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A MULTISCALE 1D-2D COUPLED MODEL OF THE SCHELDT ESTUARY, RIVERS, AND THE EUROPEAN CONTINENTAL SHELF

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ABSTRACT

This study presents a model for simulating the interaction of river influxes with tidal propagation in region of varying complexity for the Scheldt basin (river, tributaries and estuary) and the European continental shelf. While the domain for inland rivers is one-dimensional and extends until the limit of tidal influence, the estuary and shelf region are dealt by means of two-dimensional equations. Within this region, there exists a hydraulic structure in one of the Scheldt tributaries (Dyle River), that is implemented to simulate the bidirectional flow of the tide. In this model a tidal forcing at the shelf break, metrological forcing at the free water surface and hourly discharges for the rivers and tributaries at the upstream boundaries are applied. Using this, the coupled model was firstly calibrated for the Manning coefficient for a relatively quiet period. Then it is extensively validated using available measurements for simulations in the month of January (2021), which is generally marked by strong tides. Moreover, the shelf region of the model was evaluated with the existing literature for the harmonic analysis of the dominant M_2 tide. The simulated results show good agreement with a RMSE under 0.3 meters for the measured water levels.

KEYWORDS: Tidal modelling, Scheldt, European continental shelf, Multi-scale processes, River Flow.

1 INTRODUCTION

The Scheldt basin is a complex system with the tide propagation from the North Sea and the influx from the rivers and tributaries that merge in the estuary to form a transition region. Such systems, in part or in combination are primarily impacted by tides, wind and hydrological processes, including fresh water flow. Therefore, in terms of modelling, it is essential to simultaneously represent the coastal region and the river flow, especially if the aim is to simulate the influence of strong tides (Fringer et al., 2019). Moreover, the Scheldt system represents a domain of multiscale nature that deals with everything from the sea to the more shallow environment of rivers. The interaction of the physical forcings within such a domain can result in a highly variable distribution of energy (Arndt et al., 2007).

Among the regions in the Scheldt ecosystems that can be characterized based on flow energy distribution, the freshwater riverine section, the estuary, and the European Continental Shelf are the most important ones. In contrast to the deep ocean, the currents over the European continental shelf (henceforth referred to as the shelf region) are stronger and can amplify the oceanic tide that can form several amphidromic systems (Reynaud and Dalrymple, 2012). Additionally, since the shelf region has exceptionally rich data, there has been a particular interest in modeling these amphidromic systems (Coughlan and Stips, 2015). On one hand, taking into account all the small-scale systems surrounding the shelf region, like the Scheldt, can make it very complex, without affecting the accuracy in the shelf region. The shelf hydrodynamics, on the other hand, has a large influence on the coastal ecosystems, where the environment is quite shallow. Therefore studies concentrating on shelf hydrodynamics, that can adequately represent the amphidromic system, do not require to consider such small-scale systems. But in terms of water quality, the fresh water systems tend to have an influence on coastal water, as can be seen in the case of salinity (Lacroix et al., 2004).

The interaction of the tidal motion from the shelf region with the fresh water flow in the Scheldt estuarine part produces a unique ecosystem. Therefore, the few studies that have been conducted to capture the multiscale nature of the Scheldt basin are employed to examine water quality mainly in the estuarine region (Arndt et al., 2007; de Brye et al., 2010). But the strong tidal influence of the shelf region can extend up to around 180 km from the mouth into the Scheldt river and its tributaries before subsiding (van Rijn, 2013). Due to dissipative processes, the tidal amplitude gradually decreases upstream of the river and fresh water dynamics begins to become predominant. Also, particular consideration needs to be given to the hydraulic structure in order to accurately represent the flow dynamics in one of the tributaries, the Dyle River.

In this study, we develop a model that aims to simultaneously reproduce not only the flow in estuaries but also the flow in rivers and the European continental shelf. Therefore, in order to represent the river, the hydraulic structure module is implemented in the discontinuous Galerkin finite element method for the tidal motion. Later, the model simulation is compared for the estuary and rivers, including tributaries, using measurement data that includes a period of strong tides in 2021 (January). The amphidromic system derived based on measurements are used to assess the model's performance in the shelf region. The model proposed here will be further developed in the near future to capture the fate of contaminants such as radioactive elements.

2 MULTISCALE MODEL

2.1 Model Domain

The entire multi-scale system of the Scheldt in Belgium, including its rivers, estuaries, and shelf regions, as represented by the model's domain, is shown in Figure 1. The tidal part of the Scheldt river extends from Ghent to the mouth of the estuary at Vlissingen, with a width ranging from 50 m at Ghent to 8 km in Vlissingen. Due to the presence of the sluice upstream, the influence of the tide in the Scheldt river does not extend beyond Ghent. Therefore, the model domain for the Scheldt river is extended until Ghent, whereas all of its major tributaries, such as Durme, Rupel, Dyle, Kleine Nete, Grote Nete and Zenne are considered up to the limit of tidal influence.

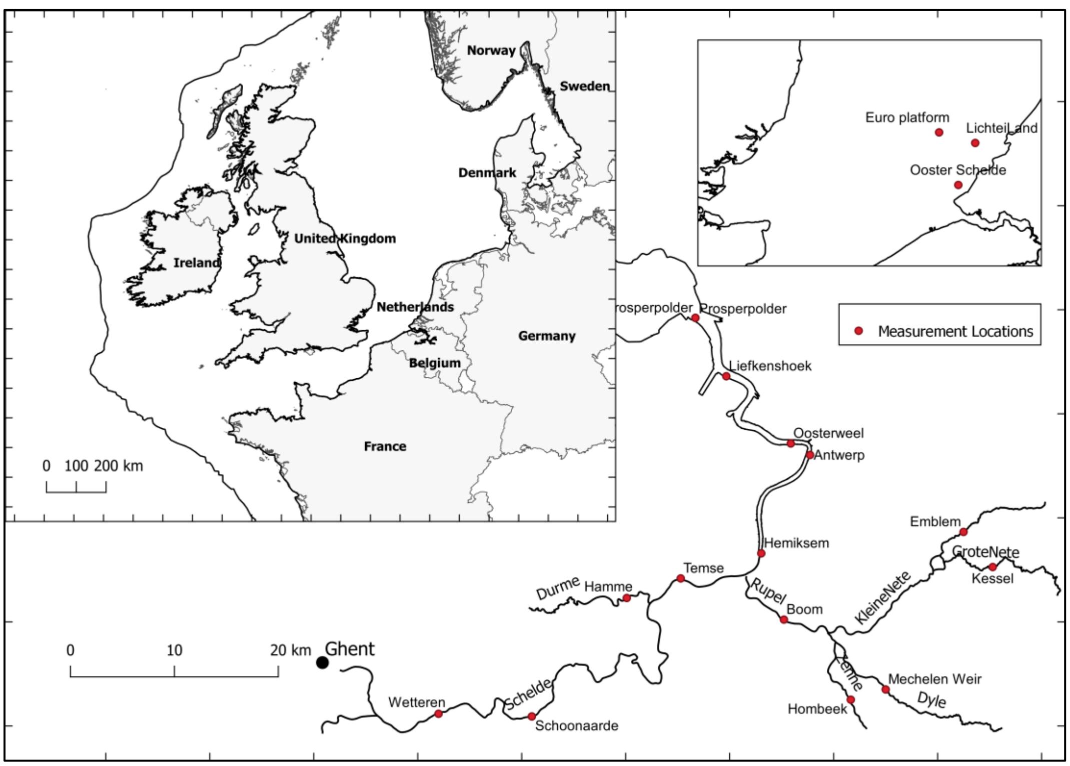

Figure 1. Model domain for the one-dimensional component that includes the Scheldt River and its tributaries and the two-dimensional part that includes the Scheldt Estuary and the Shelf Region, with the measurement locations used for comparing numerical results with field data.

2.2 Model Setup

Since the variation of scales for such systems is very large, the domain is divided into two components: firstly, the inland Scheldt river and its tributaries and secondly, the estuarine and shelf parts. The Scheldt River upstream of Hemiksem, just after the confluence with the Rupel, is simulated using one-dimensional section averaged equations, to which an hourly discharge is applied to the upstream boundary of rivers and tributaries. Here, the cross-section profile for the rivers is extracted from the hydrographic surveys collected by 'Flemish Government'. The second component of the domain is simulated using two-dimensional depth-averaged equations with an unstructured mesh of around 28000 triangular elements with a finer resolution in the estuary and the Southern Bight of the North Sea (Belgian Coastal Region). The bathymetric data from EMODnet was interpolated on the mesh and the tide was imposed at the shelf break using the elevation and velocity harmonics of the global ocean tidal model (TPXO9.1) (Egbert and Erofeeva, 2002). The wind fields (10m above sea level) from the Copernicus climate data source (Hersbach et al., 2020) were used for the meteorological forcing to define the free surface stress. The two-dimensional model was coupled with the one-dimensional model in order to represent a continuous transition between the Inland Rivers and the Estuary–Sea continuum. The whole system of equations is solved using the discontinuous Galerkin (DG) method of SLIM's (Second Generation Louvain-la-Neuve Ice-ocean Model, www.slim-ocean.be) modelling framework. A comprehensive description of the governing equations, the DG method and the coupled solver used in this model are provided in Bladé et al. (2012) and Draoui et al. (2022, 2020).

2.3 Hydraulic Structure Implementation

The weir present within the zone of tidal influence of one of the Scheldt tributaries (i.e., the Dyle River) exhibits a bidirectional flow. For this, the one-dimensional DG method used to solve the shallow water equations is developed in order to incorporate additional modules for hydraulic structures. The DG method computes the state variables of one-dimensional governing equations ($U = [Area \quad Discharge]^T$) between the nodes of its non-overlapping elements using the Riemann problem solver (left and right nodes in Figure 2). For the implementation of the structure, at the node of this location, the Riemann problem solver is replaced by the stage-discharge equation for the weirs in order to compute the variables (center node in Figure 2).

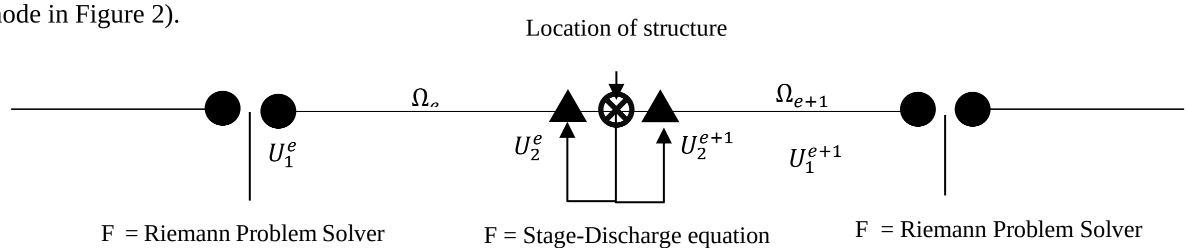

Figure 2. Representation of the nodes in DG method and the treatment of flux by stage-discharge relationships for the imposed discontinuity at the location of a hydraulic structure.

The stage–discharge relationship calculates the discharge over the weirs as a function of the water levels upstream (H_{us}) and downstream (H_{ds}) of the structure (Figure 2) using Equation (1). Two conditions relating H_{ds}, H_{us}, and H_w are applied in order to determine whether the downstream water level influences the upstream flow.

$$Q = \begin{cases} C_1 W (H_{us} - H_w)\sqrt{(H_{us} - H_w)} \quad for \quad \frac{(H_{ds} - H_w)}{H_{us}} < \frac{2}{3} \; Free\ flow\ Condition \\ C_2 W (H_{ds} - H_w)\sqrt{(H_{us} - H_{ds})} \quad for \quad \frac{(H_{ds} - H_w)}{H_{us}} \geq \frac{2}{3} \; Submerged\ flow\ Condition \end{cases} \tag{1}$$

Since the DG method transfers information in both directions, the flow characteristics are inherently bidirectional. In the stage discharge relationship, the water level variables are employed according to the direction of dominant flow, i.e., the side with the highest water level becomes H_{us} and the lower level is H_{ds}, as illustrated in Figure 3. Consequently, the flow of water will always be from a higher water level to a lower one, making it possible to calculate the flow across the structure in both directions. Since the DG method is less sensitive to flux treatments, the model handles the transition from one direction to another quite efficiently.

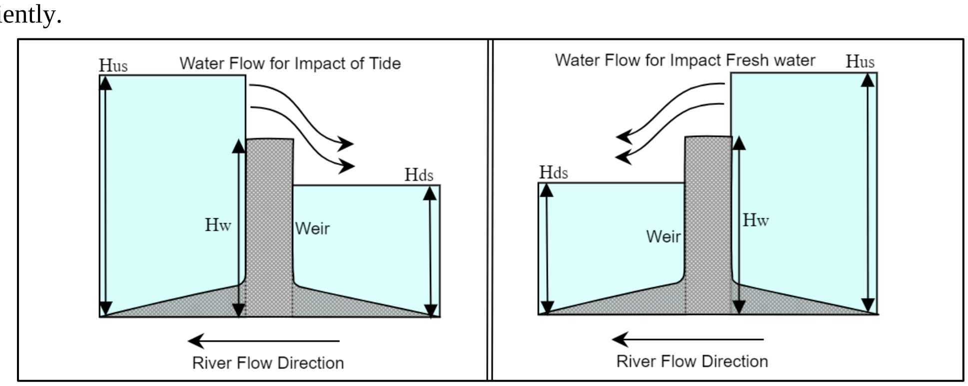

Figure 3. Schematic of the weir and the terms corresponding to the computation of the discharge in the weir equations.

2.4 Model Calibration

The model is calibrated for the Manning coefficient with observed water level data during a relatively calm summer period (July 2021). During the calibration, it was found that using two different Manning coefficients for the two-dimensional and one-dimensional parts yielded better results. However, in the case of hydraulics structures, since the dimensions of the structure are not available to the author, the model is calibrated for the weir height for the measurements done upstream (to river flow) the structure.

The simulation results for the two locations of the measurements used to calibrate the model—Euro-platform (2D part), which is located close to the shore, and Schoonarde (1D part), which is located upstream of the Scheldt River—are presented in Figures 4a and 4b. The figures in this study show the water levels in their original reference system of measurement, where TAW (Tweede Algemene Waterpassing) refers to the Belgian reference system and NAP (Normaal Amsterdams Peil) refers to the Dutch reference system. The root–mean–square error (RMSE) was used to assess the accuracy of the model. These criteria are defined in Equation (2).

$$RMSE = \sqrt{\frac{\sum(M-D)^2}{n}} \qquad (2)$$

where D is the measurement data, M is the corresponding modeled data and n is the total number of pairs. The RMSE value obtained for Euro-platform is 0.17m and that of Schoonarde is 0.21m, and the calibrated Manning coefficient was 0.03 and 0.028 $m^{1/3}s$ for two-dimensional and one-dimensional parts respectively. These small differences in the RMSE indicate that the model achieved good performance.

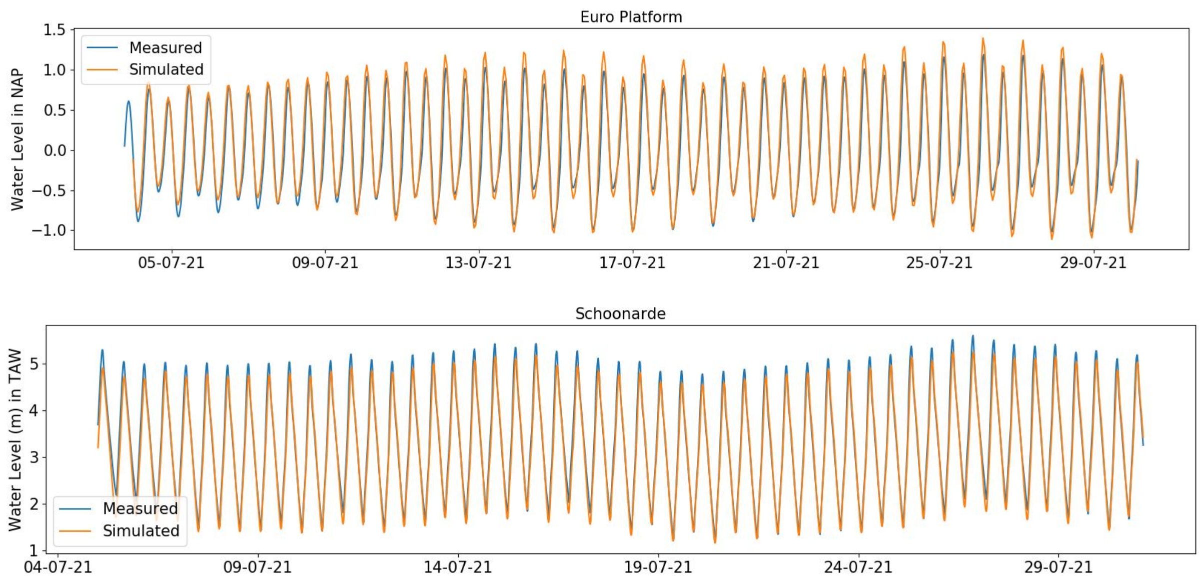

Figure 4 (a) Euro-Platform : comparison of simulated and measured water levels and (b) Schoonarde: comparison of simulated and measured water levels located at the upstream reach of the river (Bottom): location used for model calibration

3 RESULTS AND DISCUSSION

The model was assessed by comparing the model simulations with measurements located along the rivers, the estuary and the Belgian coast for the month of January 2021. All the measurement locations used for validation are presented in Figure 1. In the estuary and the river, the majority of the measurements used for validation are water level, except at Oosterweel, where both the direction and velocity of water flow are used for comparison. On the other hand, the harmonic data comparisons for the dominant M_2 tide were used to access the model performance on the European continental shelf.

3.1 Scheldt Estuary

In the estuary the model results were compared with measurements at several locations. In this section, however, the water level comparison at Antwerp is presented in Figure 5a and the RMSE value of the other station used is presented in Table 1. Since Antwerp is situated in the lower portion of the estuary and is distant from the shelf break, it is an appropriate location to demonstrate the model's ability to simulate an estuarine region with distant boundary conditions. However, the only comparison in terms of velocity and flow direction for the water flow at Osteerweel (Figure 1) is shown in Figures 5b and 5c respectively. Due to the lack of data following the tides on January 12th, the velocity and directions are presented only for a short period of time.

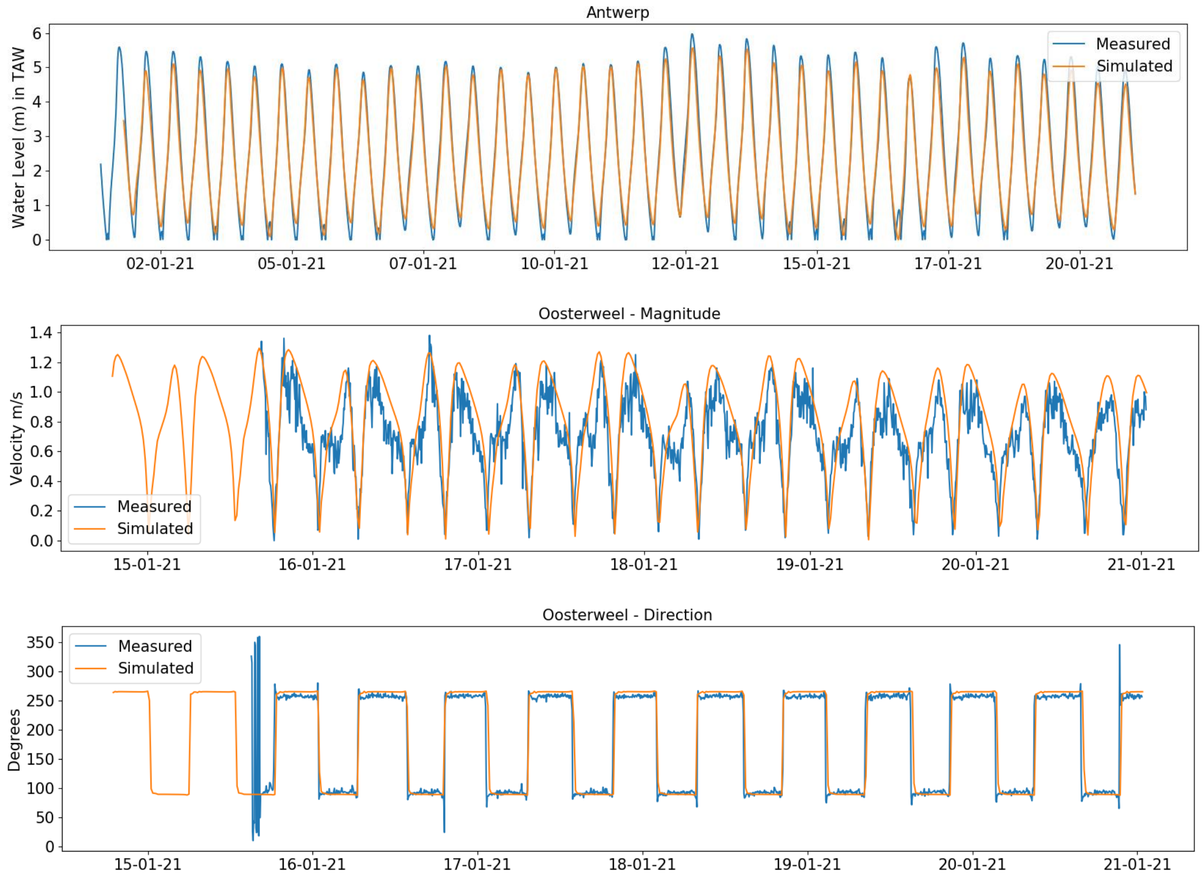

Figure 5 (a) Antwerp: comparison of simulated and measured water levels (b) Oosterweel: comparison of simulated and measured magnitude of velocity and (c) Oosterweel: comparison of simulated and measured direction of flow

Figure 5a illustrates the good agreement for the water level in Antwerp with an RMSE value of 0.26 meters. This shows that the model is able to simulate the water levels far down in the estuary rather satisfactorily. The differences in water level seen in Figure 5a, however, might be the result of less-than-accurate boundary conditions or the need for a better wind parametrization in the shelf region, that can be attenuated in such relatively shallow regions. Such conclusions were found by Gourgue et al. (2015), who observed that for the global TPXO model utilized in TELEMAC-2D, more accurate results were achieved in the shelf region with a tidal forcing shift of -0.1 to -0.15 meters at the deeper parts of Atlantic ocean. Moreover, the model is able to reproduce the shifts caused by the storm surge on January 12th and 13th. For the Oosterweel measurements that are carried out at a position closer to Antwerp, the model prediction for both measurements is remarkably accurate, with the model being able to replicate the change in the water flow's direction. This shows that such variations in water level have no appreciable impact on the water flow characteristics, which are crucial for studies related to water quality.

Additional measuring stations in the Scheldt estuary and the coastline area close to the estuary are used to validate the results of the simulations. The Table 1 presents the RMSE value computed at each location for period of January 2021. It is apparent that the model's representation of the coast is much better than that of the estuary. This is not surprising because of its proximity to the seaward boundary and relatively smaller tide attenuation in comparison to the estuary. The range of the tide along the coast is approximately 2 meters, but it can reach up to 6 meters in the lower estuary.

Table 1. RMSE values obtained for the model comparison in regard to water levels at other locations in the coast and estuary

Location	RMSE Value (m)	Scheldt Basin
Prosperpelder	0.26	Estuary
Liefkenshoek	0.25	Estuary
Ooster Schelde	0.12	Coast
Liechtland	0.14	Coast
Euro-platform	0.15	Coast

3.2 Scheldt River

The Scheldt River simulation was validated using two measurement locations: Temse, which is closer to the estuary (downstream of the river), and Schoonarde, which is in the river's upstream reach. The results are shown in Figures 6a and 6b, respectively.

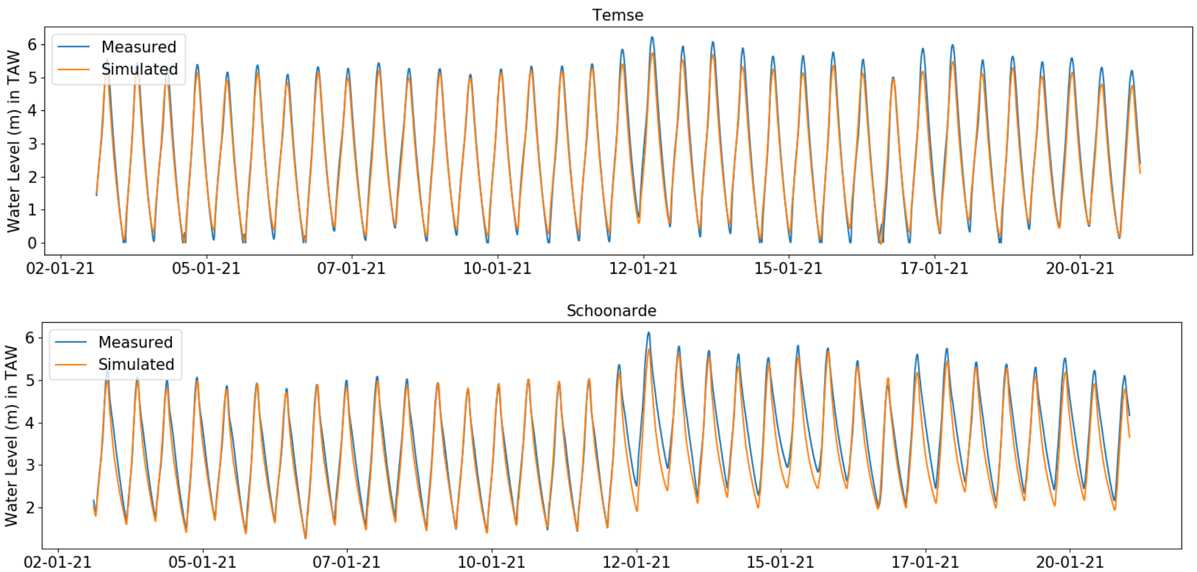

Figure 6. Model comparison for the simulated and measured water levels in the Scheldt River at (a) Temse located downstream (Top) (b) Schoonarde located upstream (Bottom)

The RMSE of the hourly water level comparison between the measured and model values is 0.3 meters for Schoonarde and 0.24 meters for Temse. Among all the measurement stations in the Scheldt basin that were taken into consideration for comparison, Schoonarde had the highest RMSE value. The comparatively higher value from others can be attributed to the deviation from observation during the strong tide period after January 12th. Since the model prediction can be quite accurate at other periods, this suggests that additional physical parameters such as wind (that is not included in the one dimensional part) that affect the tidal propagation towards the upstream portion of the river could have led to lower water levels in the simulation results. On further observation of meteorological data, the wind speed over Schoornarde on January 12th reached up to 32 km/h in comparison to a maximum of 13 km/h during calm periods (NOAA Global Forecast System). Overall, the model does represent the tides and can simulate the shifts in water level due to the impact of strong tides to a certain degree in the Scheldt River. In fact, the model prediction for the peak values of both low and high tides is represented exceptionally well in the case of calmer periods, with an maximum of 16 cm. However, for the period of strong tides the deviation is up to 50 cm, as shown in Table 2. A similar impact can be seen in regards to Temse, but with lower deviations compared to Schoonarde.

Table 2. Peak values of the measured and simulated water level for both the low and high tide shown in Figure 6b during the periods for calm and strong tides.

		Low Tide Peak			High Tide Peak		
	Date	Measured (m)	Simulated (m)	Error (m)	Measured (m)	Simulated (m)	Error (m)
Calm Period	05/01	1.73	1.73	0.00	4.83	4.70	0.13
	07/01	1.68	1.62	0.05	4.99	4.82	0.16
	09/01	1.52	1.51	0.01	4.77	4.80	-0.03
Strong Tide Period	12/01	2.53	1.99	0.54	6.12	5.73	0.39
	13/01	2.98	2.54	0.43	5.79	5.61	0.18

3.3 Scheldt Tributaries

There are several available measurements of the water level in Scheldt's tributaries, which were compared for accuracy. However, in this section, the measurements done at locations for farther-reaching tributaries, such as the Kleine Nete and the Grote Nete are shown. Additionally, water level measurements upstream and downstream of the structures in the Dyle River at Mechelen are presented for the hydraulic structure implementation in the model.

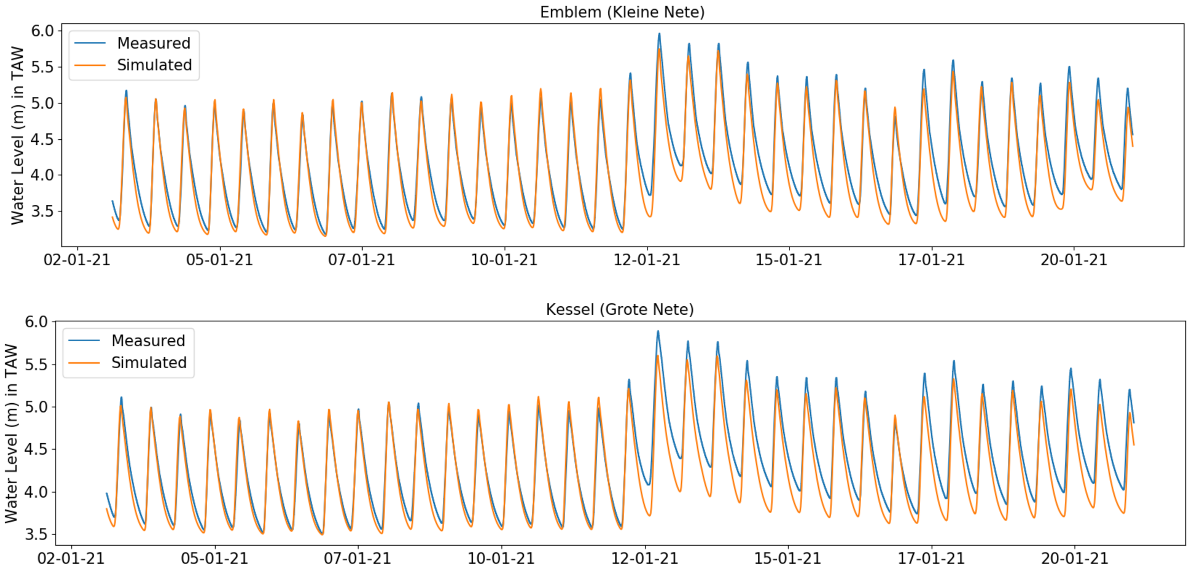

Figure 7. Model comparison for the simulated and measured water levels in Scheldt tributaries at (a) Emblem in the Kleine Nete River (Top) (b) Kessel in the Grote Nete River (Bottom)

Figure 7a shows the water level comparison of simulated results and measurements at Emblem in the Kleine Nete River and Figure 7b shows the comparison of water level at Kessel in the Grote Nete. Since these two locations are situated so far away from the sea, the influence of the tide is considerably reduced. This becomes even more apparent when looking at tidal range, where it is just around 1.8 meters here and about 5 meters near the confluence with the Scheldt River. At both locations, the root mean square error (RMSE) is approximately 0.15 meters, indicating a high level of agreement with the observed value. However, as we examine Figures 7a and 7b, we can see that the model has a slightly lower performance in the later phase (that is, following the January 12th tides) of the water levels. Since the effects of tidal influence have receded and the impact of river discharge increases, it is likely that lateral water sources not represented in the model—such as river runoff, point discharge flash floods originating from urban areas etc.—are the cause of the deviations. Nevertheless, with its low RMSE value, even for the distant measurement location, the model shows a good performance in representing the flow.

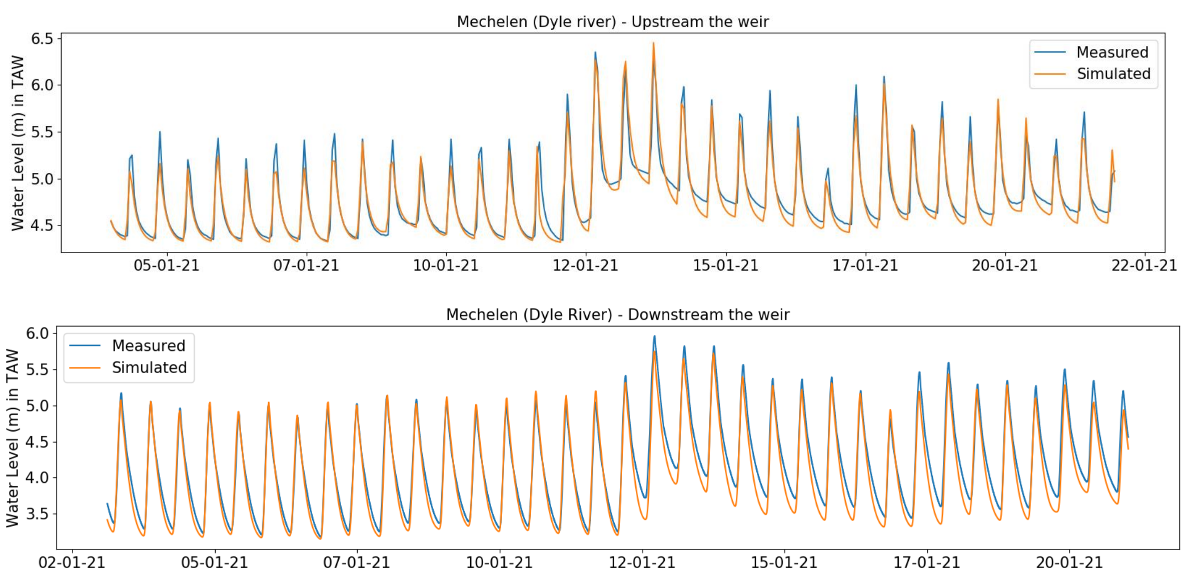

Figure 8. Model comparison for the simulated and measured water levels in Dyle river at Mechelen (a) upstream the weir (Top) (b) downstream the weir (Bottom)

Figure 8a shows the comparison of water levels for the measurement located upstream of the river flow for the hydraulic structure and Figure 8b shows the comparison of water levels for that located downstream of the structure. Both measurements are located in close proximity to the structure. In contrast to the downstream measurements, the upstream water level (Figure 8a) show a relatively flat gradient at low tide, which shows the influence of structure that does not allow the water level to fall below a threshold value. With the calibrated model for the hydraulic structure, it can be seen that the model does predict the water levels rather well, with an RMSE value of 0.25 meters. The reason for deviation from measurements in the later phase (after the January 12th tides) is that the structures can be operated to change the height, as evidenced by measurements where the water level can drop to up to 2.8 meters. Since the authors lack information on the operating rules, they are not applied in the model. But in the case of the water level comparison downstream of the weir, as shown in Figure 8b, a lower RMSE value of 0.21 is achieved than that of upstream measurements. A good performance both downstream and upstream suggests that the discharge calculation and implementation of the stage-discharge relationship in the DG method are quite accurate. Furthermore, a lower RMSE value downstream indicates that the operation of the structures has an effect on the water level upstream. Similar to the model results in the Kleine Nete and Grote Nete, the water level is underestimated at this location as well, which can also be attributed to the deficiencies of lateral discharge in the model.

3.4 European Shelf Region

The model validation on the European continental shelf was done using the harmonic data comparisons for the dominant M_2 tide. The chart for isometric lines for the co-range and phases of the M_2 tide is plotted and the amphidromic points are obtained. The model results were compared with available charts based on measurement (Figure 9) and show a good prediction of these amphidromic points. However, the point at the southern tip of Norway shifts towards the western direction in comparison to measurements reported in some studies (Coughlan and Stips, 2015; Otto et al., 1990), while it matches well with the chart reported in another one (Luxford et al., 2014). Furthermore, in the validation step, the co-range and phase lines were also compared with these charts and a good comparison was obtained, especially in the Southern Bight region.

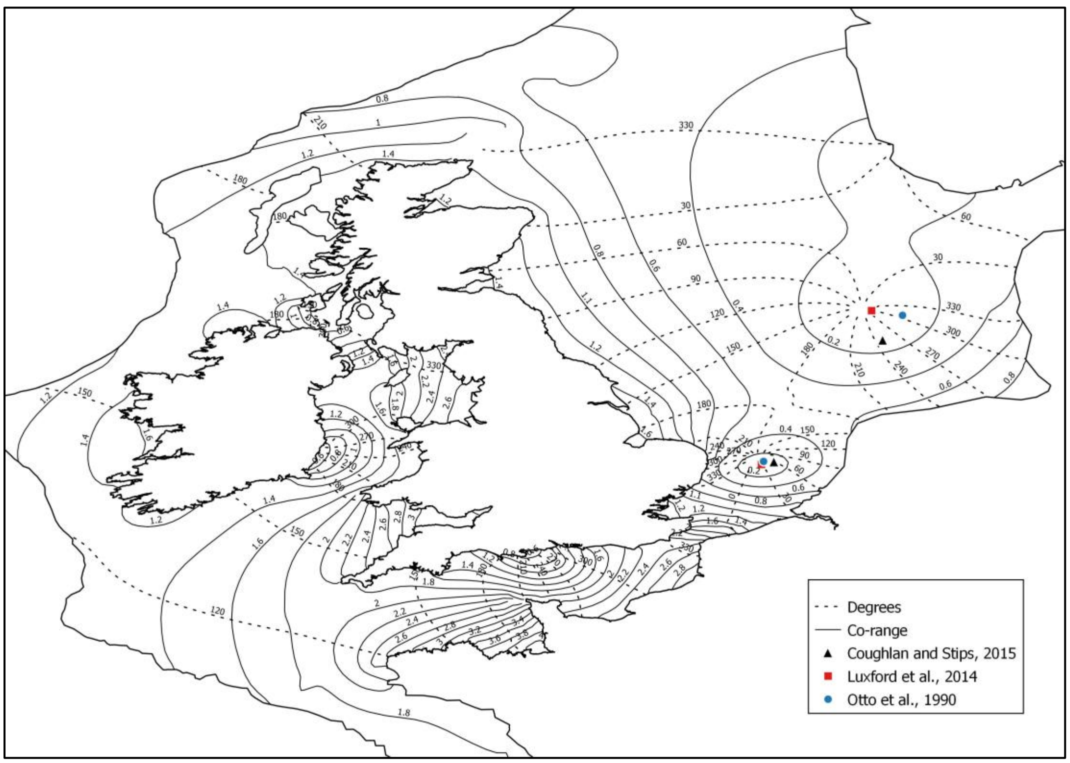

Figure 9. Model comparison for the amphidromic points and model representation for the isometric lines of the co-phase (degrees) and co-range line for the dominate M_2 tide

4 CONCLUSIONS

A single model is developed to describe the river discharge in the Scheldt basin, the amphidromic systems on the European continental shelf and their influence in the estuarine region. The simulation results were compared to the hourly measurements available in these locations, and it was shown that the model performs well and predicts the shifts in water level caused by storm surges. Though there are deviations from measurements that rise as the tide propagates upstream the Scheldt river, this does not imply that the model's accuracy is limited. But other physical phenomena, such as the effect of wind friction in one-dimensional domain, the lack of lateral inflows in these region and the operation regulation of structures, can also influence the flow dynamics. Nonetheless, it was demonstrated in the case of estuary dynamics that, despite variations in water level, the model performed well in computing the velocity components that represent the complex estuarine environment. In terms of hydraulic structure implementation, it is shown that the model accurately represents the impact of such a structure that is subjected to tidal motion. However, due to lack of data regarding the operational rules for the structures, variations from measurements, especially during low tides are observed. Furthermore, the model performs well in the southern Bight region but suffers slightly in the shelf region due to the larger mesh size.

Based on the model results obtained after calibration and validation, it is reasonable to state that the model results are in good agreement with measurements and perform quite well, especially during calm meteorological conditions. As a result, SLIM can be coupled to a water quality module to simulate pollutant fate in such a vast system over longer time periods.

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