THE IMPACT OF FLOW PATTERN AND SEDIMENT TRANSPORT ON MAINTENANCE DREDGING IN THE KALLO ACCESS CHANNEL

SAS M. : International Marine & Dredging Consultants N.V
Wilrijkstraat 37-45 bus 4
B - 2200 Antwerpen - Belgium

CLAESSENS J.: Ministerie van Openbare Werken,
Antwerpse Zeediensten
Tavernierskaai
B - 2000 Antwerpen - Belgium

76554

ABSTRACT

In the access channel to the Kallo lock, a sedimentation rate of 1.3 cm/day exits. Hence elaborate maintenance dredging works are required.

To understand how silt enters the access channel and settles out, one should know all water movements. The flow pattern is generated by three fundamental mechanisms :

- tidal filling and emptying of the area
- exchange of water between river and basin caused by the passing flow in the river, which creates a circulation in the access channel, so that water is entrained.
- exchange of salt and fresh water by density currents (due to differences in salinity).

Therefore a programme of field data collection was carried out to measure tidal level, currents, salinity and suspended sediment concentration.

The aims of the associated study are threefold:

(a) the acquisition of data to reconstruct the local flow pattern, with emphasis on the behaviour of bottom and surface layer
(b) the setting up and testing of numerical flow models
(c) the future setting up of a sediment model to enable the prediction of sediment flow patterns and their impact on maintenance procedures and equipment.

This paper describes the field measurements and the results of the flow models.

1. INTRODUCTION

The Western Scheldt is the maritime approach channel to the port of Antwerp. Between the locks and the river, access channels have been dredged to provide the required manoeuvring area for the vessels. The Kallo lock is situated on the left bank (Fig.1). The capital dredging works in the entrance channel were carried out from June 1980 till May 1982. At present a reduced area is maintained with a width of 200 m and a depth of 9m (Fig.2).

In this navigation channel about 1.5 $10^6 m^3$ of siltation occurs annually. The degree of siltation depends clearly on the shape of the sedimentation area, the depth and the influence of saline-fresh water exchanges. The silt transport mechanism is complex and prediction of siltation depends often on a number of uncertain hypotheses. Furthermore the behaviour of silt cannot easily be accommodated in a hydraulic scale model, in contrast with non-cohesive sediment transport.

Hence in situ measurements must permit to acquire enough data for accurrate silt balances and for calibrating mathematical models.

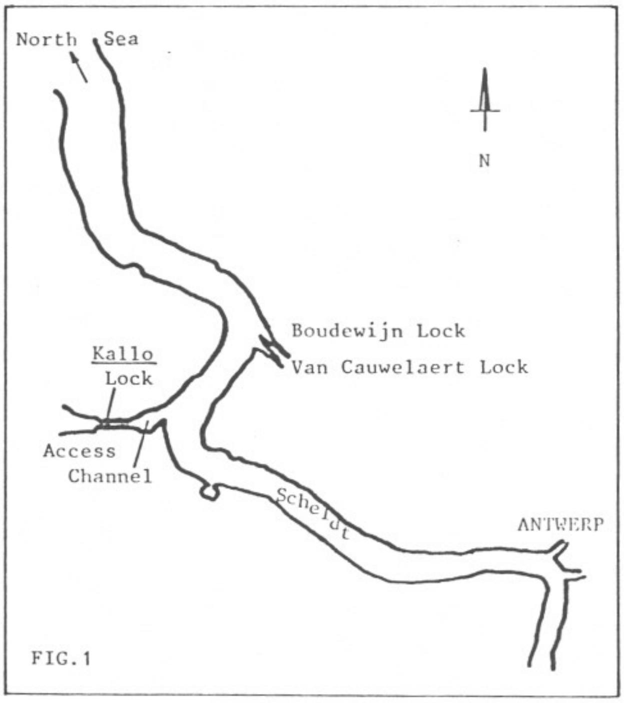


FIG.1

On the basis of both the identification of the siltation mechanism and the simulation of it by such models, the effectiveness of measures against siltation or alternative maintenance dredging works can be evaluated.

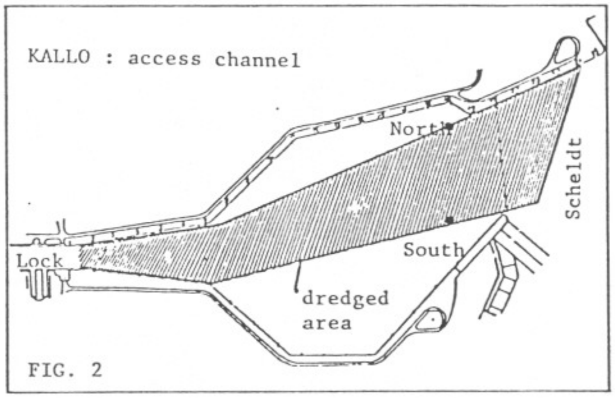


FIG. 2

2. SILT INTRUSION INTO THE ACCESS CHANNEL

The transport of silt into the entrance channel can occur in different ways.
First of all it can settle out from a homogeneous suspension at rather low concentrations. Secondly irregular clouds of silt moving in the river may enter the channel. And finally mud layers can enter over the bottom.
It is anticipated that these mechanisms occur together in the entrance channel. Hence it is hard to generate a picture of the individual transport phenomena. And prior to investigate the silt behaviour, one should understand the flow pattern in the basin.

3. WATER EXCHANGE IN THE ENTRANCE CHANNEL

The currents inside the semi-enclosed access channel to the lock are much weaker (and more complex) than the velocities on the river. Evenso the sediment transport capacity reduces largely in the basin. Consequently an important part of the sediment carried by the penetrating water will settle.
The exchange of water between the access channel and the river is caused by three phenomena (Fig.3).

1. the tidal prism
2. the horizontal eddy at the entrance, generated by the passing flow
3. the density current, due to the difference in salinity between the water in the river and in the basin

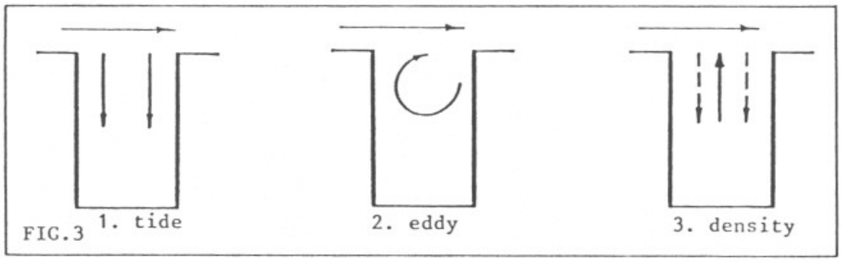


FIG.3 1. tide 2. eddy 3. density

4. FIELD PROGRAMME

Due to the complexity of the flow pattern in the access channel a field study was set up. The programme was made up of several individual exercises, which will be described as separate elements :

1. tidal currents, salinities and suspended sediment
2. float tracking
3. in situ fall velocity of the mud
4. vibrocoring

4.1 Tidal currents, salinities and suspended sediment concentrations

The objective of this exercise was to make observations at 3 selected positions for both spring and neap tide conditions, and high and low salinity values on the river.

All parties were convinced that simultaneous occupation of as many stations as practical was desirable. Nevertheless, no more than three could be attempted because of the problems of finding sufficient suitable vessels and of assembling enough sets of specialised measuring equipment.

Furthermore free passage to the lock had to be guaranteed, so that the vessels were anchored outside the central navigation channels (both on the river and in the basin) (Fig.2).

Maximum salinity on the river Scheldt occurs at the end of the summer (September), which is the period with low fresh water from the tributaries.

Minimum salinity was expected in March or April. To restrict the number of observations a neap and a spring tide (3/10/86) were chosen in summer conditions and a check was executed at spring tide at minimum salinity (30/4/87). For practical reasons the neap tide was split up in an ebb (26/9/86) and a flood (30/9/86) exercise within close limits of tidal range. Hence data obtained on different days could be considered simultaneous.

As stated above, current-metering and suspended sediment sampling were realised from vessels at anchor. The underwater unit comprised 2 current meters, a direction sensor, a salinometer, a turbidity probe and a water intake. The latter was used to enable the pumped collection of suspended sediment samples at the surface, mid-depth and near-bed. Readings were obtained over the desired tidal cycle at 30 minutes intervals and with 1 m spacing in the vertical for the depth profiles.

4.2 Float tracking

Special attention has been payed to float tracking. Prior investigations revealed the presence of two layers flowing in opposite directions, mainly driven by differences in density. Since the current data from the anchored vessel observations were limited to one cross section, float tracks were to reveal information on the flow pattern in the basin. Again, traffic in the entrance channel couldn't be stopped, so a procedure with one vessel was worked out.

Floats of different types were used :

- surface floats:they were made of wood, 1.65 m long and ballasted to have enough draught.
- subsurface floats:they consisted of a submerged aluminium body connected to a small surface float by a thin adjustable line. The immersed depth was chosen so that information was gathered on successive depths by releasing several floats synchronously.

The floats were tracked by a vessel using the radio positioning unit of an automatic survey system. In this way the vessel could handle (and keep track of) up to 20 floats with a positioning frequency of at least once in 10 minutes, spread over an area of 1.5 by 0.5 km.

Two surveys were undertaken : one on 1/10/86 in summer conditions, one on 30/4/87, concurrently with the winter spring tide current, salinity and suspended sediment observations.

4.3 In situ fall velocity of mud

The settling velocity of fine cohesive sediment particles depends upon the degree of flocculation, which depends on the type of mud, the water salinity, the concentration of the suspension, the temperature and the degree of turbulence. In principle higher concentration leads to greater settling velocities, caused by progressive flocculation. This acceleration continues till the concentration becomes so high that hindered settling occurs, owing to the water displacement. The limit for hindered settling is often determined around 2000 to 5000 ppm.

Owen has shown that especially due to the effect of turbulence, there are great differences between the settling velocities of mud flocs in nature and those measured in laboratory (ref. 1).

For this reason a field survey was carried out in the entrance channel. The Owen-tube (ref.2) was used to take undisturbed samples of the flow with mud flocs in their natural state. In situations with suspended concentrations greater than about 50 mg/l, this instrument allows accurate estimation of settling velocities. For this reason 10 samples were taken near-bed to catch enough solid matter.

Although the bottom-withdrawal tube has been used worldwide, a new field instrument has been proposed, called the side-withdrawal tube, which shows accurate results for initial concentrations larger than 20 mg/l (ref.9). It is out of the scope of this paper to discuss factors influencing the settling velocity (ref. 3,4,5,6,7,8) or the choice of an adequate instrument (ref. 9,10), hence we refer to literature.

In general a reasonbale assumption for the settling velocity in brackish water is 0.5 mm/s at low silt concentrations. The objective of the field survey was to check the order of magnitude of the settling velocity and the variation of this silt property with increasing concentrations.

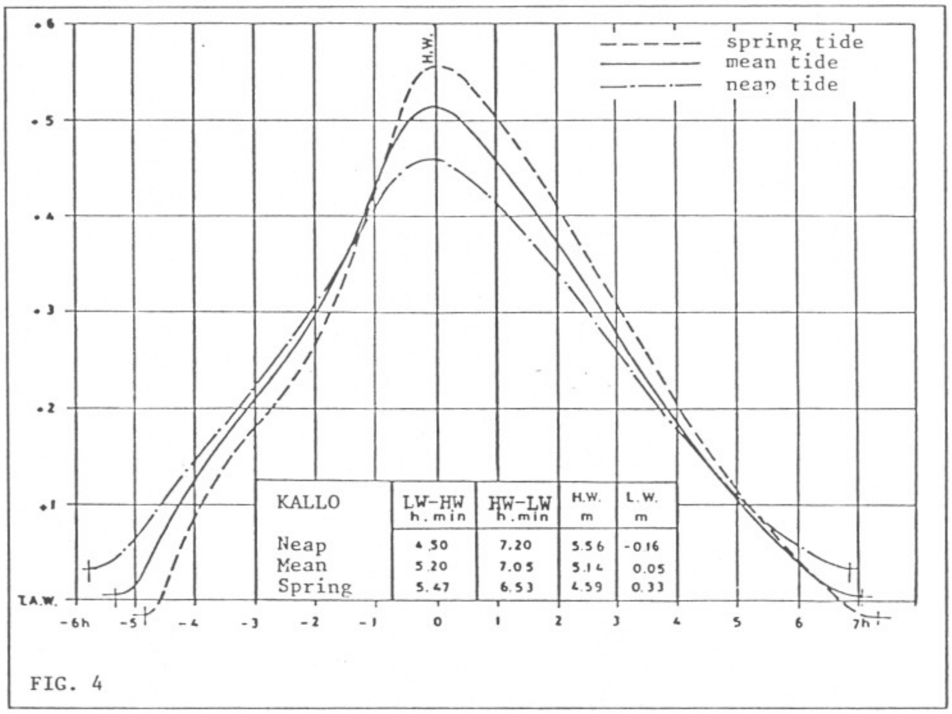
4.4 Mud deposit analysis

It was recognised that a lot of information on the composition of the muddy bed had been collected in an earlier survey (ref. 11). Nevertheless a limited number of bottom samples were taken, using a vibrocoring technique. These samples were used to determine the in situ density of the bed by a radioactive probe. Hence the mass of the sediment on the bed and density profile were determined.

5. RESULTS OF FIELD OBSERVATIONS

5.1 Tidal currents, salinities and suspended sediment concentrations

In Fig. 4 the average tidal curves at spring, mean and neap tide in Kallo are represented (ref. 12).



KALLO	LW-HW h.min	HW-LW h.min	H.W. m	L.W. m
Neap	4.50	7.20	5.56	-0.16
Mean	5.20	7.05	5.14	0.05
Spring	5.47	6.53	4.59	0.33

FIG. 4

The tidal extremes on the respective days were :

	HW (m+TAW)	LW (m+TAW)	Range (m)
26&30/9/86	4.31	0.30	4.01
3/10/86	5.24	-0.35	5.59
30/4/87	5.60	-0.24	5.84

TAW : local reference level (= 0.45 m above chart datum)

The current velocities on the river Scheldt have two velocity peaks during flood tide, one shortly after low water and the other just before high water. The ebb tide is characterised by a somewhat smaller velocity peak followed by a gradual reduction (Fig.5)

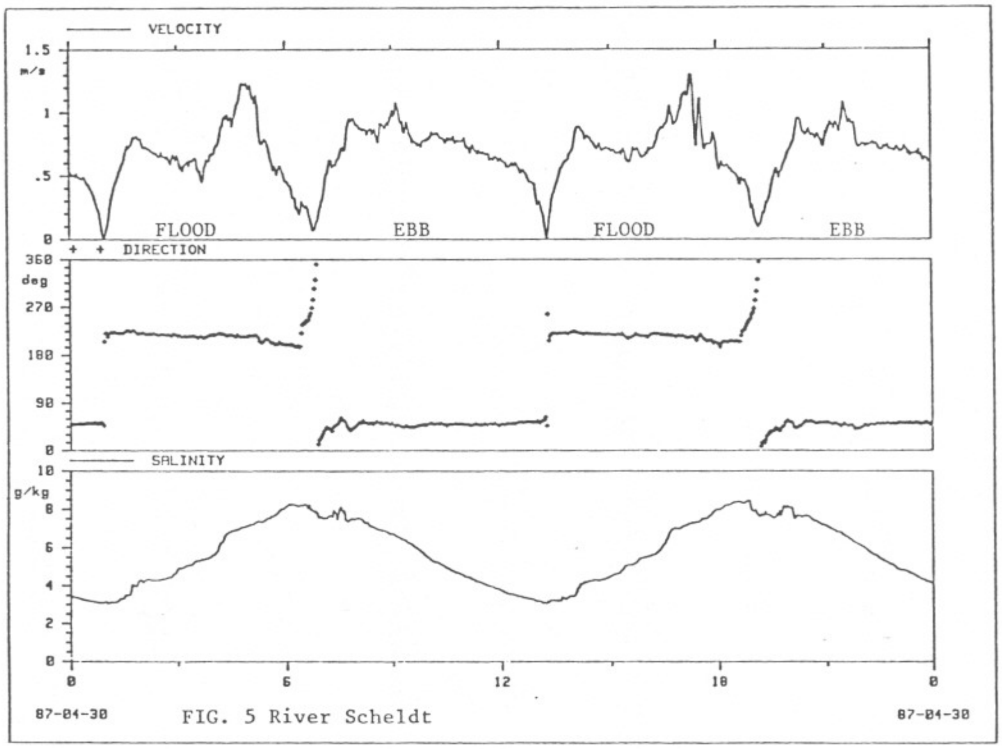


FIG. 5 River Scheldt

The flow pattern in the access channel is more complicated (Fig.6) and almost independent of the freshwater input in the river, and the spring-neap tide cycle. The surface layer tends to flow out of the basin during flood tide with velocities up to 0.20 m/s in the northern part and almost negligible velocities in the southern half. During ebb tide the surface layer shows incoming peak velocities of 0.35 m/s at the northern position and a "slack situation" in the southern part.

This flow pattern corresponds to the incoming (saline) water in the bottom layer, with significant velocities during flood in the southern position (0.4 m/s) and reduced values (0.20 m/s) in the north. The velocities during ebb are much weaker : outflow over the whole width with velocities smaller than 0.15 m/s.

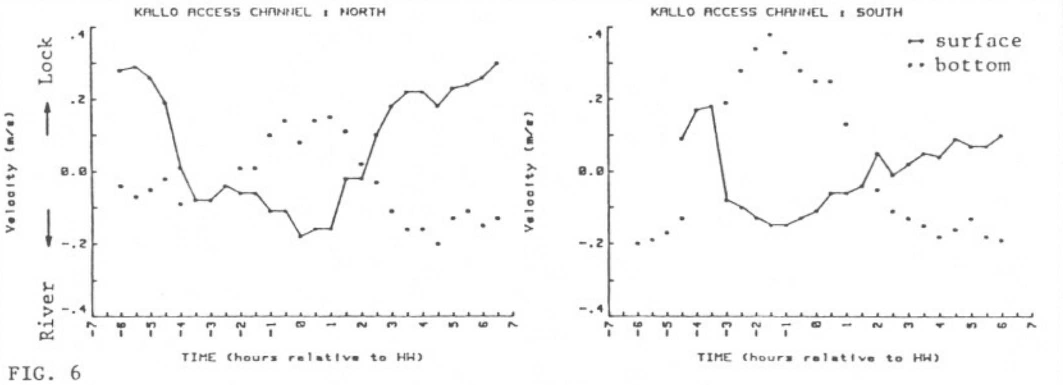


FIG. 6

River salinity in general changes with tidal range and freshwater input. Near Kallo it was found that the salinity range doesn't change much between summer and winter conditions. A typical curve is shown in Fig.5. The maximum occurs near the high water slack, the minimum at the low water slack. Although the mean salinity value varies during the year, the range doesn't change much : 7,5 o/oo in summer (7,5 - 15 o/oo) and 6 o/oo in winter (2 - 8 o/oo).

Whilst the vertical salinity gradients are small in the river, there is a marked difference in salinity between surface and bottom in the access channel: up to 7 o/oo near high water (Fig.7)
This difference in density is the driving force for density-currents, which is the predominant water exchange mechanism.

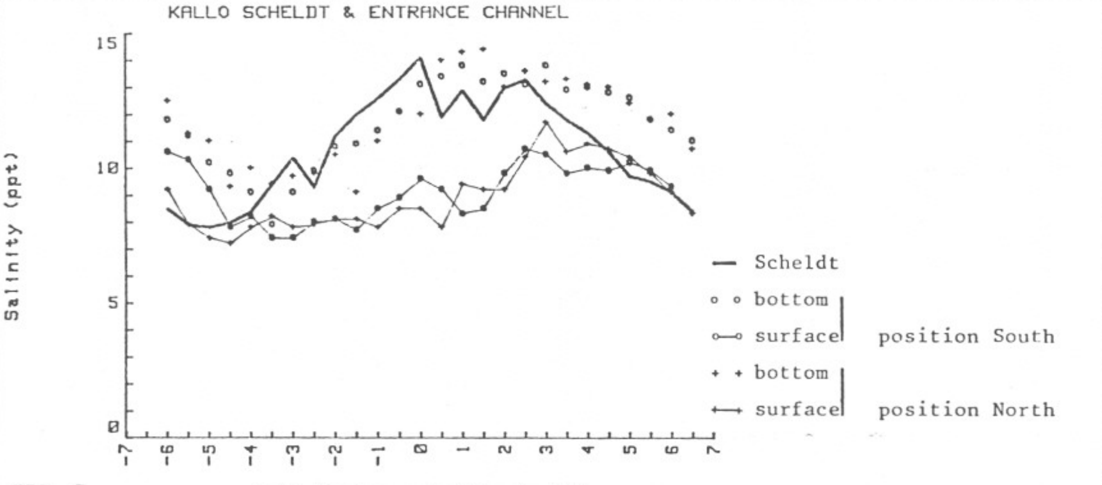


FIG. 7 TIME (hours relative to HW)

The turbidity in the access channel reaches a maximum value near high tide. Especially near bed the turbidity increases during the period of inflowing saline water. During the field investigations it was hard to observe an "analogue" picture of turbidity in the access channel at spring and neap tide, as was obtained for the flow pattern and the salinity. This seems to illustrate that an important part of the silt is entrained into the basin as irregular clouds.

5.2 Float tracking

The float measurements confirmed the observations from the anchored vessels. From about 4 hours before HW the surface and 6 m subsurface floats flow towards the river Scheldt, whilst the bottom layer is flowing from river to lock (8 to 10m subsurface floats). Around high water slack (1h after HW), both layers flow out of the access channel. Later on, the surface layer reverses and after a period of circulation (anti-clockwise), with stagnant water at the southern wall (4 to 5h after HW), the velocities reach a maximum (0.35 up to 0.40 m/s) at the northern side of the access channel. The inflow in the surface layer continues over LW and LW-slack and reverses about 4 hours before HW.
Concurrently the bottom layer flows to the river, discharging the saline water, which is stored in the access channel during flood, into the brackish water on the river.

5.3 In situ fall velocity of mud

The settling velocity of mud flocs was determined using an Owen-tube. This field study gave rather poor results. Probably due to the small velocities and the low concentrations of suspended sediments in situ, the total amount of solids in the tube varied between 0.07 to 0.4 grams. The corresponding settling velocities varied from 0.02 to 1.5 mm/s. Previous investigations reported a value of 0.2 mm/s at 300 ppm for river Scheldt mud (ref.6).

5.4 Mud deposit analysis

Analysis of the bed, performed on samples taken by vibrocoring, revealed an almost uniform mud-deposit, with 4% sand (0.06 - 2mm), 65% silt (0.002-0.06 mm) and 31% finer cohesive material. Only at the southern entrance a somewhat coaser deposit was found. This corresponds with the observations of Vollmers who found that normally the coarse material deposits at the outer edge of the primary eddy (ref. 13) (Fig.8).

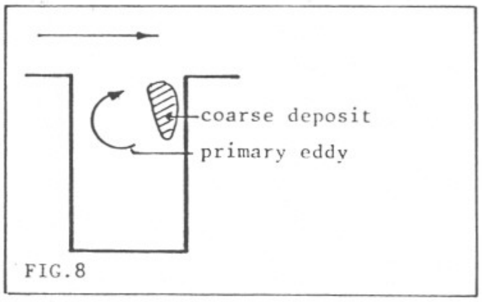


FIG.8

The rheological properties of the mud were determined in a Brookfield-viscometer. The critical yield stress varied between 0.12 and 0.95 N/m^2 for densities between 1.08 kg/l and 1.17 kg/l.
No deposition, consolidation or erosion tests were performed. The erosion and deposition characteristics (rate and critical bed shear stress) were taken, as a first approximation from tests in Hydraulics Research, Wallingford (ref.14)

6. Flow models

6.1 Introduction

Based on the observed concentrations of suspended sediment, it was judged that hydrodynamic and mud transport equations could be solved uncoupled. Since the river Scheldt is a well mixed estuary it was decided to use a 2D-horizontal model to simulate flow on the river, and tidal exchange and eddy circulation in the access channel.
Density currents in the entrance channel itself were calculated in a two layer 1 dimensional model (with longitudinal variation of width and depth-averaged flow characteristics). The latter model was based on an implicit double sweep finite difference method, the former on a finite element solution scheme. The final flow pattern in the access channel was constructed by superposition of the 2D velocity field and the density induced velocity in each layer and grid point.

6.2 Results

The exchange of water between the river and the access channel was modeled in a simplified way : 'density currents' and 'tidal filling and eddy-formation' were considered independent. Nevertheless the results of the models were in agreement with the field observations.

1) The velocities in the access channel are much smaller than those on the river Scheldt: the maximum calculated value in the bottom layer was 0.30 m/s, whereas the observed maximum average velocity was 0.34 m/s.
2) The currents induced by differences in density predominated the exchange phenomenon, as is illustrated in next table.

Exchanged Volume ($10^3 m^3$)

	3/10/86		26&30/9/86		30/4/87	
		%		%		%
Tidal prism	1285	20	945	16	1534	23
Eddy	299	5	184	3	267	4
Density currents	4857	75	4604	81	4729	73
TOTAL :	6440		5773		6530	

3) There are no significant differences between the exchanged volumes at spring or neap tide, nor are there between summer and winter.
4) About 4 hours before HW almost the whole access channel is "fresh", only in the deepest part of the gully remains saline water.
   From that time till high tide the saline water enters the access channels at relatively high velocities and with an increasing thickness of the salty layer. Just before slack water on the river almost the whole basin is saline.
   Between 2 and 6 hours after HW fresh water enters the access channel in the surface layer.

7. MAINTENANCE DREDGING

7.1 Sediment transport

The calculation of sediment transport will be based on a numerical model to solve the convection diffusion equation. This model simulates transport by convection and by diffusion, decay due to physical, chemical or biological processes and growth or decay due to local sources or sinks.
At the moment of writing this paper, the results of the sediment transport model are not yet available. Therefore, a first estimate of daily siltation was calculated.
Bijker and de Nekker (ref.15) compute the tidal component of the siltation (S_{tide}) by multiplying the volume of water exchanged in one tide cycle by the difference in sediment concentration between inflowing and outflowing water.
The influence of the density current is computed using the velocity of the 'dry bed curve' :
$V = 0.45 \quad dgh$ with d = the relative density, g = gravity acceleration, h = the water depth.
Half of the exchanged water enters along the bottom, with the intruding salt wedge and carries high sediment concentrations ($S_{d,bottom}$)
The other half enters along the surface when the saline water retreats ($S_{d,surface}$).

For the Kallo entrance channel the siltation quantities are :

S_{tide} = 72.50 ton/tide
$S_{d,bottom}$ = 372.75 ton/tide
$S_{d,surface}$ = 124.25 ton/tide

TOTAL : 569.50 ton/tide

The daily siltation rate varies between 2000 and 6000 m^3/day, based on variable frequency fathometers (30 - 210 kHz). The above calculated silt deposition matches well with the siltation rate of the soundings (2070 m^3/tide), since the corresponding in situ density lies around 1.25 ton/m^3.

7.2 Impact of flow pattern on maintenance dredging

Most of the entrance channels along the river Scheldt are maintained by a low cost dredging technique. With a trailing suction dredger one can expect a limited efficiency because access is difficult, the area is small and the in situ density of the silt is too low. Therefore mud layers are pushed to the river by a plough towed by a tug (ref. 16).

Hence the question arised whether it could be useful to agitate the sediment loosened by the blade of the plough so that the material could be moved by the currents(with or without installing an airlift).

From the flow measurements and the flow simulations some conclusions were drawn :

- During flood it is of no use to agitate silt in such a way that it stays in the bottom layer. All silt in suspension in this layer is carried towards the lock and will settle in the basin. It is anticipated that e.g. a sidecasting technique can be beneficial, since the upper layer flows towards the river during this period.
- It is obvious that the efficiency of such a dredging method depends much on the distance to the river. The longer the distance, the more silt will settle to the bottom layer and hence be transported into the access channel.
- During ebb tide the velocity in the bottom layer is directed to the river Scheldt. A great deal of silt brought in suspension in this layer will be carried out of the entrance channel. Again the distance to the entrance of the basin is important in determining the final efficiency of the dredging technique.

8. CONCLUSIONS

Most of the objectives of the field studies in the access channel to the lock of Kallo have been met.

Float tracking, together with current data from anchored vessel observations enabled the identification of the local flow pattern. It was found that density currents predominate the water exchange between basin and river, although the density differences are small.

These data were used to calibrate a set of mathematical hydrodynamic models.

From the flow simulations it is anticipated that agitation dredging can be beneficial if proper dredging schemes are scheduled.

It is recognised that the siltation study to date was exploratory. Furthermore it is expected that the simulation of mud transport by mathematical modelling will provide more information on natural siltation rates and on the efficiency of different low cost dredging techniques based on agitation.

Probably this exercise will require more information on mud deposition and erosion and on the consolidation process to enable sediment budget computations.

REFERENCES

1. Owen, M.W., The effect of turbulence on the settling velocity of silt flocs , I.A.H.R Conference, Paris, 1971, Vol. 4, pp 27 - 32.
2. Owen, M.W., Determination of the settling velocities of cohesive muds , Hydraulics Research , Wallingford, Report IT 161, 1976.
3. van Leussen W. ,Laboratory experiments on the settling velicity of mud flocs, Third Int. Symposium on River Sedimentation, University of Mississippi, 1986 , pp. 1803-1812.
4. Puls W., Kuehl H. , Settling velocities of mud flocs; measurements in the field and in the laboratory, Euromech 192, Munich, 1985.
5. Puls W., Kuehl H., Field measurements of the settling velocities of estuarine flocs, Third Int. Symposium on River Sedimentation, University of Mississippi, 1986 , pp. 525-536
6. Burt N.T. , Field settling velocities of estuary muds, in Lectures Notes on Coastal and Estuarine studies, Vol. 14, Springer Verlag, Berlin , 1986 , pp. 126-150.
7. Burt N.T., Stevenson J.R., Monitoring cohesive sediment transport in estuaries, Int. Conference on Measuring Techniques of Hydraulic Phenomena in Offshore Coastal & Inland Waters, London , 1986, pp. 325-335.
8. Ariathurai R., Mehta A.J., Fine Sediments in waterway and harbor shoaling problems, Int. Conference on Coastal and Port Engineering in Developing Countries, Colombo, 1983, pp. 1094 - 1108.
9. Van Rijn L.C. , Nienhuis L.E.A. , In situ determination of fall velocity of suspended sediment, 21st. I.A.H.R Congress, Melbourne , 1985, pp. 144 - 148.
10. Van Rijn L.C. , Schaafsma A.S., Evaluation of measuring instruments for suspended sediment, Int. Conference on Measuring Techniques of Hydraulic Phenomena in Offshore Coastal & Inland Waters, London , 1986, pp. 401-423.
11. Dredging International, Toegangsgeul Kallosluis, Grondonderzoek 1983.
12. Claessens J., Belmans H., Overzicht van de tijwaarnemingen in het Zeescheldebekken gedurende het decenium 1971 - 1980, 1edeel, Tijdschrift der Openbare Werken van België,2, 1984, pp. 117-159.
13. Vollmers H., Harbour inlets on tidal estuaries, 15th Coastal Engineering Conference, Honolulu, 1976, pp.1854 - 1867.
14. Puls W. , Erosion characteristics of estuarine muds, Hydraulics Research, Wallingford, Report IT 265, 1984.
15. Bijker E.W., de Nekker J., Density Currents in Harbours, Course on Coastal Engineering, Part 1 , Delft, 1982, pp. 126 - 146.
16. Marain J., Claessens J., Low budget dredging methods for the maintenance of the entrance channel to the Kallo Lock, 9th International Harbour Congress, Antwerp, 1988.