Conference Paper, Published Version

Maximova, Tatiana; Vanlede, Joris; Smolders, Sven

Two-Dimensional Hydrodynamic Model of the Port of Terneuzen (Scheldt Estuary, The Netherlands)

Two-dimensional hydrodynamic model of the port of Terneuzen (Scheldt estuary, The Netherlands)

T. Maximova[1,2], J. Vanlede[1], S. Smolders[3,1]

[1]Flanders Hydraulics Research, Berchemlei 115, 2140 Antwerp-Borgerhout, Belgium
Joris.Vanlede@mow.vlaanderen.be
[2]Free University of Brussels, Pleinlaan 2, 1050 Brussels, Belgium
[3]University of Antwerp, Universiteitsplein 1, 2610 Antwerp-Wilrijk, Belgium

Abstract—**This paper describes the development and calibration of a two-dimensional hydrodynamic model of the port of Terneuzen. The model is calibrated using a cost function against a combination of water level, discharge and ADCP data. The calibrated model is used to calculate flow fields for the ship manoeuvring simulator of Flanders Hydraulics Research (FHR). The use of an unstructured grid allows for local grid refinement in the study area.**

I. INTRODUCTION

The lock complex at the port of Terneuzen provides access from the Western Scheldt to the port of Ghent located in Belgium (via the canal of Ghent – Terneuzen). Each year, about 10.000 seagoing vessels, 50.000 inland vessels, and about 3.000 pleasure crafts pass the locks.

The ship manoeuvring simulator of FHR consists of a mathematical model that calculates the effect of different forces on a sailing vessel, and a navigation bridge from where the pilot can see how the vessel behaves and can steer it. It is possible to simulate different types of vessels, tugboat assistance, movement of other ships, etc. The ship manoeuvring simulator is used for training purposes for river pilots and for research on the feasibility of an extension of the lock complex. The numerical model is used to calculate accurate velocity maps with a high spatial resolution, which are provided as flow fields for the simulator.

Before setting up the TELEMAC model presented here, the best hydrodynamic model for the port of Terneuzen was the NEVLA model [1], [2], which includes the entire Scheldt estuary in a curvilinear grid. The grid resolution of the NEVLA model is 130 x 50 m near Terneuzen, which is too coarse for a meaningful application of the model results in the ship simulator. The use of an unstructured grid allows for local grid refinement in the study area, which is necessary to take the complex geometry of the study area into account (e.g. accurate representation of the quay walls).

II. THE NUMERICAL MODEL

A. Model grid

A 2D model for this project is developed in the TELEMAC software, which is based on the finite element method. The model domain is discretised into an unstructured grid of triangular elements and it is locally refined in the study area.

Google Earth and Blue Kenue [3] were used to define the outline of the model. Afterwards, the triangular computational mesh was generated in the Blue Kenue software. The model domain is shown in Fig. 1. The downstream boundary of the TELEMAC model is located at Vlissingen; the upstream boundary is located at Liefkenshoek.

The final grid has a resolution of 100 m at the model boundaries, 50 m in the area around the port of Terneuzen and 10 m at Terneuzen (Fig. 2). The total number of nodes in the grid is 95.105 and the total number of the elements is 186.877.

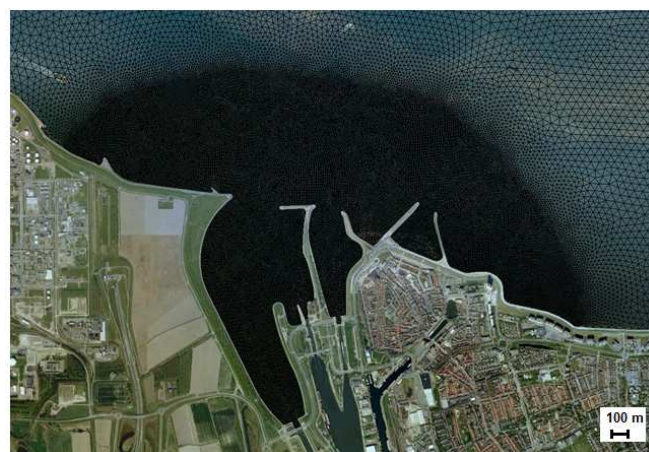Figure 1.   Numerical model domain

Figure 2.   A detail of the mesh for the port of Terneuzen

B. Bathymetry

The bathymetry of the Western Scheldt and Lower Sea Scheldt is defined based on the samples from 2011 provided by Rijkswaterstaat and Flemish Hydrography respectively. Bathymetry for the port of Terneuzen and its surroundings is taken from the Scheldt ECS server (data for 2010 – 2012). TAW (Tweede Algemene Waterpassing, the standard vertical reference in Belgium) is used as a vertical reference.

The bathymetric samples are not available for a number of relatively small areas located far from the area of interest (e.g., port of Hansweert and Vlissingen). The bathymetry for these areas was defined based on the maps of Flemish Hydrography (2011).

C. Boundary conditions

The boundary conditions for the TELEMAC model in this study are generated by nesting the model in the NEVLA model. A 10 minute time series of total discharge at Vlissingen is imposed at the downstream boundary and a 10 minute time series of water level at Liefkenshoek is imposed at the upstream boundary.

D. Simulation period

Based on the tidal conditions during which ADCP and discharge measurements are available (see further), the model is run from 28/07/2009 00:00 to 28/08/2009 00:00.

III. AVAILABLE MEASUREMENT DATA

Measured water levels are available in 9 different stations (location in Fig. 3). 10 minute time series of water level were retrieved from the Hydro Meteo Centrum Zeeland database (HMCZ) for the stations on the Dutch territory and from Hydrologisch Informatie Centrum (HIC) for station Liefkenshoek in Belgium.

Six different ADCP measurement campaigns are available (Table I and Fig. 3). During such a measurement campaign, a ship-mounted ADCP measures continuously during one tidal cycle, while the ship follows a fixed transect across the river. The resulting dataset consists of velocity vectors distributed over the transect and over the water depth, during one tidal cycle. Four of these datasets are used for the model calibration, two are used for the model validation.

TABLE I. ADCP MEASUREMENTS USED FOR THE MODEL CALIBRATION

Measurement	Date	Tidal Conditions	Used for
R7 Everingen	04/06/2008	spring tide	calibration
Terneuzen port	21/03/2007	spring tide	calibration
Waarde	23/03/2006	neap tide	calibration
Waarde	28/09/2006	average tide	calibration
R7 Everingen	05/07/2011	spring tide	validation
R7 Terneuzen	06/07/2011	average tide	validation

Discharge data are obtained by integration of ADCP data over the cross section, and are available for 15 cross sections

in the Western Scheldt. Discharge data are used during the model calibration.

Figure 3.   Available measurement data

IV. MODEL CALIBRATION

A. Methodology

The main objective of the model calibration is to optimize the representation of the flow velocity in the port of Terneuzen. Bed roughness and velocity diffusivity are used as calibration parameters. The results of model simulations are compared with measured water levels, velocities and discharges.

Comparison between modelled and measured water levels is done by comparing the time series, the individual high and low waters, and the harmonic components obtained from a harmonic analysis.

For ADCP measurements and discharge data, comparison with the model results is done for a selected modelled tide that is comparable to the tidal conditions during the measurements (Table I). Working with comparable tides means that differences between the calculated and measured velocities and fluxes are expected when the agreement between the measured and modelled tides is not sufficient. Differences between the model bathymetry and the actual bathymetry during the measurements can be another reason for the differences in discharges.

B. Cost function

In order to select the best calibration run, a cost function (1) is calculated for each simulation. The cost function is intended to get one value that represents model performance. The factors in the cost function are defined in such a way that a lower value represents better model performance. The cost function is made dimensionless in relation to a reference run, so a value lower than 1 indicates an improvement over that reference run [2]. The model run with the best accuracy has the lowest score.

$$Cost = \sum \frac{Factor_i}{Factor_{i,ref}} * Weight_i \qquad (1)$$

Several parameters are selected as factors for the calculation of the cost function (Table II).

TABLE II.   FACTORS FOR THE CALCULATION OF THE COST FUNCTION

Factor	Weight	
RMSE water level time series	7%	Total weight for WL = 28%
RMSE high waters	7%	
RMSE low waters	7%	
Vector difference[a]	7%	
RMSE velocity magnitude R7 Everingen	8%	Total weight for velocities and discharges = 72%
RMSE velocity direction R7 Everingen	8%	
RMSE velocity magnitude Terneuzen port	8%	
RMSE velocity direction Terneuzen port	8%	
RMSE velocity magnitude Waarde 23/03/2006	8%	
RMSE velocity direction Waarde 23/03/2006	8%	
RMSE velocity magnitude Waarde 28/09/2006	8%	
RMSE velocity direction Waarde 28/09/2006	8%	
RMSE discharge	8%	
Sum	100%	

a. Vector difference combines the evaluation of both amplitude and phase between the observed and modeled tidal components.

In the cost function more weight is given to velocities than to water levels because the main objective of this project is to improve the model accuracy for the flow velocities.

C. Results

In order to improve the representation of water levels, the upstream boundary condition was corrected by subtracting 6 cm from the water level at Liefkenshoek calculated in the NEVLA model. The model was further calibrated by varying the roughness and diffusivity parameters. The adaptation of the bed roughness resulted in an improvement of the M2 amplitude.

Run simTZ_44 produces the best results. A varying roughness field (0.023 $m^{-1/3}s$ in the downstream part of the model and 0.021 $m^{-1/3}s$ upstream) and a velocity diffusivity of 2 m²/s are used in this simulation.

V.   QUALITY ASSESSMENT OF THE FINAL MODEL

This paragraph gives a quantitative assessment of the performance of model run simTZ_44 during the calibration.

A. Water levels

The RMSE (root mean square error) of high, low waters and complete water level time series is about 10 cm for most stations. The RMSE of high and low water phase is smaller than 10 min.

The M2 harmonic component has the highest amplitude in the zone of interest, implying that the tidal amplitude will depend to a large extent on the amplitude of M2. The difference between the calculated and measured M2 amplitude is very small (1 to 2 cm) at most stations (Fig. 4). The biggest difference (4 cm) is observed at Borssele and Terneuzen. These stations are located in the downstream part of the model near the discharge boundary. The difference in the M2 phase is 3 degrees at Liefkenshoek and 1 to 2 degrees at other stations (Fig. 5).

B. ADCP velocities

An example of the plot of time series of the measured and modeled velocities at Everingen is shown in Fig. 6. Each point on this plot represents a depth-averaged velocity magnitude or direction for a certain transect measured with ADCP or calculated in the model. Fig. 7 presents a vector plot of the modeled and measured velocities for one of the transects in the port of Terneuzen.

The absolute value of bias of the velocity magnitude at Everingen is smaller than 10 cm/s for most transects. The RMSE of velocity magnitude varies between 7 and 20 cm/s over a tidal cycle. The total RMSE for all transects is 16 cm/s. The RMSE of velocity direction is smaller than 20 degrees for most transects. It is maximal during slack.

The bias of the velocity magnitude at Terneuzen varies between -9 and 11 cm/s. The total RMSE of velocity magnitude is 11 cm/s. The RMSE of velocity direction changes from 13 to more than 100 degrees (in the beginning of flood). The model accuracy for the velocity direction is good when the velocity magnitude is high. It worsens in the areas where velocity magnitude is very small. This results in an increase of the RMSE value of the entire transect.
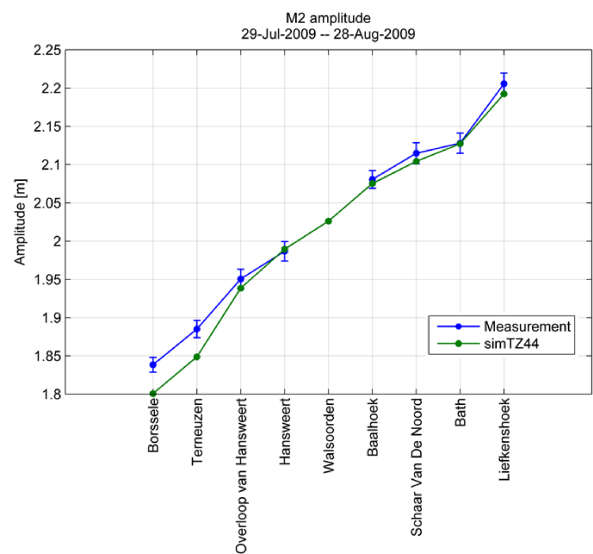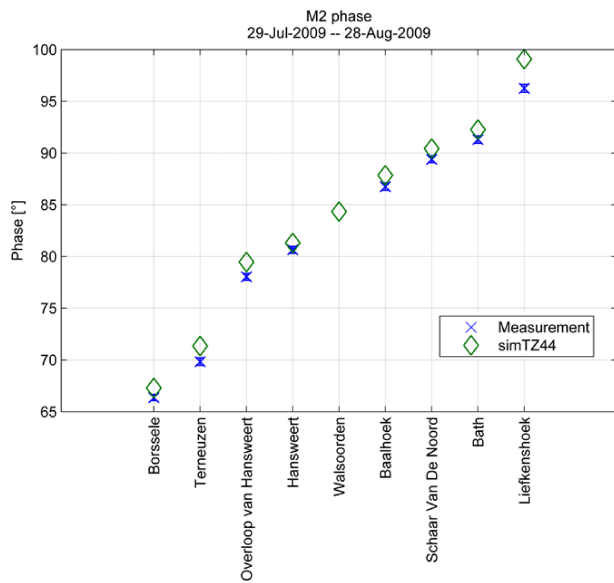

Figure 4.   M2 amplitude

Figure 5. M2 phase

The modelled velocities at Waarde are slightly underestimated in the model for most transects. The total RMSE of velocity magnitude is 14 cm/s; the total RMSE of velocity direction is 32 degrees. During ebb and in the beginning of flood this RMSE increases up to 40 to 60 degrees. This is related to uncertainties in the ADCP measurements.

C. Discharges

The shape of the discharges is well represented in the model for most cross sections. The RMSE of the discharge time series is 4 to 13% of the maximum discharge at a certain location. An example of the measured and calculated discharge time series is shown in Fig. 8 for R7 Pas van Terneuzen. The model results and measurements are analysed for the comparable tides.
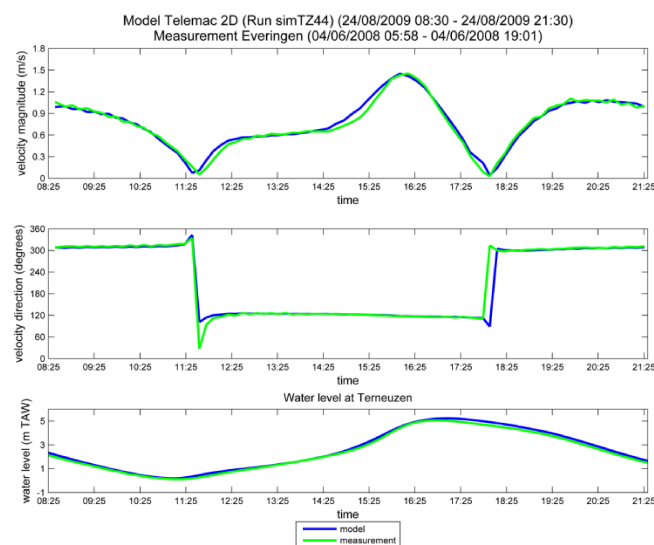

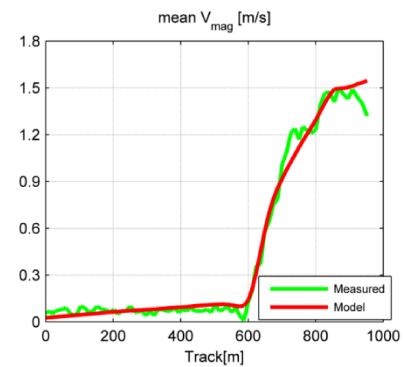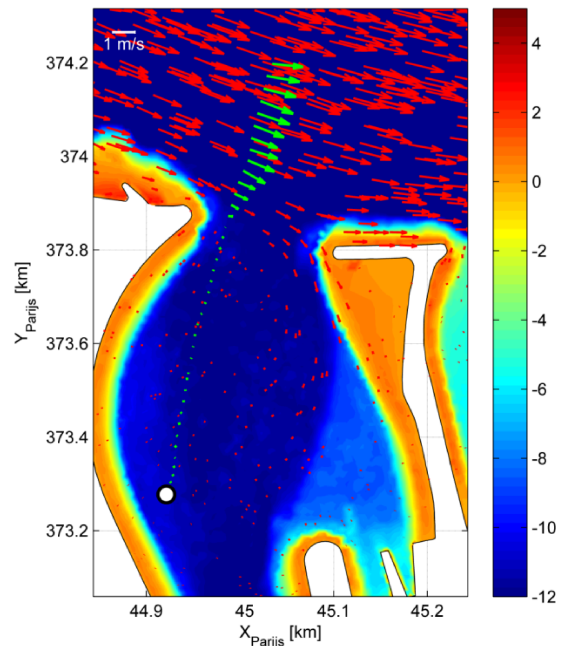Figure 6. Time series of the measured and modeled velocity magnitude and direction at R7 Everingen

Figure 7. Vector plot of the modeled and measured velocities at Terneuzen (white circle on the figure shows the location of the first measurement (0 m))
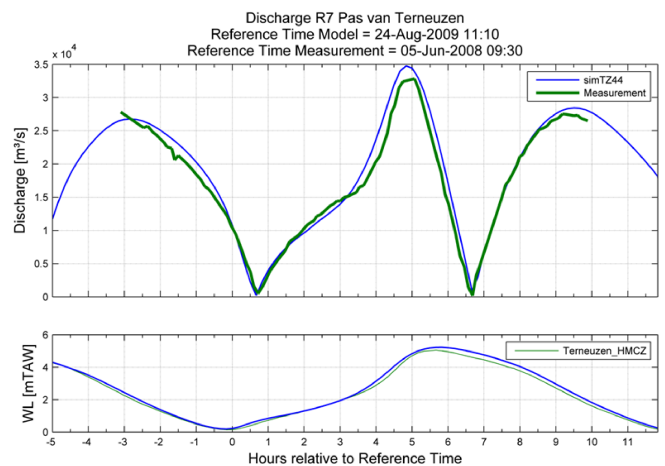

Figure 8. Measured and modeled discharges at R7 Pas van Terneuzen

VI. Model validation

For verification purposes, an independent set of ADCP measurements that were not used for the model calibration is used. The measurement campaigns are listed in Table I.

The model performance during the validation period is comparable with the performance during the calibration. The absolute value of bias of the velocity magnitude at Everingen is smaller than 10 cm/s for most transects. The total RMSE of velocity magnitude is 14 cm/s. The RMSE of velocity direction is smaller than 20 degrees for most transects. It increases around slack. The total RMSE for all transects is 24 degrees.

The flow velocities at R7 Terneuzen are underestimated in the model during ebb (the bias varies between -1 and -16 cm/s). The model accuracy is better during flood. The total RMSE for all transects is 18 cm/s. The RMSE of velocity direction is 35 degrees. The maximum differences are observed around slack.

VII. Application of the flow fields in the ship simulator

A. Export of the modelled velocity maps

The calibrated model was used to calculate the velocity maps for the ship simulator of FHR. The model maps were calculated every 10 min from 25/08/2009 16:00 to 26/08/2009 8:00 (spring tide).

Since a 2D model was used for this study, no depth averaging was implemented. The modeled velocities were exported only for the points with a water depth larger than 1 m. For the points with a smaller depth, velocities were set to NaN (not a number).

B. Research in the simulator

The modelled velocity fields are used in the ship manoeuvring simulator of FHR for the training of canal pilots and for testing specific proposals for the design of new infrastructure (e.g. new sea lock in Terneuzen). This lock will improve the access for seagoing vessels to the ports of Ghent and Terneuzen and will ensure a smooth transit of inland vessels between the Netherlands, Belgium and France [4].

Qualified pilots can assess whether a new design does not hinder navigation so that the limits for safe traffic can be defined (e.g. the maximum dimensions of the vessels calling at a port, the maximum allowed wind or current on entry, what action to take by poor visibility etc.) [5].

It is also possible to examine if new nautical procedures and auxiliary resources improve safety (e.g. use of tugboats, moving of buoys etc.) [5].

It is possible to simulate sailing into and out of the lock, assistance of tug boats, different weather conditions, interaction with other vessels etc. The evaluation of simulations is based on the recorded trajectory, the values of important parameters during the simulation and the reactions of the pilots after the simulations [6].

The following documents are used for the evaluation of simulation results:

- Sailing course plots that describe the trajectory of the simulated ship (including an indication of the positions where a contact occurred between the ship and a hard structure).

- Summary graphs with information about the ship parameters and the use of tugboats etc.) [6].

The view of the port of Terneuzen in the ship manoeuvring simulator is shown in Fig. 9. An example of the sailing course plot is presented in Fig. 10. It shows positions of the simulated ship and tug boats every 60 seconds.

The simulator can be used for the training of river pilots. They can sail into locks and carry out anchoring manoeuvres; approach various jetties and moor to these; learn to work with tugboats; etc. The position, velocity components and forces acting upon the vessel during simulation runs can be saved and can thereafter be used for further analysis [5].

VIII. Conclusions

A TELEMAC model was developed for the port of Terneuzen. After calibration and validation it was used to calculate velocity fields for the ship simulator of FHR. The TELEMAC model was successfully integrated into the existing software of FHR for the statistical analysis during calibration and validation. This model was calibrated based on the available water levels, velocity and discharge measurements.

The model accuracy for high and low waters and harmonic components of the tidal wave was improved during the calibration process. Discharges are well represented in the model at most locations. For the model calibration the calculated velocities were compared with the ADCP measurements at R7 Everingen, port of Terneuzen and Waarde.

Figure 9.   View of the port of Terneuzen in the ship manoeuvring simulator

Figure 10. Sailing course plot: vessel entering the port of Terneuzen

The model accuracy is good at all three locations. The RMSE varies between 11 cm/s at the port of Terneuzen and 16 cm/s at Everingen.

The ADCP measurements from 2011 at R7 Everingen and R7 Terneuzen were used for the model validation. The RMSE of velocity magnitude is 14 cm/s at Everingen and 18 cm/s at R7 Terneuzen.

The modeled velocity fields will be applied in the ship manoeuvring simulator of FHR for the training of river pilots and for testing specific proposals for the design of new infrastructure.

REFERENCES

[1] T. Maximova, S. Ides, T. De Mulder, and F. Mostaert, (2009). Verbetering 2D randvoorwaardenmodel. Deelrapport 4: Extra aanpassingen Zeeschelde. WL Rapporten, 753_09. Flanders Hydraulics Research, Antwerp, Belgium.

[2] B. Verheyen, G. Leyssen, J. Vanlede, G. Schramkowski, and F. Mostaert, (2013, concept version). Verbetering randvoor-waardenmodel: Deelrapport 7: Afregeling van het 3D Scheldemodel. WL Rapporten, 753_09. Flanders Hydraulics Research & IMDC: Antwerp, Belgium.

[3] Canadian Hydraulics Centre, (2011). Blue Kenue. Reference manual.

[4] Port of Ghent, (2013). Engineering office to design new sealock in Terneuzen [online]. Available from: http://en.havengent.be/nieuwsdetail.aspx?id=3247 [Accessed 02/08/2013].

[5] Flanders Hydraulics Research, (2010). Nautical research. Towing tank and ship manoeuvring simulator. D/2010/3241/119. Antwerp, Belgium.

[6] J. Verwilligen, K. Eloot, and F. Mostaert, (2010). KGT – Zeesluis binnen complex: Simulatiestudie. Versie 2_0. WL Rapporten, 803_05. Waterbouwkundig Laboratorium: Antwerpen, België.