EDDY-INDUCED CROSS CURRENTS IN THE WESTERSCHELDE ESTUARY: NUMERICAL SIMULATION, PHYSICAL DRIVING MECHANISMS AND NAVIGATION ASSISTANCE

by

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MOTS-CLEFS

Navigation, courants transversaux, modèle mathématique, tourbillon

1. INTRODUCTION

1.1 GROUNDING OF THE FOWAIRET

In September 2005 the Qatari container carrier Fowairet grounded near the Dutch town of Walsoorden in the Westerschelde Estuary on its way to the Port of Antwerp. Surprisingly, the 276.5 m long and 12.5 m draft sea vessel hit a sand bank not during low water but at spring tide high water. When the tide subsequently receded -with low water almost 6 meter below the high water level- the ship, only supported near the centre, experienced serious strains and risked to break over the middle (Figure 1, on the next page). It was feared that containers with dangerous goods would end up in the estuarine waters.

The pilot, specifically trained to guide large vessels from the North Sea to the inland Port of Antwerp, experienced a rare flow phenomenon during which large flow velocity gradients existed with a flow direction switching 180 degrees over the ship's length. This flow pattern was probably caused by a large vortex or eddy.

Figure 1: The Fowairet container carrier grounded

1.2 RESEARCH OBJECTIVES

After these events the Belgian and Dutch authorities started a monitoring and hydraulic research programme studying the problematic cross currents in the Scheldt Estuary. The following research questions were to be answered:

- What is the cause of the cross current?
- Can we predict the cross currents?
- Can we make detailed simulations of the cross current field?
- Are measures possible to reduce the intensity and frequency?

1.3 THE SCHELDT ESTUARY

The River Scheldt is a lowland river originating in the North of France. Over its 350 km course downstream it passes Belgium and The Netherlands to discharge its flow in the Southern North Sea. The cone shaped estuary forming the marine part of the river is about 80 km in length with its banks converging upstream and is referred to as the 'Westerschelde'. The large tidal range (3 – 6 m) forces strong currents and induces a morphology characterised by ebb and flood channels forming so-called morphological cells (Winterwerp et al, 2001). The estuary has a very active morphology with channels and intertidal areas in constant movement. However, the current shape of the estuary is largely the result of anthropogenic influences such as dikes, dredging and dumping, quays and jetties (Wang et al., 2002). Maintenance dredging is performed on the more shallow sills located between the morphological cells where ebb and flood channels cross (Sas et al, 2007).

The sills have been dredged in the past to maintain the navigation channels to the Ports of Antwerp, Ghent and Vlissingen and the maximal bed level has been deepened in the 1970's to 14.5 m below NAP (the Dutch Ordnance Level, about at mean sea level) and in the 1990's to 16 m below NAP. Currently a third deepening/widening of the navigation channel to 17.5 m below NAP is under construction to allow ships with maximum draft of 13.1 m to reach the harbour independently of the tidal phase.

1.4 THE STUDY AREA

The study area is located in the centre of the estuary where it has a width of about four kilometres. Only a small section of the width is available for navigation, the sandflat-channel system is very pronounced with tidal flats at about 0 m NAP and the channels at 20 to 30 meter below NAP (Figure 2 on the next page). Since the tidal prism (the volume of water that has to pass a section during rising and falling tide) is large and the channels are relatively narrow high velocities occur in this part of the estuary. In the study area the navigational channel makes a 180° U-turn (Figure 2) leading to strong secondary flows. At the inner bend of the curved channel, a highly dynamic intertidal sandflat of about 4 km² is located (Figure 2); flow velocities up to over 2 m/s have been recorded in this intertidal area. East of the tidal flat, between sand flat and channel, lies an area of 2x1 km with a bed level at about 8 m below NAP which will prove to be of major importance in the development of a large horizontal eddy and associated cross currents.

In the main channel flow velocity is slightly out of phase with the water level signal. The velocity peaks about 1 hour before high water, and slack water is about 1 hour after high water. Ebb velocity peaks are lower than during flood (Figure 3, on the next page)

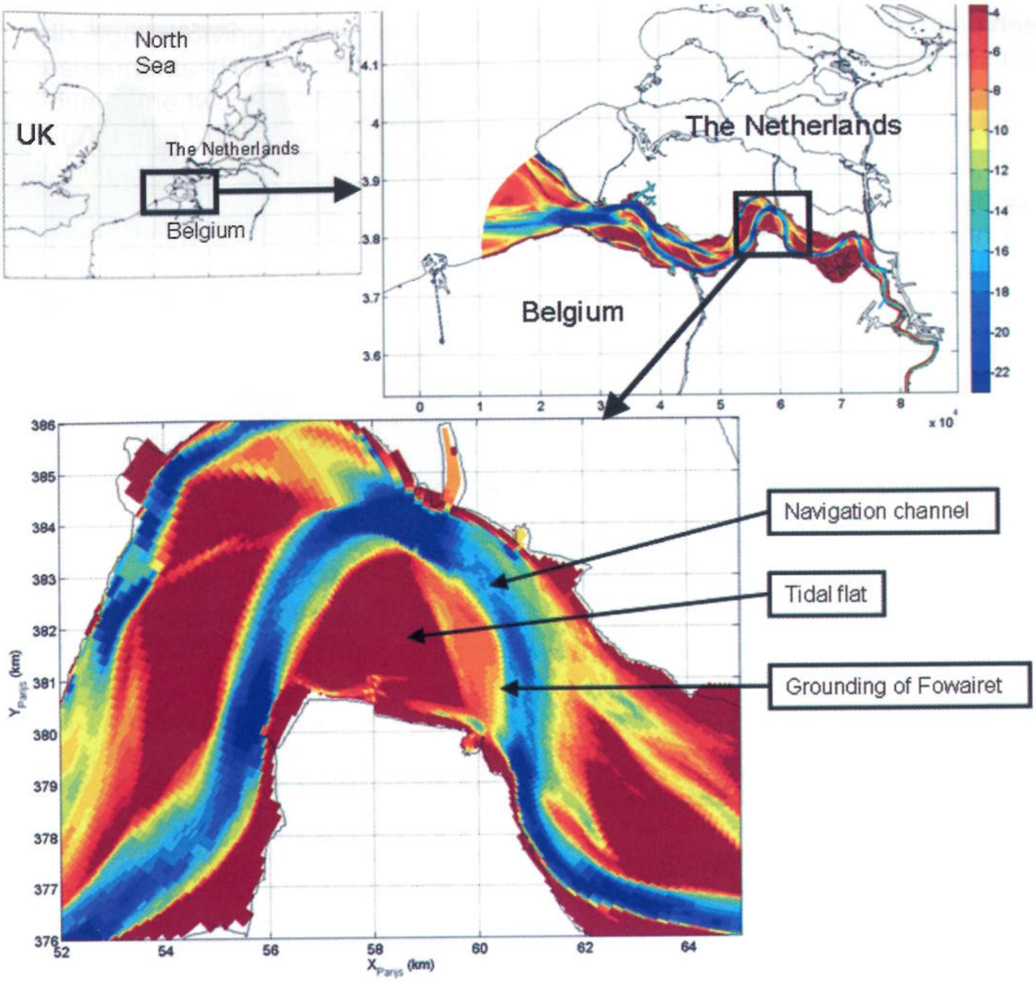


Figure 2: Bathymetry and location of the Westerschelde Estuary (in meter NAP)

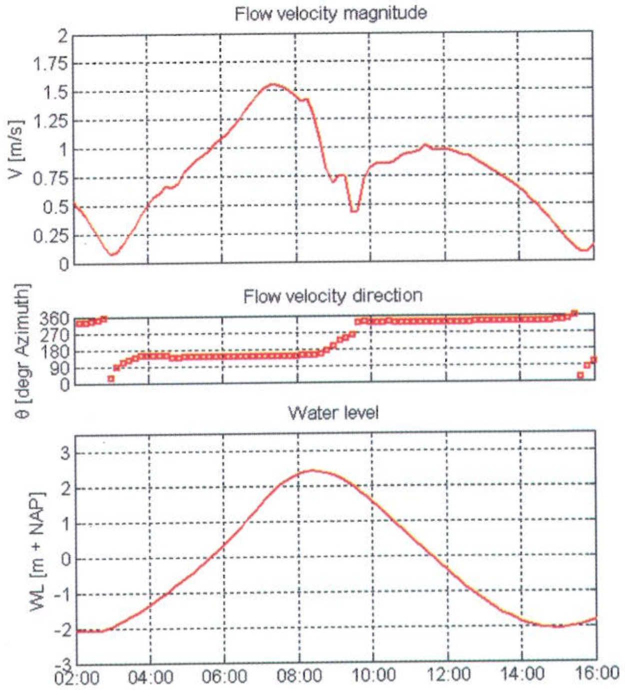


Figure 3: Horizontal tide (top, middle) and vertical tide (bottom) in the main channel of the study area

2. AVAILABLE DATA

The Westerschelde Estuary owes an intensive monitoring network to its economical importance: water level, salinity and temperature are monitored continuously at some 14 stations. The instruments are connected to a network allowing real-time consulting of data. Furthermore, Acoustic Doppler Current Profiler (ADCP) flow measurements along sailed transects are executed regularly and the complete bathymetry is recorded bi-yearly by depth sounding. The incident with the Fowairet urged the authorities to further intensify the monitoring in that particular area.

2.1 WATER LEVEL

Water level time series are available at stations Hansweert and Walsoorden, resp. 2.5 km north and 2 km south of the centre of the eddy. The water level series at Terneuzen, about 15 km seaward, has also been used in order to make a water level gradient of the incoming tidal wave.

2.2 FLOW VELOCITY MEASUREMENTS

Since the cross currents are probably caused by a large horizontal eddy stretching over the entire width of the estuary the observation of current velocity in the area is crucial in studying the phenomenon.

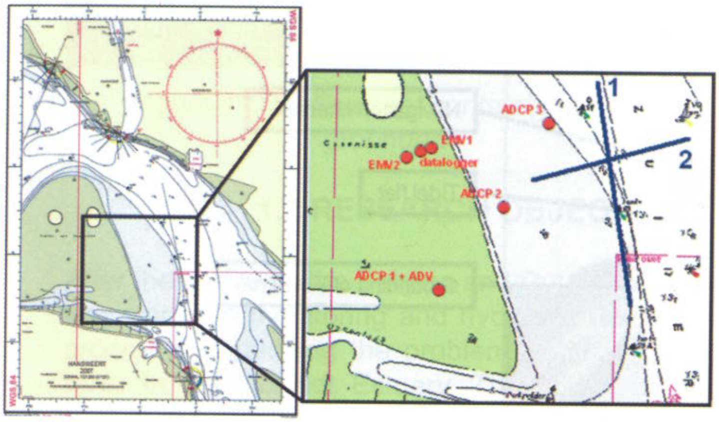


Figure 4: Location of the fixed flow measurements (red) and of the sailed transects with ADCP on board (blue)

2.2.1 Stationary

Three ADCP's, two Electromagnetic Velocity meters (EMV) and an Acoustic Doppler Velocity meter (ADV) have been installed at positions ranging from the edge of the navigation channel up to the tidal flat (Figure 4) between March 7th and April 12th, 2008. This period has been selected since it comprised two expected extreme spring tides during which the large eddy and cross currents were most likely. The ADCP instruments were installed vertically on the river bed, facing the water surface, measuring flow velocity and direction at every 25 cm (ADCP1) or 50 cm (ADCP2, deeper water).

All instruments functioned properly except for ADCP3 (Figure 4), no data could be recovered. At the location of ADCP2 the mean water depth was about 7 m, peak velocities were observed of 0.8 m/s during neap tide and 1.5 - 2 m/s during spring tide.

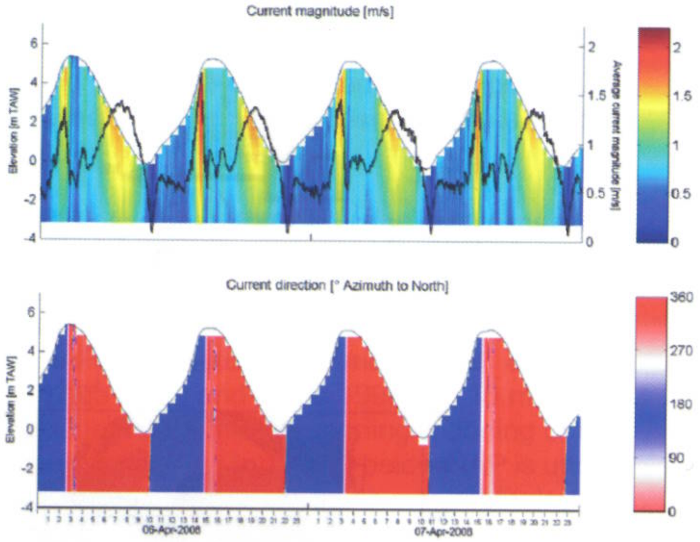


Figure 5: ADCP2 measurements on April 8-9, 2008. Flow velocity (upper panel) and direction (lower panel) profiles are shown.

When mooring a frame with ADCP on a highly dynamic sandy river bed the risk of burial exists. So, the other ADCP's were positioned in less dynamic areas away from the channel and have therefore not measured the cross current directly although an anomaly in the flow direction around high water during some spring tides was an indication of an eddy. In Figure 5, flow measurement data is shown for two consecutive days (out of a total of 33 days). The time is on the x-axis and the level on the left y-axis (relative to low water). The top panel shows the velocity magnitude profile at every burst time in colour coding; the black line indicates the depth-averaged flow velocity (right y-axis). In the lower panel an anomaly in the flow direction due to an eddy is shown just after the last high water in the figure. Based on this anomaly the model will be validated for long term performance.

2.2.2 Sailed ADCP measurements

In order to complete the spatial picture of the flow field, ADCP measurements from sailing monitoring vessels were used. At every extreme spring tide the Dutch Marine Authorities (Rijkswaterstaat Zeeland) have been executing this type of measurements ever since the grounding of the Fowairet. On April 7th, 2008 a Belgian monitoring vessel joined the measurements in order to sail along two perpendicular transects at the location where the eddy was expected.

A large eddy with high revolving velocity occurred during the measurements (HW to HW+1h) and was visualised due to the two perpendicular measured transects (Figure 6). Near the centre of the horizontal eddy, the component of the current velocity perpendicular to the navigation channel reached a value of 1.2 m/s (2.4 knots) with a 180° shift in current direction over a distance of 200 m. This is obviously an extremely dangerous situation for navigation.

On April 6th and 8th 2008 too, ADCP measurements observed the large eddy as well from one sailed transect along the edge of the navigation channel.

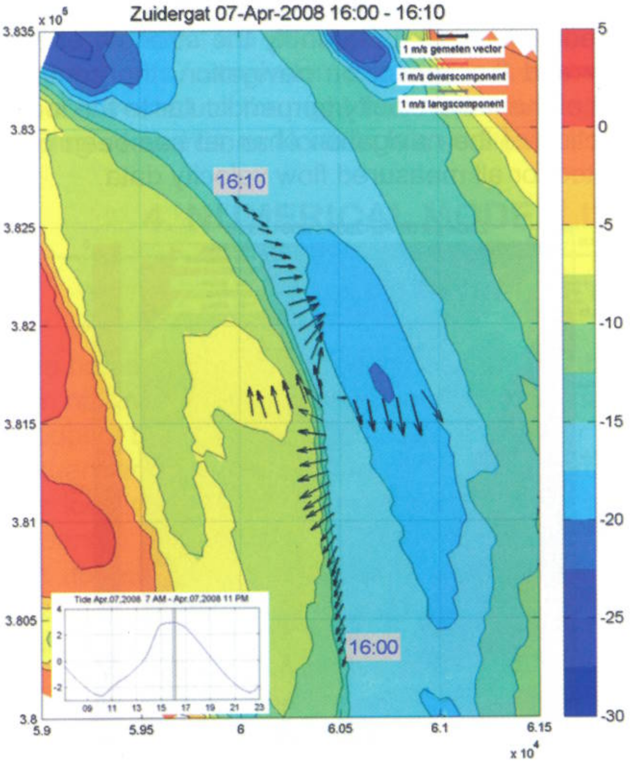


Figure 6: Field observation of a large horizontal eddy (2 km across) in the Westerschelde Estuary. X and Y coordinates in m (RD Paris).

3. DATA ANALYSIS

3.1 HARMONIC ANALYSIS OF THE TIDE

The long-term data set of water levels in the Westerschelde Estuary provided input for the harmonic decomposition of the tidal signal. General theory of harmonic analysis uses the following equation (e.g. Godin, 1972):

$$h(t) = Z_0 + \sum_{i=1}^{N} f_{n,i} A_i \cos(\omega_i t + \varphi_i)$$

where Z_0 is the mean water level, i=1,…,N with N the number of components, $f_{n,i}$ the nodal factor of component i, A_i the local amplitude of component i ω_i the angular speed of component i and φ_i is the phase shift of component i.

The tidal wave in the Westerschelde Estuary is characterised by a semi-diurnal lunar M2 component combined with a solar S2 component with slightly higher frequency, leading to the typical neap tide-spring tide variation with a period of about 13.5 days. Other important components include M4 (associated with an asymmetric tidal signal with different flood and ebb durations) and M6 which is expressed by the different water level rising velocity after low water compared to before high water (Figure 7).

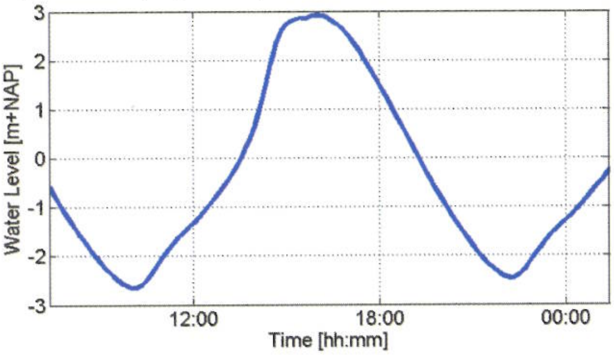


Figure 7: The shape of the tidal signal during a spring tide in the centre of the Westerschelde Estuary near Hansweert.

A least-squared-error method (Pawlowitz et al, 2002) was used to perform the harmonic analysis on the tidal signals of the stations Terneuzen, Hansweert and Walsoorden, located respectively at 30 km, 50 km and 55 km of the estuary mouth. The area where the centre of the eddy was observed in the past lies at 53 km from the mouth. The results for M2, S2, O1, M4 and M6 are shown in Table 1.

	Terneuzen		**Hansweert**		**Walsoorden**	
	A(m)	**Φ (°)**	**A(m)**	**Φ (°)**	**A(m)**	**Φ (°)**
M2	1.76	272	1.85	282	1.90	285
S2	0.71	136	0.73	148	0.75	152
O1	0.14	309	0.14	316	0.14	316
M4	0.09	183	0.08	212	0.10	224
M6	0.07	49	0.07	99	0.08	118

Table 1: Harmonic analysis of the tidal signal

3.2 WATER LEVEL GRADIENT AND WATER LEVEL RISING SPEED

Both the water level gradient and the speed of water level rise (usually expressed in cm per minute) are important parameters that can be related to the probability of occurrence of a large eddy with cross currents. The navigation authorities in The Netherlands are today using the water level difference between Terneuzen and Hansweert to send out a navigation warning for moderate and strong cross currents when it surpasses 84 cm and 88 cm respectively. The predictive capability of this heuristic model is lacking because (i) it not always predicts cross currents (false negatives) and (ii) it predicts cross currents without occurring in reality (false positive).

During the planning of the measurement campaign described above, a prediction has been made of the tidal elevation for the complete year 2008 based on 54 harmonic components resulting from the harmonic analysis of tidal signals of Terneuzen and Hansweert. The difference between both signals results in the predicted water level gradient. In this way a period can be selected in which as many water level gradient peaks occur as possible (Figure 8). This led to the selection of the period March 7th to April 12th, 2008 for the measurement campaign.

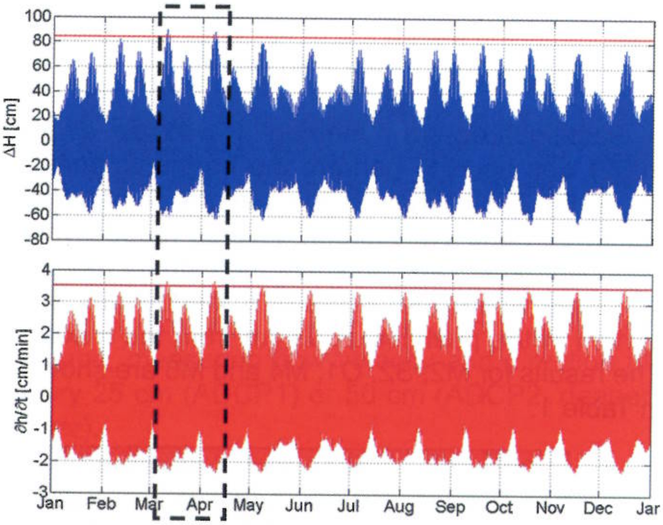


Figure 8: Predicted water level gradient in cm (top panel) with threshold for navigation warning indicated at 84 cm and the rising speed with a threshold at 3.5 cm/minute (lower panel). The optimal period for measurements is indicated.

The second parameter used in this research for roughly forecasting the cross currents is the speed at which the water level rises, expressed in cm/minute. In case the tidal wave would always propagate with the same speed through the estuary, the water level gradient and rising speed would be equivalent. Especially during storm surges entering from the North Sea the water level gradient might not be that large, while the high water levels make the tidal wave travel faster and cause fast water level rise.

3.3 CROSS-COMPONENT OF THE CURRENT

The mobile ADCP measurements offer a visualisation of the current vectors along a transect across the eddy. In order to quantify the strength of the eddy and the impact on navigation, the component of the flow velocity perpendicular to the local direction of the navigation channel has been calculated for all measured flow velocity data.

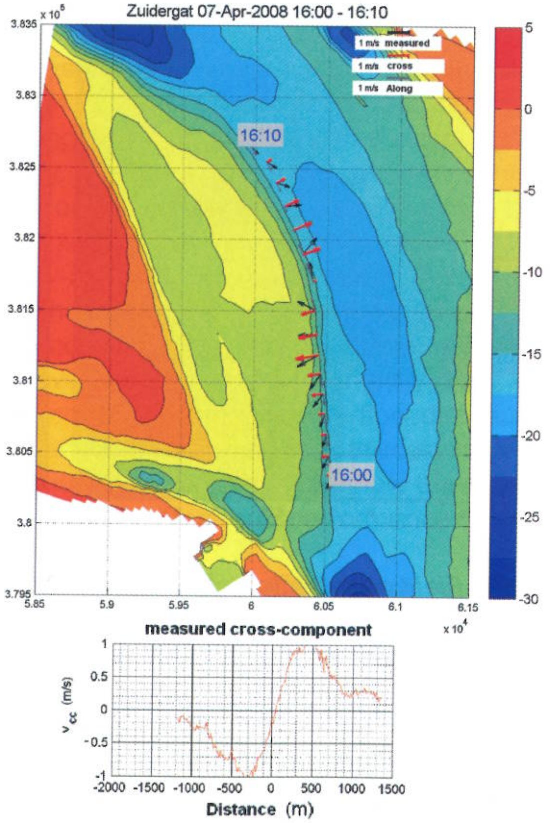


Figure 9: Flow measurement at high water. Measured current velocity vectors in black, calculated component perpendicular to the navigation channel in red vectors (top panel), the cross-section of the eddy's cross current is given below right.

Figure 9 on the previous page gives an example of the calculation of this component for the eddy on April 7th 2008 at around high water. The tidal amplitude had a return period of about 1 year and was a typical extreme spring tide during which cross currents occurred before. The black vectors show the measured current, the red vectors show the magnitude and direction of the component of the flow velocity perpendicular to the navigation channel (cross component). The figure shows also the cross section of the eddy in terms of cross current. It can be seen that the centre of the eddy was located at about Y=3.817x10^5 m. This location corresponds to X=50 m in the plot below right, where indeed the cross current is equal to zero. At X=450 m the maximal cross current south of the centre of the eddy is 1 m/s and at X=-350 m (North of the centre of the eddy) the maximal cross current is -1 m/s (convention: cross current is positive when directed to the right hand side for vessels sailing seawards, or North in this section).

4. NUMERICAL MODELLING

4.1 MODEL SETUP

The numerical modelling comprised the combination of 2 nested models. An overall hydrodynamic model of the complete 150 km Scheldt River tidal estuary and a smaller model of the region around the location where the cross current have been observed (Figure 10). The large model has been set up with the SIMONA software, whereas the nested model was developed in the Delft3D software.

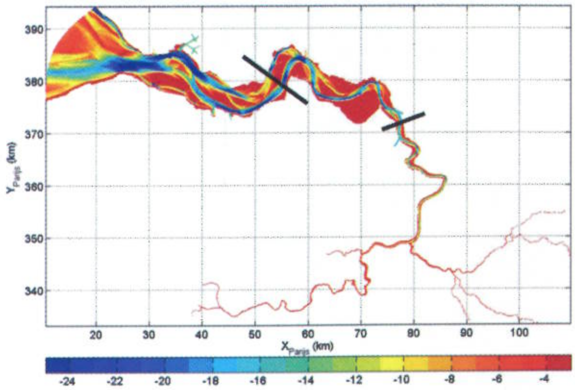


Figure 10: Computational domain of the large model (bed elevation in m NAP). Black line indicates the boundaries of the nested smaller model used for eddy simulation.

4.2 MODEL CALIBRATION

As a first step the overall model was calibrated on water level, discharge and harmonic components of the tidal signal (Vanlede et al, 2009). After a sensitivity analysis of the model parameters (Vanlede et al, 2008) the model was calibrated and a good agreement with measured water levels and discharges was obtained as well as improved values for the phase and amplitude of M2, S2, M4, M6 and O1 harmonic components. In particular the M4/M2 amplitude ratio (Figure 11) and the $2\varphi_2-\varphi_4$ phase lag have been improved (indicating tidal asymmetry).

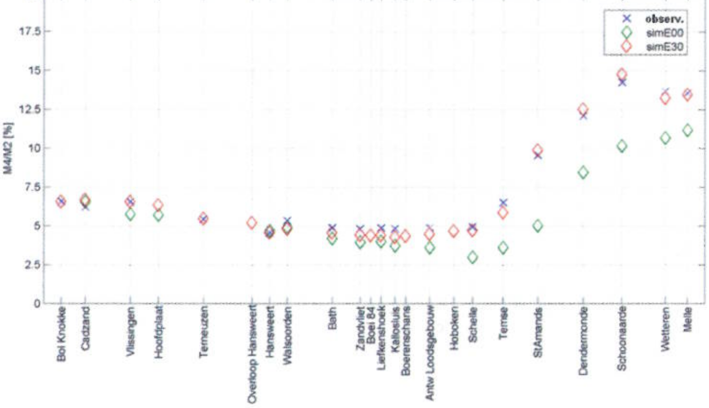


Figure 11: Improvement of the M4/M2 tidal asymmetry (%) along the entire estuary. SimE00 is before and SimE30 is after recalibration of the model.

The satisfactory calibration of the overall model then allowed for the extraction of flow and water level data to be applied as boundary conditions for the detailed model.

The calibration of the detailed model focused on the development of the large eddy at the desired location and during the tidal cycles when it has been observed. After calibration, the eddy was simulated with very similar shape and position compared to the measurements.

4.3 MODEL PERFORMANCE

The model is evaluated for the correct simulation of the strength of the cross currents along the navigation channel. During the extreme spring tide of April 7th 2008 an extensive measurement effort provided detailed information about the eddy and cross current. This data was compared to the model results. The component of the flow velocity lateral to the navigation channel axis has been calculated from the model results and from the measured flow. An example is shown in Figure 12.

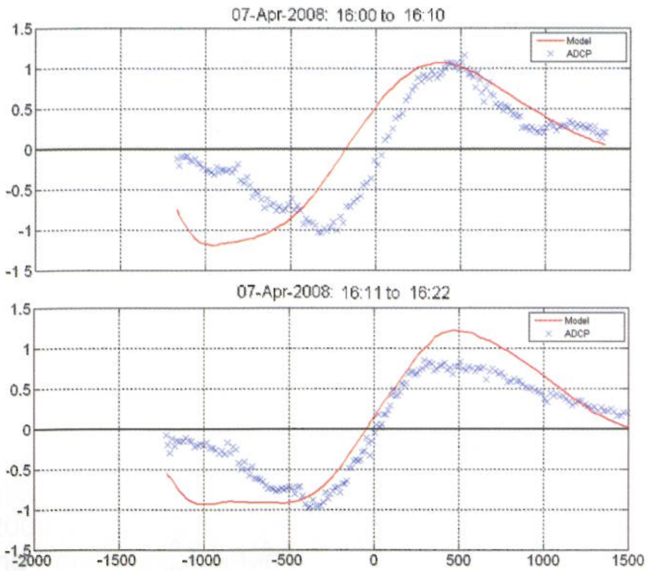


Figure 12: Simulated versus measured cross currents in the large eddy during two sailed transects of about 10 minutes. X-axis: distance (m), Y axes: cross current strength (m/s).

The shape of the eddy in the horizontal dimensions is visualised to show the complete flow field around the eddy. As shown in Figure 12 and in Figure 13, the simulated eddy has about the same strength as the measured flow, although the centre of the eddy is located slightly more to the north in the simulations.

Because the simulation of the shape of the eddy and the strength and timing of the cross currents was successful, the flow fields have been extracted from the model results and used in the nautical simulator of the Flanders Hydraulics institute. Pilots are currently being trained for navigation through the cross currents in the nautical simulator.

The long-term prediction capability of the model was validated by ADCP2 data and an independent data set of flow measurements taken in September 2006 at two locations on the western edge of the navigation channel. The validation result depends on the measurement location. This indicates how difficult it is to capture the eddy with variable position over a long-term measurement campaign. Overall, the model is rather conservative with more eddy occurrences than observed.

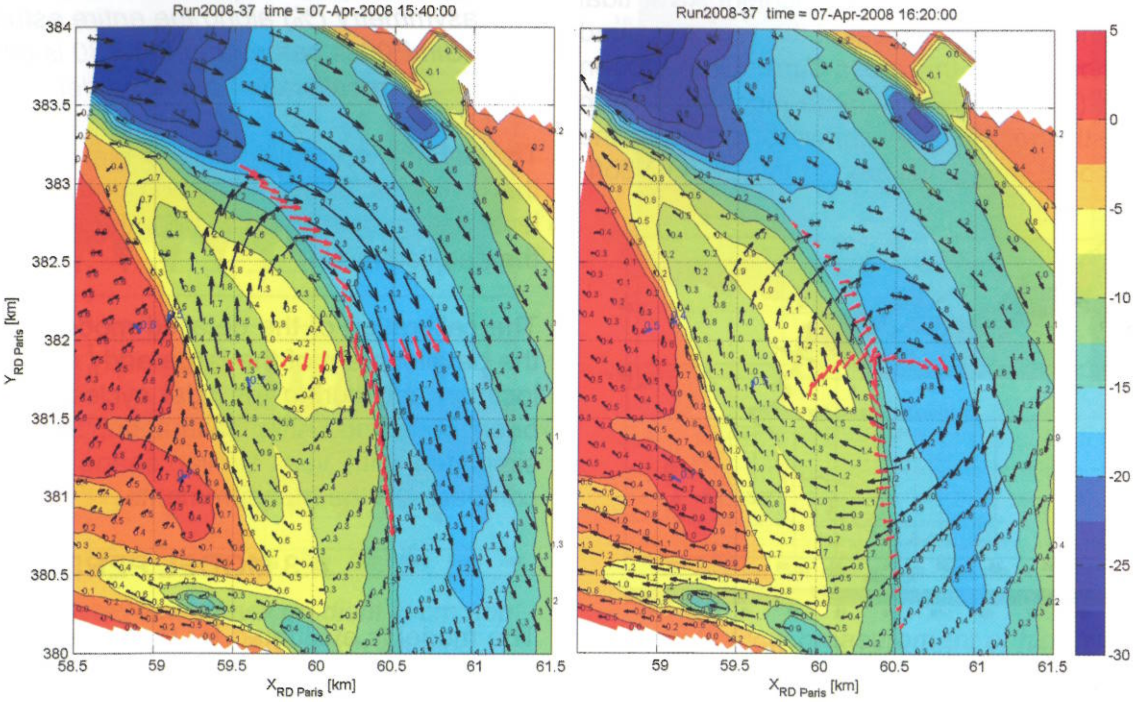


Figure 13: Simulated flow field (black vectors) and measured flow vectors: ADCP (red) and stationary instruments (blue). Flow pattern at initiation of the eddy is shown left (20 minutes before high water), fully developed eddy shown right (20 minutes after high water).

5. PHYSICAL PROCESSES

5.1 EDDY DEVELOPMENT AND ITS DECAY

The successful simulation of the large horizontal eddy allows for a detailed analysis of the phenomenon since it provides a detailed vector field of the currents.

The temporal evolution of the flow field shows that the intertidal area is experiencing a delayed water level rise compared to the channel in which the tidal flow experiences less friction due to the higher water depth. The delayed water level rise on the intertidal sand flat induces a local water surface depression which is pushed to the northeast of the flat and into the channel by the flood front (Figure 14, top panel). Note that this water surface depression has also been observed by measurements.

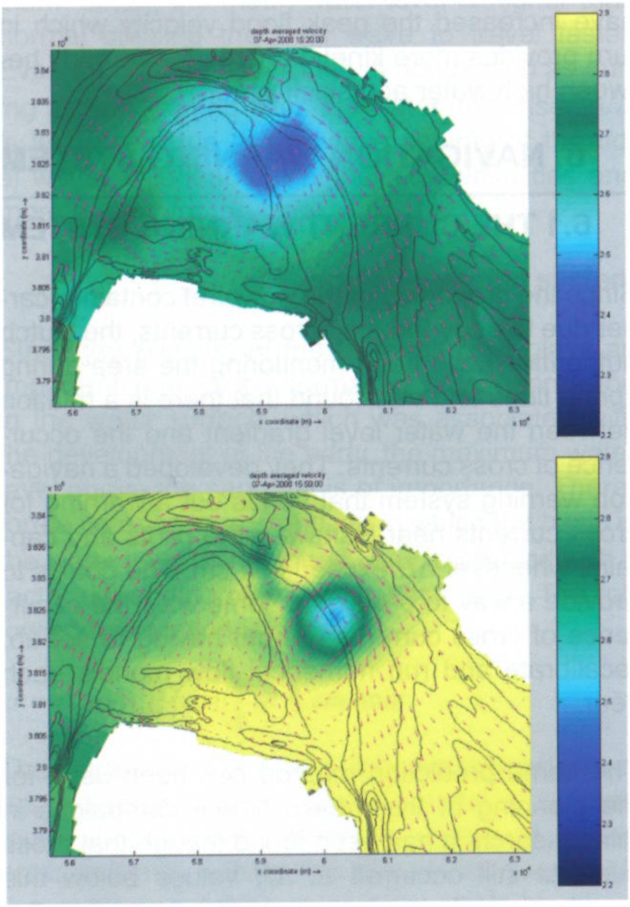


Figure 14: Current field in the simulated eddy, colour bar indicates water level. Flow vectors not to scale. The depression in the water surface is clearly visible. Top panel is at 30 minutes before high water and lower panel at high water.

In the mean time, the top of the tidal wave passes the area causing the water surface to slope down seaward, while the flow in flood direction does not reverse immediately due to its inertia. For this reason slack water occurs about one hour after high water in this area. At this point, the water in the channel flows inland (south in this area), while in the more shallow areas directly east of the sand flat the water starts flowing seaward under influence of the water level gradient. Two flows with opposite direction exist next to each other.

When the depression of the water surface joins the flow field with opposing directions (Figure 14, top panel), the flow starts to curve under influence of the pressure gradients in the depression. The eddy forms and starts moving to the navigation channel (Figure 14, lower panel).

A momentum balance shows that the centrifugal acceleration of the water circulating in the eddy (equation 5-1) is balanced by a pressure gradient in the shape of a local depression in the water surface, shown in Figure 14 and expressed by equation 5-2. Because of the large scale of the eddy it should be verified whether the contribution of Coriolis force (equation 5-3) is of importance

$$F_c = \omega r^2 \tag{5-1}$$

$$F_g = -g\frac{\partial \zeta}{\partial r} \tag{5-2}$$

$$F_{co} = fu \tag{5-3}$$

Where:

$$f = 2\omega_a \sin\varphi \tag{5-4}$$

With r the radial distance from the centre of the eddy f the Coriolis factor, ω_a is the Earth's angular velocity, φ the local latitude and u is the tangential velocity in the eddy.

It can be shown that in the early phase of the development of the eddy the centrifugal acceleration is equal to 1.10^{-3} m/s^2 and that the radial pressure gradient force per unit of mass measures -4.10^{-3} m/s^2. The Coriolis force is one order of magnitude smaller, i.e. about -1.10^{-4} m/s^2, which means that it is small but can not be neglected.

Applying Newton's 2^{nd} law in the radial direction of the eddy the sum of the forces per unit of mass should balance the radial acceleration terms. When the eddy is stable and the water particles follow perfect circular paths the following 'gradient wind balance' applies (e.g. Stegner & Dritschel, 2000):

$$\frac{u^2}{r} + fu - g\frac{\partial \xi}{\partial r} = 0 \qquad (5\text{-}5)$$

When the terms are evaluated, we see that for the developing eddy the balance is not reached yet: the outward radial acceleration does not balance the (larger) inward forces and thus the water particles do not follow circular paths but are spiralling inwards. This leads to a weakening of the pressure gradient in the eddy which in turn forces the balance to equilibrium. At this point the eddy is in its strongest state in terms of cross currents in the navigation channel (as shown in Figure 13). From then on, friction further reduces the revolving frequency of the eddy, but the lowered pressure gradient (of the disappearing depression in the water surface) makes that the balance turns in favour of the outward centrifugal acceleration. The eddy widens subsequently, loses its momentum and disappears.

5.2 INFLUENCING FACTORS

In this section the ambient conditions influencing the eddy will be discussed. An explanation for the increased frequency of occurrence of the eddy and cross currents is worked out.

5.2.1 Tidal range

As shown above a correlation exists between the water level gradient (ΔH) and water level rising speed ($\partial h/\partial t$) at one hand and the development of a large eddy in the navigation channel on the other hand. One could therefore assume that the increase in frequency and strength of the eddy is due to an increase of the peaks in both influence factors. The peak values of ΔH and $\partial h/\partial t$ during spring tide could have increased in the past and could be due to an increase of the tidal range. It is known that the tidal range in the Westerschelde Estuary has been rising for centuries due to the deepening of the channels due to natural and anthropogenic factors.

The increase in tidal range, however, was most pronounced during the 1970's (20 cm increase in the study area) and seems to have stabilised between 1990 and 2000 (Kramer, 2002).

5.2.2 Tidal asymmetry

The area of the occurrence of the eddy is the only location in the estuary where the tide is ebb-dominant, i.e. falling tide duration is shorter than the rising tide duration. Wang et al (2002) report a decrease in the $2\varphi_2$-φ_4 phase lag between the M2 and M4 harmonic components, which is a measure of the nature of the tidal asymmetry. A value of $2\varphi_2$-φ_4 between 0° and 180° indicates flood-dominance, otherwise the tide is ebb-dominant. For this study, the tidal analysis of the year 2006 at Hansweert showed a value of -7°. Wang et al (2002) further show a strong increase between 1970 and 1985. This means that the ebb dominance has weakened and has thus been moving towards flood-dominance. This evolution may have increased the peak flood velocity which in turn provides more kinetic energy for an eddy between high water and slack water.

6. NAVIGATION WARNING SYSTEM

6.1 THE CURRENT WARNING SYSTEM

Since the grounding of the Fowairet container carrier due to eddy-induced cross currents, the Dutch authorities have been monitoring the area during spring tides and also found that there is a relation between the water level gradient and the occurrence of cross currents. They developed a navigation warning system that sends out a warning for cross currents near Hansweert to pilots and captains whenever ΔH exceeds 84 cm. The goal is to provide a way to predict, in some way, the occurrence of cross currents without having to set up, recalibrate and run numerical flow models each year.

The same prediction method has been used for the planning of the measurement campaigns in this research. It has been found though that cross currents still occurred at ΔH values below this threshold, while it was not possible to reduce the threshold because too many warnings would be generated by the system.

The numerical model developed is used to propose an improved warning system.

6.2 ANALYSIS OF THE SYSTEM

The 33-day period simulated with the model was analysed for correlations of eddy occurrence with tidal characteristics such as ΔH, $\partial h/\partial t$ and high water levels.

On March 12th 2008 a storm above the North Sea with winds from Northwest forced a water level setup at the Belgian and Dutch coastlines. Although not during spring tide, this event caused high water levels of 70-80 cm above normal spring tide high waters. Because on that day there was no spring tide, ΔH was not very high and no warning has been given. Due to the strong cross currents that day 2 ships have been driven off course.

An explanation for the occurrence of an eddy under relatively low ΔH is the following: during a storm setup, the mean water level is higher than normal causing the tidal wave to travel faster. Even though the tidal range is not as high as during extreme spring tides the water level rise $\partial h/\partial t$ is increased due to the wave celerity of the tidal wave. This leads to higher flow velocities and more energy for the eddy.

6.2.1 An improved warning system

Since the flooding of the tidal sand flat plays an important role in the formation of a depression in the water surface, which was associated with the development of the eddy, the maximum water level above the sand flat is of importance. Therefore a criterion cr is proposed in which the basis is the water level rising speed $\partial h/\partial t$, corrected with a factor depending on the high water level. The following formulation is chosen:

$$cr = (1+a(h_{HW}-b))\left(\frac{\partial h}{\partial t}\right) \geq 4\ cm/\text{min}$$

The parameters a and b are determined in an analysis of the model results, aiming at a maximum success rate for the prediction of strong cross currents, with as few as possible false positive outcomes (when a warning would be given but no cross currents occur).

After an optimisation, the parameters a and b have been found to give the best performance with values a=1 m^{-1} and b=2.85 m.

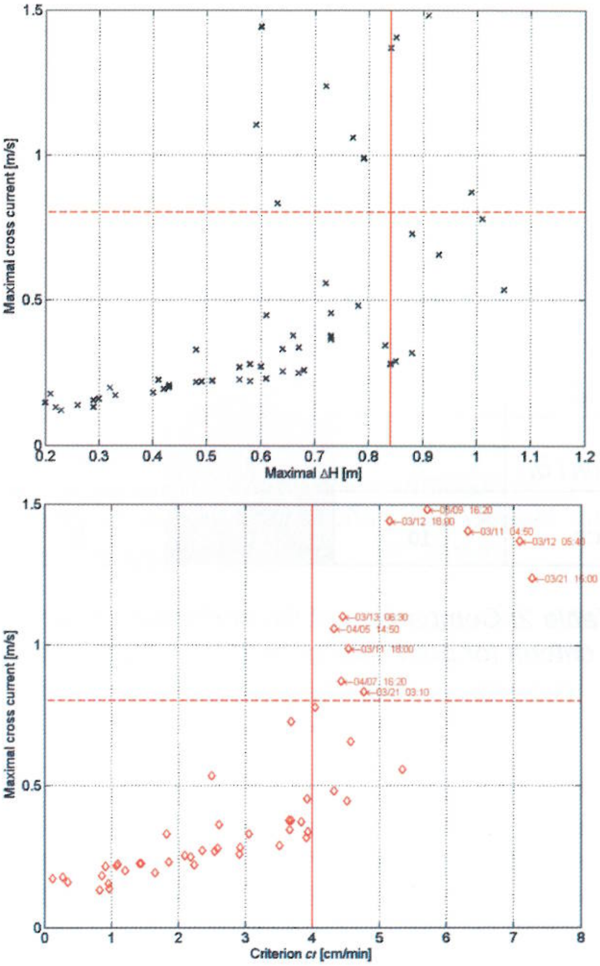
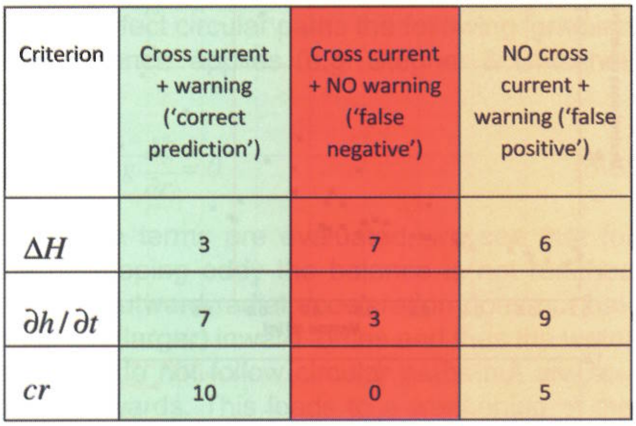


Figure 15: Comparison of the performance of the proposed criterion cr against the currently used criterion (ΔH). Thresholds for sending out a warning are shown by full red line. Dashed red lines indicate a 0.8 m/s cut-off for cross currents.

In Figure 15 (bottom) is shown that the proposed criterion cr would produce a warning (cr>4) for all events with cross currents stronger than 0.8 m/s. Every marker indicates the maximal value during one tidal cycle. For five of the tides the criterion would send out a warning while the cross current would be only weak. In the top panel of Figure 15 is shown that for the actual criterion ΔH only 3 out of the 10 tides with strong cross currents would have been detected and warnings given (ΔH>0.84). That means that during 7 of the tides with cross currents this criterion would not produce a warning.

The performance of the proposed criterion is compared to two other criteria in Table 2 on the next page. Using *$\partial h/\partial t$ >3.5 cm/minute* as a criterion gives better results than the use of criterion

ΔH>84 *cm*, but sending out warnings using cr >4 *cm/minute* gives the most accurate coverage of all cross current events.



Criterion	Cross current + warning ('correct prediction')	Cross current + NO warning ('false negative')	NO cross current + warning ('false positive')
ΔH	3	7	6
$\partial h / \partial t$	7	3	9
cr	10	0	5

Table 2: Comparison of the performance of three criteria for prediction of, and warning for cross currents: ΔH*>84 cm,* $\partial h/\partial t$*>3.5 cm/min and* cr*>4 cm/min.*

Since now a new tool has been developed to generate a warning, the tidal properties can be hindcasted (for e.g. the year 2006) and a cr value can be calculated for each tide. The probability of exceedence is then calculated which gives the percentage of the tides for which a warning would be given.

For the year 2006 the cumulative probability density for the cr criterion shows that in about 4 % of the tides cross currents would be predicted (Figure 16).

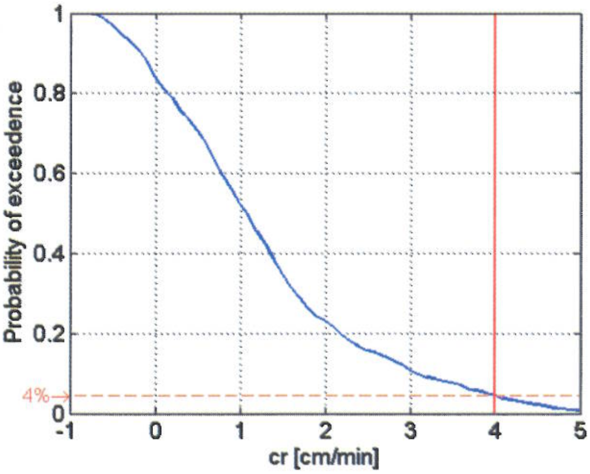


Figure 16: Cumulative probability density for the cr *criterion. A value of 4 cm/minute is exceeded in 4 % of the tides in 2006.*

Due to the relative positions of Earth, Moon and Sun the stronger spring tides occur often during early spring and early fall, but the number of strong spring tides per year is strongly varying. In 2008 a high number of extreme spring tides occurred, while during the year 2009 hardly any were foreseen during the second half of the year.

When tidal predictions are made for all years between 2005 and 2011 we see a trend of increasing probability for cross current occurrence (Figure 17), probably due to the rising tidal range caused by the 18.6 year cycle in tidal harmonics. This is a worrying evolution and makes that the monitoring and prediction capacities should be increased.

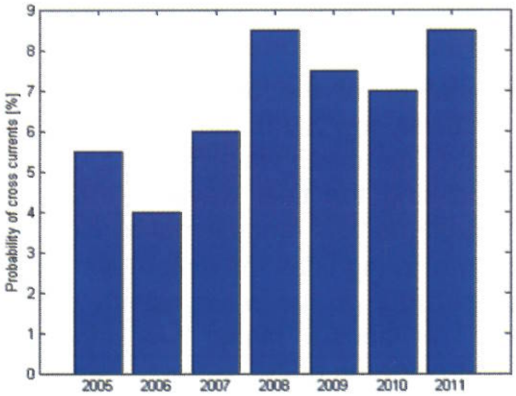


Figure 17: Evolution in the predicted probability of cross currents.

Nowadays, pilots already have great difficulty sailing safely trough these cross currents. An increase in strength in the future would hamper navigation, therefore measures are to be developed to reduce the strength and frequency of these currents.

7. CONCLUSIONS

The present study aimed at understanding the mechanisms behind the formation of a large eddy in the navigation channel of the Westerschelde Estuary during strong spring tides. Short term observations of the flow velocity with high spatial resolution (from sailing vessels) as well as long term measurements have been analysed and revealed insights in the flow pattern.

A numerical model has been set up and calibrated for the simulation of the large horizontal eddy. The shape of the eddy with associated cross currents has been simulated with good accuracy. The flow fields have been extracted from the model results and inserted in the Flanders Hydraulics' nautical simulator, where they are serving as a training environment for pilots.

The model gives a slighty -conservative- overprediction of eddy occurrence frequency. Due to the difficulties in observing an eddy from the point measurements, the long term measurements could not completely confirm the prediction performance of the model.

Therefore, more long-term flow measurements from a buoy near the edge of the navigation channel are foreseen to further validate the long term predictions of the model.

Based on the analysis of the data and the flow fields provided by the numerical model, more insight was gained in the physical mechanisms generating the large eddy causing cross currents in the navigation channel. Starting from these insights a new criterion is proposed for the long term prediction of the occurrence of cross currents without the necessity to set up and run complex numerical simulation models for each year in the future. The proposed criterion is formulated as a function of forecasted water rising speeds and high water levels. The criterion for the occurrence of cross currents forecasts an increase in the probability of cross currents in the next two years.

Additional measurements should be carried out in the future to validate the parameters used in the formulation of the prediction criterion. More and stronger cross currents are expected in the next two years and therefore an accurate prediction is needed to maximise the instances when a warning for navigation is given in case of cross currents.

Future research will focus on the cause of the apparent increase in the frequency of cross currents. Subsequent research will focus on the design of mitigating measures to steer the local morphology of the estuary to a shape less favourable for cross currents.

8. ACKNOWLEDGEMENTS

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SUMMARY

The Westerschelde estuary is located in The Netherlands and is a major shipping route connecting the North Sea to the Port of Antwerp (Belgium). Cross currents up to three knots occur at high water during extreme spring tides and are increasingly hampering navigation in the Westerschelde near Hansweert resulting in one major incident leaving a container vessel stranded on a nearby sand bank.

This study aimed at the simulation, prediction and assessment of a large eddy (stretching over the complete navigation channel) which produces these cross currents. A numerical model was set up and a detailed calibration of the hydrodynamic model was executed. A good agreement was obtained between model and measured data on the location of the eddy and the strength of the cross currents. Flow fields produced by the numerical model subsequently have been implemented in a nautical simulator in which pilots are trained on sailing in these exceptional conditions.

Currently, a warning is sent out to Traffic Control whenever at least one of two parameters is being foreseen to pass a critical value according to forecasting models (high water level and water level gradient). This system has been proven to yield false negatives in some cases. The simulation results and analysis have clarified the conditions in which the eddy grows sufficiently (2 km across) to cause cross currents in the navigation channel. A new criterion for sending out a navigation warning is proposed. It shows a better correlation with the occurrence of cross currents, hence pilots will have a higher probability to be warned in case of cross currents.

RÉSUMÉ

L'estuaire de l'Escaut occidental est situé aux Pays Bas et est une voie maritime majeure reliant la Mer du Nord au Port d'Anvers (Belgique). Des courants transversaux atteignant jusqu'à 3 nœuds apparaissent à marée haute lors des plus grandes marées de vives eaux et gênent de plus en plus la navigation dans l'Escaut occidental près de Hansweert, allant jusqu'à provoquer un incident majeur au cours duquel un porte-conteneurs s'est échoué sur un banc de sable local.

L'étude avait pour objectif la simulation, la prédiction et l'évaluation de l'important tourbillon (qui s'étend sur l'ensemble du chenal de navigation) qui produit ces courants transversaux. Un modèle numérique a été établi et le modèle hydrodynamique a été calibré de façon détaillée. Une bonne concordance entre le modèle et les données mesurées concernant l'emplacement du tourbillon et la force des courants transversaux a été obtenue. Les champs de courant issus du modèle numérique ont été intégrés par la suite dans un simulateur nautique dans lequel les pilotes sont entraînés à naviguer dans ces conditions exceptionnelles.

Actuellement, une alerte est envoyée au contrôle du trafic quand il est prévu qu'au moins un des 2 paramètres dépasse une valeur critique selon les modèles de prévision météo (niveau d'eau à marée haute et gradient du niveau d'eau). Ce système s'est révélé insuffisant dans certaines conditions et des bateaux ont encore navigué sans être alertés de courants transversaux dangereux. Les résultats et l'analyse de la simulation ont clarifié les conditions dans lesquelles le tourbillon se développe suffisamment (2 km de diamètre) pour causer des courants transversaux susceptibles de générer des incidents. Un nouveau critère d'alerte à la navigation a été proposé : le nouveau critère combine en un paramètre différentes données ambiantes telles que le niveau d'eau à marée haute et le taux d'augmentation du niveau d'eau. Il présente une meilleure corrélation avec l'apparition de courants transversaux, les pilotes auront donc une plus grande probabilité d'être alertés en cas de courants transversaux.

ZUSAMMENFASSUNG

Das Westerschelde Ästuar befindet sich in den Niederlanden und ist eine bedeutende Seeschifffahrtsstraße, die die Nordsee mit dem Hafen von Antwerpen (Belgien) verbindet. Querströmungen von bis zu 3 Knoten kommen bei Hochwasser während extremer Springtiden vor und behindern mehr und mehr die Schifffahrt in der Westerschelde nahe Hansweert. Dadurch kam es zu einem bedeutenden Vorfall, als ein Containerschiff auf einer nahe gelegenen Sandbank strandete.

Ziel dieser Studie war die Simulation, Vorhersage und Bewertung eines starken, sich über die gesamte Fahrrinne erstreckenden Wirbels, der diese Querströmungen erzeugt. Mit Delft3D wurde ein numerisches Modell aufgesetzt, welches einen 20 km Bereich des Ästuars umfasst und in größere Modellen des gesamten Ästuars und der Nordsee eingebettet ist. Da auf Grund einer großen Messkampagne sehr viele Messergebnisse vorlagen, wurde eine detaillierte Kalibrierung des hydrodynamischen Modells durchgeführt. Es wurden gute Übereinstimmungen zwischen den Modelldaten und den gemessenen Daten hinsichtlich der Lage des Strudels und der Stärke der Querströmungen erreicht. Die mit dem numerischen Modell erzeugten Strömungsfelder wurden in einem nautischen Schiffsführungssimulator eingesetzt, mit dem Schiffsführer trainiert werden, unter diesen Ausnahmebedingungen ein Schiff zu navigieren.

Gegenwärtig wird an die Verkehrskontrolle eine Warnmeldung geschickt, wenn mindestens für einen der beiden Parameter vorhergesehen wird, dass der kritische Wert gemäß den Vorhersagemodellen (Hochwasserstand und Wasserspiegel-Gradient) überschritten wird. Dieses System hat sich in einigen Fällen als unzureichend erwiesen und Schiffe sind ungewarnt in die gefährlichen Querströmungsbedingungen gefahren. Die Simulations-ergebnisse und Analysen haben die Bedingungen, unter welchen der Wirbel genügend groß wird (über 2 km), um Querströmungen mit dem Potenzial Unfälle zu verursachen, ausreichend geklärt. Es wurde ein neues Kriterium für das Versenden von Schiff-fahrtswarnungen vorgeschlagen: Das neue Kriterium vereint verschiedene Umgebungsbedingungen, wie Hochwasserstand und Grad des Wasserstandanstiegs in einem Parameter. Es zeigt eine bessere Korrelation mit dem Erscheinen der Querströmungen, daher werden Schiffsführer mit größerer Wahrscheinlichkeit vor Querströmungen gewarnt.