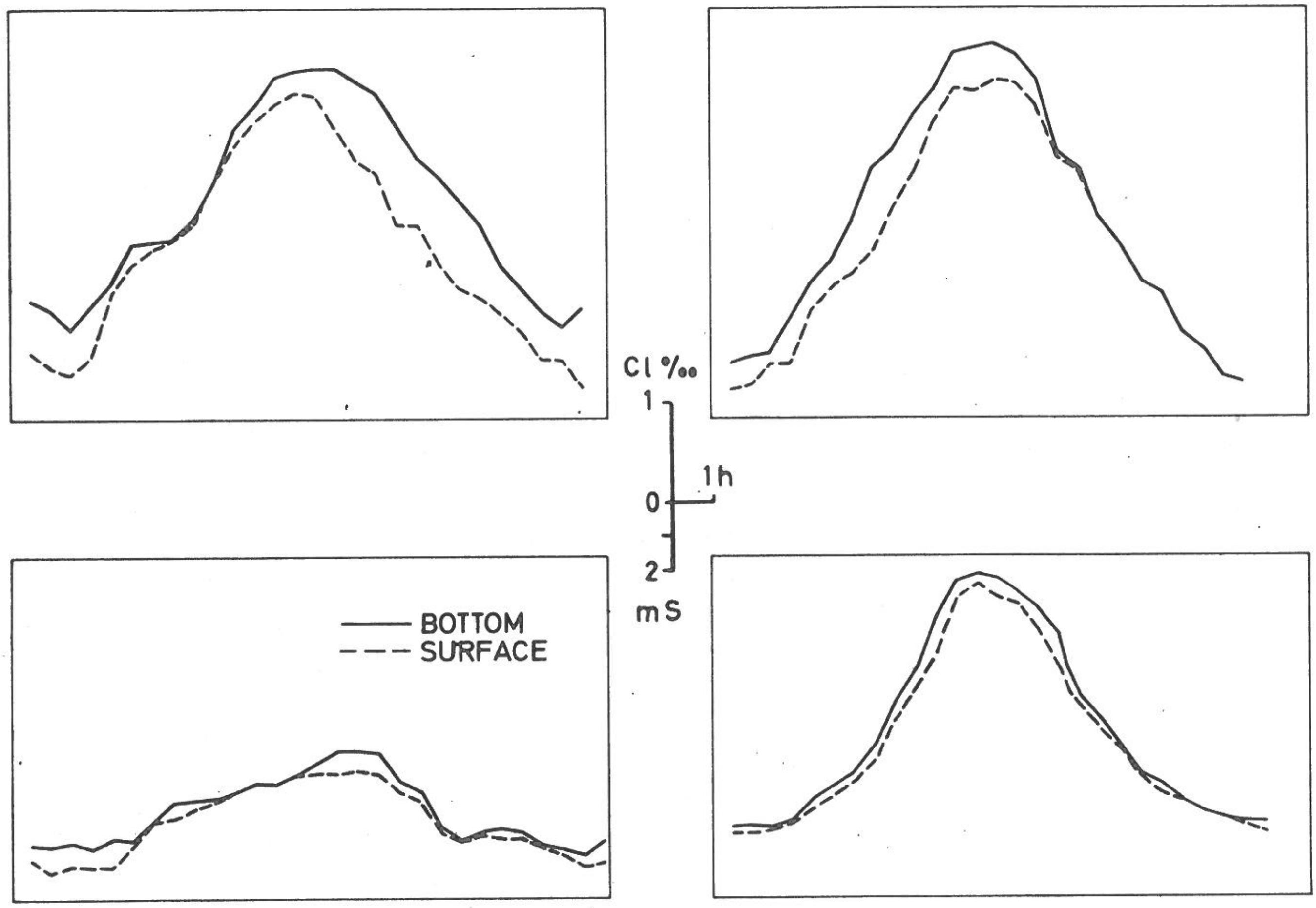

FIG. 11 - DIFFERENT TYPES OF VARIATION OF SALINITY STRATIFICATION WITH TIDE

was already described by SCHULZ and SIMONS, 1957.
In the Scheldt estuary deceleration during ebb and acceleration of the current velocities near the bottom make no more doubt (PETERS, 1967, 1972; STERLING and PETERS 1973).
Some authors called this phenomen "underflood" (Rijkswaterstaat, 1934) or "ontmenging" (EGGINCK, 1965).

4. 3. Lateral salinity distribution.

Because of the multiple channels located between the mouth of the estuary and Bath , it is difficult to establish a representative cross-section. Therefore it is also difficult to determine a lateral salinity distribution.

Measurements in the cross-sections Ossenisse-Baerland (km 30), Perkpolder-Waarde (km39), Zandvliet-Prosperpolder (km 55) and Doel (km 61), gave a rough idea of the possible transverse salinity gradients. The salinity differences between two opposite banks can reach about 2 g Cl °/ₒₒ . Fig. 12 shows the salinity distribution at slack LW in the cross-section Zandvliet-Prosperpolder.

During a tidal cycle, the lateral salinity differences vary . The highest values can occur near each bank.

In the cross-section Ossenisse-Baerland two deep channels (Middelgat and Gat van Ossenisse) are separated by a large shoal. The differences between the salinities in these channels can reach 0. 5 g Cl °/ₒₒ. (cfr. Fig. 13).

4. 4. Salinity gradients at mean river discharges.

The longitudinal salinity gradient varies continuously from zero in open sea to a maximum in the area Baalhoek-Bath, and

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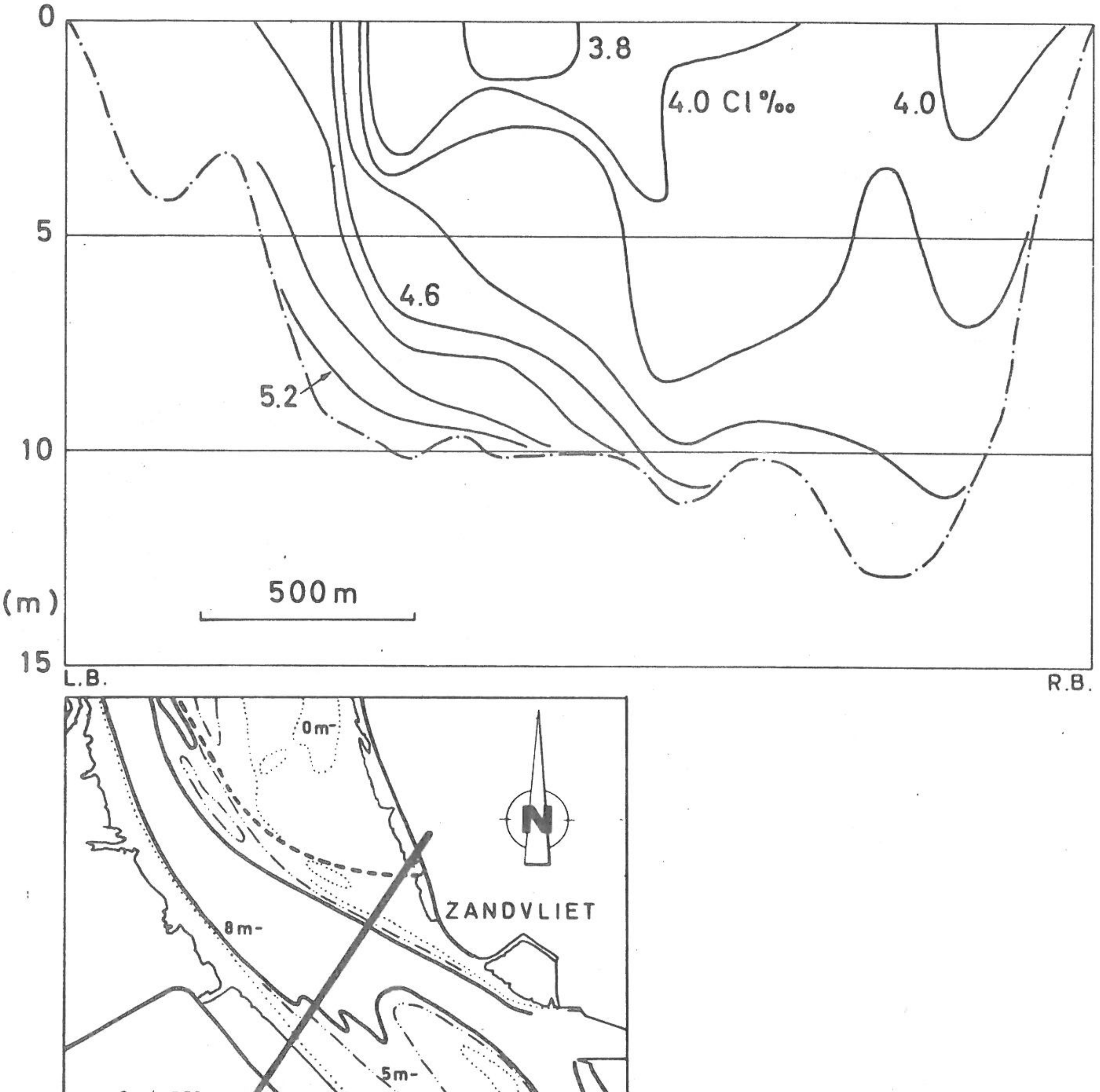

FIG. 12 – SALINITY STRATIFICATION IN CROSS-SECTION ZANDVLIET AT SLACK HIGH WATER.

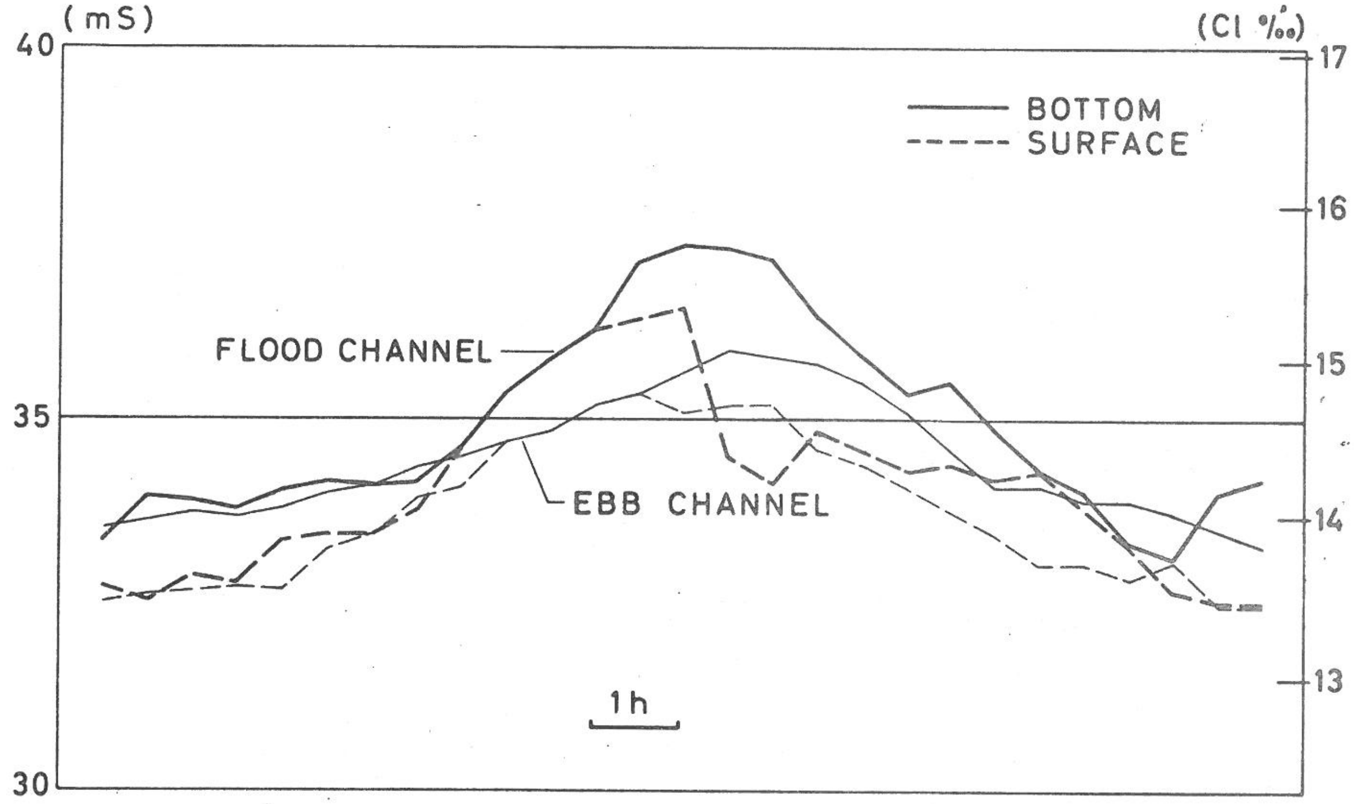

FIG. 13 - SALINITY VARIATION WITH TIDE
CROSS-SECTIONS GAT VAN OSSENISSE-MIDDELGAT 30-1-1973

again to zero in the freshwater zone.

At Vlissingen (km 2)the gradient reaches generally 0. 1. 10^{-3} g Cl/l/m (°/oo/m) ; in the area Baalhoek-Bath it reaches 0. 25.10^{-3}g Cl/l/m (°/oo/m). At fixed stations, the longitudinal salinity gradient does not vary much, even during the tide.

The lateral salinity gradient varies during the tides and may reach 10^{-3} g Cl/l /m (°/oo/m). The highest salinities can be measured at the left or at the right border.

The vertical salinity gradient may vary during the tides from zero to 0. 25 g Cl/l/m (°/oo/m). The highest values were found in the area Baalhoek-Bath, and downstream Baalhoek in the flood channels.

5. DISCUSSION AND CONCLUSIONS.

5. 1. Longitudinal salinity distribution.

Two aspects may be taken into consideration .
The first relative to ecological problems, the second one to hydrodynamical problems. We previously referred to the classification of brackish waters used by ecologists, in which primarily the salinity magnitudes are important. From a hydrodynamical point of vue on the contrary, variations or gradients are more important than magnitudes. We thus can define three different zones :

- The first zone, zone 1,is characterized by an almost constant salinity which generally does not exceed 1 g Cl °/oo. The downstream boundary of this first zone is located near Hemiksem at slack LW. at low river-discharges ,near the mouth of the Durme at slack HW. ; and near Bath at slack LW at high river-discharges, near Antwerp at slack HW .

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The variation in river-discharge may result in a longitudinal shift of this boundary over of about 50 km while the longitudinal movement with tide is approximately 15 km. (compare Fig. 3 and 10). In normal conditions, i. e. at a mean river-discharge, the downstream limit of the freshwater zone is located near Antwerp, halfway the estuary between Vlissingen and Ghent.

- The second zone, zone 2, is characterized by a fast downstream increase of the salinity. The longitudinal salinity gradient has an order of magnitude of 0. 250 g Cl °/₀₀/ km.

The downstream boundary of this seconde zone is situated near Hansweert. It may shift from Terneuzen to Baalhoek and appears very clearly at normal or low river-discharges, mainly at slack HW.

For the station located 40 km upstream from Vlissingen and which corresponds roughly with the downstream limit of zone 2 , the salinity variation with river-discharge is given in Fig. 14, relating to measurements of 1967, 1968, 1972 and 1973. For the evolution from March 1967 to Januari 1968 an hysteresis appears very clearly (See also Fig. 8). Fluctuations in river-discharge occurred in the estuary, therefore the line representing the salinity variation at slack HW. for steady conditions, is an estimate. This point will be discussed later in chapter 5. 3.

- The third zone, zone 3 , is characterized by a slighter salinity increase.seawards. The rate of increase is about 0. 100 g Cl °/₀₀/ km at the upstream boundary and decrease to zero in the open sea. Measurements of the salinity variation near the surface at slack LW. and slack HW. 40 km upstream from Vlissingen to the channel between Calais and Dover, in September 1973, are represented in Fig. 15.

The salinity was very high because of the very dry weather in Europe, mainly in August.

Vlissingen is generally considered as the mouth of the estuary. This fact is acceptable for purely hydraulic studies, but not for any study related to salinity or mixing processes.

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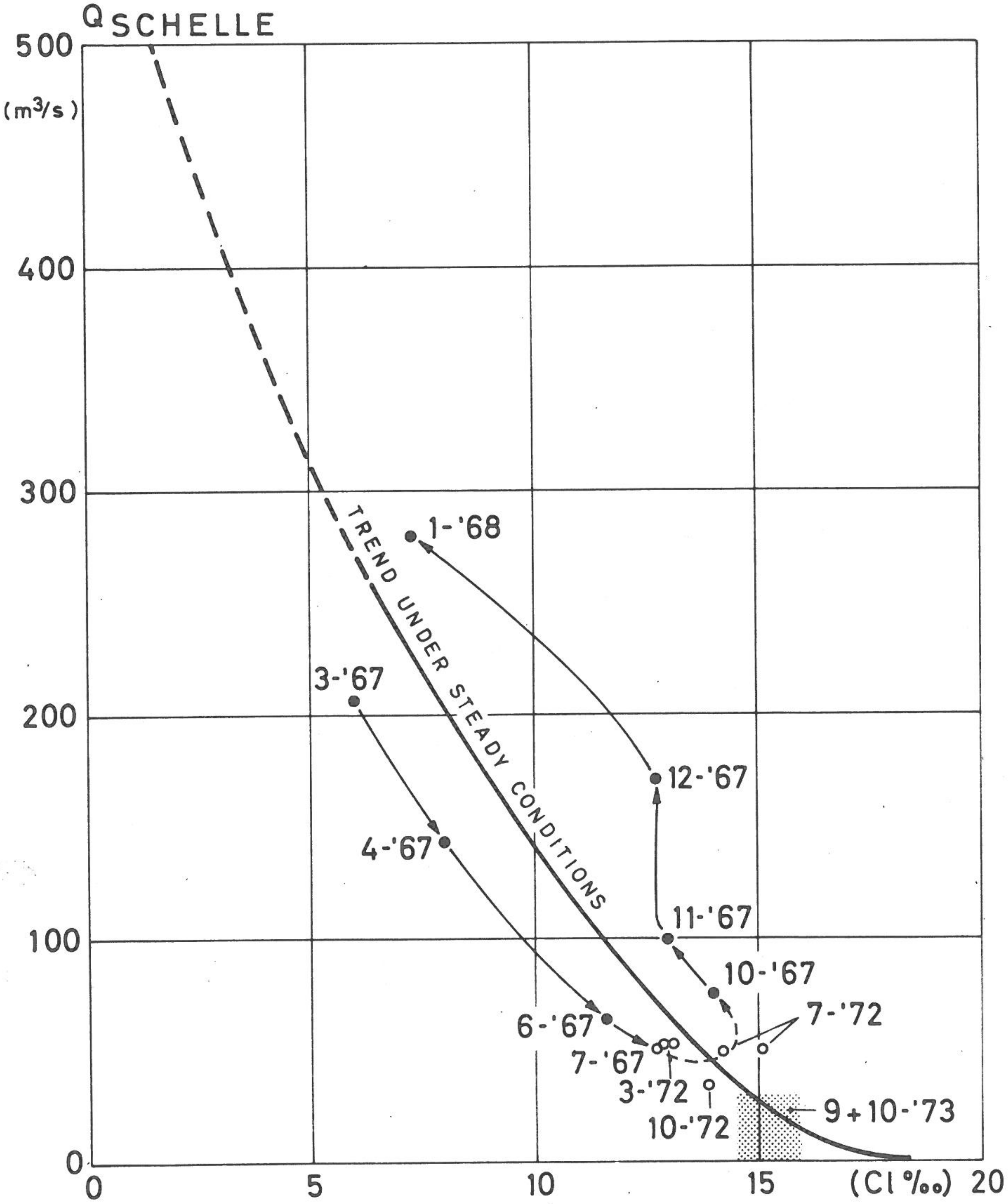

FIG. 14 - RELATION BETWEEN RIVERDISCHARGE AT SCHELLE AND CHLORINITY NEAR WALSOORDEN (km 40) AT SLACK HIGH WATER

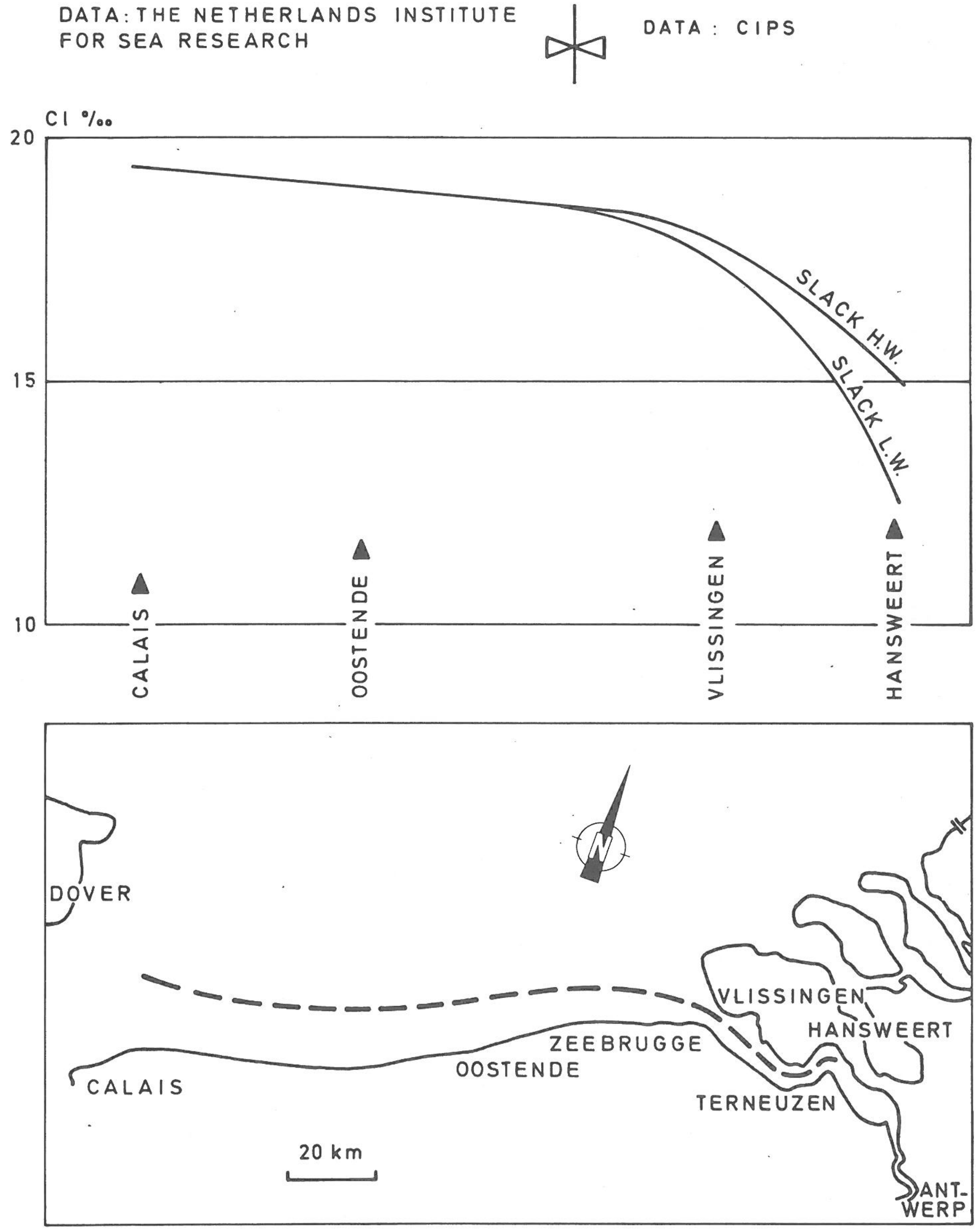

FIG. 15 - EVOLUTION OF SALINITY ALONG A PROFILE FROM THE CHANNEL (NORTH SEA) TO HANSWEERT (SCHELDT) SEPTEMBER 1973

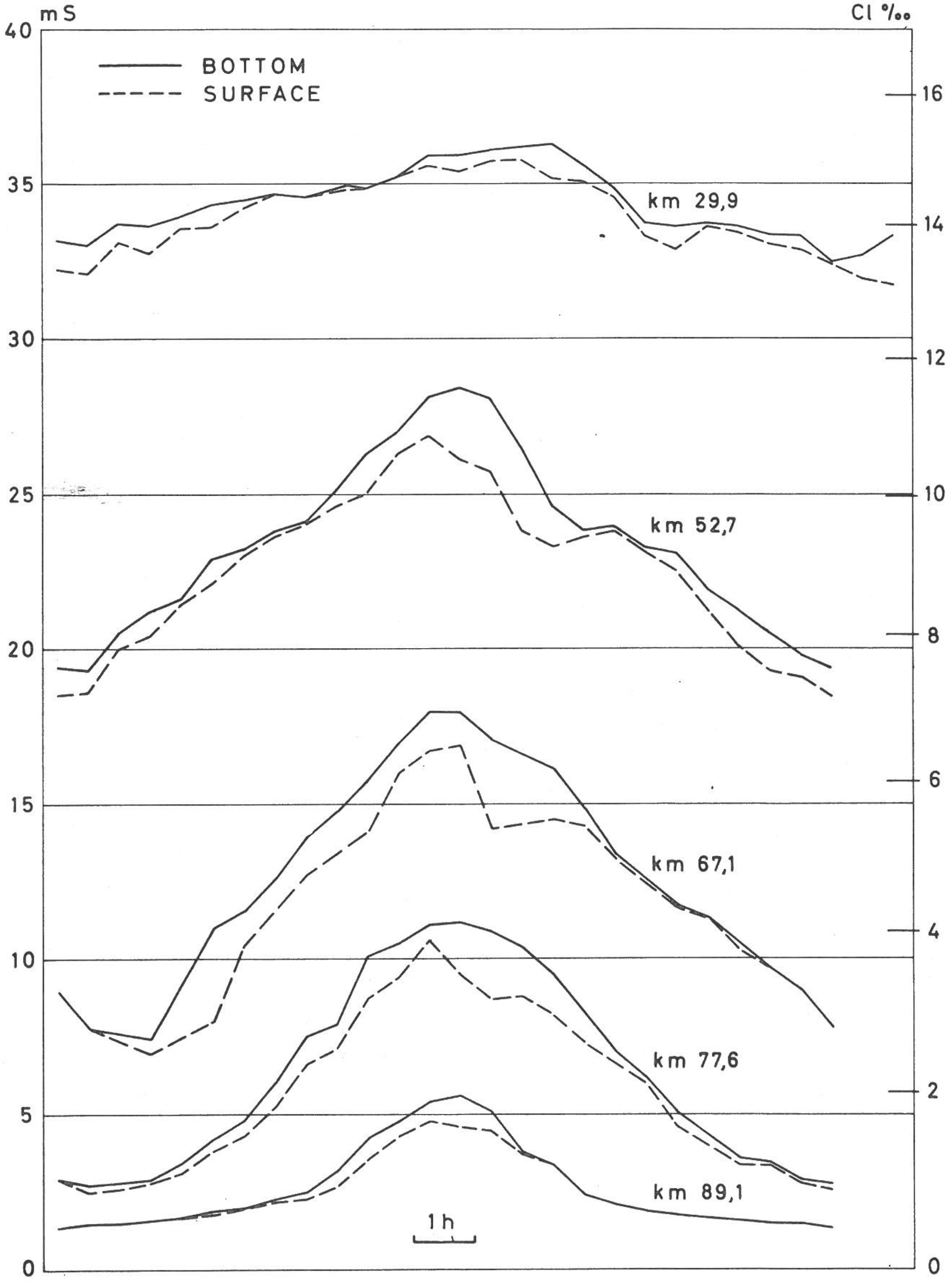

FIG. 16 - CHLORINITY VARIATION WITH TIDE
PERIOD OCTOBER 1972 - JANUARY 1973

In Vlissingen, there is still a measurable variation of salinity with river-discharge.
The longitudinal salinity profile of the Scheldt estuary was already described by CODDE (1951, 1958).

The downstream boundary of the zone 2 corresponds with a discontinuity in the longitudinal profile of both the wet area and the width(for a mean fresh water inflow).
This confirms that the mixing process is determined by the hydrographical properties of the estuary.(Sterling and Peters 1973).

The longitudinal salinity profile shift, up and downstream with changing river-discharge, modified immediately the upper limit of the of the zone 2
The change in salinity at downstream stations occurs after a certain lag in time(see Fig. 14).

Variation of the longitudinal salinity with tide was already described by CODDE in 1958. Analogue results are in Fig. 6.

Salinity variations with tide at fixed stations located between Hemiksem (km 89) and Ossenisse (km 30) on the other hand are represented in Fig. 16.

The amplitude of the variations is maximal in the area Bath-Zandvliet and do not shift much with changing river-discharges.

5. 2. Vertical and lateral salinity distribution

Until recently the Scheldt estuary was generally described as completely homogeneous (CODDE, 1951, 1958).

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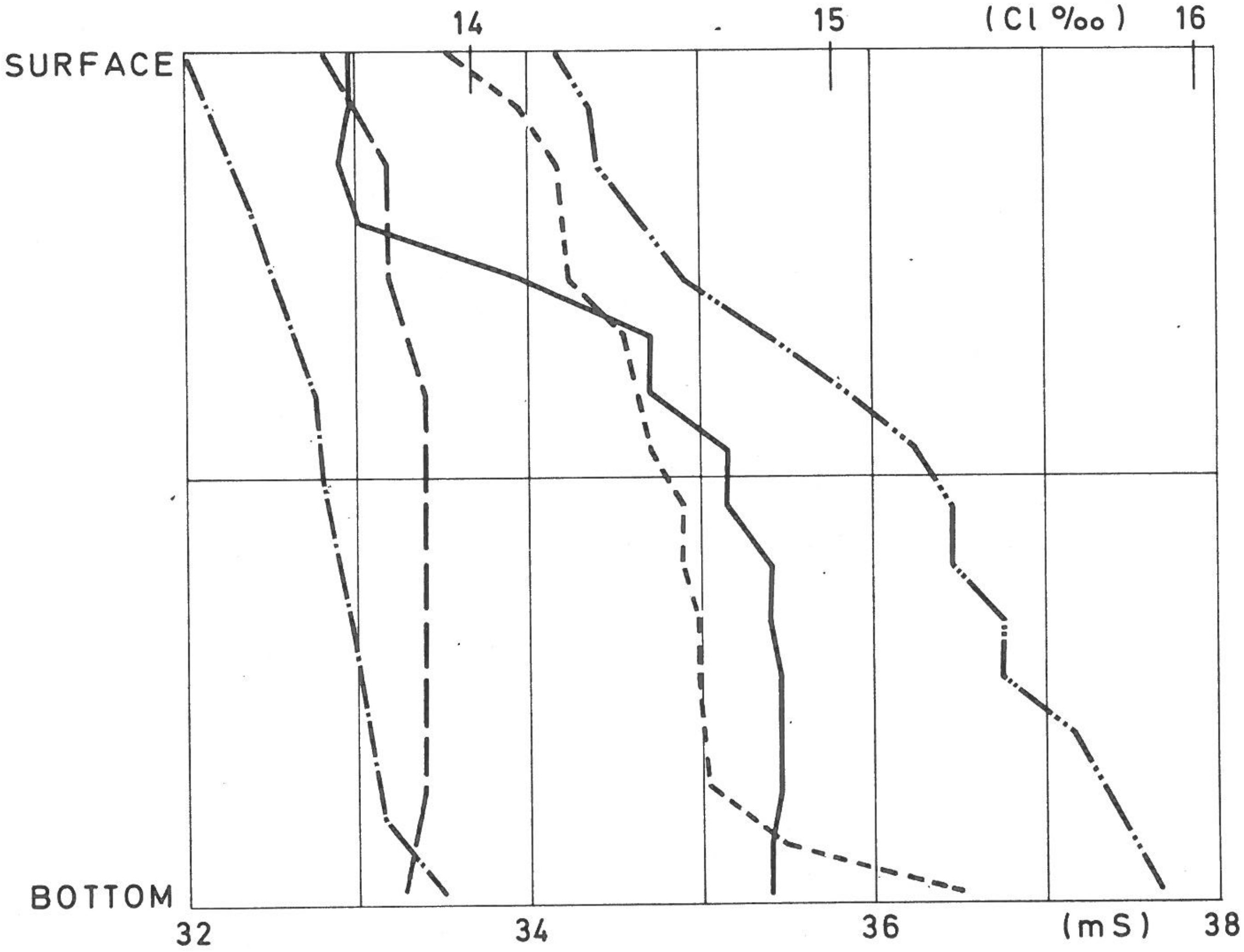

FIG. 17 - VERTICAL SALINITY GRADIENTS IN THE SCHELDT ESTUARY MIDDELGAT - JANUARY 1973

However recent investigations revealed the existence of vertical salinity gradients in the brackish water zone of the estuary. An indication of the possible influence of stratification on currents could only be found in a report of the Rijkswaterstaat (1934).

Vertical salinity stratifications appear when longitudinal salinity gradients exist.

The differences of chlorinity between surface and bottom layers are nearly always lower than 1.5 g Cl °/₀₀ and generally do not exceed 0.5 g Cl °/₀₀.

In most cases measurements were made at the edge of the navigation channel and higher values might be found in the deeper zones of the thalweg. It is difficult to predict these salinity differences because they depend upon many parameters such as location of the station, position in the cross-section, moment of the tide, tidal range, river-discharge, configuration of the cross-section etc..

In fact, various forms of vertical salinity gradients could be observed in the Scheldt estuary , as already demonstrated in Fig. 17.

Salinity stratification is given by both salinity differences between surface and bottom layers and the shape of the curve of the vertical salinity variation(cfr. Fig. 11, 16 and 17).

The degree of stratification was represented in three different was (cfr. Fig. 18, 19 and 20).

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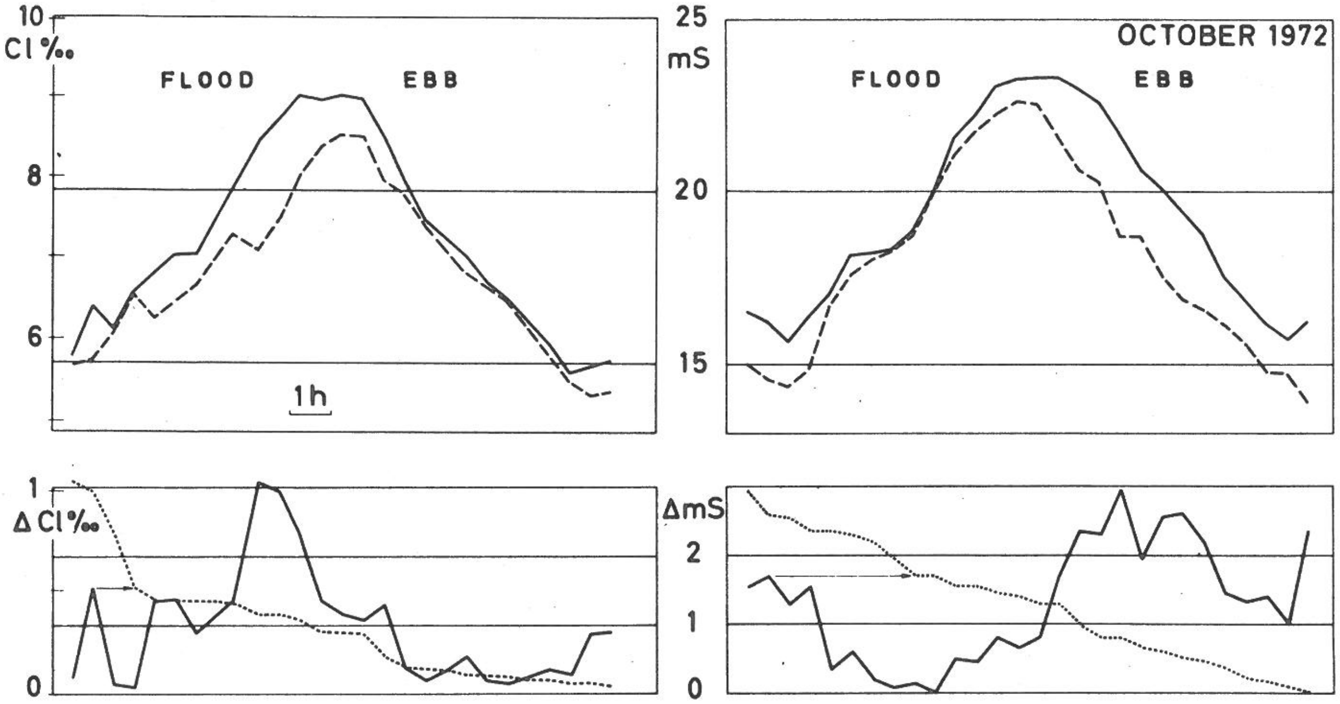

FIG. 18a - SALINITY STRATIFICATION IN TWO STATIONS OF CROSS-SECTION DOEL

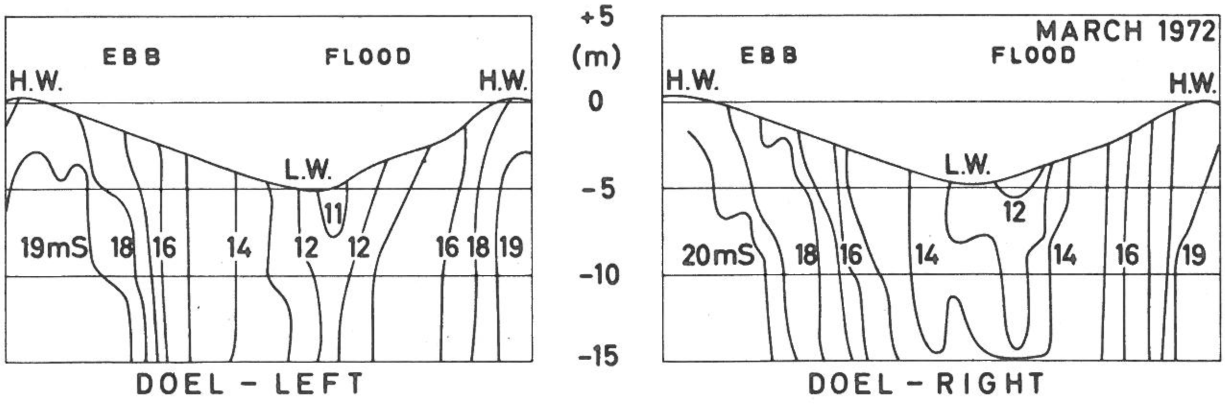

FIG. 18b-SALINITY STRATIFICATION IN TWO STATIONS OF CROSS-SECTION DOEL

The first one consists in the representation of the evolution of both surface and bottom salinities during the tidal cycle.

The second one consists in a classification of salinity differences between bottom and surface layers in decreasing order of the values measured every 30 minutes during a complete tidal cycle.

The third one consists in a representation of the isohalines in a depth-time diagram.

5. 2. 1. Differences of stratification in a cross-section.

a) In a single channel

Stratification may vary in a single channel. However, the average situation during the whole tidal cycle may differ greatly or not from one channel to **another**.
Two examples are given for the cross-sections in Doel and in Perkpolder (in the Zuidergat).

- Doel.

In 1972 the salinity variation during tidal cycles were measured at the left edge and the right edge of the navigation channel in March, July and October. The river-discharge was always quite constant. The evolution of salinities at both edges was comparable. The results are represented in three different ways as described in the foregoing chapter 5. 2 (cfr. Fig. 18 a and b).

Stratification at the left border of the channel occurs mainly during flood, at the right border mainly during ebb.

The 25 values of salinity differences (resulting from the measurements made in the surface and bottom layers) were classified in decreasing order, the highest value at the left, the lowest at the right. It can easily be seen that the average stratification is lower at the left edge, Fig. 18b, shows

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the third manner of representation. The differences between ebb and flood appear also very clearly.

The data of the three campaigns are given in Table II .

Date	Monthly average river-discharge in Schelle (m3/sec)	Average salinity difference		Ratio $\frac{LB}{RB}$
		left border (LB)	right border (RB)	
20-21.3.72	58.5	0.305	0.370	0.824
26-27.9.72	49.8	0.354	0.266	1.330
4-5.10.72	34.0	0.301	0.419	0.718
Average	47.4	0.320	0.351	0.911

-Zuidergat.

In the "Zuidergat", stratification near the left border of the navigation channel was much higher than near the right one. This is probably due to water circulations between the "Zuidergat" (ebb channel) and the "Schaar van Waarde" (flood channel) over a shoal lying at the right hand side of the navigation channel of the "Zuidergat."

The influence of Coriolis forces could not be demonstrated clearly although from a theoretical point of view (cfr. PRITCHARD, 1967) it should exist in the Western Scheldt estuary.

b) <u>In a multiple channel system.</u> (cfr. Fig. 19).

In a multiple channel system it is difficult to etablish a cross-section. More attention has been given to salinity variation rather than to magnitudes. Two different types of multiple channel systems were studied.

The cross-section of Perkpolder constitutes a typical example of a flood and an ebb channel system. The "Schaar van Waarde" (Flood channel) decreases in depth in upstream direction.

The cross-section of both ebb and flood channels are similar.

Salinity stratifications are low in the ebb channel (Zuidergat) and high in the flood channel (Schaar van Waarde). The flow over the shoal separating the ebb and the flood channel, is responsable for the salinity stratification near the shoal.

In the cross-section "Ossenisse" it is difficult to distinguish the ebb from the flood channel from the morphology.
Before 1969, the "Middelgat" was the main channel or ebb channel. The flood channel, "Gat van Ossenisse" ended near Hansweert with a sill called the "Overloop van Hansweert". The sill is eroded, mainly since 1969, and the downstream reach of the "Middelgat" narrowed.

Actually, the "Gat van Ossenisse" is used for navigation. Comparing the salinity stratifications between these two channels (Fig. 19), It appears very clearly, that the "Gat van Ossenisse" is the ebb channel with a slight stratification, and the "Middelgat" the flood channel with a pronounced stratification.

A slight stratification was found in the ebb channels where the depth and the morphology of the cross-sections do not vary much as in the ebb channels. Mixing is important during the whole total cycle (Fig. 19).

A pronounced stratification on the contrary was found in the flood channels or near shoals were the morphology varies considerably with depth during the tidal cycle (Fig. 19).

Comparison of salinity stratification occuring in different cross-sections has to be made very carefully because of the intricated influence of geometric characteristics.

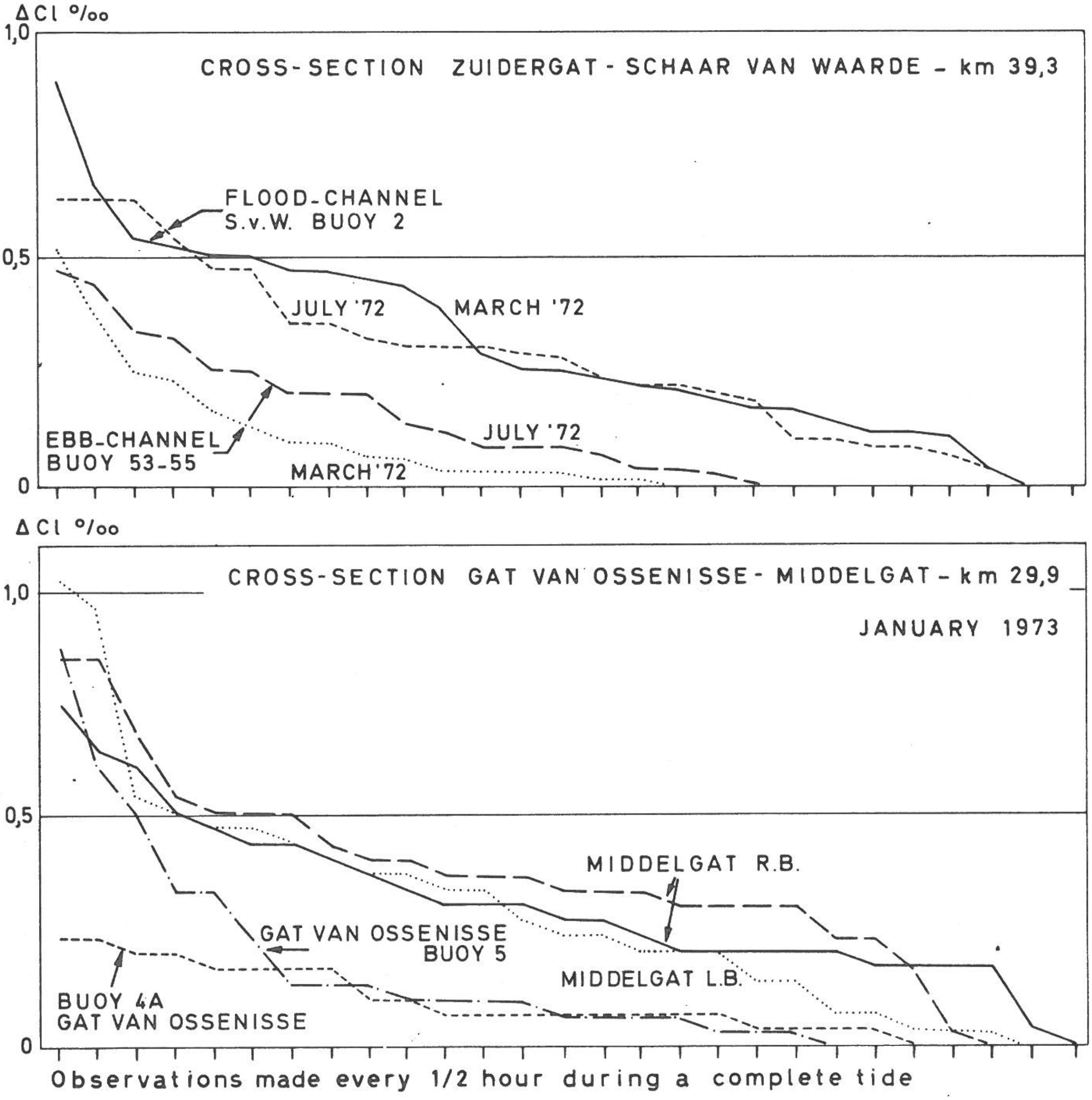

FIG. 19 - CLASSIFIED SALINITY DIFFERENCES BETWEEN SURFACE AND BOTTOM IN CROSS-SECTIONS

5. 2. 2. Longitudinal variation of stratification.

All the measurements made in 1972 and 1973 at fixed stations are comparable because the river-discharge and salinity remained rather constant. The evolution of salinity along the longitudinal profile may be represented in two different ways by classifying salinity differences between surface and bottom, or by the evolution of the average salinity difference between these two.

a) Classification of salinity differences between surface and bottom layers.

Measurements made in March 1972, July 1972, October 1972 Januari 1973 between Hemiksem and Ossenisse are represented in Fig. 20.

Salinity stratification increases from Hemiksem (km 89) to Doel (km 61), and decreases from Doel to Ossenisse (km 30). The distribution during the tidal cycle also seems to be important.

b) Evolution along the estuary of the salinity stratification averaged over a complete tidal cycle (cfr. Fig. 21).

In 1972 the salinity stratification occured till 105 km upstream from Vlissingen. This area is the upper boundary of the zone 2 at slack high water. At Hemiksem (km 89) the salinity varies only during a part of the tidal cycle, when the upper limit of the zone 2 is situated upstream from this station. Only during that period stratification may be observed.

At Hoboken (km 85), which under normal conditions is the limit of the zone 2 at slack LW. a salinity stratification may exist

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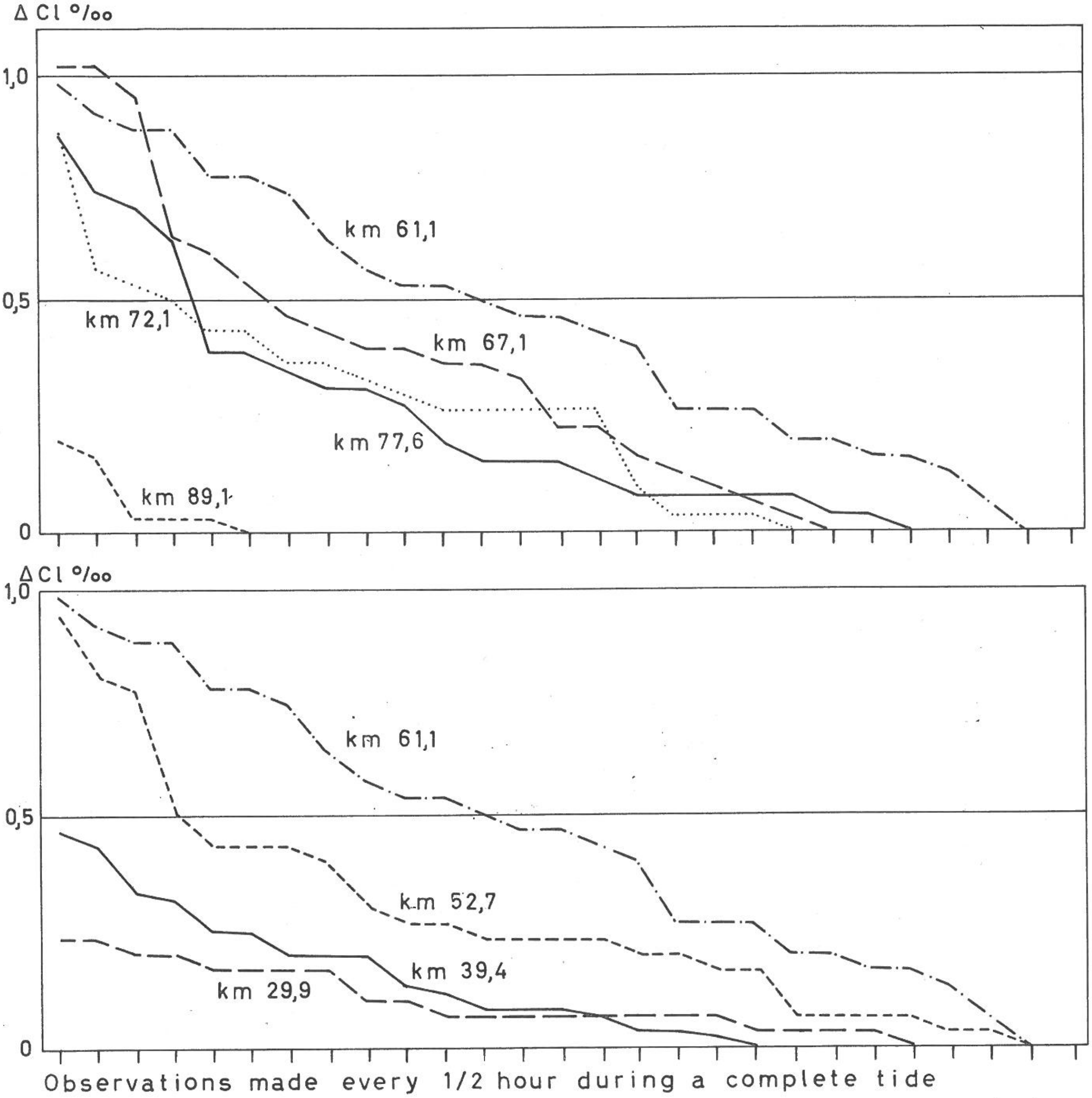

FIG. 20 - EXAMPLES OF CLASSIFIED SALINITY DIFFERENCES BETWEEN SURFACE AND BOTTOM IN DIFFERENT STATIONS LOCATED ALONG THE MAIN CHANNEL BETWEEN HEMIKSEM AND GAT VAN OSSENISSE — PERIOD MARCH 1972 - JANUARY 1973

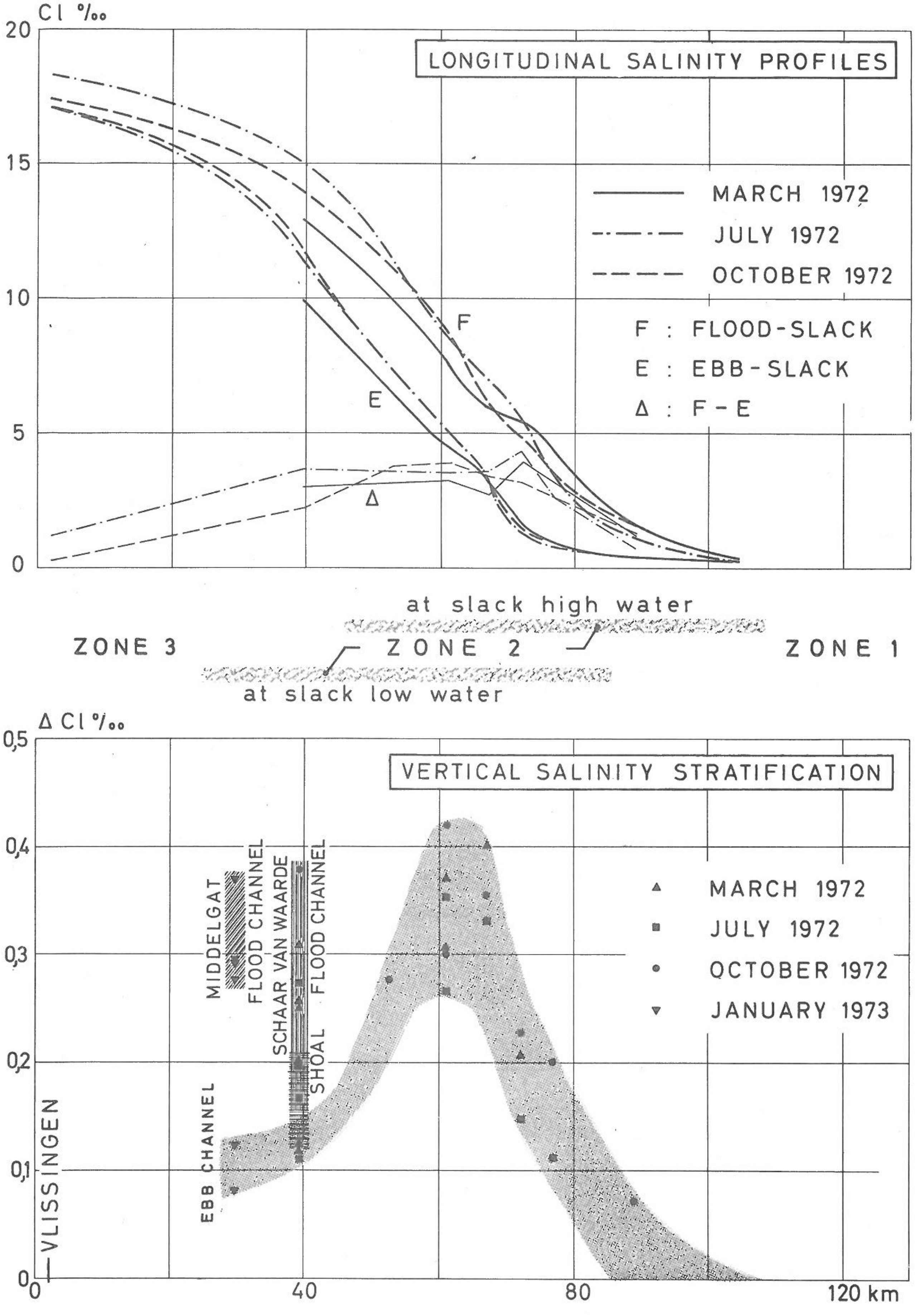

FIG. 21 - CHLORINITY CHARACTERISTICS OF SCHELDT ESTUARY IN 1972 AND 1973

at any moment of the tide. Between Hoboken and Buoy 94 (km 67) the stratification increases to a maximum which is then maintained up to Zandvliet. Further downstream the stratification decreases to Baalhoek (km 45), which is the downstream boundary of the zone 2 at slack HW. There is still a slight decrease to Ossenisse lying a few kilometers upstream the lower limit of the zone 2 at slack LW.

For 1972, no measurements from downstream Ossenisse are available. We therefore suppose that the stratification tends to zero in the open sea.

On the same figure we may compare the values of the average salinity stratification in the flood channels and near the shoals (see chapter 5. 2. 1) downstream Baalhoek. They can be of the same order of magnitude as the maximum values observed in the area Zandvliet-Fort De Parel (Buoy 94).

For the period March 1972-Oktober 1972 the salinity variations during tides, the salinity stratifications and the longitudinal salinity gradients were maximal in the area Baalhoek-Antwerp.

This confirms the existence of zone 2 where salinity stratification strongly influences the waterciculation (PETERS 1972, STERLING and PETERS 1973).

5. 3. Influence of variation of river-discharge on the salinity distribution.

Variation of river-discharge will modifie both salinity magnitudes and salinity stratification.

We already mentioned the longitudinal shift of isohalines under influence of changing river-discharges (cfr. Fig. 10).

In Fig. 14 the salinity variations as a result of the changing riverflow in 1967 has the shape of an hysteresis. For different reasons it is not possible to find a good correlation between salinities and river-discharges.

First, steady conditions of fresh water inflow seldom exist, in the Scheldt estuary.

Second, salinity of the North Sea varies throughout the year (cfr. chapter 4. 1. 2).

The trend of the relation between salinity and river-discharge indicated in Fig. 14 is given for a constant salinity in the North Sea near the mouth of the estuary (about 18 g Cl/l) and for steady conditions of fresh water inflow. Such conditions occured in 1966 (high river-discharges) and in 1972 (low river-discharges).

This relation could be usefull in comparative studies on, for example, pollution problems or modification of the salinity intrusion after changing the morphology of the river.

For other studies, calculations have to be made with data collected in situ.

In Fig. 14 only salinities measured in the surface layers at slack high water were used. The same relation might be calculated with chlorinities averaged up to depth and time.

During our investigation period (mainly 1972) variations of salinity stratifications could not be observed because of the rather constant fresh water inflow.

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However , it seems realistic to assume that stratification will increase with increasing riverflow. Indeed, as we know from the work of Pritchard (1967) ,the mixing process depends on the ratio of the volume of water flowing upstream the estuary through a given section during the flood tide (flood volume) to the volume of fresh water flowing into the estuary upstream the section during a complete tidal cycle (fresh water volume). The ratios of these volumes vary from the mouth to Gentbrugge, and so does the stratification (STERLING and PETERS 1973).

The flood volume is high at the mouth and decreases fast going upstream, while the fresh water volume is small and increases slightly from Gentbrugge to the mouth (Vlissingen).

During a fresh water flood, the fresh water volume varies greatly. From neap tide to spring tide the flood volumes vary slightly.. The ratios flood volume-fresh water volume at fixed station depend thus primarily on the fresh water inflow.

When this ratio is small (on the order of unity) the stratification and circulation approximates those of a salt wedge estuary; when the ratio becomes larger (on the order of from 10 to 100), the waterway has the characteristics described for a partially mixed estuary; vertically homogeneous estuaries occur only when the ratio if of the order of 1, 000. (PRITCHARD 1967).

At Fig. 22 are indicated the positions of these different ratios for different river-discharges. For a mean river-discharge (about 80 m3/s in Schelle) the zone of the estuary where the ratio passes from 10 to 100 correspond roughly with zone 2 mentioned in chapter 5. 1. Going downstream in zone 1 , the ratio increases up to 200 at Vlissingen (km 2) and stratification becomes very low.

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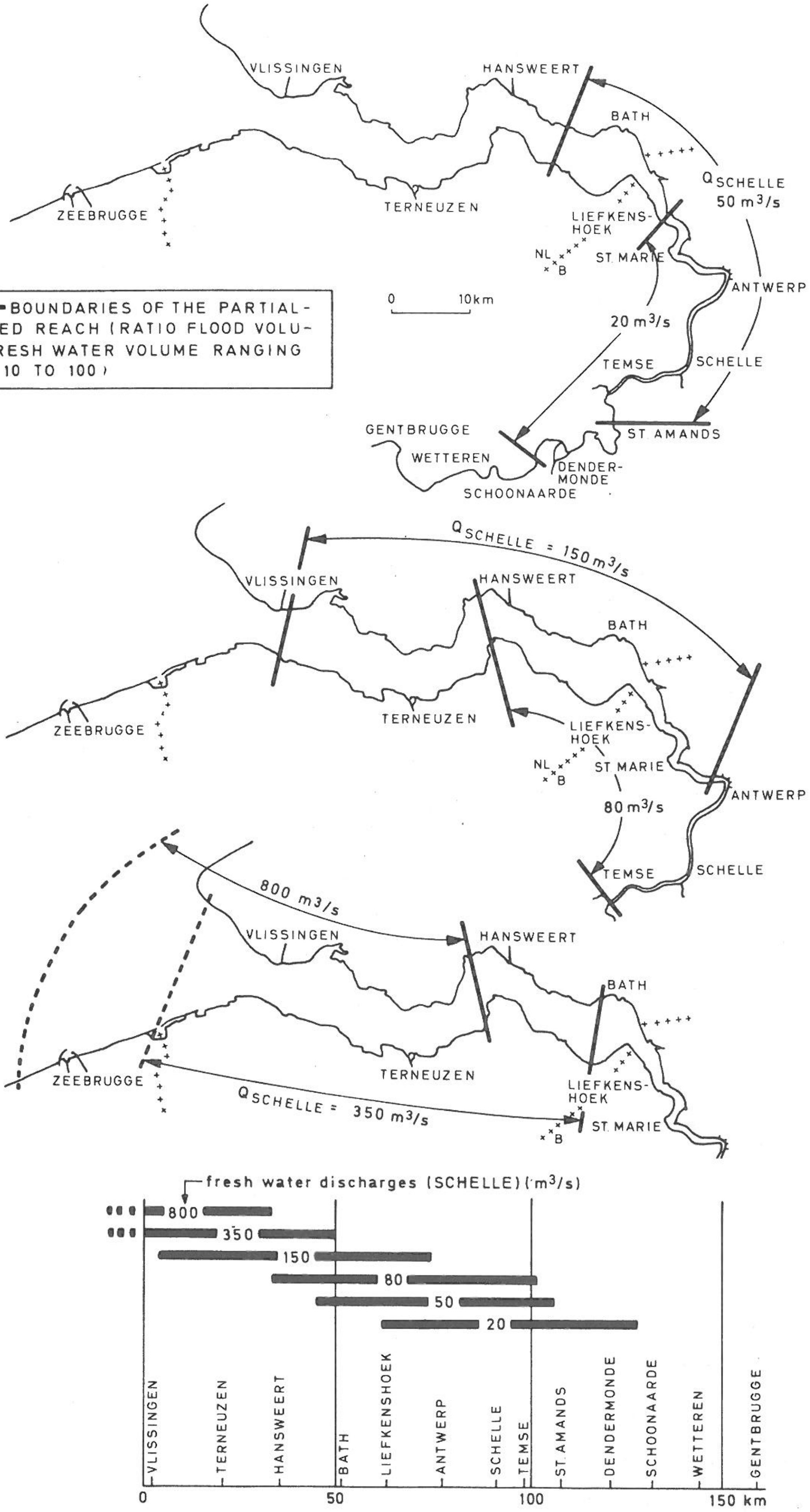

FIG. 22 - RATIOS FLOOD VOLUME / FRESH WATER VOLUME FOR DIFFERENT RATES OF FRESH WATER INFLOW

When the river-discharge in Schelle amounts to 150 m3/sec, the ratio flood volume -fresh water volume is about 100 near Vlissingen.

When river-discharges are extremely low, for example about 20 m3/sec in Schelle, the ratio is about 100 near the border between Belgium and Netherland.

At fixed stations, an increase of river-discharge will thus increase salinity stratification, because the mixing in the Scheldt estuary depends primarily on the tides, the ratio flood volume - fresh water volume being generally large in the brackish water zone of the estuary. This could be confirmed by contineous salinity measurements made near the surface and near the bottom at fixed stations along the estuary. The increase of salinity stratification may be lessened because of an increase of eddy diffusivity (WOLLAST 1973 in preparation).

There is furthermore a certain time lapse between the variations of fresh water inflow and the variations of salinity and salinity stratification. This phenomenon is called "buffering effect" (BOWDEN 1967).
The effect of a fresh water flood will first be noticed at the upstream end of the brackish water zone of the estuary and later on more downstream.

GENERAL CONCLUSIONS.

The Western-Scheldt is a moderately stratified estuary. It can be devided in three parts, called zone 1, 2 and 3 .

For mean rates of fresh water inflow, these zones extend respectively from Gentbrugge to the Rupelmouth, from the Rupelmouth to Hansweert, and from Hansweert to the North Sea.

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Zone 1 is characterized by a rather constant and very low salinity (in most cases limnetic).

Zone 2 has the characteristics of a partially mixed estuary.
In this zone the highest values of vertical , horizontal and lateral salinity gradients are encountered.

Zone 3 has the characteristics of a well mixed estuary with low vertical and horizontal salinity gradients decreasing in seaward direction.

Worth noticing is the fact that in this zone the flood channels have a more pronounced vertical salinity stratification than the ebb channels.

As a consequence of extreme river-discharges, the longitudinal shift of the boundaries of zone 2 may be considerable and amounts to more than 50 km .

For hydraulical studies which do not take into account the influence of salinities, the limits of the estuary may be fixed at Vlissingen and at the dams of the Scheldt and his tributaries.
Examples are calculations on tides or mean currents.

For all studies involving the mixing process of seawater and fresh water, the existence of the three zones of the Western-Scheldt estuary has to be taken into account in the choice of the boundaries of the mathematical models.

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Acknowledgment

We are grateful to the many contributors of this manuscript. We would like to mention some of them.

Dr. R. Wollast gave freely of his time and knowledge in discussing and commenting with us the phenomenons observed.

Dr. Ir. E. Jaspers reviewed the manuscript.

A number of colleagues have made data available to us. These include Dr. K. Vaas, Drs. R. Peelen and Drs. C. Bakker, Delta Institute for Hydrobiological Research, Yerseke, Ir. X. Broosens, Provincial Institute for Hygien, Antwerp, Dr. R. Wollast, Laboratory of Industrial Chemistry (Free University Brussels), and Ir. I. Coen from the Hydrographical Service in Antwerp.

Laboratory facilities were provided by Ir. A. Sterling, Laboratory of Hydraulic Research, Borgerhout, Prof. Dr. F. Evens, Laboratory of General Biology, State University Center Antwerp, Dr. K. Vaas, Delta Institute, Yerseke, and Prof. Dr. G. Persoone, Laboratory for Biological Research in Environmental Pollution, State University Ghent.

Vessel facilities were provided by the staff and personnel of the Belgian Hydrographical Service in Antwerp, the Royal Belgian Navy, the Department of Roads and Waterways in the Netherlands and the Delta Institute for Hydrobiological Research, Yerseke.

Finally we are indebted to our devoted research technicians, particularly M. E. Biebout and M. J. Engels.

* * *

LITERATURE CITED

ANONYMOUS Bulletin de l'Institut Royal Météorologique.

ANONYMOUS, 1934. Verslag over de in 1930, 31 en 32 op de Westerschelde verrichte metingen en waarnemingen.

ANONYMOUS, 1959. Symposium on the Classification of Brackish Waters. Final Resolution. Archo-Oceanogr. Limnol , 11 (suppl).

ANONYMOUS, 1964. Stroomkaart Westerschelde. Chef Hydrografie - Den Haag.

ANONYMOUS, 1966. Standard methods for the examination of water, sewage and industrial wastes. Americ. Public. Health. Assoc. 12 th. Edit.

ANONYMOUS, 1972. Modèle Mathématique. Projet Mer - Comité Interministériel de Programmation Scientifique-Belgique.

BASTIN, A. , 1964. Sedimentologische kaarten Westerschelde (unpublished).

BOWDEN, K. F. , 1967. Circulation and Diffusion In Estuaries - A. A. A. S. 83 : 15-36.

CASPERS, H. , 1959. Die einteibug der Brackwasser - Regionen in einem Ästuar.

CODDE , R. E. L. , 1951. Etudes physico-chimiques du Bassin Maritime de l'Escaut. Bull. C. Etud. , Recherch. Essais Scient. Construct. Génie Civ. et Hydraul. Fluviale 5 : 333-342.

CODDE, R. E. L. , 1958. Het verloop van het zoutgehalte in de Zeeschelde. Revue-C-Tijdschrift . 1 (6): 1-6.

./..

HARTOG, C. DEN, 1961. Die fanistische Gliederung im südwestniederländischen Deltagebiet.
Int. Revue Ges. Hydrobiol. 46 : 407-418.

DE RIDDER, M. , 1954. Het voorkomen van Zoet - en Brakwater in België. Biol. Jaarb. Dodonaea. 21: 313-317.

DE RIDDER, M. , 1956. Bijdrage tot de kennis van het chemisme der brakke wateren van België.
Biol. Jaarb. Dodonaea 23: 72-103.

DE PAUW, N. , 1971. Milieu en Plankton in de Westerschelde.
Meded. Hydrobiol. Ver. 5 (1) : 3-16.

DE PAUW, N, 1973. Bijdrage tot de ekologische kennis van milieu en plankton in het Westerschelde -estuarium.
Doct. thesis-in preparatie.

DORRESTEIN, R. , 1960. On the distribution of salinity and some other properties of the water in the Ems-estuary.
Verh. Kon. Ned. geol. Mijnb. Gen. geol.serie 19:43-74 .

EGGINCK, H. J. , 1965. Het estuarium als ontvangend water van grote hoeveelheden afvalstoffen. Afvoer van het veenkoloniale afvalwater naar de Eems.
Meded. Rijksinst. voor Zuivering van Afvalwater (R. I. Z. A.) 2 : 144 pag.

PEELEN, R. , 1969. Morfometrisch en hydrometrisch overzicht van het Deltagebied van Rijn, Maas, en Schelde.
Intern. Rapport Delta Inst. Hydrobiol. Onderzoek Yerseke.

PETERS, J. J. , 1967. Rapport de stage - non publié.

./..

PETERS, J. J., 1972. Les transports de sédiments dans l'estuaire de l'Escaut.
Laboratoire de Recherches Hydrauliques - Borgerhout-Anvers.

PRITCHARD, D. W., 1967. Observations of circulation in Coastal Plain Estuaries.
In Estuaries A. A. A. S. 83 : 37-44.

REDEKE, H. C., 1922. Zur Biologie der Niederländischer Brackwassertypen.
Bjdr. Dierk. Amsterdam 23: 72-103.

SCHULTZ, E. A., and H. B., SIMONS, 1957.
Fresh water - salt water density currents, a major cause of siltation in estuaries.
19th. Congress Intern. of Navig. London
Section II-Communication 3.

STERLING, A., and J. J. PETERS, 1973. (en préparation)
Contribution à l'hydrodynamique de l'estuaire de l'Escaut.

STRICKLAND, J. D. H., and J. R. PARSONS, 1965.
A manuel of sea water analysis. Bull. Fish. Bd. Can. 125 : 1-203.

THEUNS, J., and I., COEN, 1973.
Overzicht van de tijwaarnemingen in het zeescheldebekken gedurende het tijdperk 1961-1970. Tijdschrift der Openbare Werken van België. 3 : 139-222.

./..

TIJSSEN, S. B., 1968-1970. Hydrographic and Chemical observations in the Southern Bight, Ann. Biol. 25 :51-59 and 26 : 73-81.

VALCKE, E., and AL., 1966. Stormvloeden op de Schelde. Ministerie van Openbare Werken, België.

VAN MEEL, L., 1972. La Mer du Nord Meridionale - Le Pas de Calais et la Manche. Vol. 1
Etude du Milieu-Patrimoine Inst. Roy. Sc. Nat. Belg. : 1-619.

WARTEL, S., 1972. Sedimentologisch Onderzoek van de Opbouw- van het Schelde estuarium. Doct. thesis Leuven.

WOLFF, W. F., 1973. The estuary as a habitat. An analysis of data of the soft-bottom macrofauna of the estuarine area of the rivers Rhine, Meuse and Scheldt.
Proefschrift Leiden, Brill.

WOLLAST, R., 1967. Contribution à l'étude de l'envasement de l'Escaut.
Lab. Chimie des Solides, U. L. B., 3.

WOLLAST, R., 1973. in preparation.