Damping of ship-induced primary waves

Damping ship-induced primary waves in rivers by modifying groynes with the aim of increasing fauna habitat quality

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HKV LIJN IN WATER

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Summary

Recent ecological studies (Collas et al., 2018; Gabel et al., 2017) show that ship-induced waves reduce the suitability of fish habitats along the river banks, especially for eggs and young fish (Wolter & Arlinghaus, 2003). For the river Waal in the Netherlands the breeding and growing season of this fauna is from April to September, which generally corresponds to flow conditions where the groynes in the river are emerged. The living habitat of eggs and young fish is in the shallow zones close to the bank, which experience a high degree of hydrodynamic variability due to ship-induced waves. The goal of this study is to explore whether fish habitat during the growing and breeding season can be improved by reducing the flow impact of passing ships through structural modifications of groynes.

Hydraulic modelling is used to simulate ship-induced waves and their impact on groyne fields. Ship-induced waves can be categorized in two types; primary waves and secondary waves. Both wave types exhibit very different spatial and temporal scales and need different model capabilities to be accurately modelled. Modelling both wave types simultaneously is computationally intensive and limited validation material is present for modelling of secondary waves. Additionally, the ecological effect (both direct and indirect) is greater for primary waves. So, it is decided to limit the model study to a simulation of primary waves only. The generation and propagation of primary waves and its effect on the river and groynes can be modelled by both Boussinesq-type models and non-linear shallow-water (NLSW) type models. A NLSW-type model is less computationally expensive whilst it is not qualitatively inferior to a Boussinesq-type model and thus chosen for this study. Two NLSW-type models frequently used for modelling ship-induced waves are Delft3D and Xbeach. Research by (M. de Jong et al., 2013; Zhou et al., 2014) states that XBeach shows better results and is more advantageous than Delft3D and as such chosen for the study.

The bed topography and model setup are based on river and groyne characteristics from the Waal. The largest allowable vessel on the Waal (CEMT class VIc) is modelled by applying a constant pressure head on the water surface moving along a predefined track. A grid dependence study is performed to find the most suitable grid size for this study. The optimal grid size is determined by finding the convergence point for water level and flow velocity in a system with discharge and no ship passing, and in a system without discharge but with ship passing. The final model setup is validated using laboratory test data.

Ecological research states that fauna habitat quality can be assessed by analysing water level range and flow velocity range in a timestep of 60 seconds. Current ecological studies develop methods to correlate the fish density to these ecological parameters. The groyne field is a highly dynamic, so these parameters are calculated for every location in the groyne field. This calculation is executed for both the traditional groyne field and the modified groyne field. A comparison between the two gives insight in the improvement or deterioration of the fauna habitat. Results from the modelling study show that notched groynes can have a positive influence on the fish habitat in groyne fields but L-shaped groynes do not. Further research shows that notched groynes have the potential to improve habitat quality in side channels, however this finding requires further research to verify.

Results from the modelling study show that notched groynes have a positive impact on the fauna habitat and the two dominant notch characteristics driving this change are the location of the notch and the discharge through the notch. The location of the notch should be placed as close to the river banks as possible without the jet directly impacting the living habitat of the eggs and young fish, and the discharge which follows from the notch flow area has an optimal value which depends on the size of the groyne field. A large groyne field requires more discharge through the notch to have an impact on the area of interest then a small groyne field. The fish habitat around the notches may become less suitable locally due to high flow velocities through the notch but in large parts of the groyne field the fauna habitat improves, because of the inter-connection between neighbouring groyne fields.

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1 Introduction

1.1 Background

The effects of ship-induced waves on local fish habitats have traditionally received little attention in scientific studies. Only recently ecological value is factored into river engineering decisions in the Netherlands. However, in recent years, Rijkswaterstaat (executive agency of the Ministry of Infrastructure and Water Management in the Netherlands) has invested significant time and energy into preserving ecological habitats within the river system. The construction of various side channels in the Dutch rivers aimed at increasing ecological activity and flood safety while retaining the economic functionality of the river. On broader scales, the European parliament and council of the European Union passed the overarching directive “Kaderrichtlijn Water (KRW)” (European Commission, 2001) outlining goals to preserve water quality along the Rhine. These goals all called for measures to reach a good ecological status.

The economic value of the Rhine is undeniable. The Rhine is one of the largest rivers in Europe, with a watershed encompassing the Netherlands, Germany, Belgium, Luxemburg, France, Switzerland, Italy, Liechtenstein and Austria for a total area of 185.000 km^2. It is also the most navigated river in Europe. The heaviest navigational traffic occurs between the North Sea and the Ruhr Area of Germany. A subsection of this stretch (flowing between Pannerden and Woudrichem) is the Waal river. The energy efficiency of inland navigation in the Rhine basin is not only very high compared to other modes of transport, it is also steadily increasing. In general, the more recent the vessel and convoy type, the larger its carrying capacity and the lower its energy consumption per tkm (Pauli, 2010). However, despite the energy efficiency advantages, the shipping capacity of the European inland waterways is considerably underused in terms of infrastructure and vessels (Wolter & Arlinghaus, 2003). The notion that fossil fuel combustion is identified as a major source of greenhouse gas emission causing the threat for global warming (EC, 2001) and the previous statements will likely result in an increase of inland navigation.

Higher navigational activity and ecological preservation, however, do not always interact synergistically. A local program called “Waalweelde” was initiated on the Waal. The restoration of the Loenensche outer polder (located at Rhine kilometre 982) was one of the many projects in the program to increase the spatial quality and water safety in the Waal. However, side channels struggle with interference from ship-induced waves (Gabel et al., 2017), which propagate into the side channel and result in direct and indirect negative effects on the habitat of the local fauna (Wolter & Arlinghaus, 2003). Decreasing these disruptive wave patterns is expected to result in an increase of fish density for both rheophilic and eurytopic species (Collas et al., 2018).

Given that navigation is expected to increase along the Waal, the Loenensche outer polder will be used as a case study to better understand the propagation of ship-induced waves in groyne fields and around side channels. Using computational modelling, we will study how different groyne design might dampen these ship-induced waves and create a more hospitable habitat for local fauna throughout the Waal.

1.2 Objective

The objective of this research is to give recommendations on methods to dampen ship-induced waves in groyne fields and side channels by modifying the groynes with the aim of increasing the quality of fauna habitats.

1.2.1 Scope of the research

Rijkswaterstaat has asked HKV to research possibilities for damping ship-induced waves in the Loenensche outer polder side channel. While preliminary research by HKV has resulted in several recommendations, questions remain on how L-shaped groynes and notches in groynes might affect wave propagation to dampen ship-induced waves, see Figure 1. In addition to the original question by Rijkswaterstaat, this project presents interesting research questions which are applicable to broader scenarios.

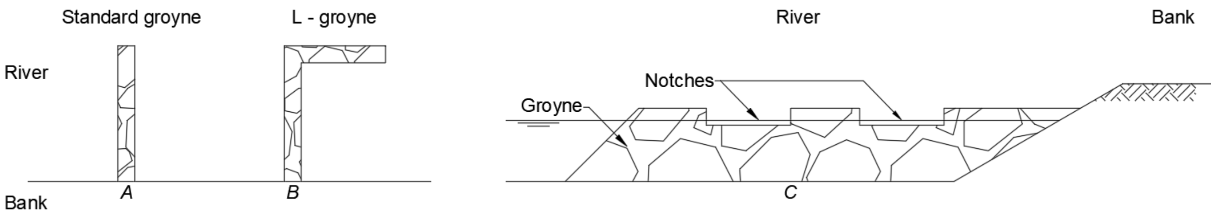


Figure 1: Visualization of modified groynes. Top view of a standard groyne (A), an L-shaped groyne (B) and side view of notches in groynes (C).

The research is based on an ecological principle. The biggest impact on fauna are the fluctuations in water velocity and water level. This research will therefore be limited to hydrology. Despite the fact that morphological research will be excluded from the present study, it is important that a follow-up study will be performed investigating the effect of morphology. Side channels are unstable systems with active sediment transport, and altering groynes will impact the morphological dynamics throughout the groyne field. These side channel processes can in the long term possibly limit the effect of the modifications.

To clarify the effect of the damping methods on fauna, the data or model will be shared with ecologists. Ecologists have information correlating the change in water dynamics to a change in fauna density of a wide range of organisms. The correlation of this data can be used to give quantitative estimates about the improvement in fish density due to the modification of the groyne.

1.2.2 Research questions

The following main and subquestions have been formulated to answer the objective.

Main question

- How can ship-induced waves in groyne fields and side channels be damped by using L-groynes or by creating notches in groynes to increase ecological value of the river habitat?

Sub questions

- Which hydrological indicators can be used to quantify ecological value?
- What flow dynamics ensue in a groyne field when ship sail by?
- Which notch design optimizes fauna habitat quality in a groyne field?
- Which L-shaped groyne design optimizes fauna habitat quality in a groyne field?
- Which flow dynamics ensue in a side channel when a ship sails by and how can the optimized damping structure dampen the ship-induced waves in side channels?

1.3 Research approach and thesis outline

To reach the objective and answer the research questions, the research is set up in 4 steps.

Literature study

The research study starts with a literature review. This review is focused around three subjects: flow dynamics in- and around groyne fields, generation and propagation of ship-induced waves, and the impact of ship-induced waves on ecology. The information obtained from this study gives insight in the vulnerability of the fauna and characteristics and dynamics of ship-induced waves. This study is captured in Section 2.

Model choice and setup

In Section 3 a hydraulic model will be chosen for the study. The characteristics of the ship-induced waves and its effect on the ecology is determined using the literature study. Based on this information, desired model capabilities and outcome parameters are determined. Several hydrological models will be assessed and the optimal model will be chosen. Section 4 contains the model setup. The river and groyne characteristics near the Loenensche Outer Polder (a side channel in the Waal) are used to set up the geometry and boundary conditions of the model. A grid dependency study is performed to find the optimal grid size and the entire model setup is validated using laboratory tests.

Results

The results from the model study should give insight in the following three main characteristics: the optimal notch geometry and location in the groyne to increase fauna habitat quality, the optimal L-shaped groyne geometry for increase in fauna habitat quality, and an optimal design of the best modification. The latter is used to gain insight in the effect of the modification on high water, smaller vessels and a side channel. These results are displayed and discussed in Section 5.

Discussion, conclusions and recommendations

In Section 6 a critical reflection on assumptions and study methodology is performed. Based on this reflection and the model results the research questions are answered and a recommendation to dampen ship-induced waves in groyne fields is given. These conclusions and recommendations are shown in Section 7.

2 Literature study

The literature study discusses three aspects. In Section 2.1 the groyne characteristics and impact on the flow pattern in the river are discussed. Section 2.2 explains the generation and propagation of ship-induced waves as well as the change in flow pattern due to the passing of a ship along a groyne field. Section 2.3 clarifies the impact of ship-induced waves on the fauna habitat.

2.1 Groyne fields in the Waal

Originally the Waal was a wide river with the tendency to meander and form multiple channels. This natural flow pattern caused problems as flood risk was high and the shallow main channel limited navigation. To solve these problems the Dutch government has carried out river normalizations, commonly referred to as training the river. Dikes and groynes were constructed to narrow the river, and river bends were removed to shorten the river length. Over time, these river normalizations have driven a degradational process in the main channel. In the past sixty years the longitudinal channel slope of the Waal has decreased and the mean flow velocity and thus sediment transport capacity has increased (Blom, 2016). The construction of groyne fields and increase in navigation due to the incised main channel resulted in an inhospitable fauna habitat in the groyne field as explained in the introduction.

2.1.1 Design of groynes

Groyne fields consist of a series of structures perpendicular to the river bank. They are generally made of stone, gravel, rock, earth or piles beginning at the river bank and ending at a predefined line with a head. The main function of groynes in the Netherlands is to keep a deep enough channel for inland shipping. The most important design parameters influencing the behaviour of the groyne according to (Przedwojski et al., 1994) are discussed below.

Emerged or submerged groyne

Most groynes can be separated into two categories: emerged or submerged groynes. Emerged groynes are designed with a crest height above average water levels and are mostly impermeable, blocking and deflecting the river flow. These groynes are not part of the flow conveying cross section of the river. Submerged groynes, meanwhile, are designed to stay below design water levels and are mostly permeable, allowing water to flow through and over the groynes at a reduced velocity. Because river flow can flow over and through the permeable groynes, submerged groynes are considered part of the flow- conveying cross section of the river.

Groyne shape

Groynes can attract, deflect or repel flow depending on the angle between the groyne itself and the river bank. Attracting groynes point downstream and attract flow towards themselves. Deflecting groynes are short and used for local protection, they divert the flow without repelling it. Repelling groynes point upstream and force the flow towards the opposite bank.

Groyne sizing

The spacing between the groynes is often related to river width, groyne length, flow velocity, angle to the bank, orientation to the flow, bank curvature and purpose. It is mostly expressed as a multitude of the groyne length (Yossef, 2015). Recommendations for a groyne field for bank protection are 2 – 6 times the groyne length and for realizing and maintaining a suitable main channel for navigation 1.5 – 2 times the groyne length. The length of the groyne depends on the purpose; bed protection or maintaining a deep channel, but is mostly around a quarter of the mean width of the river. The cross section of the groyne is between 1 – 6 metre and is based on desired strength and available materials.

2.1.2 Flow near groynes

Flow patterns within groyne fields have been studied extensively. Studies have shown that the magnitude of the ambient river current has a small influence on the shape of the flow pattern in the groyne field. However, a decrease in the water depth affects the flow pattern as the influence from bottom friction is more pronounced (Uijttewaal et al., 2001b). Additionally, Section 2.1.1 clarifies how the angle of the groyne influences the attraction or deflection of the flow. The ratio between intermediate groyne spacing and groyne length also influences the flow pattern due to large scale eddy development. Six types of eddy patterns occurring between the groynes due to different spacing can be described (Klingeman et al., 1984), see Figure 2:

- Type one: a single eddy driven by the main current develops inside the groyne field deflecting the main current from entering the groyne field resulting in a deep continous main channel;
- Type two: a second eddy with opposite sense of rotation driven by the downstream eddy is formed and the main current is still deflected outside the groyne field;
- Type three: the main current is directed into the groyne field creating greater turbulence and an eddy near the upstream groyne;
- Type four; the upstream eddy is washed out and a single reverse current inside the groyne field develops;
- Type five; the main flow is directed to the bank between the groynes and eddies form on both sides;
- Type six; the downstream eddy disappears and the flow directly attacks the banks.

Groyne fields of type three and larger create flow circulations where the flow penetrates into the groyne field. In all cases a small eddy forms at the tip of the downstream groyne, this eddy sheds from the field and moves to a downstream groyne field merging in the flow pattern.

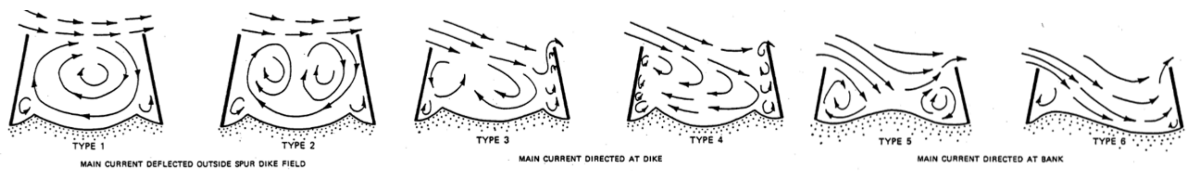


Figure 2: Large-scale optimized eddy patterns in groyne fields formed due to ambient river current. The groyne spacing increases with type number (Klingeman et al., 1984).

The whole circulation pattern is driven by the main current via exchange of momentum through the mixing layer. The mixing layer between the groyne field and main channel originates at the tip of the groyne and widens towards the next groyne downstream. This flow pattern changes along the groyne from the tip to the base. Around the tip of the groyne the flow is three-dimensional, however, moving towards the base of the groyne the flow patterns become more two-dimensional. Due to the limited water depth no strong large-scale three-dimensional structures can form to create mass and momentum exchange along the groyne (Krebs et al., 1999).

The function of the groynes in the Waal is to create a deep main channel. This is done by deflecting the flow from entering the groyne field. To obtain this result the groyne spacing / length ratio needs to be small, so we expect a type 1 – 2 large scale eddy pattern. In (Uijttewaal et al., 2001b) the flow patterns in groyne fields based on the river Waal by model experiments are researched. In Figure 3 a flow from a groyne field with a length / spacing ratio and lateral slope similar to groyne fields in the Waal is depicted. This corresponds to a type 1 – 2 groyne type.

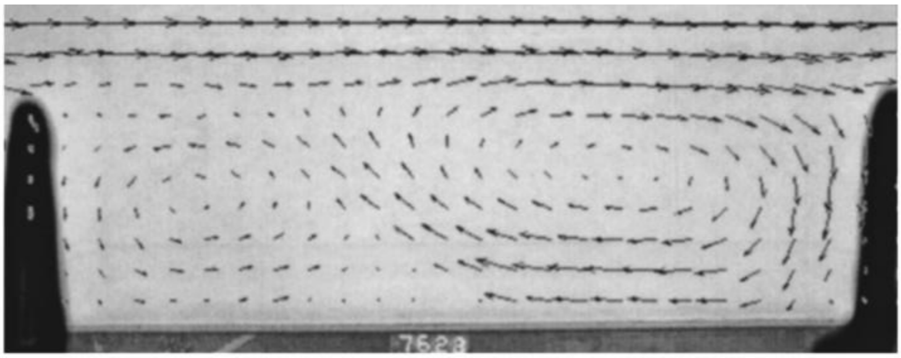


Figure 3: Top view visualization of a horizontal flow pattern in a groyne field studied using a laboratory scale model (Uijttewaal et al., 2001a).

2.1.3 Groyne fields characteristics along the Waal

The general characteristics of the groyne fields along the Waal were estimated by (Schans, 1998), during field campaigns between 1996 and 1997. The results are summarised in Table 1. The parameters that have the most influence on the flow and intrusion of waves are groyne spacing, groyne length and orientation of the groyne. We use these parameters to set up our model research.

Table 1: Characteristic values of groyne fields in the Waal (Schans, 1998)

Parameter	**mean**	**min.**	**max.**	**standard deviation**
Spacing between groynes [m]	198.2	50	420	37.7
Groyne length [m]	67.9	0	175	28.6
Length along the waterline [m]	215.1	100	480	43.5
Distance normal to thalweg [m]	129.8	10	320	93.6
Main channel width [m]	279.5	252	412	35.2
Orientation of the groyne [deg.]	-8.0	-30	10	8.7
Beach slope [-]	0.042	0.03	0.05	0.008

2.2 Ship-induced waves

A vessel navigating through a waterway constantly pushes water to the front and aside, while at the same time a corresponding amount of water is being supplemented at the stern. This displacement generates waves and currents, see Figure 4. The dominant disturbances have been labelled as water level depression, return current, secondary waves and propeller jets. The water level depression and return current resulting from the displacement of water form the primary waves. Wash waves and associated orbital motion form the secondary waves. Screw race resulting from the ships propeller jets are limited to the navigational lane behind the vessel and has minimal influence on the groyne field and will be neglected in this study.

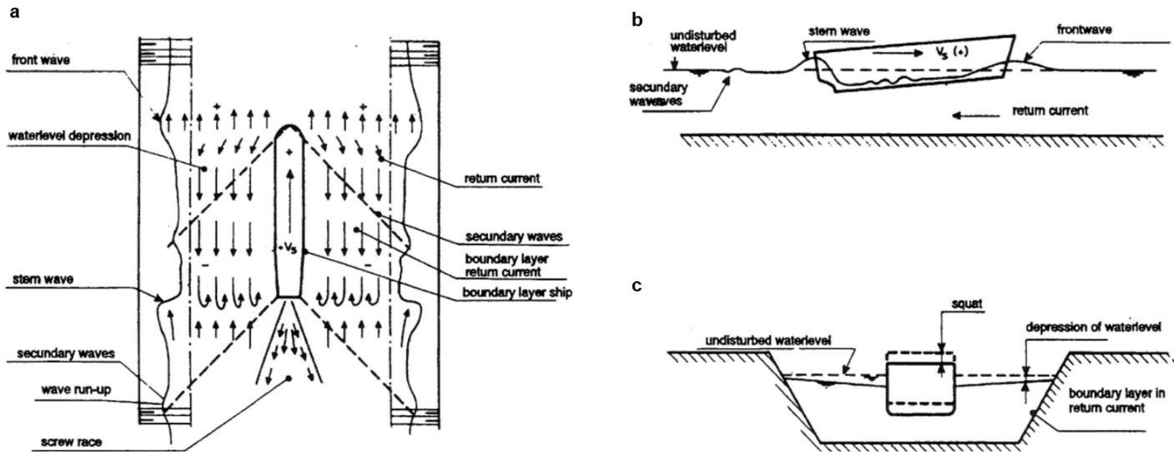


Figure 4: Ship-induced wave dynamics around a vessel in three different views. Top view (a), side view (b) and back view (c) (Verheij & Vermeer, 1987).

2.2.1 Primary waves

The displacement of water triggered by the movement of a vessel results in primary waves, see Figure 4. When a vessel moves through a body of water it breaks the natural path of the flow and diverts it from its straight path. The flow will accelerate at the bow (front of the ship) and stern (back of the ship) which requires an increase in pressure, along the hull (side of the ship) the acceleration reduces and the pressure is lower. The pressure distribution is followed by the water surface profile causing the surface to rise at the bow (front wave) and stern (stern wave), and produce a lateral water depression at the hull (Sorensen, 1997), see Figure 4b. The flow along the sides and under the ship is called the return current and flows opposite of the ship direction. Together with the water depression it is called the primary water movement. The height and period of this movement depends on the sail velocity and the ratio between vessel cross section and channel cross section. This depression causes the water level to decrease in shallow areas along the shoreline which results in dewatering of the river bank (Hall & Benham, 2007). The supply flow follows the stern wave with the sailing direction of the vessel to supplement the region of water level depression with new water after the drawdown.

Primary wave effect on groyne field

In Section 2.1.2 flow patterns in groyne fields due to natural stream flow are described. When a vessel passes a groyne field these flow patterns change due to the primary wave motions. Measurements and lab experiments have been carried out to gain insight into the flow patterns of groyne fields during a push tow passage going upstream. In Figure 5, five stages of passage advancing in time have been visualized. (Ten Brinke et al., 2004) concludes as follows: when the bow of the ship passes the tip of the groyne (step 1), the return current causes a downstream directed flow in the groyne field. As the vessel moves further into the groyne field (step 2) the return current becomes stronger, the eddies are washed out and the downstream flow becomes stronger. When the stern of the vessel moves along the groyne field (step 3) accompanied by the supply flow, the direction in the groyne field rotates. This supply flow fills the groyne field until the stern passes the upstream groyne (step 4) where the supply flow meets the return flow from the upstream part of the groyne field, diverting the flow back into the channel. When the vessel has passed the upstream groyne (step 5) the supply flow can enter the upstream part of the groyne field as the return current weakens. Important conclusions by (Havinga et al., 1984; Termes et al., 1991) resulted in:

- Increase in return and supply flow results in larger velocities in the groyne field, especially immediately downstream from the groynes;

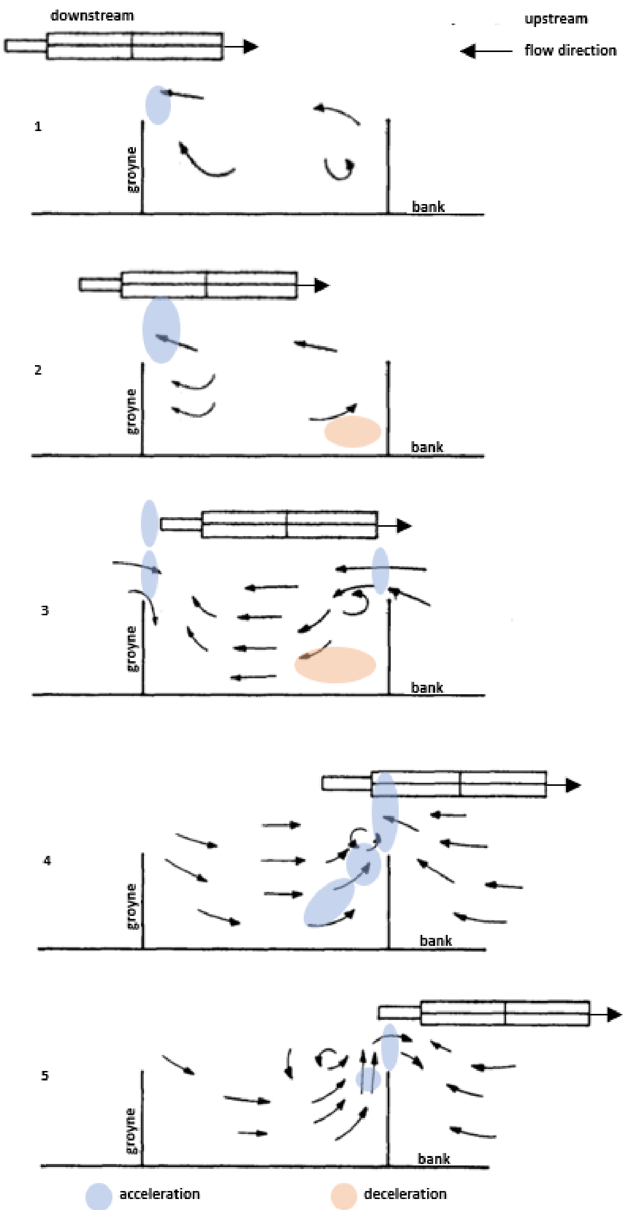


Figure 5: Flow dynamics in groyne field due to primary waves during passage of a vessel. Figures based on (Ten Brinke et al., 2004; Termes et al., 1991

- A correlation between increase in flow velocity and decrease in distance between ship and groyne is found;
- Small groyne fields have lower velocities due to the smaller effect of the supply flows;
- Field experiments showed that push tows produce a considerable effect on the groyne field while self-propelled vessels up to 2000 ton had very little effect.

2.2.2 Secondary waves

The secondary water movement consists of ship-induced short waves. The pressure pattern along the hull is not continues due to primary wave processes. Strong discontinuities are found at the bow and stern of the vessel which both emit waves. These wave emissions can be seen as disturbances and each disturbance creates a circular wave, see Figure 6a. The envelope of these circles created behind the ship are the diverging waves and the remnants of these waves are called the transverse waves, see Figure 6b. Where the divergent and transverse waves meet, interference cusps are formed on the so-called cusp line.

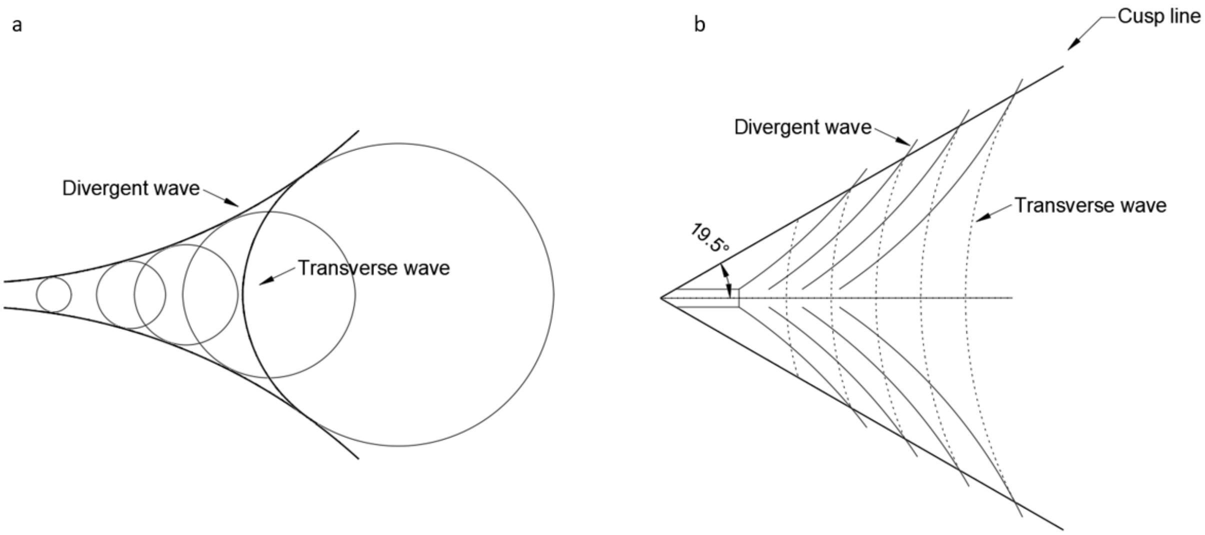


Figure 6: Visualization of the generation of secondary waves

Divergent waves are observed as wake waves and they propagate differently in deep and shallow water. In 1887 William Thomson found that the angle at which the wake fans out is always the same as long as deep-water conditions apply, namely ≈ 19.47^{0}. This is due to the fact that in deep water the group velocity is half the phase velocity and the phase velocity depends on the wavelength. For the mathematical derivation see (Zawischa, 2020). Transverse waves move in general faster than divergent waves and propagate in the same direction and with the same velocity as the vessel.

The height of these waves is strongly determined by the speed of the ship but also depends on the shape and ship's main dimensions. Due to surface tension below a relative speed of 0.233 m/s no waves arise. Furthermore, the secondary water movement is strongly influenced by the magnitude of the primary water movement.

The orbital motion of the secondary waves creates turbulence in the water column and shear stress on the bed. Two situations can occur. In the main channel the waves might propagate according to deep-water properties where no influence on the bed takes place and only part of the water column experiences additional turbulence. If the waves propagate into shallow water regions then the entire water column is excited and the bed experiences additional shear stress. At the interference cusps or "cusp line" the wave energy is at its maximum thus at this location the influence on the river system is highest.

2.3 Ecology

It is important to understand the regional ecology in the Waal and how human-caused disturbances affect the flora and fauna. Here we focus on the mechanisms through which ship-induced waves impact fauna in the Waal river system.

2.3.1 Direct impact of ship-induced waves on fauna

The physical forces generated by vessels directly impact fish. The magnitude of impact depends on a host of factors, including the life stage of the fish, which are categorized as eggs, larvae, juveniles and adult fish. We review the prominent disturbances related to primary waves (return current and drawdown) and secondary waves (wash waves) and discuss how these disturbances affect fish habitat.

As previously discussed, primary waves generate drawdown, where the water level on both sides of the ship decrease. This drop in water level causes dewatering of the shore line and presents two dangers to fish: exposure to air and stranding potential.

The exposure to air during dewatering does not cause fish eggs mortality, but with a dewatering frequency of 8 times a day there is significant observed mortality of larvae (Holland, 1987). The stranding potential during drawdowns where larvae or juveniles which are adapted to shallow low-velocity littoral zones, are less vulnerable to stranding compared to the species which inhabit the main- or side channels (Adams et al., 1999). The swimming performance of juveniles and adult fish is related to the speed and stamina and are crucial factors in determining the survival rate. The swimming performance affects the exercise performance, migration abilities and predator-prey interactions. Additionally, it determines the fish' ability to withstand the physical forces of the ship-induced waves, in specific the return current and wash waves. The swimming performance of fish can be separated in three groups; maximum speed, burst speed and critical speed. The maximum speed of a fish is held for 2-3 s (Hammer, 1995) which drops in the burst speed range < 20 s (Webb, 1975) and these speeds have a similar timescale as wash waves. The critical swimming performance of fish with a timescale of < 1 h. (Brett, 1964) has a timescale comparable to the return current. Research by (Wolter & Arlinghaus, 2003) found correlation between the length of fresh water fish and the burst and critical speed. The increase in fish length results in an increase in burst and critical speed. Concluding from this study is that the return current is the significant cause of the high fish larvae mortality, and the velocity of the return current exceeds the critical speed of the juveniles and as such the juveniles are unable to withstand this current.

2.3.2 Indirect impact of ship-induced waves on fauna

Several indirect effects on fish due to navigation are known. Adult fish move away from the nest due to the disturbances which leaves the nest open for predators (Mueller, 1980). The waves create extra frictional forces near the bed bringing inorganic (sediment) and organic (food) material into suspension which increases turbidity and thus limits the juveniles and adult fish from feeding (Barret, 1992). Additionally, the organic matter may stay in suspension to be transported downstream, while the inorganic matter settles, causing a restricted food availability (Brunke et al., 2002). The frictional forces can also cause dislodgement of eggs and redistribution of eggs and larvae to less suitable habitats (Jude, 1998). Measurements by (Ten Brinke et al., 1999, 2004) showed that the shear stress due to the frictional forces is highest when the water flows back into the groyne field after drawdown, this is called the supply flow. The research also concluded that the relative contribution to shear stress of the primary waves versus the secondary waves vary with vessel size. Small vessels mainly induce secondary waves with neglible effect for shear stress compared to larger vessels. For larger vessels the influence of primary waves increases with increasing underwater volume of the vessel.

3 Model choice

This chapter discusses the model choice used for this study based on several considerations. In Section 3.1 the impact of primary and secondary waves on ecology is studied as well as the capabilities of the modified groynes to dampen these waves. In Section 3.2 the desired model capabilities and outcome are explained and in Section 3.3 a numerical model for the study is selected.

3.1 Primary vs secondary waves

Primary and secondary waves exhibit very different spatial and temporal scales. In this section the impact of primary and secondary waves is evaluated.

3.1.1 Wave characteristics

We calculate relevant wave parameters using (Verheij, 2008) to gain a general idea of the magnitude of the waves. The results are summarized in Table 2. We consider the primary wave as both a free wave and non-free wave in our calculations. Near the ship itself, the primary wave can be best approximated as a non-free wave. In the groyne field, however, the free-wave approximation is more accurate. Thus, we calculate the parameters for both scenarios to gain insight in the full domain. When the primary wave is considered as a free wave, the dispersion relation can be applied. For the calculation and assumptions see Appendix A.1. The secondary waves always follow the dispersion relation. Our calculation suggest that primary waves have both a higher height (factor 2) and period compared to secondary waves. These findings agree with the Fourier analysis performed by (Roo & Troch, 2010) on field data from a channelized river.

Table 2: Wave characteristics of primary and secondary waves of a CEMT Class VIc vessel on the Waal. The kh-value represents the relative depth and the applicability of various models can be determined using this value.

	wave height [m]	**wave length [m]**	**wave speed [m/s]**	**wave period [s]**	**wave number [m^{-1}]**	**kh-value [-]**
Primary wave non-free	0.41	270	4.34	62	0.023	0.13
Primary wave free	0.41	474	7.56	62	0.013	0.077
Secondary wave	0.23	8.04	3.54	2.27	0.78	4.53

3.1.2 Ecological impact

Waves' direct impact on the ecology is mostly related to dewatering and the increased flow velocities resulting from the return current and wash waves. We have found that the velocities and period of secondary waves are smaller than those of the primary waves, see Table 2. The short-term burst speed of fish is expected to overcome the secondary wave with lower velocities and shorter periods more frequently, than the primary waves with larger velocities and longer periods. This makes the velocity related impact on ecology due to primary waves substantially higher than the impact of secondary waves.

The indirect impact of waves on ecology is mostly related to the shear stress. Navigation on the Waal is made up of ≈ 80% of CEMT class IV or higher vessels (Rijkswaterstaat, 2008). The influence of larger vessels is dominant over the smaller vessels and according to Section 2.3.2 the contribution to shear stress of primary waves is, in comparison to secondary waves, relatively higher for larger vessels.

Thus, we conclude that primary waves produce the dominant impact (both directly and indirectly) on ecology.

3.1.3 Effectiveness of modifications

This research studies the effect of two modifications on groynes: notches and L-shaped groynes, see Figure 1 in Section 1.2.1. The influence of these structural features on both primary and secondary waves is discussed below.

Notches in groynes

The primary waves are impacted by the notches. Primary waves cause large-scale water depression which can influence an entire region between two groynes. This can result in significant water level differences on both sides of the groyne which causes strong flows, especially around the tip of the groyne. The notches create an opening in the groyne to shorten the flow distance and reduce the velocity as well as the volume of water which has to pass the tip of the groyne, see Figure 7a.

The secondary waves are short surface waves and they can freely travel into the region between two groynes. From Figure 7c it can be concluded that only limited wave action can penetrate through the notches in the groyne in the form of diffracted waves (see red circle). This is due to the angle of the secondary waves and the width of the groyne. The connection between two groyne fields is limited, so it can be assumed that the groynes with notches have minimal impact on the height and velocity of secondary waves.

L-shaped groynes

The groynes have a branch at the tip to partly close the groyne field. However, due to basic flow in and out the groyne field and to maintain the original function, the groyne field will never be fully closed.

The behaviour of a primary wave in an L-shaped groyne can be approached by a single impulse caused by the ship passing, see Figure 7b. The wave propagates into the groyne field adapting itself based on the wave length and amplitude, the resistance in the groyne field, and reflection at the closed end. These factors determine whether the amplitude and wave velocity increase or decrease. The damping or possible resonation of the waves in the L-shaped groynes partly depends on the wave length. The wave length is similar to the length of the vessel. The focus lays around damping of waves of the larger vessels (e.g. push tows) as these have the highest impact on ecology. However, research has to be done to visualize what effect the designed L-shaped groyne for large vessels has on smaller vessels and thus smaller wave lengths.

Secondary waves are able to freely propagate into the groyne field and partly affect the river bed and banks as without the structure, see Figure 7d. However, diffraction will take place which reduces the wave height. This is mainly concentrated behind the groyne extension and limits the effect of wave attack on the river bed and banks.

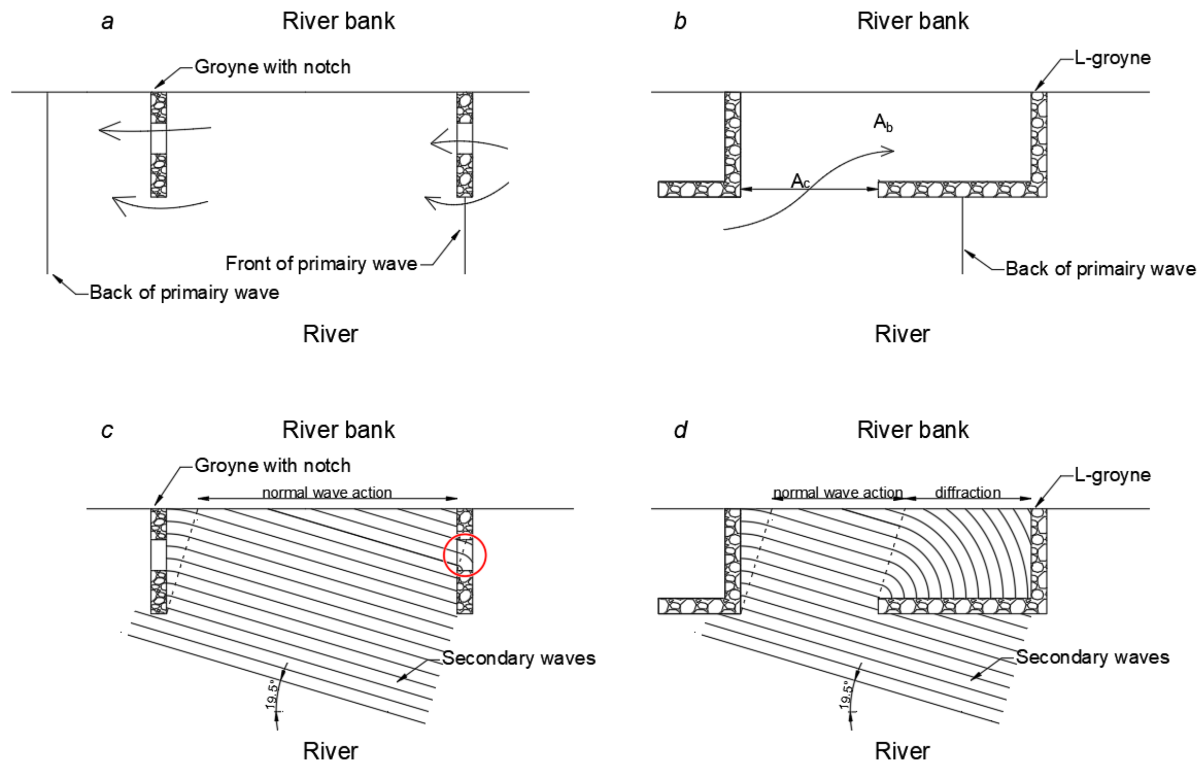


Figure 7: Primary wave propagation in groyne field with notches (a) and L-shaped groynes (b), flow direction visualized with arrows. Secondary wave propagation in groyne field with notches (c) and L-shaped groynes (d).

3.1.4 Conclusion

The results in Table 2 and considerations based on the field study discussed in Section 3.1.1 show that the magnitude of the wave characteristics is larger for primary waves. The ecological impact, both direct and indirect, is larger for primary waves compared to secondary waves, see section 3.1.2. From a practical point of view it is hard to model secondary waves as it is computationally intensive and limited validation material is present. Combining these conclusions with the assumptions made in section 3.1.3 that the modified groyne structures have limited impact on the damping of secondary waves, it is decided that the model study will be limited to a simulation of primary waves only.

3.2 Model parameters

The model should facilitate the simulation of a vessel sailing with and against the flow of a river with complex geometry in the form of modified impermeable groynes while simultaneously generating primary waves. Below the necessary capabilities and outcomes of the model are discussed.

Model outcome parameters of interest

To research the influence of the modifications on the primary wave and connect them to ecological indicators the following parameters are of interest:

- Water level changes with a spatial accuracy of 5 cm;
- Water level velocity 15 cm above the bed with an accuracy of 5 cm/s.

The model resolutions are based on the required resolution needed to model the above parameters with sufficient accuracy. A vertical resolution of one layer is sufficient since the flow is predominantly two-dimensional with horizontal eddies (Krebs et al., 1999). The horizontal grid requires a spatial resolution in the order of magnitude of metres to provide enough information about the flow around the notches in the groynes.

Wave propagation

The primary wave can be modelled as a non-linear long wave ($kh < \pi/10$), see Table 2. If the wave enters the field under an angle, diffraction along the tip of the groyne takes place. Long-wave energy is effectively reflected by a structure (the groyne) or the mildly sloped river bank. Due to the shallow water level and long-wave properties shoaling and refraction will also be expected to take place. The primary wave of the vessel causes dewatering of the river banks. This corresponds to the processes of wave run-up and run-down. The model needs to be able to calculate the above-mentioned wave propagation processes.

3.3 Conclusion

The focus of the study resolves around the generation and propagation of primary waves and its effect on the river and groynes. Boussinesq-type models are capable of simulating these long primary waves as well as relatively short dispersive waves (secondary waves). However, they are computationally more expensive than models based on non-linear shallow-water (NLSW) (Tavakkol & Lynett, 2017), which can only model long primary waves. Since secondary waves are not of interest for our specific study no Boussinesq-type model is needed and the choice for the less computationally expensive NLSW-type models is made. XBeach and Delft3D are two widely used and well verified NLSW-type models to model ship-induced waves and research by (Zhou et al., 2013) concluded that XBeach and Delft3D could both simulate the generation and propagation of primary waves well. However, the similarities between the measured data and simulated data as well as the practicability makes XBeach more advantageous than Delft3D. Additional research (M. P. C. de Jong et al., 2013; Zhou et al., 2014) shows good results with XBeach in making qualitative assessments to increase insights in the phenomena of ship-induced waves. So, XBeach is chosen for the model study.

XBeach is a free-surface numerical model developed to simulate hydrodynamic and morphodynamic processes on sandy coasts with a domain size of kilometres and on time scales of storms. Since then, the model has been applied to other types of coasts and purposes. The model is based on non-linear shallow-water equations and includes long-wave transformation processes and currents as well as the effect of hard structures. The model has two modes: a hydrostatic mode and a non-hydrostatic mode. The non-hydrostatic mode can be used for more complete calculations but results in more computational demand. Recently a module for XBeach has been implemented which allows for the generation and propagation of ship-induced waves. The model and module have been validated with a series of analytical, laboratory and field test cases.

4 Model setup

This chapter elaborates the setup of the river model in XBeach. The desired output parameters from the model are defined in Section 4.1. The grid and bed topography setup are shown in Section 4.2. The underlying equations for the model and utilization of the ship module are described in Section 4.3, and the imposed boundary conditions are described in Section 4.4. The grid dependency study is performed in Section 4.5 and the validation of the model setup in Section 4.6.

4.1 Output parameters

The output generated from the model should be comparable to measured in-situ data from ecologists evaluate the impact of the modifications on fauna habitat. It was concluded from the literature study that variability in water level and variability in flow velocity have a high impact on the habitat quality, further referred to as ecological parameters. To be published research found a relation between the fish density and the above-mentioned parameters. Using this data in combination with the output of the model a quantitative conclusion about the impact on the habitat can be given. So, the model has to provide insight in the variability in water level, the variability in flow velocity, and provide an overview of the general flow patterns.

Variability in water level

The variability in water level is a parameter that is used to measure perturbations to mean water level. In situ, water level perturbations are measured using a water pressure sensor. The sensor is placed at a fixed point on the bed and measures the change in pressure at 1 Hz, which can be translated to water level. Note that the measurements from the water pressure sensor are from a Eulerian frame.

In the model this data can be obtained by sampling the water level at 1 Hz from a fixed point on the grid. This data also comes from a Eulerian frame so this can readily be compared to the in-situ data.

Variability in flow velocity

The variability in flow velocity is a parameter that is used to measure perturbations to mean flow. In situ, flow velocity is measured at 1 Hz using a hand-held flow velocity device. This device uses a magnet which rotates from which the velocity vector can be determined. In this case the immediate direction and magnitude of the velocity is known. The measurements from the flow velocity device are from a Eulerian frame.

In the model we mimic the data from the flow velocity device by sampling the velocity vector in x- and y- direction at 1 Hz for a fixed point on the grid. This data also comes from a Eulerian frame so this can readily be compared to the in-situ data.

Flow patterns

Besides the above-mentioned parameters to quantify the fish habitat quality, the general flow patterns in and around the groyne fields as a result of the ship passing are also important. These patterns give insight in general changes due to the groyne modifications. By analysing these patterns, the effect of the notch on the flow is better understood, these findings help in choosing an improved groyne design and contribute to our understanding of the mechanisms.

4.2 Computational grid and bed topography

XBeach uses a coordinate system where the x-axis is always oriented towards the coast, approximately perpendicular to the coastline and the y-axis is alongshore. These definitions are changed to apply for a river situation. The coast boundary is downstream, sea boundary is upstream and the river banks are perpendicular to the coast, see Figure 8. The applied grid is a staggered curvilinear grid, where the bed levels, water levels and water depths are defined in the cell centres with x- and y-points and the velocity is defined at the cell interface with u- and v- points. The computational domain must be large enough to prevent boundary disturbances from entering the area of interest, this is explained in Section 4.4. Additionally, the resolution of the grid should be high enough to accurately depict the processes of interest, however, a higher resolution leads to an increase in computational time. The optimal grid size will be defined in Section 4.5.

Data specified in Table 1 and multibeam data from Rijkswaterstaat have been used to schematize the bed topography. The bed topography resulting from the multibeam data has been averaged over the lateral width and a constant longitudinal slope is applied in the model domain. Additionally, a constant lateral river slope from the main channel to the river banks is applied. By smoothing the bed topography, small scale disturbances are reduced. In Figure 8a the bed topography top view from the model domain is depicted in a situation with an upstream sailing vessel and in Figure 8b the top view with an downstream sailing vessel is depicted. The difference between these two situations is explained in Section 4.4.

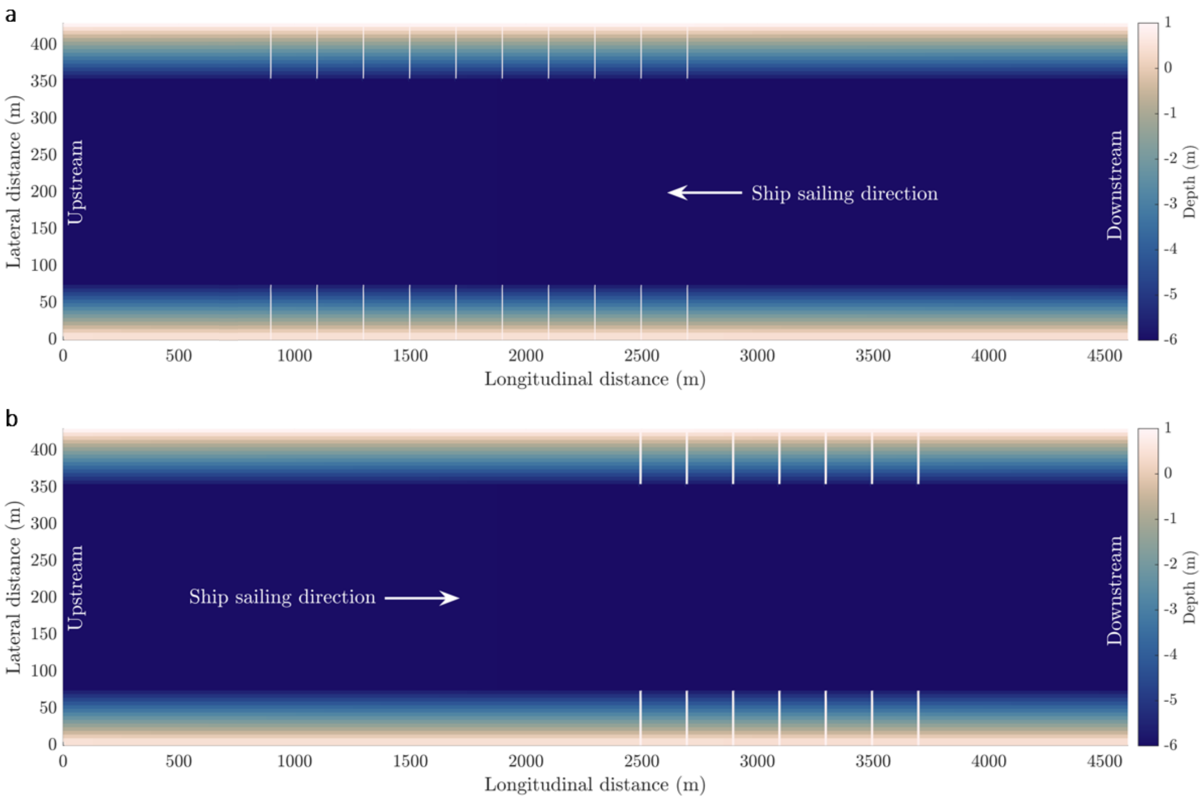


Figure 8: The top view of the river bed topography with upstream sailing vessels and groynes located from longitudinal distance 700 metres to 2700 metres (a) and downstream sailing vessels with groynes located from 2500 metres to 3700 metres (b). Upstream is left, downstream is right and the river banks are perpendicular to this reference at lateral distance 0 metres and 430 metres.

4.3 Module set up

For computing ship-induced waves the non-hydrostatic 2DH mode of XBeach has to be used. This mode uses the non-linear shallow-water equations with a pressure correction term to solve low-frequency waves and mean flows. This depth-averaged dynamic pressure is computed from the mean of the dynamic pressure at the surface and at the bed by assuming the dynamic pressure at the surface to be zero and linear change over depth. For the equations and derivations see (Roelvink et al., 2015). This approach is possible as the primary wave length of the vessel (270 m) is much larger than the depth (5 m). The variables are solved with explicit numerical schemes. This results in a numerical stability restricted by the timestep or grid size. The system has to comply to the CFL-condition:

$$C = \frac{u\Delta t}{\Delta x} \leq 1 \quad \textit{Eq. 1}$$

We do not model short-wave energy and morphodynamic activity so these functions are turned off for the model. Since the morphodynamic activity is turned off the groynes can be modelled as bed elevations.

XBeach represents a moving ship by applying a constant pressure head that moves along a pre-defined track through the model domain. The representation of the ship by a moving pressure head results that waves and currents do not reflect off the ship but pass “through” the imaginary ship. Around the ship this results in unrealistic signals, however this is a local problem and will not affect the quality of the signals propagating into the groyne field.

If the pressure head (vessel) is suddenly activated in the domain with a large velocity, waves and currents develop due to the pressure head and its propagation. These signals are a result from numerical continuity and do not represent actual effects. To minimize these non-physical effects the vessel accelerates according to a cube root function. This formula ensures that the vessel accelerates without velocity jumps to the cruising speed. This gradual acceleration of the vessel requires an undisturbed river stretch to reach the cruising speed before entering the groyne field. The pressure head is inserted and extracted within the boundaries of the domain to prevent non-physical disturbances caused by crossing the boundaries.

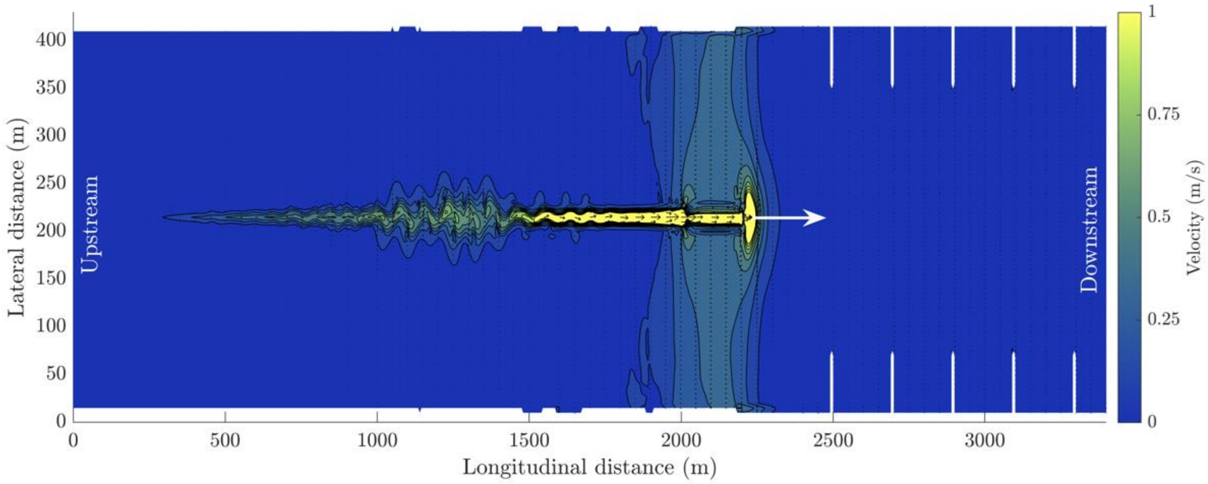


Figure 9: Zoomed velocity vector plot of a vessel sailing downstream through the model domain specified in figure 8b. No current is present in the river.

Figure 9 shows a velocity vector plot of a vessel sailing downstream in a section of the domain specified in Figure 8b. The model contains no discharge so the disturbances are solely a result from the vessel. The flow pattern around the ship complies with the theory defined in Figure 4. Behind the ship between 500 and 2000 longitudinal metres a velocity disturbance is visible, this is not the effect of the propeller of the vessel. The flow seeks to return to its equilibrium state after the change in pressure head, this results in a long “tail” of varying flow and water levels. The disturbance behind the vessel is narrow and will not propagate or influence the groyne area so it has minimal impact on the results.

4.4 Boundary conditions and geometry

To solve the non-hydrostatic model, boundary conditions have to be provided at all open boundaries. Three types of boundary conditions have been applied at the boundaries of the domain: water level (called Abs2d in XBeach), discharge and no flux walls. Since we only want ship-induced wave activity in the model, no wave boundary conditions are applied.

Since XBeach uses a predefined grid orientation not all boundary conditions can be applied to every domain boundary. At the upstream boundary a discharge condition is applied, for the boundary conditions at the river banks a no flux wall is applied, and for the downstream boundary condition a water level is applied.

No flux wall
This boundary type is a simple no flux boundary condition. This boundary condition is applied at the river banks. Since the river bed is laterally sloping, the bed level is above the water level at the no flux boundary. Thus, this boundary has practically no influence on the system.

Water level (called Abs2d in XBeach)
The water level boundary condition is a constant water level over the width of the domain and allows for obliquely-incident and obliquely-reflected waves and currents to pass through the boundary and is set at the downstream river boundary. After the last groyne an uninterrupted stretch of river should be present to diffuse the eddies and disturbances resulting from the groyne field. These eddies have to diffuse before leaving the domain through the boundary or it creates disturbances at the boundary which will propagate upstream through the domain, negatively impacting the results.

Discharge
The discharge boundary condition excites the system by imposing a flow and is set at the upstream river boundary. The current is simulated by setting a discharge on the boundary. The magnitude of the discharge increases slowly in time to minimize non-physical reactions by the activation of the boundary condition, similar as the slow increase of vessel velocity. Between the upstream boundary and the first groyne an uninterrupted river stretch should be present to facilitate the development of a fully developed flow. This removes disturbances in the groyne field as a result from the boundary condition.

Since a discharge is defined at the upstream boundary and a constant water level at the downstream boundary, a free surface gradient relative to the bed gradient forms between the two boundaries.

In Figure 10 on Page 19 a non-physical change in flow velocity is visible at the downstream boundary near the river banks. This non-physical observation can be contributed to the constant water level over the entire width, which is set as the downstream boundary condition. The bed topography near the banks is laterally sloping resulting in a decrease in water depth, here the flow velocity and water level changes comply to the non-linear shallow-water equations. However, the downstream boundary condition states a constant water level so the flow velocity has to change to comply to continuity. The upstream boundary is defined by a discharge, as such the water level can adjust freely and no non-physical change in flow velocity is visible.

River geometry
In Figure 8 on Page 15 the different geometry for upstream and downstream sailing vessels is depicted. The difference between the two is based on the ship sailing direction and the river flow direction. The discharge is always defined at the upstream boundary (left), so the sailing direction has to change to model upstream and downstream sailing. As explained in Section 4.3 a long uninterrupted stretch of river is needed to slowly increase the speed of the vessel. This stretch is for downstream sailing vessels on the upstream side of the domain and for upstream sailing vessels on the downstream side of the domain, additionally this leads to the different location of the groyne fields. The model with the upstream sailing vessel has more groynes than the model with the downstream sailing vessel. This is due to contractional flow which occurs when a current or vessel enters a region with a decrease in flow area, in this case flow width. The contractional flow alters the flow pattern in the groyne field and does not correspond to a normal flow, resulting in invaluable results for this study. The contractional flow returns to a normal flow after three groyne field lengths so, the first three groyne fields have to be disregarded. In the geometry with upstream sailing vessels contractional flow is present at the

upstream side of the groyne field due to current entering the groyne field, and at the downstream side of the groyne field due to the vessel entering the groyne field. As such six groyne fields have to be disregarded. In the geometry with the downstream sailing vessel the contractional flow is only present at the upstream side of the groyne field, caused by both the current and the vessel. Compared to the upstream sailing vessel only half of the groynes (three) have to be disregarded which explains the difference in the number of groynes for both models.

4.5 Grid dependency study

This study is executed using numerical modelling. Output resulting from this modelling is based on the definition of the boundary conditions and the grid. Uncertainties are part of the modelling practice. Part of these are due to the grid size. A more accurate the grid size results in a more accurate solution and the closer you get to the convergence point. However, a smaller grid size also results in a larger computational time.

The solution (convergence point) to the model is unknown so, to find the optimal grid a grid dependency study is performed. In this study a model is run with different grid sizes, however all the other parameters are identical. This results in model output with (in general) decreasing differences between grid sizes as grid size decreases. If the difference of the solution between two grid sizes is within the acceptable range it can be assumed that convergence has been reached and the larger grid size of the two is chosen.

The grid sizes used for the study are based on the needed accuracy to model the waves and the dimensions of the groynes to accurately model these. As a rule of thumb 25 points in a wavelength is necessary to model a wave with good accuracy (Zijlema, 2015). With an expected wave length of 270 metres this results in grid size of 10.8 metres. According to (Rijkswaterstaat PDR, 2012) the minimal width of the groyne crest is 2.5 metres and the maximal above water width is 15 metres. This results in some freedom in modelling the width of the crest of the groyne. The remarks above result in the grid size which starts with a size of 10x10 metres and halves each step until a grid size of 2.5x2.5 metres. At first a smaller grid size will not be used due to the steep increase in computation time which isn't practical for an optimisation study. This increase in computation time is due to the explicit property of XBeach, which states that the model has to follow the CFL-condition, see Equation 1 on Page 16. This condition states that a decrease in grid size results in a decrease in timesteps and thus an increase in computational time since more computational cells are present which have to be calculated in smaller time steps. If a grid size of 2.5x2.5 metres doesn't give enough certainty in simulating the water levels and velocities a smaller grid size will be added to the grid dependency study.

The model describes three main aspects; discharge, ship passage and complex geometry in the form of groynes. The grid dependency study is split up in two parts to study the effect of the grid on the current and the vessels independently, namely; a model where discharge and complex geometry is set up and a model where a ship sails in a river with complex geometry.

4.5.1 River with current and groynes

To set up the grid dependency study to study the effect on discharge and complex geometry, the following choices are made:

- The groyne dimensions are based on the mean values of specified in Table 1;
- The bed topography layout of a downstream moving vessel is used, see Figure 8b. However, the model setup is without a vessel so no long undisturbed channel to account for acceleration of the vessel before the first groyne is needed. To save computational time, the domain length before the first groyne is shortened. The length is defined only for the development of an equilibrium flow, see Figure 10;

- The discharge boundary condition has been set at the upstream side and the water level boundary condition has been set at the downstream side.

The model setup and measuring points for this grid dependency study is shown in Figure 10. The locations of point 1 (red) and point 3 (green) are chosen to gain insight in disturbances at the boundaries of the model. The second point (blue) is chosen in the middle of the groyne field to obtain information about the stability in the groyne field. Point 2 and the transect (dashed black line) are chosen at the location of the fifth groyne field as this region is outside the zone of contractional flow and a potential area for modifying the groynes in the optimisation study.

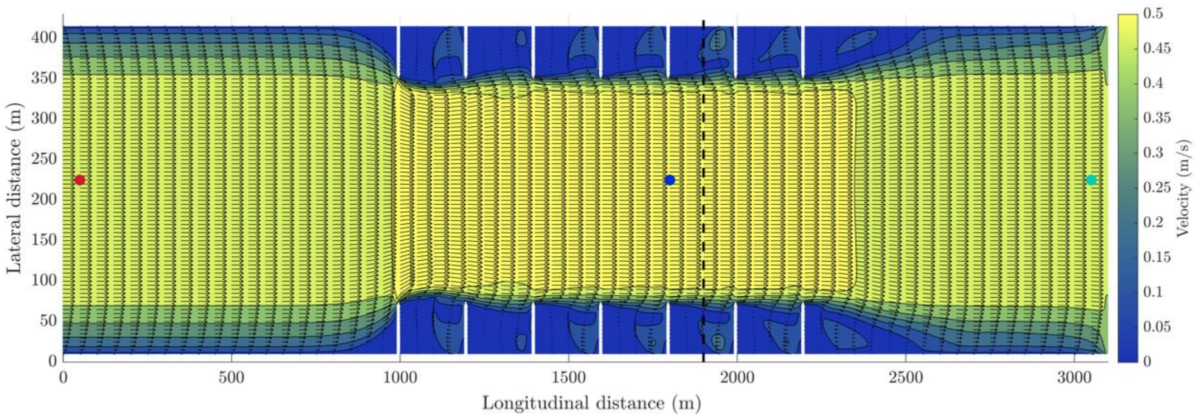


Figure 10: Velocity vector plot due to discharge at the left boundary. Three measuring points and a transect are defined.

The optimal grid size is determined by comparing three different flow signals; the mean water level after spin up time and its stability for the three measuring points defined in Figure 10, and the water level and flow velocity in the lateral cross section at the transect.

Figure 11 shows the mean water depth after spin up time for the different grid sizes and measuring points. It is concluded that the difference in grid size between 10x10 and 5x5 is 0.9 mm and the difference between 5x5 and 2.5x2.5 is 0.6 mm. The difference in water levels for various grid sizes is small compared to the expected magnitude of water level changes due to ship passing. Decreasing the grid size has minimal impact on the quality of the water level output in the main river and a grid size of 10x10 is sufficient.

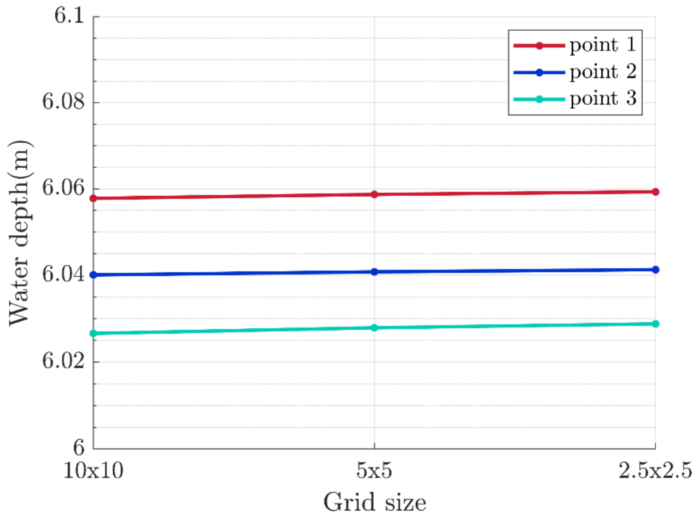


Figure 11: Result from the grid dependency study about the water level in the measuring points

Appendix A.2 shows the timeseries of the water level for the three measuring points specified in Figure 10. These plots show that with decreasing grid size the water level fluctuations are larger and seemingly more irregular after spin up time. The spin up time ends after approximately 10.000 seconds. The origin of the change in fluctuations can be physical or numerical; Since the courant number is constant the timestep decreases with decreasing grid size, so smaller physical processes can be modelled (e.g. turbulence). The origin of the change in fluctuation can also be numerical. To understand these fluctuations, observations are made which results in the following insights:

- The timeseries have been extended to 50.000 seconds and from this it was concluded that after 10.000 seconds the fluctuations reached a constant repetitive pattern, they didn't increase or decrease in size;
- The largest fluctuations occur in the middle of the domain at the longitudinal height of the groyne field, in point 2. This is valid for all grid sizes.
- When the model setup is defined without groynes, no fluctuations are present in any grid size.

Without groynes the fluctuations are not present but with groynes the fluctuations are present and reach a constant oscillatory pattern in time. These fluctuations are largest near the groyne field where the current interacts with the complex geometry creating the turbulent flow pattern (the fluctuations). This turbulence diffuses in space which results in smaller fluctuations at measuring points one and three. Using these insights, it is concluded that these fluctuations have a physical origin as a result of the groyne field, instead of a numerical one. These fluctuations, though physical in origin, will not have to be modelled accurately since these fluctuations are a factor 100 smaller than the fluctuations resulting from a ship passage. Thus, decreasing the grid size will not increase the quality of the output and a grid size of 10x10 is sufficient.

In Figure 12 the mean water level and mean flow velocity after spin up time at the transect are plotted. From this figure can be concluded that the water level difference between the grid sizes is small, and a similar conclusion as derived from Figure 11 is applicable here. The flow velocity in the main channel is similar for all the grid sizes, however along the length of the groyne the values start to deviate from each other. The 10x10 grid cannot reproduce the steep slope around 80 metre and drops down far before that point, additionally values closer to the shore deviate a lot. At around 65 metre the values between grid 5x5 and 2.5x2.5 start to deviate and closer to the shore the difference is approximately 0.05 m/s. The shape and values of the velocity signals of grid size 10x10 differs significantly from the 5x5 and 2.5x2.5 grid size and therefore a finer grid than 10x10 is needed. Since grid size 5x5 and 2.5x2.5 show a similar shape, a model with a grid size of 5x5 metre is sufficient enough to provide qualitative insight in the phenomena in the groyne field.

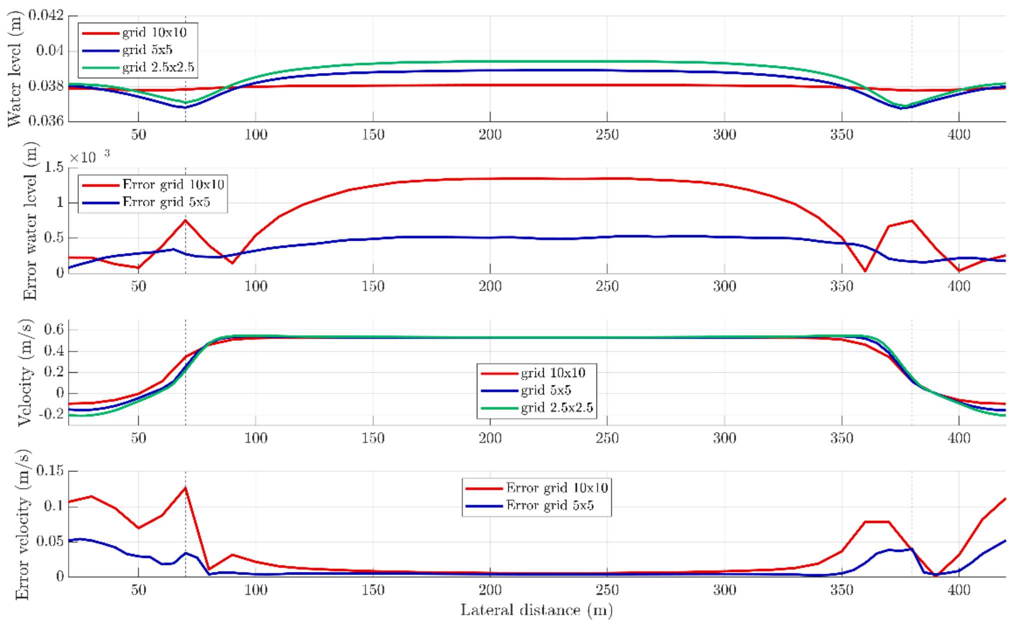


Figure 12: Mean water level and flow velocity at the transect defined in Figure 10. Dashed line at around 65 m and 385 m represent the tip of the groyne. In the first and third plot the water level and velocity of the transect is plotted for different grid sizes and in the second and fourth plot the difference compared to the 2.5x2.5 grid size is plotted.

4.5.2 River with passing vessel and groynes

Part 1, Section 4.5.1, of the grid dependency study takes discharge and groynes into account. In the second part of the grid dependence study the model is altered to gain insight in the effect of the grid size on the ship passing in a groyne field by modelling a ship passage in a river without discharge.

The model used for this part slightly deviates from the model used for the first part of the grid dependency study:

- The model length before the first groyne is extended and corresponds to the original bed topography as defined in Figure 8b to facilitate acceleration of the vessel;
- The upstream boundary condition has been changed to a water level boundary so no flow is present in the domain.

The model set up and measuring points for the second part of the grid dependency study is shown in Figure 13. Three measuring points are placed with decreasing distance to the river banks, because from Figure 12 it was concluded that the velocity signal increasingly differs when closer to the shore. This way it can be researched if and possibly how this difference grows in the groyne field for ship passing signals. The first point (green) is located just outside the groyne field to visualize the signals without the influence of the groynes. The second point (red) is chosen in the middle of the groyne field to see the influence the groynes have on the signal. The last point (orange) is located as close to the shore as possible outside the rundown level so the point never runs dry.

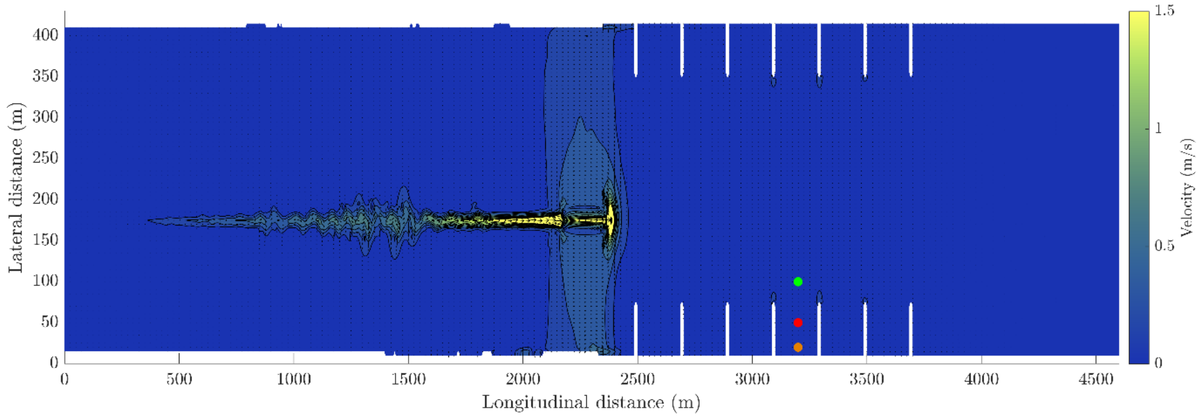


Figure 13: Velocity vector plot due to vessel movement. Three measuring points are defined; green is point 1, red is point 2 and orange in point 3.

The timeseries for the water level, u-velocity (velocity vector in longitudinal direction) and v-velocity (velocity vector in transversal direction) for point 1 are plotted in Figure 14. The first increase in water level and u-velocity at around 400 seconds to 600 seconds is a result of a wave propagating in sailing direction due to the acceleration of the vessel and does not represent a physical process applicable to this study. At around 700 seconds a small increase in water level and u-velocity is present before the drop as a result from the ship bow pushing the water. The water level depression and return current due to ship passing are visible in the subplot water level and u-velocity between 700 and 800 seconds, respectively. The signals observed and explained above are also visible in point 2 and 3 and are induced by the same source, these figures are shown in Appendix A.3. However, due to the decrease in water depth and confined location between the groynes the magnitude of the signals increase approaching the river banks.

Due to space discretization it is expected that the numerical solution travels with some other speed differing from the exact solution depending on number of grid points per wave length. Mathematical proof by (Zijlema, 2015) states that more grid points result in more accurate numerical representation of the propagation. Since the different grid sizes have a different number of grid points the phase lag from the exact solution differs per grid size, resulting in the signal shift between the grid sizes seen in Figure 14 and point 2 and 3 in appendix A.3.

In Figure 14 at around 800 seconds oscillations are present in the water level signal for a grid size of 10x10, these are probably due to a dispersion problem. Dispersion implies that higher frequency components travel at slower speeds than lower frequency components. In solutions with sharp gradients the effect of dispersion results in non-physical oscillations as seen in the figures. By refining the grid around steep gradients, the amplitude of the numerical oscillations is often small enough to tolerate these wiggles. Therefore, these wiggles aren't visible in smaller grid sizes. This is a well-known numerical problem and for further explained we refer to (Zijlema, 2015).

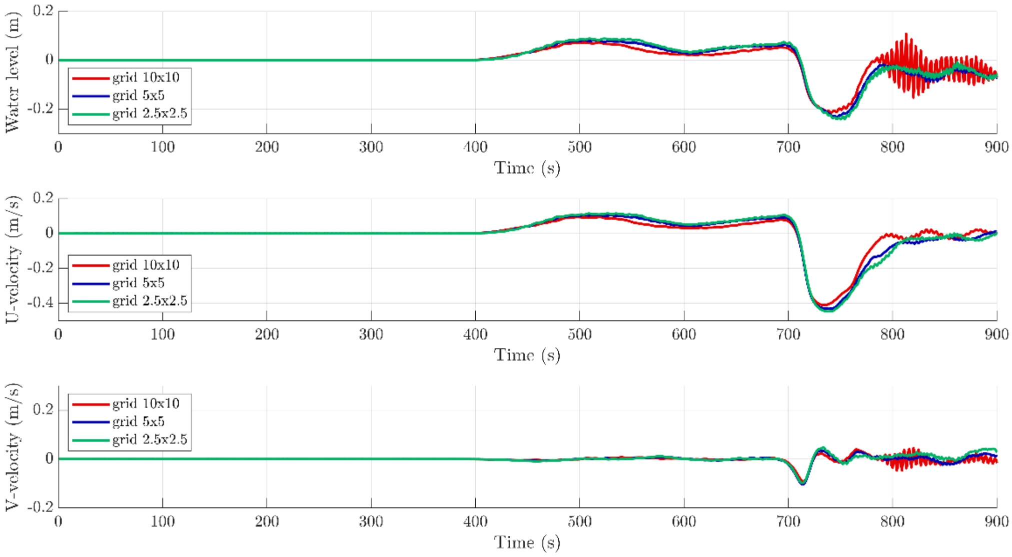


Figure 14: Signals of ship passing in point 1 (green) for various grid sizes. Top plot shows the water level signal, the middle plot shows the longitudinal velocity vector (u-velocity), and the bottom plot shows the lateral velocity vector (v-velocity).

In Figure 14 the timeseries for the water level, v-velocity and u-velocity for point 1 (green) are visualized. The magnitude of the water level depression and return current is more pronounced at a grid size of 2.5x2.5 and the deviation to this value increases with grid size, however the difference between grid 5x5 and 2.5x2.5 is small. After the drop the shape of the water level is similar for the different grid sizes with a deviation that grows with increasing grid size. The difference in shape of the u-velocity after the drop is present between all thee grid sizes and likely a result from a difference in horizontal viscosity. The v-velocity has an overall good agreement in the shape and only the magnitude changes a little bit with increasing grid sizes.

The timeseries for the water level, v-velocity and u-velocity for point 2 (red) is depicted in Appendix A.3. Similar findings as in point 1 can be concluded from this plot with a few exceptions. A phase lag between the grid sizes is present, this is probably due to two reasons; the space discretization problem and the location has a sloping bed. Section 4.2 states that the bed level is defined at the middle of a grid cell, since the 2.5x2.5 grid size has more grid points than 10x10 and 5x5 the bed level gets updated more often. This results in different propagation speeds of the signals in the model.

The timeseries of the water level, u-velocity and v-velocity of point 3 (orange) are shown in Appendix A.3. Just like point 2 a small phase lag is present between the grid sizes. The 10x10 grid does show different signals, specifically the v-velocity deviates a lot from the other grid sizes. This is probably due to location, which is close to the banks in very shallow water and the model cannot accurately represent these signals.

To quantify the effect of grid size of the ship-induced signals, the water level range and velocity range (difference between the maximum and minimum value) is calculated, see Table 3. The difference between the results from two grid sizes indicate the dependency on grid size. A small difference means that the model is less dependent on the grid size.

Table 3: Parameters used to quantify the effect of grid size of the ship-induced signals.

	Water level range			**Velocity range**		
	Point 1	**Point 2**	**Point 3**	**Point 1**	**Point 2**	**Point 3**
Grid 10x10	0.25	0.29	0.31	0.51	0.52	0.96
Grid 5x5	0.29	0.31	0.32	0.54	0.55	0.58
Grid 2.5x2.5	0.31	0.32	0.33	0.56	0.57	0.61

4.5.3 Conclusion grid size

From part one of the grid dependency study, Section 4.5.1, can be concluded that the grid size has minimal effect on the water level in the model. Additionally, the size of the physical oscillations in the water level after spin up time is a factor 100 smaller than the expected signals resulting from ship passing. From the transect of the flow velocity is concluded that the velocities in the groyne field deviate more when approaching the river banks. This effect is larger with increasing grid size. This observation returns in part two of the grid dependency study, Section 4.5.2. Three measuring points have been placed with decreasing distance to the banks, the corresponding time series show an increase in deviation when approaching the banks. However, the water level range and velocity range in Table 3 show limited difference between the grid sizes even when close to the river banks.

The shape of the timeseries and magnitude of the water level- and velocity range of grid size 5x5 and 2.5x2.5 are in general similar over the lateral length of the groyne field. In the model study we are looking at the effects on water level and velocity, a 5x5 grid size already gives qualitative insight in the effects of the modifications. A grid size of 2.5x2.5 has a significant longer running time than a 5x5 grid which isn't practical for an optimization study. Additionally, a 5x5 grid is flexible enough to model the groynes and modifications in the groyne to perform a valuable study. So, for the study a 5x5 grid is used.

4.6 Model validation

In this section the model setup with a grid size of 5x5 metres is validated using three different methods:

- The flow patterns in groyne fields due to a current in the main channel will be verified with the literature in a qualitative way;
- The flow patterns in groyne fields due to passing of a vessel upstream will be verified with literature in a qualitative way;
- The water level and flow velocity model output during a passing of a ship will be verified in a quantitative way using measured data obtained from a laboratory test setup.

4.6.1 Flow pattern validation river discharge

Section 4.5.1 explains the set-up of the model when only discharge is applied on the domain. This results in flow patterns in groyne fields excited solely by the current in the main channel. These patterns are compared to the theory described in Section 2.1.2 for validation.

The model consists of 6 groyne fields on each side of the river. In Figure 15 the penultimate groyne field in the steady state of the river is depicted. This groyne field is chosen since a this point the flow in the channel is fully developed and limited influence from contracting or expanding flow patterns in the main channel are present. This is based on Figure 10 of Section 4.5.1 by observing the flow patterns in the main channel. In Figure 15 the theory from (Uijttewaal et al., 2001a) in Section 2.1.2 is compared to the model output. The result from the model complies qualitatively to the theory; at the downstream part of the groyne field a large horizontal flow pattern is formed which moves at approximately halfway the groyne field in a diagonally direction towards the main channel. At the upstream part a smaller eddy is formed which rotates in opposite direction. These processes are visible both in the model and in the laboratory test, so it is concluded that XBeach can qualitatively model the horizontal flow pattern due to current – groyne field interaction accurately.

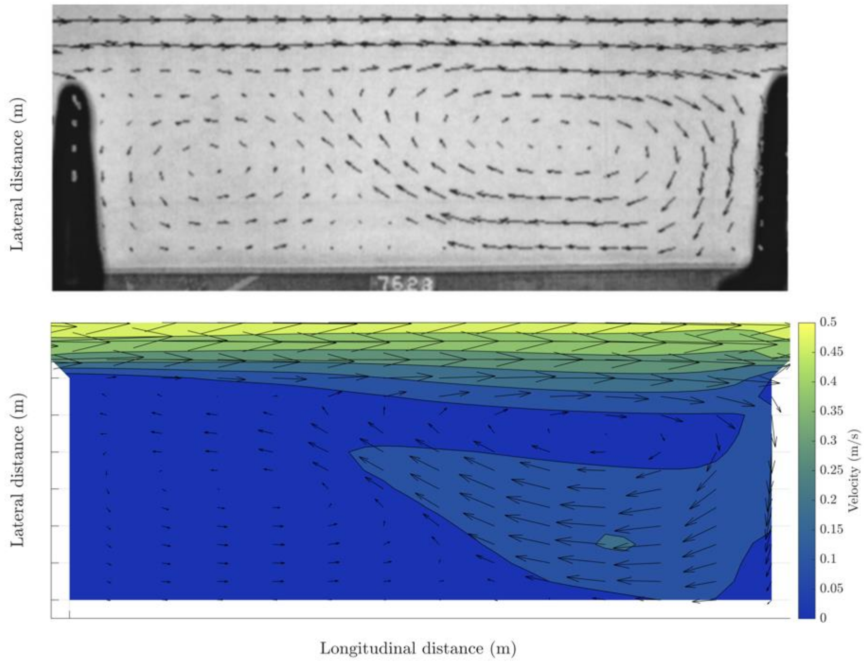


Figure 15: Comparison of flow pattern in groyne field between laboratory tests (top) and model output (down)

4.6.2 Flow pattern validation ship passing

In this section the flow pattern modelled with XBeach for an upstream sailing ship passing a groyne field is compared to the theory from section 2.2.1. Flow direction is to the right and the ship is sailing to the left. It is important to note that the figures from the literature are distorted, which means that the ship isn't sailing as close to the groynes as the figure might show. The validation is performed in five steps, with each step a different passing point to compare to the literature.

The first step is visualized in Figure 16. The ship passes the downstream groyne and the water level depression almost enters the groyne field. The general flow is directed to the tip of the downstream groyne and an acceleration of this flow is visible which agrees with the literature.

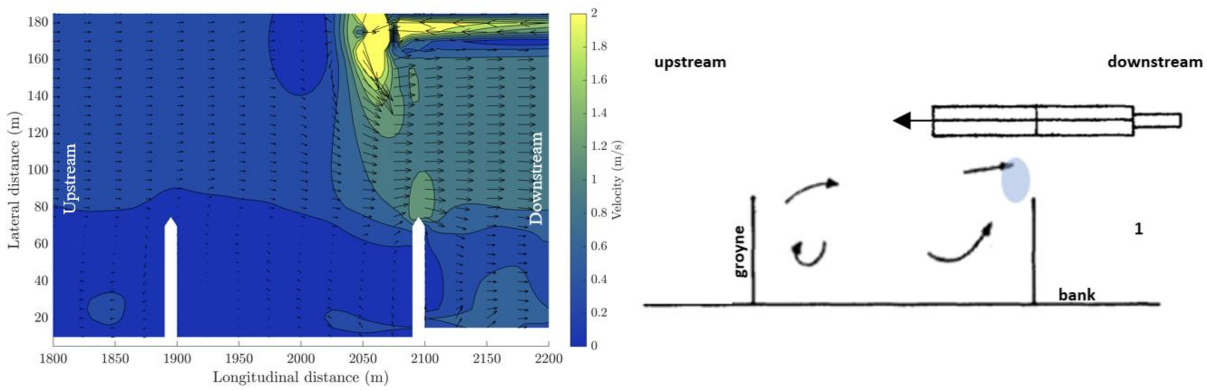


Figure 16: Step 1: velocity vector model output during passing of ship with front ship at 2045 m (left) and flow pattern during passing of ship according to literature (right). Vessel sails upstream.

The second step is shown in Figure 17. The front of the ship is halfway the groyne field and the water level depression has entered the groyne field. The acceleration of the flow near the tip of the downstream groyne grows in magnitude and size which agrees to the literature. The deceleration near the banks is located at a different location as visualized in the literature. However, this is probably due to the location of the ship and the propagation speed of the signals.

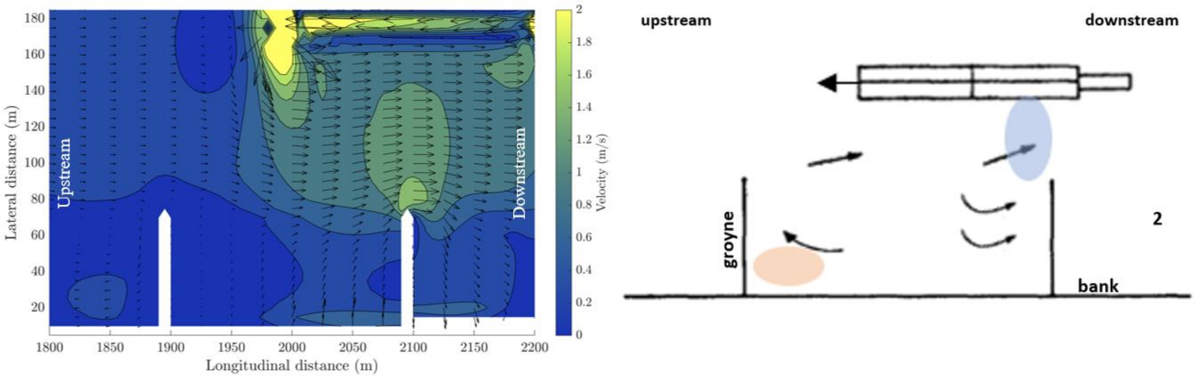


Figure 17: Step 2: velocity vector model output during passing of ship with front ship at 1950 m and back at 2170 m (left) and flow pattern during passing of ship according to literature (right). Vessel sails upstream.

Step three is shown in Figure 18. The bow of the vessel has passed the upstream groyne and the stern has passed the downstream groyne. The general flow pattern agrees with the literature and a developed return current between the groynes is visible. The acceleration near the downstream groyne has reduced and the area is split up in an acceleration near the vessel and at the tip of the groyne. Additionally, an acceleration near the tip of the upstream groyne forms. The deceleration has increased in size and magnitude and is located near the banks of the upstream groyne.

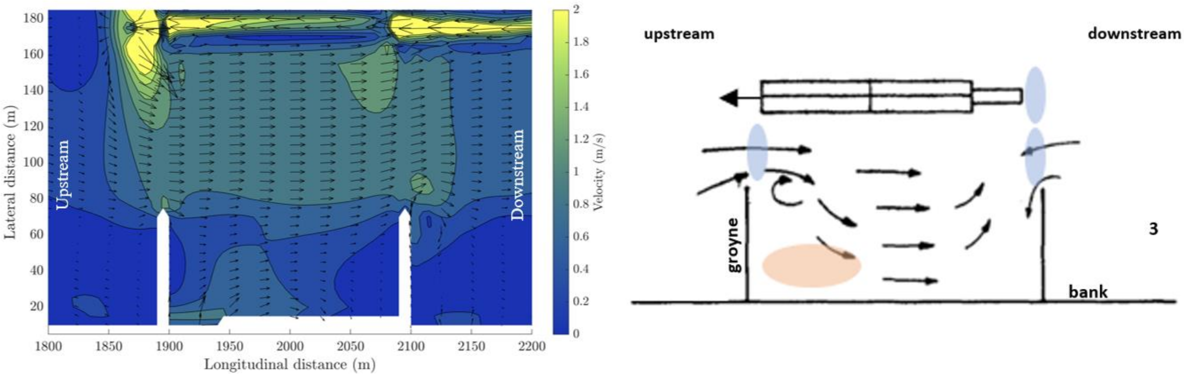


Figure 18: Step 3: velocity vector model output during passing of ship with front ship at 1860 m and back at 2080 m (left) and flow pattern during passing of ship according to literature (right). Vessel sails upstream.

In Figure 19 the fourth step is visualized. The stern of the vessel almost passes the upstream groyne and the return current between the groynes has reduced and makes way for the supply flow. In the model this rotation in flow, as visualized in the literature, is hard to see since the river flow velocity exceeds the supply flow velocity. However, the vectors decrease in size indicating a serious influence of the supply flow. Additionally, the acceleration near the tip of the upstream groyne increases in size and magnitude.

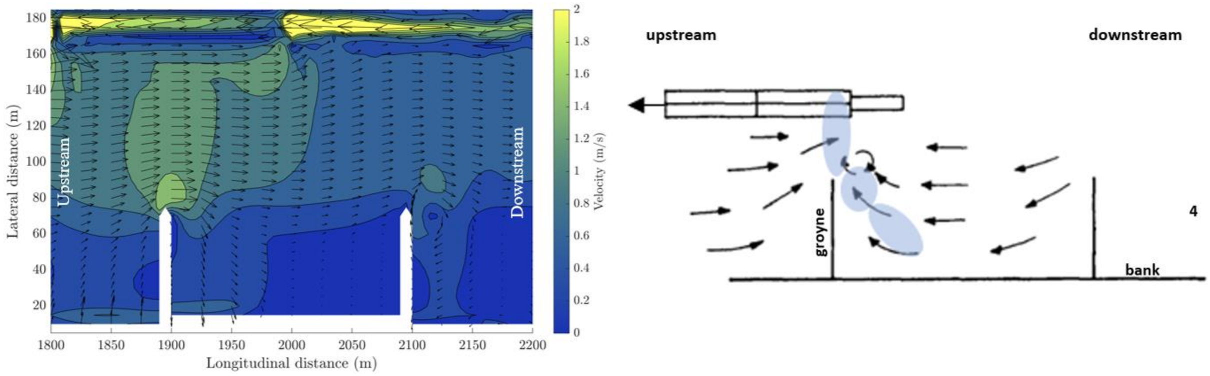


Figure 19: Step 4: velocity vector model output during passing of ship with back of ship at 1990 (left) and flow pattern during passing of ship according to literature (right). Vessel sails upstream.

The last step is shown in Figure 20. The stern of the vessel has passed the upstream groyne and the return current between the groynes has been taken over by the supply flow. Similar as in the previous step the vectors do not completely change direction but decrease in size. Near the tip of the groyne a small rotating eddy is formed.

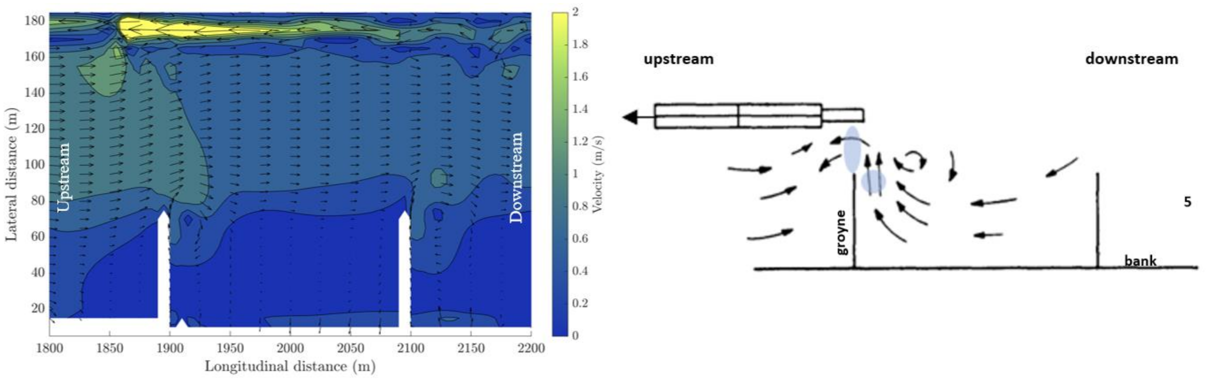


Figure 20: Step 5: velocity vector model output during passing of ship with back of ship at 1850 (left) and flow pattern during passing of ship according to literature (right). Vessel sails upstream.

The above five steps visualized a ship passing a groyne field. From these steps can be concluded that the flow patterns from ship passing agrees with the literature and that XBeach can qualitatively model the horizontal flow pattern induced by a vessel passing a groyne field in a flowing river.

4.6.3 Quantitative validation

A quantitative verification of the model setup is performed using the JIP Ropes (Joint Industry Project, Research On Passing Effects on Ships) study (van der Hout & de Jong, 2014). In this study water levels, velocities and forces induced by ships are determined using a laboratory scale model for various geometry layouts, currents, and ship speeds/directions. The dataset resulting from this study is used among other things for validation and calibration of numerical models, e.g. XBeach.

The dataset of the JIP Ropes study is used to compare to the XBeach model output for quantitative validation of the model setup. In Figure 21 one of the layouts of the JIP Ropes model is depicted. This layout is recreated in an XBeach model by adjusting as few input parameters and boundaries as possible. This means only the bed topography and the vessel size/speed have been altered. This way a validation of the parameters and boundary conditions is performed.

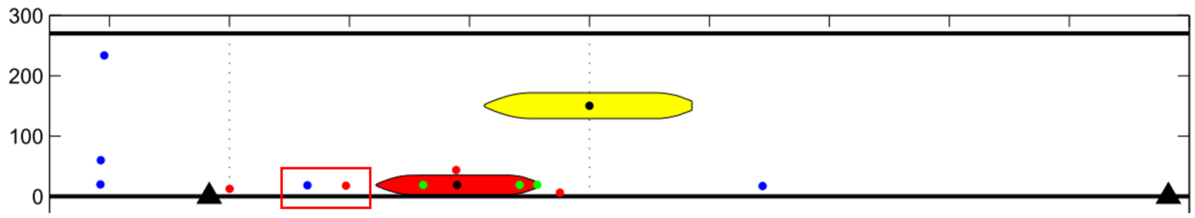


Figure 21: A physical scale model layout used in the JIP Ropes study. The yellow vessel is the moving vessel to the left and the red vessel is a stationary vessel which is not modelled in XBeach. The blue points are velocity measuring points and the red points are water level measuring points. The measuring points inside the red square are used for comparison with the XBeach model. The flow is directed to the right.

In Figure 22 timeseries from the measuring points from the test data and model data are plotted. From 1200 to 1450 seconds an increase in water level is visible which is the wave caused by the acceleration of the ship in the model. The same bump can be seen in the test data at around 1400 to 1600 for the same reason. Before the drop in water level due to the passing of the vessel at around 1750 seconds a small increase in water level is visible caused by the bow of the vessel pushing the water away. After the water level depression and return current due to passing of the ship the water level and u-velocity return to the original water level. During passing of the vessel the peak of the water level is slightly underestimated by the model and the u-velocity slightly overestimated. However, the shape and timing of these parameters match closely. The v-velocity has a good match in magnitude, however the gradient isn't steep enough to follow the test data. The water level signal and velocity signals appear slightly out of phase, this is due to the different locations of the measuring points for water level and velocity. It can be concluded that XBeach can quantitively model the shape and magnitude of the water level and velocity signals as a result of ship passing with good accuracy.

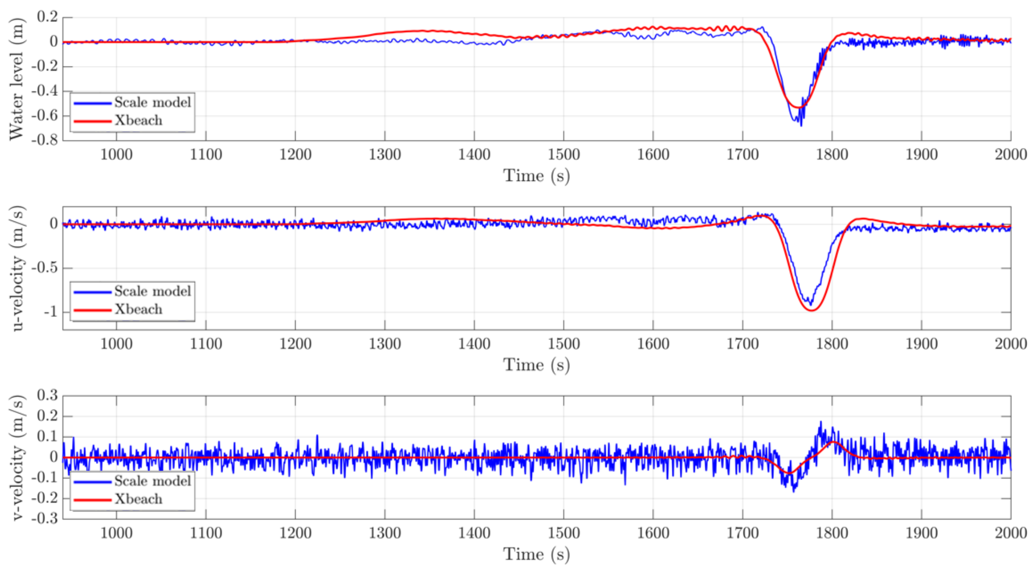


Figure 22: Timeseries of water level (top), u-velocity (middle) and v-velocity (bottom) of a ship passage in the layout specified in figure 21. A comparison between the scale model data and model output from XBeach is made.

The combined conclusions from Section 4.6.1, 4.6.2 and 4.6.3 indicate that the model is set up correctly and can be used with good confidence resulting in reliable results.

5 Method and results

This chapter discusses the approach of the optimisation study for different groyne modifications and the corresponding model results. In Section 5.1 the study approach is explained, specifically the determination of the area of interest and the calculation of the ecological parameters. In Section 5.2 the effect of the ship sailing direction on the groyne field is discussed. In Section 5.3 the results of notched groyne study are presented and in Section 5.4 the results of the L-shaped groynes. Finally, Section 5.5 shows results from a conceptual optimal design for various different model conditions, like high water, smaller vessels, and a river with a side channel.

5.1 Methods interpreting results

The literature study concluded that eggs and young fish are especially vulnerable to ship-induced waves. The breeding and growing season of this fauna is from April to September, which corresponds to in general low summer water levels on the Waal. Thus, the focus of the optimisation study is on emergent groynes. The living habitat of eggs and young fish is close to the shore with a maximum water depth of around 1.5 metres, see the marked area in Figure 23. The goal of the modifications is to improve the habitat in this area during growing and breeding season. Data from Rijkswaterstaat is used to determine average water levels and discharges corresponding to this season, and the resulting parameters are used in the study.

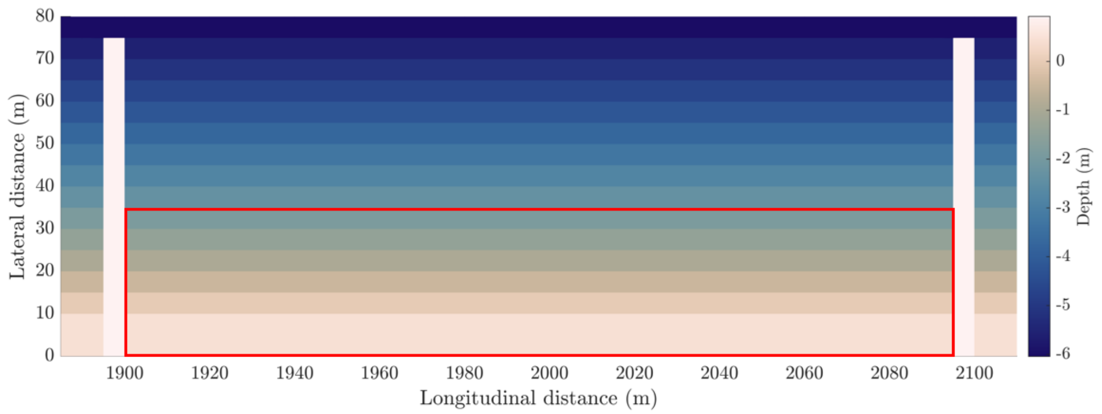


Figure 23: Bed topography of groyne field (bird's eye view). The living habitat of vulnerable fauna marked with a red square.

The selected groyne field to study the impact of the ship-induced waves on the area of interest requires a fully developed (normal) flow in the main channel. In Section 4.4 is explained that several groyne fields experience contracting flow which do not represent valuable data for this study. However, the geometry in the model is designed such that at least three groyne fields do not experience the contractional flow and normal flow is present in the main channel. Of these three groyne fields the middle one is selected to analyse the modification. For downstream sailing vessels this is the groyne field at 3400 metre longitudinal distance and for upstream sailing vessels the groyne field at 1800 metre longitudinal distance, see Figure 8 in Section 4.2.

Since larger vessels have a greater impact on the fauna than smaller vessels, we model the effects of a 3x2 push tow boat in this study. Large vessels on rivers tend to sail on one side of the river, just like cars drive on the right side of the road. It is important to distinguish between vessels sailing upstream and downstream and study the impact of the modifications individually. However, vessels do not always sail on one side of the river for a number of reasons, for instance to manoeuvre along a river bend. In this instance, the combined effect of the upstream and downstream sailing vessels is studied. The maximum sailing speed of vessels in the channel is reached when the return current reaches its maximum velocity as a function of the water level depression. This is based on the cross section of the ship and channel. This occurs when the water depth along the ship has reached critical depth. If the ship speed increases, the water movement next to the ship will pass into a critical discharge and the continuity condition cannot be fulfilled. A self-propelled ship cannot overcome this speed and will be limited by it. Based on economic and environmental considerations vessels sail at approximately 80% of the limit speed, in Appendix A.1 the limit speed is calculated which is 5.43 m/s. So, for the entire optimisation study a CEMT class VIc vessel sailing at 4.3 m/s will be used, unless stated otherwise. This vessel will sail 1/3 the width of the main channel from the groynes as this corresponds to the mean traffic path of vessels sailing through the Waal (MarineTraffic, 2007).

Ecological expertise states that the maximum water level range and velocity range in a timestep of 60 seconds is used to quantify fauna habitat quality. In Section 4.1 the measuring technique of water level variability and flow velocity variability in-situ and in the model is clarified. The maximum water level range is measured by analysing the timeseries, see Figure 24. In this figure the water level over time in a stationary point in the groyne field is depicted. The maximum water level range is determined by fitting a 60 second fit over this timeseries and obtain the highest difference, in this case that is timestep 2. The water level range in a timestep of 60 seconds is calculated for both the reference case and the modified case. By calculating the difference for these two cases the change in water level range can be determined.

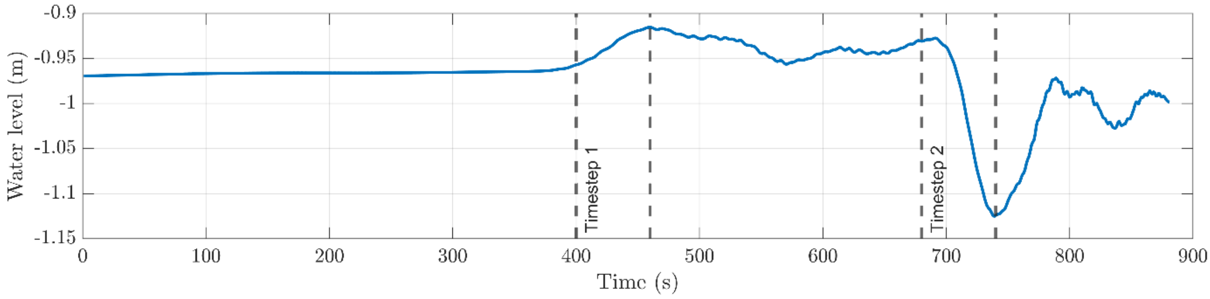


Figure 24: Water level fluctuation measured in a stationary point during ship passing

The flow velocity range must account for flow direction and magnitude. The model splits the velocity vector into a longitudinal directed and transversal directed component (u- and v- velocity respectively). The maximum velocity range is determined by plotting the u- and v- components for a specific location in the groyne field during a 60 second time interval, see Figure 25. When a circle is fitted around the velocity points, its diameter represents the maximum flow velocity range in a timestep of 60 seconds.

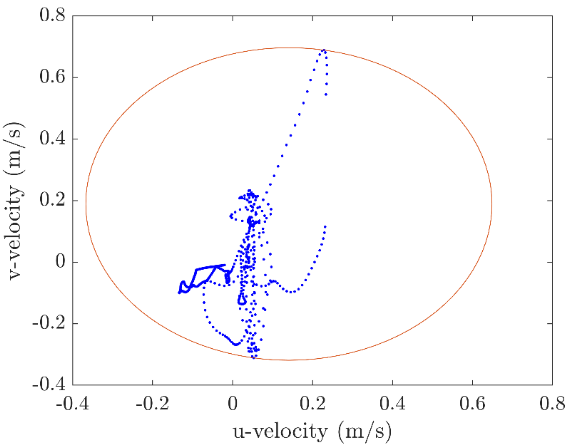


Figure 25: The u-velocity on the x-axis and v-velocity on the y-axis show the distribution of velocity vectors during a ship passing. A circle is fitted around the two points which are farthest apart to determine the maximum velocity range.

The flow patterns and fluctuations in groyne fields are dynamic and as such the maximum water level range and maximum velocity range is calculated for every location in the groyne field. These two parameters are further referred to as ecological parameters.

The calculation of these ecological parameters is performed for both the reference model (standardized groyne field without modifications) and the modified model. The difference between these two models give insight in the change of ecological parameters in the groyne field and thus the fauna habitat quality. An increase of the ecological parameters corresponds to a decrease in fauna habitat quality and a decrease of ecological parameters corresponds to an increase in fauna habitat quality. The difference between the traditional groyne field and modified groyne field of the ecological parameters in the area of interest is quantified using a boxplot. These boxplots are used to study the effect of different modifications on the ecological parameters in the area of interest. A boxplot is a method to display a set of data using a five-number summary with outliers.

Ecological research in the correlation between the ecological parameters and fish density is developing, so no conclusive statement about the quantitative effect on the fish density due to groyne modification can be made. However, the plots in Appendix C give insight in locations were either water level range or velocity range or both decrease. This gives a qualitative insight in the locations where increase in fish density is expected.

5.2 Effect of ship sailing direction

Vessels can pass a groyne field in upstream and downstream sailing direction which have a different effect on the change in ecological parameters. In this study the relative velocity between ship sailing and river flow in both sailing directions is equal, this velocity is 80% of the limited speed as calculated in Appendix A.1. The relative velocity of a vessel is the velocity difference between the river flow velocity and ship speed.

An observer standing stationary on the river banks sees a ship sailing upstream. The velocity of the ship is directed upstream and the current velocity is directed downstream, the difference between these two velocities is the relative speed. When the observer sees a ship sailing downstream, the velocity of the ship and current are both directed downstream. To reach the same relative speed the ship has to increase its sailing speed by twice the current velocity. For this reason, the absolute speed of the ship is larger when sailing downstream. The result is that the water level and velocity signal for downstream sailing vessels is shorter and the gradient steeper due to the absolute larger velocity of downstream sailing vessels. For both upstream and downstream sailing vessels the water level and velocity is approximately the same since the relative velocity is the same. This corresponds to research from JIP ropes (van der Hout & de Jong, 2014) and theory from (Verheij, 2008). The magnitude in u- and v-velocity is also similar for both sailing directions, however the direction of the u-velocity is the other way around since the return current is directed the opposite way.

The main difference between upstream and downstream sailing vessels is the gradient and duration of the water level depression and return current, and the direction of the river current compared to the sailing direction of the ship. As a result, the flow patterns and ecological values in the groyne field are different for upstream and downstream sailing vessels.

This study will continue to look at upstream sailing vessels, downstream sailing vessels and the combined effect of both. The combined effect of both is determined by combining the ecological parameters of both upstream and downstream sailing vessels individually and take the maximum value for every location. This doesn’t represent a flow pattern but the values from this study are used to study the effect of the modifications on the ecological parameters in the situation where ship passing occurs in both directions.

5.3 Results notches

In this section the effects of the notches in the groyne on the water level and velocities within the groyne field are discussed. This section is divided in various sub-sections to gain insight in the individual effects of the notches in groynes. In Section 5.3.1 the effect of the number of modified groynes in a stretch of river is discussed. In Section 5.3.2 the optimisation study is explained where a total of 15 different groyne geometries are used to understand the effect of the notches on the change in flow patterns. In Section 5.3.3 the results from the optimisation study are discussed.

The main report displays compacted results based on a large number of cases and output data. For the uncompacted results and output data a general reference towards Appendix B.1 and C.1 is made. Appendix B.1 shows the boxplots used in the dependency study and Appendix C.1 shows the notch geometry and ecological parameter plots for all different cases. The introduction in these appendices provides a guideline on how to find specific figures. In Section 5.3.1 the methodology and interpretation of the results using one specific case is described, the function of this paragraph is thus both for explanation of the methodology and to conclude the optimal number of modified groynes for this study. The methodology for the rest of this chapter is performed in a similar way and for practical reasons it is chosen to display the model output in the above-mentioned appendices.

5.3.1 River modification

The objective of this study is to find options to improve the fauna habitat in the area of interest in the groyne field. The habitat in the selected groyne field can be improved by modifying a different number of groynes in the river that affect the river system on different scales:

- A single groyne downstream of the selected groyne field can be modified with a notch. This notch affects two groyne fields, however the selected groyne field has only a notch on one side of its field so it is expected that a large part of its groyne field isn't impacted. Limited large-scale river flow change and morphological change can be expected in the main river channel;
- A groyne upstream and downstream of the selected groyne field can be modified with a notch. This notch affects three groyne fields of which the selected groyne field is impacted by notches on both sides. In contrast to a single notch, this affects the entire groyne field. Due to the notches in the groyne a discharge is diverted from the main channel through the groyne field, theoretically lowering the water level and current velocity in the main channel. However, this is a local phenomenon of only a couple groyne fields long;
- A series of modified groynes over a long stretch of river. This modification impacts the selected groyne field as well as a predefined number of other groyne fields (depending on the length of the stretch). Similar as with two modified groynes a flow can flow through the notches, however it is expected that this will be a more defined flow. The result is that the water level and velocity in the main channel will lower more than with two notches and this effect will be larger depending on the length of the modified stretch.

To examine the effect of the number of modified groynes, a notch of 15-meter-wide and 1-meter deep is modelled for the different situations specified above, see Table 4. For interpretation of the notch geometry see Figure 29 on page 34.

Table 4: Notch characteristics of various model runs to study the dependency on number of modified groynes, see figure 29 for interpretation parameters.

Variant number up-/downstream	Number of modified groynes	Location of notch from tip of groyne (a)	Width notch (b)	Depth notch below water level (c)
2.101 / 2.201	1	32.5 m	15 m	1.0 m
2.102 / 2.202	2	32.5 m	15 m	1.0 m
2.103 / 2.203	Series	32.5 m	15 m	1.0 m

First the effect of the notches on the flow pattern in the entire groyne field is visualized. This is done by plotting the ecological parameters for the entire groyne field, see Figure 26. This figure shows the water level range for downstream sailing vessels in a groyne field with two modified groynes. The figure shows the water level range for the traditional groyne field in the top plot, the water level range for the modified groyne field in the middle plot and the difference between the reference model and modified model in the bottom plot. The figure shows a high water level range near the downstream groyne which reduces away from the corner for the traditional groyne field (reference model). The modified groyne field (modified model) shows a similar pattern, however the magnitude of the water level range is lower indicating a reduction and a positive effect of the notch on the fauna habitat. The specific location and magnitude of the change in water level range between reference model and modified model is shown in the bottom plot, where reduction in water level range is depicted in blue and increase in water level range in red.

The plot in Figure 26 shows the water level range for downstream sailing vessels. Appendix C.1 shows the water level range and velocity range in similar structured figures for upstream sailing, downstream sailing, and a combination of both. These plots are made for every groyne modification and are used in interpretation of the results in this chapter. From these plots can be concluded that the water level range and velocity range pattern in a groyne field with a single modified groyne differs from the pattern in a groyne field with two or more modified groynes. The water level range and velocity range pattern in a groyne field with two modified groynes or a series of modified groynes are similar. Further study shows that the flow propagation behaves similarly for a situation with two modified groynes and for a series of modified groynes.

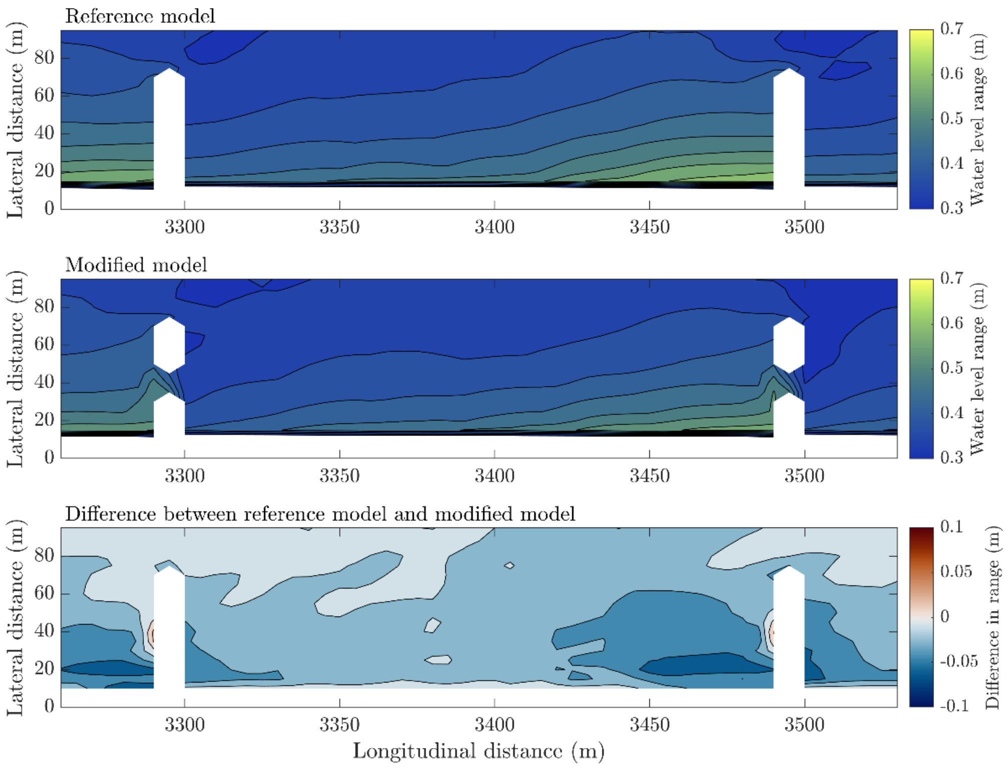


Figure 26: Water level range for downstream sailing vessels. Top plot shows traditional groyne field, middle plot shows modified groyne field, bottom plot shows difference.

As explained in Section 5.1, the difference between the reference model and modified model in the area of interest is quantified using boxplots. In Figure 27 on the next page, the boxplot for the difference in water level range for the situation with one modified groyne for downstream sailing vessels is depicted. This boxplot shows the difference in water level range in the area of interest between the traditional groyne and modified groyne. The median value is displayed with the red line, the first and third quartile with the blue lines and the minimum and maximum values are the black outer lines. In this boxplot the median difference in water level range is approximately -0.01 metres. This means that the median water level range in the area of interest decreased with 0.01 metres, which has a positive effect on the fauna habitat. The boxplot has a spread from -0.06 metres to 0 metres. This means that all the values in the area of interest, with the exception of outliers, are between this range. A large spread means much variability in the area of interest and a small spread means a low variability in the area of interest. Additionally, the skewness of this spread also says something about the variability of the area of interest. The spread can be skewed up or down. This means that on one side of the mean the spread is larger then on the other side of the mean. In Figure 27 the side below the mean has a larger spread than the side above the mean, this is called skewed down. If the side above the mean has a larger spread then it is called skewed up. This boxplot is skewed down which means that the values below the mean are further apart then the values above the mean. The outliers are depicted as blue markers. The outliers are extreme values which do not seem to fit in the distribution, they have a numerical value larger than 1.5 times the width of the "box" (distance between first and third quartile).

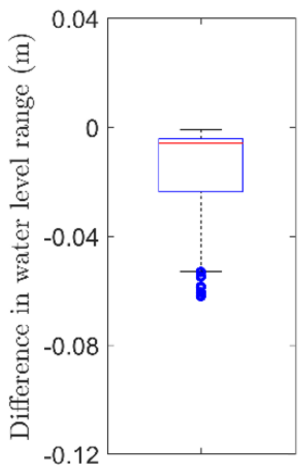
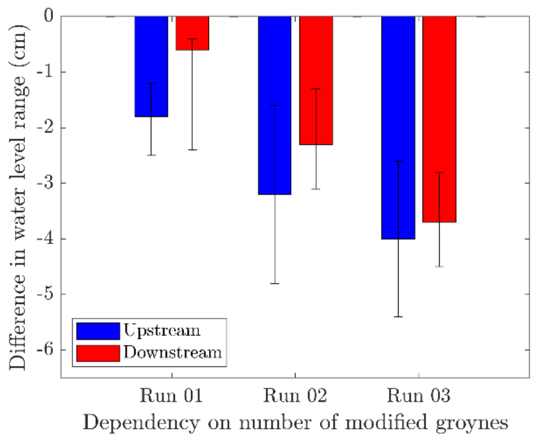


Figure 27: Boxplot depicting the water level range difference for a single modified groyne

The boxplots of various model runs are plotted beside each other to visualize the effect of the modification on the area of interest, in this case the number of modified groynes. The extended visualization of these boxplots is depicted in Appendix B.1 to B.3, and in Figure 28 this visualization is compacted to an error bar plot. In Figure 28 left the difference in water level range and in Figure 28 right the difference in velocity range for both upstream and downstream sailing vessels is depicted. The x-axis shows the run number as defined in Table 4 and the y-axis the difference in water level range or difference in velocity range. The bar shows the mean change in the area of interest and the error lines show the values of the first and third quartile.

The error bar in Figure 28 show that if more groynes are modified the water level range decreases for both upstream and downstream sailing vessels. For downstream sailing vessels this decrease is stronger. Additionally, for downstream sailing vessels the spread is skewed down for a single modified groyne but for multiple modified groynes the spread becomes normally skewed, and for upstream sailing vessels the spread is generally normally skewed. The velocity range also decreases when more groynes are modified for both upstream and downstream sailing vessels.



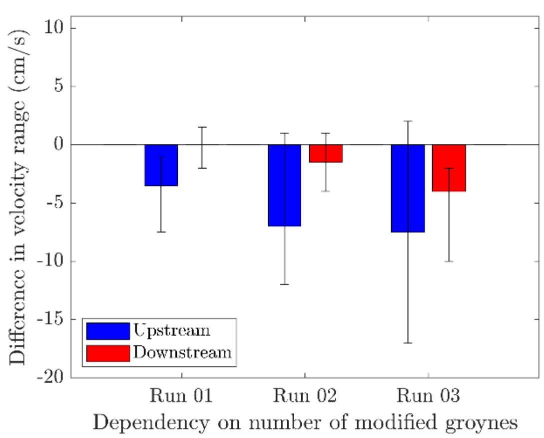


Figure 28: Error bar summarising boxplots from Appendix B.1 for upstream and downstream sailing vessels. The bar visualizes mean change and error lines show the first and third quartile. Dependency on number of modified groynes where run 01 has fewest modified groynes and run 03 most modified groynes

The water level range and velocity range pattern in a groyne field with two modified groynes or a series of modified groynes is similar. Further study shows that the flow pattern in the groyne field as a result from the notches behaves similarly for a situation with two modified groynes as for a series of modified groynes. The error bars shows that more modified groynes have a more positive effect in the area of interest. However, the water level range and velocity range pattern as well as the wave propagation behaves similar for two modified groynes as a series of modified groynes. The situation with two modified groynes is complex enough to study the effects of the modifications but keeps the study limited. So, the study is continued by modifying two groynes.

5.3.2 Optimisation study

To study the effect of notched groynes on ecological parameters in the area of interest, various notch variants are modelled in a groyne with a length of 65 metres. Figure 29 shows a standardized side view of a groyne with a notch. By altering the three defined parameters; location of notch from the tip of the groyne (a), width of the notch (b), and the depth of notch below water level (c), various notch geometries are realized. The notch geometries are structured such that the dependency on notch location, notch width, notch depth, notch shape, and number of notches can be studied. As a starting point for the notch dimensions and locations, the study (Shields Douglas Jr., 1988) is used. An overview of the notch geometries for every dependency is displayed in the tables of this sub-section and for more detailed information about the geometry of the notches, see Appendix C.1.

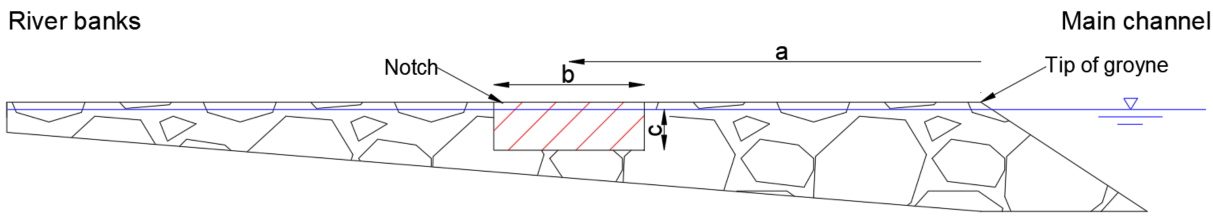


Figure 29: Side view of groyne with notch. Geometry of the notch can be altered based on three parameters a/b/c which are detailed in the tables in this sub-section.

Dependency on notch location

The notch can be placed at different locations in the groyne. Without a notch the wave passes the groyne field along the tip of the groyne. A notch shortens this path by diverting the wave from the tip to the notch. Table 5 shows the notch geometries used to study this effect, a notch of equal size is placed at various locations in the groyne field.

Table 5: Notch characteristics of various model runs to study the dependency on notch location, see figure 29 for interpretation parameters.

Variant number up- /downstream	Number of notches	Location of notch from tip of groyne (a)	Width notch (b)	Depth notch below water level (c)
2.104 / 2.204	1	15 m	10 m	1.0 m
2.105 / 2.205	1	25 m	10 m	1.0 m
2.106 / 2.206	1	35 m	10 m	1.0 m
2.107 / 2.207	1	45 m	10 m	1.0 m
2.114 / 2.214	1	55 m	10 m	1.0 m

Dependency on notch width

The width of the notch can be increased and decreased in size. This will affect the flow as a wider notch allows more discharge to pass and directly flows into a wider part of the groyne field. Table 6 shows the notch geometries used to study this effect, a notch with increasing width is placed with the centre of the notch at the same location in the groyne. The centre of the notch in run 2.102 / 2.202 couldn't be placed exactly at the same point due to the grid size. However, this is taken into account when interpreting the results.

Table 6: Notch characteristics of various model runs to study the dependency on notch width, see figure 29 for interpretation parameters.

Variant number up-/downstream	Number of notches	Location of notch from tip of groyne (a)	Width notch (b)	Depth notch below water level (c)
2.108 / 2.208	1	30 m	10 m	1.0 m
2.102 / 2.202	1	32.5 m	15 m	1.0 m
2.109 / 2.209	1	30 m	20 m	1.0 m
2.115 / 2.215	1	30 m	30 m	1.0 m

Dependency on notch depth

The depth of the notch can be changed. This will affect the flow as a deeper notch allows more discharge to pass through the notch. Table 7 shows the notch geometries used to study this effect, a notch with increasing depth is placed with the centre of the notch at the same location in the groyne. The location of the notch is equal to the location of the notch used in the study of the dependency on the width. Since the location and flow area for different notch layouts is equal (e.g. run 2.109 and 2.117 both have a flow area of 2 m^2 at a location of 30 metres from the groyne tip) a comparison between the effect of increasing the discharge by increasing the width or depth can be analysed.

Table 7: Notch characteristics of various model runs to study the dependency on notch depth, see figure 29 for interpretation parameters.

Variant number up-/downstream	Number of notches	Location of notch from tip of groyne (a)	Width notch (b)	Depth notch below water level (c)
2.108 / 2.208	1	30 m	10 m	1.0 m
2.116 / 2.216	1	30 m	10 m	1.5 m
2.117 / 2.217	1	30 m	10 m	2.0 m
2.118 / 2.218	1	30 m	10 m	3.0 m

Dependency on notch shape

In the study about the dependency on the width and depth of the notch, two parameters were varied, the width-depth ratio and the discharge flowing into the groyne field. To study the effect of the shape on the flow pattern, the width-depth ratio is varied but the flow area remains equal and as such trying to minimize the difference in discharge. Table 8 shows the notch geometries used.

Table 8: Notch characteristics of various model runs to study the dependency on notch shape, see figure 29 for interpretation parameters.

Variant number up-/downstream	Number of notches	Location of notch from tip of groyne (a)	Width notch (b)	Depth notch below water level (c)
2.110 / 2.210	1	27.5 m	5 m	2.0 m
2.105 / 2.205	1	25 m	10 m	1.0 m
2.111 / 2.211	1	27.5 m	15 m	0.67 m

Dependency on number of notches

Previous modifications are applied on one notch per groyne. Multiple notches in a single groyne influences the flow pattern by potentially creating a more evenly distributed flow disturbance. This will be tested by making one, two and four notches in a groyne which have in total the same flow area. Table 9 shows the geometries used.

Table 9: Notch characteristics of various model runs to study the dependency on number of notches, see figure 29 for interpretation parameters.

Variant number up-/downstream	Number of notches	Location of notch from tip of groyne (a)	Width notch (b)	Depth notch below water level (c)
2.109 / 2.209	1	30 m	20 m	1.0 m
2.112 / 2.212	2	15 / 35 m	10 m	1.0 m
2.113 / 2.213	4	15 / 25 / 35 / 45 m	5 m	1.0 m

5.3.3 Results

In this section the results from the optimisation study of the notched groynes are discussed. The results are divided in various sections. First the change in flow pattern in the entire groyne field due to the notches without ship passing is discussed. Secondly, the change in flow pattern in the entire groyne field with ship passing is discussed. Thirdly, ecological parameters in the area of interest are investigated and the dependencies on various notch parameters as specified in Section 5.3.2 are discussed. Lastly, a conclusion ends this section.

Flow pattern in groyne field without ship passing

In the situation with no ship passing the water level in the groyne field isn't influenced by the notch in the groyne. This is probably due to the fact that no large flows propagate through the notch and as such do not significantly interfere with the overall system. For bigger notches the water level pattern changes as a result of a bigger impact on the system and a local change in water level takes place. However, this change is very small and neglectable.

In the situation with no ship passing the horizontal flow pattern as depicted in Figure 3 in Section 2.1.2 is still largely present in the modified groyne field. The strong forcing mechanism of the flow in the main channel creates this eddy pattern and dominates the influence of the relatively small notch. This results that only a small flow propagates through the notch, which only has a small impact on the local magnitude of the flow. However, with increased notch size the impact on the flow pattern in the groyne field increases as more flow can propagate through the notch.

Flow pattern in groyne field with ship passing

During a ship passing the water level range pattern in the groyne field changes. For upstream sailing vessels the highest water level range is present near the upstream groyne close to the river banks. This is due to the fact that most of the flow due to water level depression and return flow is directed towards this area. The flow is trapped here and reflects on the groyne and river banks, resulting in an increased water level range. This water level range reduces with decreasing distance from this location. For downstream sailing vessels the water level range has a similar shape but is mirrored. The highest water level range is at the downstream groyne close to the banks. When the notch is placed in the groyne, the flow which originally was directed to the corner between the river banks and the groynes can divert through the notch. Compared to the reference case the water level range near this corner is lower, and so the water level range lowers throughout the entire groyne field. The most improvement in the water level range is created near banks of the downstream groyne and upstream groyne. The water level range for upstream and downstream sailing vessels is mirrored. This results that for the combined effect the water levels near the upstream groyne are dominated by upstream sailing vessels and near the downstream groyne by downstream sailing vessels.

The velocity range pattern during ship passing is more complex. To exemplify the results, the groyne field is split up in 5 different sections, see Figure 30.

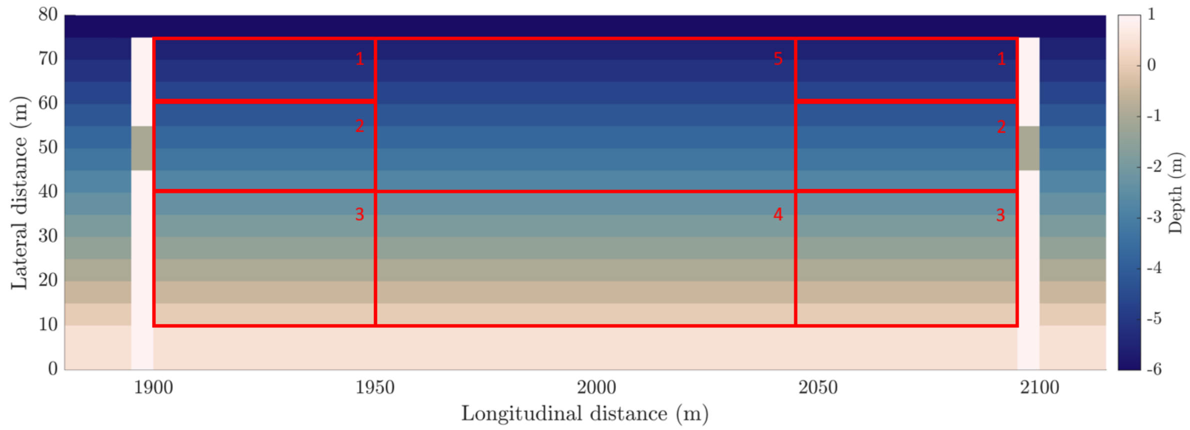


Figure 30: The groyne field split up in 5 different sections, each with different impacts due to the notch. The current flows from left to right.

Near the tip of the groynes (section 1) the velocity decreases in u- and v- direction. This is a combined result from the constricting / expanding flow from the notch which creates a stagnant rotating flow just next to the sides of the notch, and the decrease of the amount of water which has to pass the tip of the groyne due to the presence of the notch. This occurs for both upstream and downstream sailing vessels. Near the notches (section 2) the velocity increases. Specifically, the magnitude of the u-velocity and gradient increases and at the same location the magnitude and gradient of the v-velocity decreases. This is as a result of the opening in the groyne and the alternate in u- directed flow route. Due to the dynamic origin of the groyne field this jet disperses relative quickly in different directions with reduced velocity for upstream sailing vessels, however for downstream sailing vessels the velocity doesn't dissipate quickly and moves through the middle of the groyne field (section 5) to the downstream groyne. The groyne area near the river banks (section 3) shows a decrease in velocity range. For upstream sailing vessels this decrease is similar for the area near banks of the upstream and downstream groyne, however for the downstream sailing vessels the decrease is small in area near the upstream groyne and large in area near the downstream groyne. Similar as in section 1, a stagnant rotating flow develops as a result from the constricting / expanding flow. Additionally, the v-velocity in this area decreases. The middle area near the river banks (section 4) decreases or increases in range based on the notch modifications. Here the u- and v-velocity have both equally large vectors and non is dominant. The rest of the area (section 5) experiences a small decrease in velocity range for upstream sailing vessels and a small increase in velocity range for downstream sailing vessels. The velocity in u-direction is dominant and the decrease or increase follows also from this direction. The small effect on velocity is probably due to the fact that the groynes are well away from this area and the flow mainly follows its original path. In general, the increases and decreases in velocity range are more pronounced for upstream sailing vessels. The velocity range pattern is different for upstream and downstream sailing vessels. Specifically, the regions of decline in fauna habitat in the area of interest are different for both sailing directions. This results that for the combined effect, in general, the velocity range increases over a larger area.

Dependency on location

Based on Figure 31 the following conclusions can be made. The water level range changes depending on the location of the notch. The notch provides a different route for the flow to leave the groyne field and reducing the overall water level range in the groyne field. This reduction increases when the notch approaches the river banks. However, flow through the notch is met with some resistance, resulting in a local increase of water level in front of the notch. Additionally, the water depth closer to the river banks in the area of interest is lower resulting in even more resistance and more local increase in water level. This has a double negative impact and results in an increase in water level range when the notch is placed too close to the river banks. This applies to upstream as well as downstream sailing vessels due to their mirrored nature.

The velocity range changes depending on the location of the notch. With upstream sailing vessels the velocity range decreases when approaching the river banks. However, when the notch is too close to the river banks the velocity range increases. This increase is due to the jet through the notch which creates large local velocities. If the notch is placed closer to the river banks, the flow jets directly into the area of interest, increasing the velocity range. Additionally, the area of the high flow velocity area behind the notch is larger for regions closer to the river banks, further increasing the overall velocity range. This is due to the fact that the discharge through the notches is equal, however closer to the river banks the water depth is less and the flow cannot disperse as quickly as in deeper water. This results in a larger area of increased flow velocities. For downstream sailing vessels the flow pattern is different and the increased velocities due to the jet consist of a larger area. This negates the positive effect of a notch approaching the river banks and thus the velocity range increases when the notch gets closer to the river banks. However, the overall velocity range does decrease for every location.

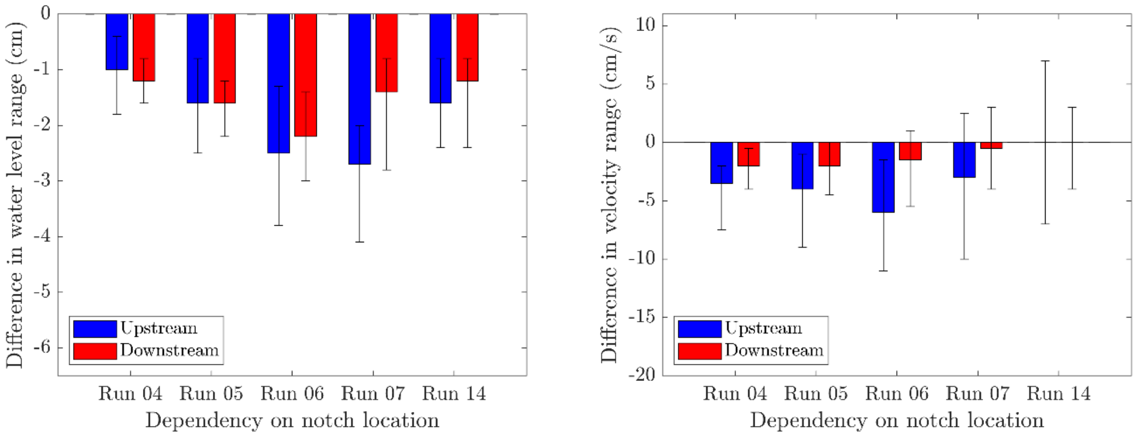


Figure 31: Error bar summarising boxplots from Appendix B.1 for upstream and downstream sailing vessels. The bar visualizes mean change and error lines show the first and third quartile. Dependency on notch location where run 04 is farthest from the river banks and run 14 closest to the river banks, for detailed information about the run characteristics see Table 5.

Dependency on width

Based on Figure 32 the following conclusions can be made. The water level range decreases with increasing notch width for upstream sailing vessels. However, the magnitude of decrease reduces with increasing width. This is due to the more or less same principles as described in the dependency on location. With an increase in width the jet approaches the area of interest resulting in a negative effect on the water level range. Additionally, the increase in width also causes the other side of the notch to approach the tip of the groyne, were the effect of the notch on the water level range reduces. Both these effects decrease the positive effect of the widening of the notch. For downstream sailing vessels the water level range stays more or less equal for changing widths. The pattern differs from upstream sailing vessels. A decrease in water level in the area of interest is observed at the downstream groyne and an increase at the upstream groyne. With increasing width, the water level changes at these locations both increase in magnitude and thus make each other equal resulting in a constant water level range.

The velocity range changes with different notch widths and for upstream sailing vessels it appears to function optimal for intermediate width. The increase in discharge through the notch as a result of the increase in width has a positive effect on the area of interest. However, the notch functions as a plane jet and if the width and thus discharge through the notch increases, the length after which the flow disperses increases. Additionally, due to the increase in width the notch approaches the area of interest and the jet flows directly into the area. These increased velocities over an extended area have a negative impact on the velocity range. An optimal width appears to be a balance between these two effects. For downstream sailing vessel the increase in width results in an increase in velocity range. This can be explained due to the flow direction. The flow through the notch is directed to the river banks creating an increased velocity in the area of interest. For wider notches the velocity and affected area increase which causes the negative correlation between notch width and water level range.

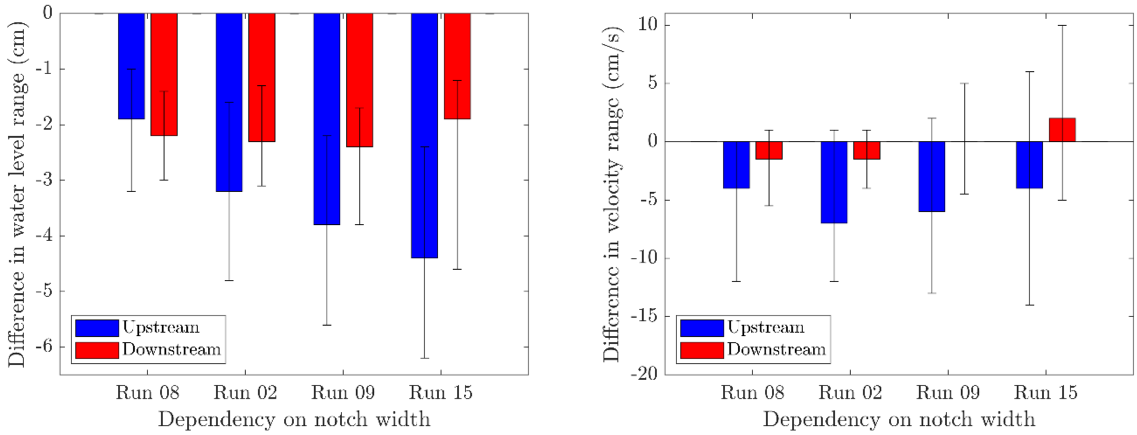


Figure 32: Error bar summarising boxplots from Appendix B.1 for upstream and downstream sailing vessels. The bar visualizes mean change and error lines show the first and third quartile. Dependency on notch width where run 08 is smallest and run 15 widest, for detailed information about the run characteristics see Table 6.

Dependency on depth

Based on Figure 33 the following conclusions can be made. The water level range decreases with increasing notch depth, however the magnitude of decrease is less as for increasing width with the same flow area. The jet is narrow and deep and disperses more vertically instead of the more horizontal dispersion which occur for wide notches. As such the flow interacts less with the area of interest compared to a notch which increases in width. The result is that the magnitude of water level range decrease in the area of interest for increasing depth is less as for increasing width. This is for both upstream and downstream sailing vessels.

The velocity range increases with increasing depth for upstream sailing vessels, however the situation is improved compared to a traditional groyne field. The velocity through the notch decreases and the flow area increases. This correlation results in a slight increase in discharge through the notch with increasing depth. If the flow area increases it draws more discharge. The velocity in the notch decreases if the difference between free flow and vertical constriction height decreases, this corresponds to the theory about vertical constriction and expansion. For upstream sailing vessels the increase in velocity range is due to the worsening of the area at the downstream groyne. For downstream sailing vessels the flow is directed towards the river banks at the upstream groyne, increasing the velocity range here. However, the velocity range near the downstream groyne decreases, resulting that the velocity range stays approximately equal in the area of interest.

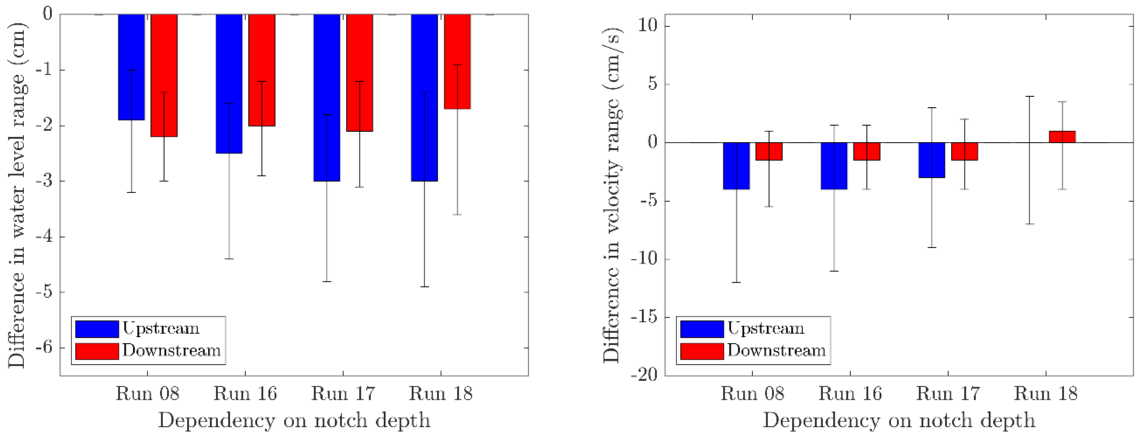


Figure 33: Error bar summarising boxplots from Appendix B.1 for upstream and downstream sailing vessels. The bar visualizes mean change and error lines show the first and third quartile. Dependency on notch depth where run 08 is shallowest and run 18 deepest, for detailed information about the run characteristics see Table 7.

Dependency on shape

Based on Figure 34 the following conclusions can be made. The water level range decreases in approximately the same locations in the area of interest for all ratios, but the water level range decrease is slightly more for ratios with a wider width for both upstream and downstream sailing vessels. From this can be concluded that the shape has a slightly more positive effect on the water level range in the area of interest if wider, but the overall discharge through the notch is dominant in changing the water level range.

Similar as for the water level range, the velocity range decreases in approximately the same locations in the area of interest for all ratios, but slightly more for ratios with a wider width for both upstream and downstream sailing vessels. From this can be concluded that the shape has a slightly more positive effect on the velocity range in the area of interest if wider, but the overall discharge through the notch is dominant in changing the velocity range.

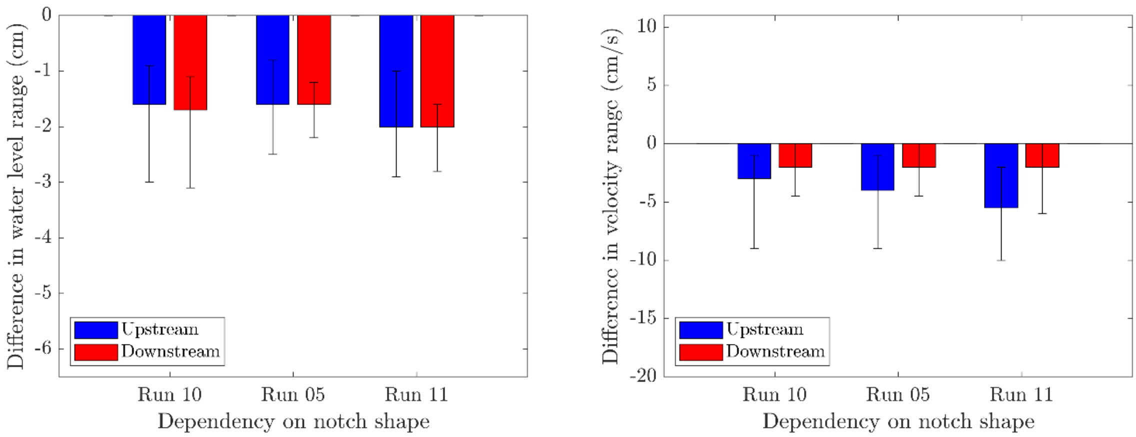


Figure 34: Error bar summarising boxplots from Appendix B.1 for upstream and downstream sailing vessels. The bar visualizes mean change and error lines show the first and third quartile. Dependency on notch shape where run 10 is narrow and deep and run 11 wide and shallow, for detailed information about the run characteristics see Table 8.

Dependency on number of notches

Based on Figure 35 the following conclusions can be made. The water level range stays approximately equal for a different number of notches in a single groyne whilst keeping the total flow area equal. This is probably due to a combination of multiple processes. The total discharge through the notch(es) is equal in all modifications and every notch contributes equally to the total discharge. Multiple smaller notches in a groyne have locally a smaller impact on the flow than one big notch, this has a positive effect. However, placing multiple notches in groynes results that the location of a notch can be close to the area of interest, having a negative effect on the water level range. Additionally, notches closer to the tip have a lower impact on decreasing the water level range in the area of interest. These processes appear to balance each other out. This is both for upstream and downstream sailing vessels.

The velocity range also stays approximately equal for both upstream sailing vessels as downstream sailing vessels. However, the overall improvement of the area of interest is higher for upstream sailing vessels. This constant velocity range decrease between different modifications is attributed to the same processes which effect the water level range explained in previous paragraph.

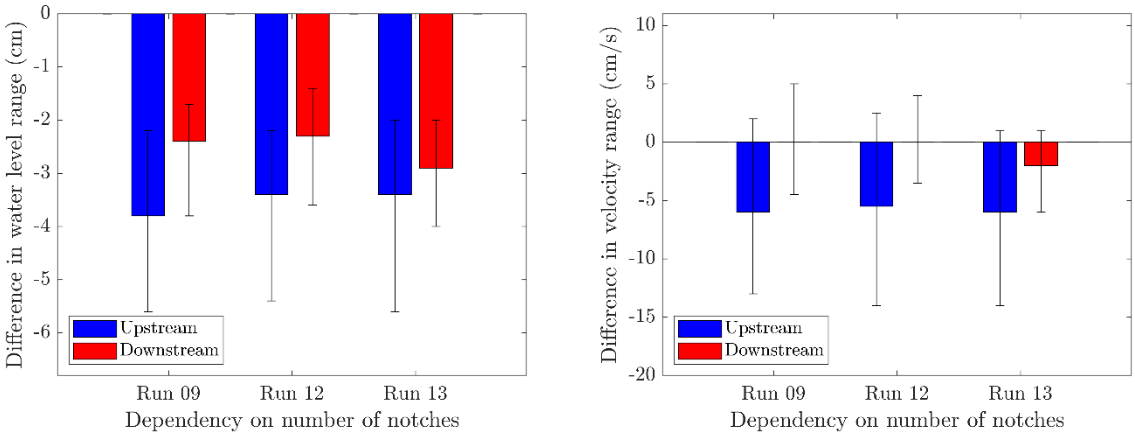


Figure 35: Error bar summarising boxplots from Appendix B.1 for upstream and downstream sailing vessels. The bar visualizes mean change and error lines show the first and third quartile. Dependency on number of notches where run 09 has fewest notches and run 13 most, , for detailed information about the run characteristics see Table 9.

Combined effect

The combined effect of the upstream and downstream sailing vessels on the ecological parameters in the area of interest have a similar conclusion for the different dependencies. The water level range for upstream and downstream sailing vessels is mirrored and the difference in water level range in the boxplot looks approximately similar for both sailing directions. This results that the combined effect also has a similar boxplot shape albeit the decrease is lower. The combined effect of the velocity range in the area of interest for the different dependencies has a negative effect on the fauna habitat quality. Due to the different areas of increase in velocity range for upstream and downstream sailing vessels, for the combined effect the area of velocity range increase is enlarged resulting that the mean velocity range for every notch modification stays approximately similar or increases.

Conclusion

Most notch geometries have a positive effect on the water level range in the entire groyne field. This effect is for both upstream and downstream sailing vessels. The velocity range improves near the river banks close to the groynes for upstream sailing vessels and for downstream sailing vessels only at the river banks near the downstream groyne. The river banks in the middle of the groyne field experience a negative effect of the notches for both the water level range and velocity range.

The two dominant notch characteristics driving change in the area of interest are the location of the notch and the discharge through the notch. The optimal location of the notch depends on two factors; the jet through the notch and the area of interest. The jet through the notch and the resulting mixing layer should not extend directly into the area of interest, and in addition, the local increase in water level around the notch should not extend into this area. This jet, caused by flow through the notch, is the main cause for deterioration of the area of interest. Flow passing through this notch causes a mixing layer on either side of the notch potentially impacting the area of interest. It is important to understand that the centre location of the notch is less of importance then the side of the notch closest to the river banks (area of interest), as the mixing layer which forms on this side can impact the area of interest. The optimal location of the side of the notch closest to the river banks should thus be based on these jet flow and mixing layer characteristics. The size of the area of interest depends on the water depth and thus the slope of the bed in the groyne field. A steep slope results in a narrow stretch of living habitat for vulnerable species and a mild slope for a wide stretch of living habitat, consequently with a steep slope the notch can be placed closer to the river banks as with a mild slope. The discharge through the notch follows from the notch flow area. The discharge through the notch should not be too small or the area of interest is not impacted, and not too large or the effect of the flow through the notch is too strong and deteriorates the area, see Figure 32 and 33. The shape of the notch should be wide and not deep and the number of notches has minimum impact on improving the area of interest, see Figure 34 and 35.

5.4 Results L-shaped groyne

In this section the effects of the L-shaped groyne on the groyne field are discussed. This section is divided in various sub-sections to gain insight in the individual effects of the L-shaped groyne. In section 5.4.1 the effect of the number of L-shaped groynes are discussed. In section 5.4.2 the effect of the branch direction is discussed, the branch is the part of the groyne laying parallel to the river banks, see Figure 36. Section 5.4.3 shows the setup of the optimisation study of which the results are shown in section 5.4.4.

The results in this section are described and studied using a similar methodology as performed in Section 5.3.1. and in this section the results are again compacted based on a large number of cases and output data. For the uncompacted results and output data a general reference to Appendix B.2 and C.2 for this section is made. Appendix B.2 shows the boxplot used in the dependency study and Appendix C.2 shows the L-shaped geometry and ecological parameter plots for all the different cases. The introduction in these appendices provide a guideline on how to find specific figures.

5.4.1 River modification

The objective of this research is to find options to improve the habitat in the groyne field at the entrance and exit of side channels. The habitat between groynes can be improved in different ways that affect the river system on different scales:

- A single L-shaped groyne upstream of the selected groyne field. This groyne affects two groyne fields, a groyne field which is semi-cut off by the branch and the groyne field downstream from the L-shaped groyne has a different outflow pattern. Limited large-scale river flow change and morphological change can be expected in the main channel;
- Two L-shaped groynes, upstream and downstream from the selected groyne field. This notch effects three groyne fields. In addition to the effect of a single L-shaped groyne the groyne field downstream from the L-shaped groyne experiences a different inflow pattern. The branches of the L-shaped groyne limit in- and outflow of the groyne field but the discharge through the main channels stays equal so no large-scale river flow change and morphological change in the main channel can be expected.

To study the effect of the number of L-shaped groyne, an L-shaped groyne with a branch of 100 metres long is modelled for the different scenarios described above, see Table 10.

Table 10: L-shaped groyne characteristics of various model runs to study the dependency on number of modified groynes, see figure 36 for interpretation parameters.

Variant number up- /downstream	Number of modified groynes	Length of branch (a)
3.101 / 3.201	1	100 m
3.102 / 3.202	2	100 m

The boxplots in Appendix B.2 on Page 79 show a distorted view of the effect of a single L-shaped groyne and two L-shaped groynes. From the boxplots can be concluded that on average the ecological parameters with a single L-shaped groyne worsen the least. However, when the plots from the ecological parameters is viewed in Appendix C.2 on Page 177 to 186 an opposite conclusion can be made. Behind the branch of the groyne the ecological parameters worsen for both situations and behind the open end of the L-shaped groyne the parameters remain equal or improve. The habitat behind the branch for both a single L-shaped groyne or two is decreasing severely compared to original groynes and we expect that no improvement can be gained here. This decrease is larger for two L-shaped groynes resulting in the higher average for the ecological parameters. However, the region at the open end is improving more for two L-shaped groynes than for one L-shaped groyne. Since at this location the improvement for the groyne region is expected to be gained, the optimisation study will continue with two L-shaped groynes.

5.4.2 Direction L-shaped groyne

The branch of the L-shaped groyne can be directed upstream and downstream. This direction might influence the flow pattern inside the groyne field but also the way the wave from a passing vessel enters the groyne field. To study which direction is optimal an L-shaped groyne similar in size pointed upstream and downstream is modelled, see Table 11.

Table 11: L-shaped groyne characteristics of various model runs to study the dependency on branch direction, see figure 36 for interpretation parameters.

Variant number up- /downstream	Direction of branch	Length of branch (a)
3.102 / 3.202	Downstream	100 m
3.103 / 3.203	Upstream	100 m

The boxplots in Appendix B.2 on Page 80 shows a varied result dependent on the sailing direction. For downstream sailing vessels the branch directed downstream is optimal and for upstream sailing vessels the branch directed upstream is optimal. The ecological parameters in the combined boxplot show that neither is dominant. Taking a look at the results in Appendix C.2 on page 182 to 191 and we can conclude that the largest area receives improvement with L-shaped groynes directed downstream. The optimisation study will continue using a L-shaped groyne directed downstream.

5.4.3 Optimisation study

The optimisation study for L-shaped groynes is focused on a single dependency. The effect of the branch length on the area of interest. To study this effect, various lengths are modelled. Detailed information about the geometry of different L-shaped groynes are shown in Appendix C.2.

Dependency on length

The length of the branch can be changed. By changing the length of the branch, the inflow area and the discharge that enters the groyne field changes. Additionally, increasing the branch length increases the length of the groyne field protected from direct wave impact. The branch lengths are chosen to gain insight in the effect of very short branches to very long branches, see Table 12.

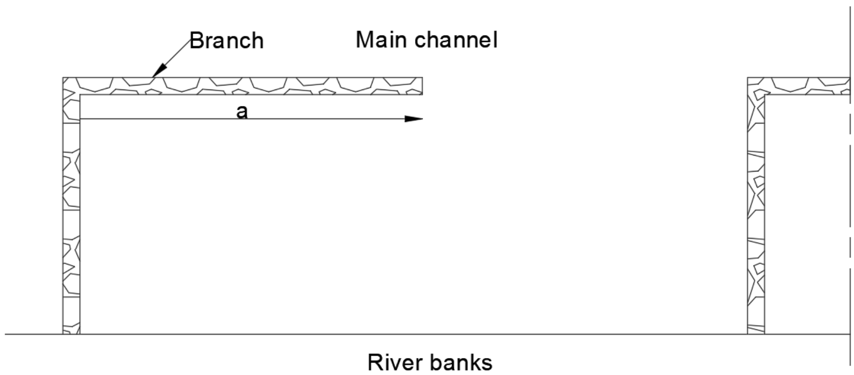


Figure 36: Top view of L-shaped groyne. Length of the branch can be altered based on parameter a which is detailed in the table in this sub-section.

Table 12: L-shaped groyne characteristics of various model runs to study the dependency on branch length, see figure 36 for interpretation parameters.

Variant number up- /downstream	Length of branch (a)
3.107 / 3.207	25 m
3.104 / 3.204	50 m
3.102 / 3.202	100 m
3.105 / 3.205	150 m
3.106 / 3.206	175 m

5.4.4 Results

In this sub-section the results from the optimisation study of the L-shaped groyne are presented. First the change in flow pattern due to an L-shaped groyne in the entire groyne field without ship passing is discussed. Secondly, the change in flow pattern in the entire groyne field with ship passing is discussed. Thirdly, ecological parameters in the area of interest are studied and the dependencies on branch length is discussed. Lastly, a conclusion ends this sub-section.

Flow pattern in groyne field without ship passing

In the situation with no ship passing the horizontal flow pattern in the groyne field as depicted in Figure 3 in Section 2.1.2 changes as well as the flow pattern in the main channel close to the groynes, see Figure 37. The eddy in the groyne field decreases in size and velocity magnitude. The size of the eddy depends on the length of the branch and a longer branch results in a smaller eddy. The flow in the remainder of the groyne field is stationary due to its location behind the branch. Due to the smaller opening between the main channel and the groyne field, less mass- and momentum exchange is possible. This results in a decrease in the velocity magnitude of the eddy. Due to the interaction of flow between the groyne field and the main channel a turbulent pattern is present between the tip of the groynes and the main channel, see Figure 37a between lateral distance 75 and 100 metres. Without the branches a large opening between the main channel and groyne field is present resulting in high exchange of flow. If branches are present the opening is smaller and less exchange of flow is present, resulting in a straighter flow pattern, see Figure 37b. The absolute discharge through the river doesn't change and no large-scale velocity changes in the main channel are present, only a small redistribution near the groynes.

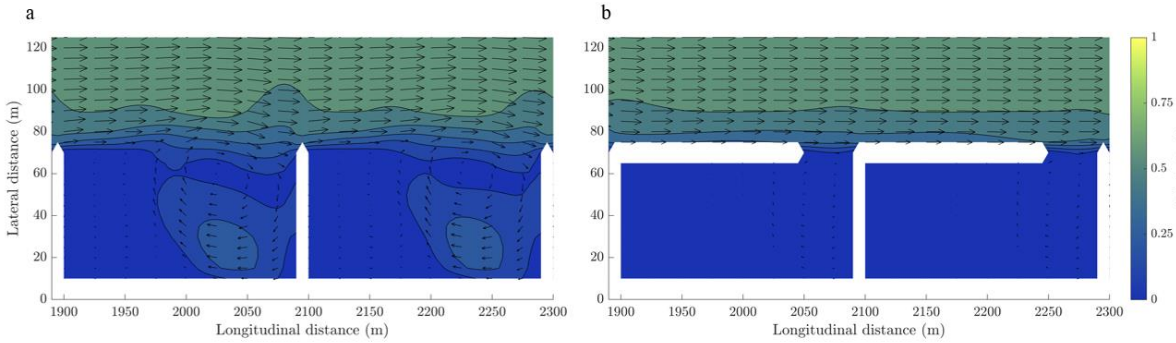


Figure 37: Flow pattern in groyne field and main channel without L-shaped groynes (a) and with L-shaped groynes (b). Flow is directed to the right.

Flow pattern in groyne field with ship passing

During ship passing the flow pattern in the groyne field changes compared to non-L-shaped groynes. The observations and conclusions mentioned below are compared to traditional groyne geometry.

To explain the effect of the modifications, the groyne field is split up in three different areas, see Figure 38; the region in the shadow zone of the branch of the L-groyne (area 1), the region at the tip from the L-branch to the river banks (area 2), and the region at the open end of the branch (area 3). The specific area of the sections varies with the length of the branch as such that area 2 is always around the tip of the branch.

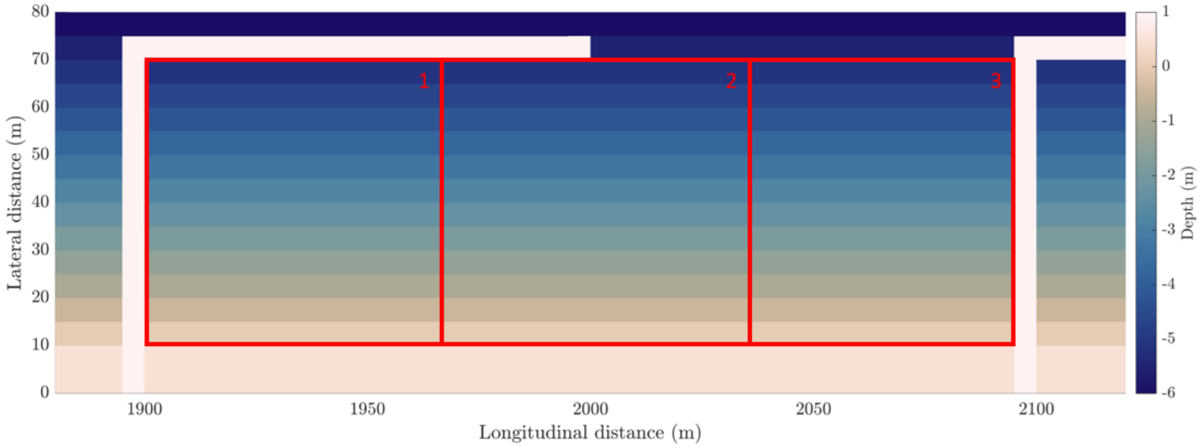


Figure 38: The L-shaped groyne field split up in three different areas. Each area experiences a similar impact due to the L-shaped groyne. The main river flow is directed from left to right.

A ship sailing through a waterway is followed by a water level depression on both sides of the vessel. When the vessel passes the L-shaped groyne, the water level depression moves into the groyne field and its magnitude increases towards the closed end (longitudinal distance 1900 metre in Figure 38). After the ship has passed a supply flow follows, this supply flow fills the groyne field. At the closed end the water level increases significantly and at the open end (longitudinal distance 2000 metre in Figure 38) the water level follows the height of the primary wave movement. The velocity is 180 degrees out of phase with the water level, meaning that when the water level is maximum the velocity is zero and vice versa. The velocity is zero near the closed end due to continuity, and maximum near the opening of the groyne. These processes change the water level and velocity pattern in the groyne field compared to a traditional groyne field. With increasing branch length, the discharge entering the groyne field reduces and the water level and velocity reduce too. Additionally, a shorter vessel also reduces the wave height and flow velocity in the groyne field due to the shorter forcing from the main channel.

For longer branches the water level increases when approaching the closed end of the L-shaped groyne. This results in an increase in water level range when approaching the closed end, due to reflection of the wave. Since the water level range increases towards the closed end, the water level range is higher throughout the entirety of area 1 and 2 compared to a traditional groyne field. The water level range decreases slightly in area 3. Here the water spreads in two directions resulting in a more effective dispersion of the wave and thus a lower water level range. Short branches have a limited effect on the water level range and small increase in average water level range is observed. The pattern of the water level range and effect of the L-shaped groynes are similar for both upstream and downstream sailing vessels. Since, the shape of the water level range is similar for both the upstream and downstream sailing vessels the combined effect is dominated by the sailing direction with the largest water level range. In this situation the upstream sailing vessel creates the largest water level range.

The velocity range is out of phase with the water level range, so in general we see a maximum velocity range at the location of a minimum water level range and vice versa. In area 2 of the groyne field the u-velocity increases and the v-velocity decreases, however the absolute velocity increases. The decrease in v-velocity is probably due to the branch which mainly blocks perpendicular (v-directed) flow. The increase in v-velocity is mainly due to the supply flow. For upstream sailing vessels this flow is directed towards the opening in the groyne field and as such evenly distributed over the width of the opening. At the entrance of the remainder of the groyne field (longitudinal distance 2000 m in

Figure 38) the velocity range is maximum. When the supply flow further propagates into this area the velocity range decreases towards zero at the closed end in area 1. The limited rotational movement and the branch blocking the flow to the main channel results in a decrease in v-velocity. For downstream sailing vessels the supply flow is not directed towards the opening of the groyne field but flows around the tip of the branch. This changes the velocity range pattern in the groyne field. The largest velocity range is present near the tip of the branch and near the river banks in area 1. In area 3 the flow velocity increases when the branch is long as the high velocity range near the opening of the groyne spreads to this area. For short branches the water level range decreases, which is probably due to effective dispersion in the area. Due to the difference between the velocity range patterns for upstream and downstream sailing vessels the combined effect shows an increase in velocity range over a larger area. The largest increase is due to the downstream sailing vessels.

Dependency on branch length

Based on Figure 39 the following conclusions can be made. The water level range stays almost constant for short branches but for longer branches the water level range increases. Since the flow isn't significantly impacted by short branches, no changes in the area of interest occur. Longer branches impact the flow significantly and increase mean the water level range in the area of interest. For a given branch length the water level range near the close end increases due to reflection. This results in the increase in water level range with increasing branch length. However, after a certain length the water level range decreases again. This is probably due to the decrease in discharge which can enter the field so the final water level range near the closed end is lower. The situation is still worse than without notches. This is for both upstream and downstream sailing vessels. Since the shape of the water level range is similar for upstream and downstream sailing vessels the boxplot also has the same shape. The boxplot follows the largest values which originate from the upstream sailing vessel.

The velocity range increases with increasing length, with the exception of really long branches which almost close the entire groyne field. As explained previously the velocity increases with increasing branch length resulting in local high velocity ranges. This pattern increases the spread of the boxplot values and the mean velocity range. When the branch is really long the discharge entering the groyne field reduces and thus reduces the velocity. The area of interest increases in mean velocity range for all lengths with the exception of the very long one. This is both for upstream and downstream sailing vessels.

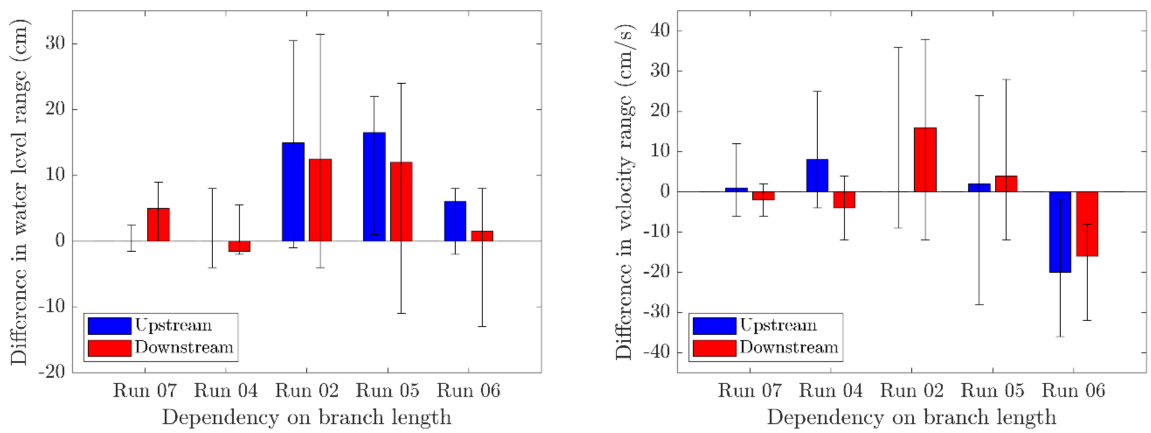


Figure 39: Error bar summarising boxplots from Appendix B.2 for upstream and downstream sailing vessels. The bar visualizes mean change and error lines show the first and third quartile. Dependency on branch length where run 07 is the shortest branch and run 06 longest branch, for detailed information about the run characteristics see Table 12.

Conclusion

L-shaped groynes with short branches create a mean increase in water level range and velocity range, which is negative. If the length of the branch increases, the water level range and velocity range increase and behave in an out of phase pattern where the primary wave reflects near the closed end of the L-shaped groyne. This results that near the opening of the groyne in area 2 the velocity range increases but the water level range decreases, and near the closed end of the L-shaped groyne in area 1 the water level range increases but the velocity range decreases. The decrease in velocity range and water level range almost never occur at the same location.

We concluded that the branch length is an important parameter. The mean water level range in the area of interest increases for all branch lengths and the mean velocity range only decreases for really long branch lengths. These statements combined with the previously concluded notion that local improvements of water level range and velocity range occur at different locations, indicates that the L-shaped groyne modification in its entirety unsuitable for improving the fauna habitat quality.

5.5 Conceptual groyne design

The results from Section 5.3 and 5.4 gave insight in the effect of the notch modification and the L-shaped groyne modification. Based on this insight a conceptual optimal design for the improvement of the area of interest can be designed. This modification is clarified in Section 5.5.1. Using this conceptual optimal design different scenarios are studied to widen the knowledge about the effect of the modifications. In Section 5.5.2 a situation with submerged groynes and in Section 5.5.3 a situation with smaller vessels is modelled. In Section 5.5.4 a side channel is modelled to explore first observations about the effect of the modification on side channels.

The results in this section are described and studied using a similar methodology as performed in Section 5.3.1. and in this section the results are again compacted based on a large number of cases and output data. For the uncompacted results and output data a general reference to Appendix B.3 and C.3 for this section is made. Appendix B.3 shows the boxplot results for the effects on the changed situations and Appendix C.3 shows the notch geometry and ecological parameter plots for all the different cases. The introduction in these appendices provide a guideline on how to find specific figures.

5.5.1 Optimal design

The effects of the notches on the flow velocity range and water level range have in some locations in the groyne field conflicting results. This means that at some locations the water level range decreases but the velocity range increases (or vice versa) which can result in an overall decrease of habitat quality. Since no definitive research is present on the correlation between fish density and the ecological parameters, we choose to optimise the groyne by using a notch geometry which has a positive effect on both the water level range and velocity range in the area of interest.

Because the L-shaped groyne does not improve the habitat quality, we restrict the optimal design to notched groynes. Based on the conclusions from Section 5.3.3. the optimal notch geometry is determined. It was concluded that a wide shallow notch has a more positive effect than a deep narrow notch so we choose to optimize the notch width. From Figure 32 is determined that the optimal reduction for both water level range and velocity range is for a notch with a width of 20 metres and a depth of 1 metre. The location of this notch is based on Figure 31 where it can be seen that the optimal location is at run 06 which has the centre of the notch at 35 meters. However, in Section 5.3.3. we concluded that not the centre but the side of the notch closest to the river banks is most important in determining the location. Since the notch in run 06 is 10 metres wide, the side closest to the river banks is located at 40 metres from the tip of the groyne. For our optimal notch design the width is 20 metres, so the centre of the notch will be located at 30 metres from the tip. Figure 40 shows the side view of the optimal notch geometry.

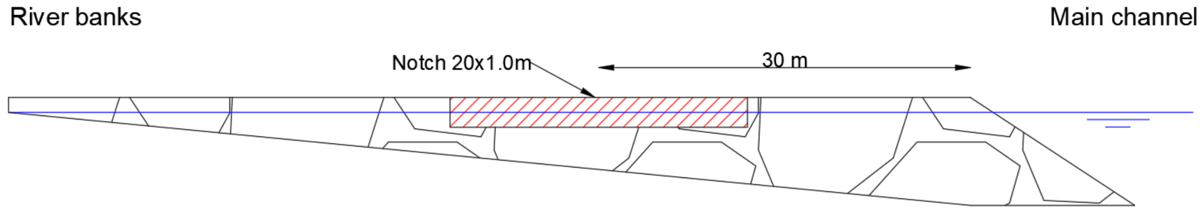


Figure 40: Sideview of modified groyne with optimal notch geometry

In Appendix C.3 from page 213 to 217 the results are presented. It is observed that a reduction in velocity range as well as in water level range is present. The flow patterns due to the notch are similar as for other notch geometries and no unexpected changes occur. The change of the ecological parameters in the area of interest are collected in the boxplot, see appendix B.3 page 82. Comparing these to the modifications defined in the optimisations study and we see that this notch geometry has the largest overall reduction for the ecological parameters. The assumptions made before to create an optimal reduction in ecological values are thus valid. However, the assumptions are made under the notion that both water level range and velocity range are of equal importance for the fish density. The notch geometry is designed to reduce both these parameters as much as possible. If future ecological research states that one parameter is of higher importance than the other, the optimal notch geometry might change to facilitate optimal reduction for the most important parameter. This notch design is used to research the other variations; submerged groynes, a smaller vessel, and a river with a side channel.

5.5.2 High water

The optimisation study for the groynes with notches and L-shaped groynes have been performed using low water levels and emerged groynes. As explained in Section 5.1 these water levels correspond to the period of breeding and growing of the fauna when they are most vulnerable. In recent years the groynes in the Waal have been lowered. This results that they are submerged for a longer period each year. So, during summer flows the groynes can also be submerged. However, these water levels aren't very high above groyne crest level. We also expect that the notched groynes have a limited effect on the flow during very high-water levels (winter flows). Insight in the effect of the notches on submerged groynes is desired for relative low water levels above the groyne crest, so the water level is limited to 50 centimetres above groyne crest height.

In Figure 41 the water level and velocity in a stationary point in the main channel during passing of a vessel is depicted. The comparison is between a vessel passage during low and high water. The ship length and velocity stay equal for both high and low water so the wavelength is equal for both. It can be concluded that the water level depression and return current (u-velocity) has decreased in magnitude. This corresponds to the theory from (Verheij, 2008). This theory states that if the water depth increases the water level depression and return current decrease.

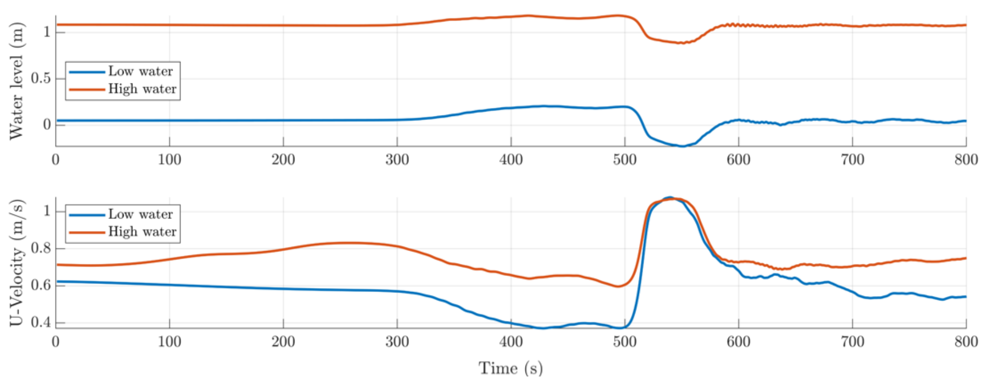


Figure 41: Water level plot (top) and return current plot (bottom) for a stationary point in the main channel for both high and low water. The bed level is defined at -5 metre.

Results

Figure 23 in Section 5.1 shows the area of interest for fauna habitat improvement. Since the water level increases, the habitat of vulnerable fauna changes. The location is altered so the evaluation area still corresponds to water depths up to 1.5 metre. The plots in Appendix C.3 from page 218 to 222 show that the water level range pattern for submerged groynes are similar to emerged groynes, so it is concluded that the ship-induced waves are also affected by the groynes when submerged. Similar as with emerged groynes the water level range increases near the upstream groyne for upstream sailing vessels, and increases near the downstream groyne for downstream sailing vessels. The relative water level increase for submerged groynes is reduced compared to emerged groynes, this is probably due to the lowered effect the groynes have on the flow. The effect of the notch on the water level is different for submerged groynes and does not have the same effect as with emerged groynes. The notch has a negative effect on the water level range in the area of interest for both upstream and downstream sailing vessels and a combination of both. However, the increase in water level range is very limited. The velocity range pattern is different for submerged and emerged groynes. The effect of the notch is limited, a small velocity increase near the location of the notch is visible. For submerged groynes the velocity range in the area of interest decreases slightly for just upstream and downstream sailing vessels, but for a combination of both the velocity range increases.

The notch doesn't have a positive effect on the water level range and velocity range in the area of interest for submerged groynes. However, these ranges are initially lower compared to the ecological parameters at emerged groynes. So, the final habitat quality isn't determined by high water levels but by low water levels. For this reason, it is more important to optimize the reduction of the ecological parameters for emerged groynes than for submerged groynes.

5.5.3 Small vessel

The optimisation study for the notched groynes and the L-shaped groynes is performed using a vessel from the CEMT class VIc, the largest allowed vessel on the Waal. As explained in section 5.1, one of the reasons a large vessel is used, is because larger vessels have a more negative effect on the fauna habitat and it is desired to improve the habitat most for this situation. However, these large vessels are only a small percentage of traffic on the Waal river. Vessels with CEMT class IV and V have a slightly smaller cross section and a significant shorter length. These vessels also have a significant impact on the habitat of the fauna. To gain insight in the effect of the modification on smaller vessels, a characteristic CEMT class Va (Groot Rijnschip) is modelled. This vessel will sail by the conceptual groyne design. Since the vessel is smaller the limit speed of the vessel is higher and the cruising speed can be increased. The relative speed of the ship is now 4.8 m/s and is calculated using the same formulas as for the large vessel, as explained in Appendix A.1.

In Figure 42 the water level and velocity in a stationary point in the main channel during passing of a vessel is depicted. The comparison is between the reference model for a large vessel and the reference model for a small vessel. It is visible that the water level depression and the increase in u-velocity (return current) for smaller vessels is less. This is due to the shorter vessel as the primary wave length is related to the length of the vessel, and due to the slightly faster vessel speed of smaller vessels. The magnitude of the water level depression and u-velocity do not change significantly. This can be explained using the theory from (Verheij, 2008). With similar sailing speed the largest vessel creates the largest water level depression and u-velocity, however, a smaller vessel can sail faster before hitting the limit speed. This increase in sailing speed results in larger water level depression and u-velocity. In this case, the wave signal for a large vessel and small vessel are approximately equal.

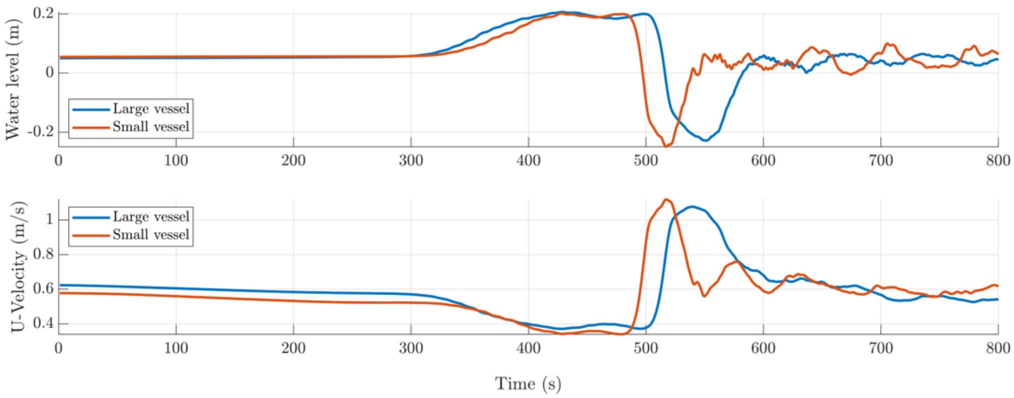


Figure 42: Water level plot (top) and return current plot (bottom) for a stationary point in the main channel for both a large vessel and a small vessel.

Results
Due to the initial larger velocity range and water level range for smaller vessels the ecological parameters in the groyne field are higher for smaller vessels. The pattern of the ecological parameters in the groyne field is equal to the signal of larger vessels and the relative reduction is similar for both large and small vessels. It can be concluded that the notch modification works similar for vessels of different sizes, see Appendix C.3 page 223 to 227.

5.5.4 Approach side channel

In this section the potential of the modified groynes in damping ship-induced waves in side channels is studied. The groynes are modified according to the design specified in Section 5.5.1, however a side channel is modelled. Geometry and placement of side channels in rivers vary extensively based on design conditions. The purpose of this study is to see the potential of groyne modifications on damping ship-induced waves in side channels. As such, the side channel location and geometry are simplified based on side channels in the Waal. A side channel located in the middle of a groyne field with a width of 30 metres, a depth of 1.5 metres, and a length of 100 metres is modelled. The opening is placed perpendicular the main channel. The boundary at the end of the side channel represents a lake with a fixed water level, see Figure 43.

In Section 5.1 the area of interest is described for the situation without a side channel. The area of interest is now extended by including the side channel, see Figure 43. The side channel is analysed by adding another area of interest, located in the side channel.

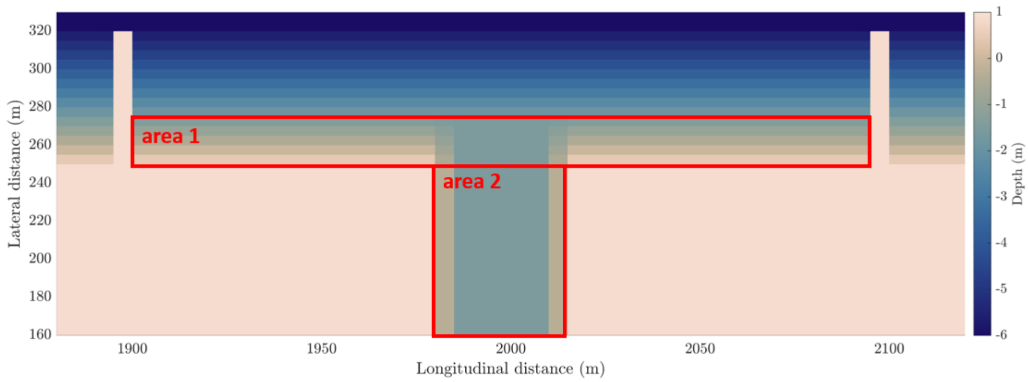


Figure 43: Bed topography top view of groyne field with side channel, two areas of interest specified

Results
The water level range follows approximately the same pattern in the groyne field as without the side channel, see Appendix C.3 page 228 to 232. The water level range is highest near the corner between

the groyne and river banks and decreases in magnitude away from this area. The water level range developing in the side channel appears to depend on the water level range at the entrance location, the notch reduces this water level and thus has a positive effect on the flow propagation in the side channel.

The velocity range also follows a similar pattern in the groyne field as without the side channel, also see Appendix C.3 page 228 to 232. However, locally around the entrance of the side channel the pattern changes. The ship-induced wave propagating into the side channel causes large flow velocities near the entrance resulting in an increase in velocity range near the river banks of the groyne field around the opening of the side channel. This velocity increase propagates several metres inside the side channel. For upstream sailing vessels, the notch has a negative effect near the entrance of the side channel and a positive effect near the middle and “end” of the side channel. For downstream sailing vessels the velocity range decreases throughout the entire side channel. The difference in the velocity range change between upstream and downstream sailing vessels is due to the location of the side channel. Results without the side channel showed that in the middle of the groyne field, at the entrance of the side channel, the velocity range changes due to the notch. For upstream sailing vessels the velocity range increases and for downstream sailing vessels it decreases at this location. Similar as with the water level range, the velocity range in the side channel depends on the initial range near the entrance. Thus, for upstream sailing vessels this results in an increase in velocity range and for downstream sailing vessels in a decrease in velocity range.

Despite the in general similar flow patterns in the groyne field with and without side channel, the side channel does change the ecological values in the original area of interest (area 1). The water level range experienced a slight increase compared to the situation without side channel but the notches still have an improving effect on the water level range in this area. The effect of the notches on the velocity range in the original area of interest is low, this is probably due to the increased velocities near the entrance of the side channel negating the initial positive effect of the notch. The water level range in the side channel (area 2) has decreased significantly when notches are placed over the entire area. On average the velocity range in the side channel also improves with notches but not throughout the entire side channel. It can be concluded that the notches have the potential to dampen ship-induced waves in side channels. However, further research with different side channel layouts and notch geometries have to performed to fully understand the effect of notches on side channels. The results used for these conclusions can be found in Appendix B.3 on page 83.

6 Discussion

Before establishing the main conclusions and recommendations, critical reflection on the conducted research is required. In this section the uncertainties and limitations of the model are discussed and the generalisation of the model setup and the effect of this on the results.

6.1 Model limitations

This study is performed using the hydraulic model XBeach based on non-linear shallow-water equations. In Section 3 the choice for a non-linear shallow-water equation model instead of a Boussinesq-type model is substantiated. The main reason is that solely primary waves have to be modelled for this study which can be accurately modelled by both model types, however the computational time of non-linear shallow-water-type models is shorter so preference to this type is given. The Boussinesq-type model should be applied if secondary waves are of importance. However, the ecological parameters are based on the maximum range of water level and velocity and for large vessels these originate from primary waves. If the primary waves remain dominant there is no need to apply a Boussinesq-type model, which in this study has been the case.

The grid dependence study was a part of the model setup to determine the optimal grid size. From this study it was concluded that a grid size of 5x5 m^2 can provide valuable results. A model validation study showed good agreements with test data, so the flow pattern in the groyne field can be modelled accurately and sufficient variation with different notch sizing is possible using this grid size. A larger grid size results in shorter model run times which is useful for the optimisation study. The grid dependence study is limited to the current state. However, to improve the model and obtain more quantitative correct values, the study can be improved by focusing on the horizontal viscosity. XBeach calculates the horizontal viscosity using the Smagorinsky model. This model uses a function based on grid size. This function states that with decreasing grid cells the horizontal viscosity decreases down until a minimum value. With big cells the viscosity is higher and more momentum can be exchanged between grid cells. This results in a smoothened flow pattern, similar as what turbulence does in real life since no infinite high velocity gradients can occur in the water. With smaller grid cells the velocity gradients can be higher and the flow is less smoothened which results in a more accurate representation of reality. By expanding the current grid dependence study with extra grid sizes a convergence study can be performed which gives more insight in the correctness of the horizontal viscosity and the convergence point. This convergence point is the “true value” and values calculated by other grid sizes are approximations to this value. However, hydraulic models using the shallow-water equations are sometimes not able to calculate the fluctuations accurately for very small grid sizes. So, with an ever-increasing grid resolution, the grid size might not be limiting but the quality of the turbulence model. As such it might be possible that the smallest grid size does not show the best results.

The result of the chosen grid size is that the ratio between notch size and grid size is relatively small which means that the flow pattern through and around the notch is simplified. If further understanding about the flow pattern through and downstream of the notch (e.g. mixing layer, flow development region, dispersion) is desired the grid size should be decreased. Additionally, the grid dependency study showed that the numerical value of the water level and velocity deviated slightly between a grid size of 5x5 and 2.5x2.5 m^2. This deviation increased approaching the river banks. Since this location contains the area of interest it is expected that the “correct” value differs from the results from this study. When interpreting or correlating these values with the fish density this has to be taken into account. Additionally, the model simulates one vertical layer. In general the wave system has long waves in shallow water which results in accurate values in a large part of the groyne field. However, in reality close to the notch the flow contracts and expands in vertical direction, which due to the single layer model cannot be simulated accurately. This results that the forces and velocities close to the notches differ from reality and this should be taken into account when interpreting the results.

6.2 Result limitations

This study assesses the results based on generalised characteristics of both the groyne field and the river. However, for groyne fields and rivers with different characteristics, the results might be different. In this Section various limitations and uncertainties related to the results and effectivity of the modification are discussed.

Uncertainties of the ecological parameters

The study is based on the ecological parameters water level range and velocity range to evaluate the fauna habitat quality. Research on the correlation between these parameters and the fish density is still ongoing so no final optimal modification design can be given. In Section 5.5 a notch geometry is chosen by assuming both parameters are of equal importance and both water level range and velocity range are decreased as much as possible. Research might indicate that one of the two parameters is more important which could change the optimal design.

Generalization of the optimal design

The optimal design is based on the generalised groyne field. The values used to describe the optimal geometry and location for the groyne field in this study might not be the optimal characteristics for groyne fields with different sizes. If the lateral bed slope in the groyne field is different the habitat area for vulnerable fauna changes. This directly influences the optimal location for the notch. If the size of the groyne field changes, the amount of discharge that has to enter the field to improve the area of interest might change, resulting in a different optimal notch geometry. Additionally, a longer groyne might also impact the optimal location of the notch. Determining the optimal notch placement and geometry differs per groyne field and during notch design the processes driving the change behind the optimisation should be taken into account and not the numerical values displayed in this study.

Effectivity of notched groynes with varying river water levels

The results from the optimisations study of notched groynes showed that the area of interest improved more when the notch is wide and shallow. However, the optimisation study is based on one water level. If a wide shallow notch is created in the groyne (as is done for the optimal design), the notch might work optimal for this water level but quickly loses this efficiency if the water level in the river increases or decreases slightly. Additionally, the groyne will completely lose functionality if the water level in the river is below the crest height of the notch. In Figure 33 on page 39 the dependency on notch depth is shown. Here we see that the maximal potential reduction of ecological parameters is lower if the notch is narrow and deep compared to a wide and shallow notch, however the efficiency of the notch for varying notch depths (or water levels) is fairly constant. Whether a wide and shallow, or narrow and deep notch is optimal depends on the water level variation in the river. When the water level in the main channel is fairly constant a wide and narrow notch is optimal but in case of a variable water level in the main channel it is better to create a narrow deep notch.

Effect of notched groynes on other groyne functions

Modifying the groynes by creating notches to maximise ecological potential in the groyne field can affect other functions of the groyne. The main function of the groynes in the Waal river is to maintain a fairway of sufficient depth and width to facilitate inland water transport. By creating notches in groynes, the discharge is diverted from the main channel through the notch lowering the discharge in the main channel. This discharge reduction in the main channel theoretically results in lower flow velocities and settling of sediment on the river bed. However, the amount of discharge flowing through the notch is a factor 100 smaller than the flow through the main channel. So, we expect no significant reduction in water level or flow velocity as a result from the decrease in discharge in the main channel. So, the modified groynes in the Waal can still fulfil the original function of maintaining a main channel with sufficient depth and width for inland water transport. Fairly recently the crest height of the groynes in the Waal have been lowered along certain reaches to reduce the effective roughness during high water conditions, thus increasing the river's flood conveyance capacity. Creating notches groynes only adds to this increase in conveyance capacity.

Simplicity of the side channel study

The study performed on the effect of notches in the side channel is highly simplified and the goal was only to gain insight in the potential for improvement in the side channel. Since the model could model the ship-induced waves and flow pattern in groyne fields without side channels accurately it is assumed that the model can also depict the flow patterns and wave propagation in groyne fields with side channels. However, additional research should validate this assumption before conclusive statements about the effect of notches on side channels based on this research are made.

The uncertain morphological effect of notched groynes

The morphological effects resulting from the notches in groynes have not been considered in this study. However, we can state the following reasonable expectations: if velocity increases erosion of the river bed takes place, if velocity decreases sedimentation of the river bed takes place. The expectations discussed below are based on average flow patterns in groyne fields with notched groynes. The flow velocity in front and behind the notch increases significantly and we expect erosion of the river bed to take place at these locations. On either side of the notch the flow velocity decreases and thus we expect sedimentation of the river bed. If the notch is located far enough from the river banks the flow velocity near the river banks also reduces, thus sedimentation of the river banks occurs. If the notch is placed close to the river banks the flow velocity increases and erosion of the river banks occur.

7 Conclusion and recommendations

Research on the effect of modified groynes on ship-induced waves has received little attention in scientific studies. This study is the first step towards the understanding of notched and L-shaped groynes and their effect on primary waves propagation in groyne fields. Based on findings of this study, the research questions are answered in Section 7.1 and several recommendations for future research and the applicability of the groyne modification are presented in Section 7.2.

7.1 Conclusion

The objective of this research is to give recommendations on methods to dampen ship-induced waves in groyne fields and side channels by modifying groynes with the aim of increasing the quality of fauna habitats. This objective is summarised in the main research question, repeated below.

> *How can ship-induced waves in groyne fields and side channels be damped by using L-groynes or by creating notches in groynes to increase ecological value of the river habitat?*

This main question is answered by presenting the conclusions to the sub-questions defined in Section 1.2.2.

1. *What hydrological indicators can be used to quantify ecological value?*

Ecological research states that the fauna habitat quality can be assessed by analysing water level range and flow velocity range both in a timestep of 60 seconds. The correlation between fish density and these ecological parameters remains a subject of ongoing research, though it is known that a decrease in water level range and velocity range in a timestep of 60 seconds improves the fauna habitat quality.

2. *Which flow dynamics ensue in a groyne field when ships sail by?*

The flow dynamics in a groyne field during a ship passing are dominated by two processes. The initial rotatory pattern in the groyne field occurs due to mass and momentum exchange between the main channel and groyne field and the primary wave induced by the vessel. The ship-induced wave causes a return current opposite to the sailing direction of the vessel, and a water level depression along the sides of the vessel. This disturbance propagates into the groyne field, changing the initial rotatory flow pattern and water level by causing drawdown near the river banks. Additionally, high flow velocities will develop near the tip of the groyne as a ship passes.

3. *Which notch design optimizes fauna habitat quality in a groyne field?*

In this study the effects of notched groynes on the fauna habitat quality in the groyne field are studied using a hydraulic model. The notched groynes do not have to dampen ship-induced waves in the entire groyne field, only in the habitat area of vulnerable fauna. The fauna habitat quality is indicated by the water level range and velocity range in a timestep of 60 seconds. The two dominant notch characteristics driving change in the area of interest are the location of the notch and the discharge through the notch. The optimal location of the notch depends on two factors; the jet through the notch and the area of interest. The jet through the notch and the resulting mixing layer should not extend directly into the area of interest, and in addition, the local increase in water level around the notch should not extend into this area. This jet, caused by flow through the notch, is the main cause for deterioration of the area of interest. Flow passing through this notch causes a mixing layer on either side of the notch potentially impacting the area of interest. It is important to understand that the centre location of the notch is less of importance then the side of the notch closest to the river banks (area of interest), as the mixing layer which forms on this side can impact the area of interest. The optimal location of the side of the notch closest to the river banks should thus be based on these jet flow and mixing layer characteristics. The size of the area of interest depends on the water depth and thus the slope of the bed in the groyne field. A steep slope results in a narrow stretch of living habitat for vulnerable species and a mild slope for a wide stretch of living habitat, consequently with a steep slope the notch can be placed closer to the river banks as with a mild slope. The discharge through the notch follows from the notch flow area. The discharge through the notch should not be too small or the area of interest is not impacted, and not too large or the effect of the flow through the notch is too strong and deteriorates the area, see Figure 32 and 33 on Page 39. The shape of the notch should be wide and not deep and the number of notches has minimum impact on improving the area of interest, see Figure 34 and 35 on Page 40 and 41. In Section 5.5.1 the optimal notch design is made based on the above-mentioned statements and this resulted in an increase of fish density of roughly 8% (DEL SIGNORE et al., 2016). Notched groynes improve the area of interest more for upstream sailing vessels than for downstream sailing vessels, and this is mostly due to its ineffectiveness in improving the velocity range of the downstream sailing vessels. The notched groynes are thus more effective in situations with mostly upstream sailing vessels, but still contribute in improving the fauna habitat quality for downstream sailing vessels. If future ecological research states that the water level range is more important than the velocity range for the quality of fauna habitat, then the effectiveness of notches for downstream sailing vessels improves. Additional research performed with this notch geometry shows that the damping effect on shorter vessels is similar as that for larger vessels. Thus, the modification is effective for a range of vessels with different lengths sailing the river. The modification is slightly less effective for submerged groynes but due to the initial lower impact of the waves on the groyne field, the fauna habitat quality at submerged groynes is better than at emerged groynes.

4. *Which L-shaped groyne design optimizes fauna habitat quality in a groyne field?*

In this study the effects of L-shaped groynes on the fauna habitat quality in the groyne field are studied using a hydraulic model. The L-shaped groynes do not have to dampen ship-induced waves in the entire groyne field, only in the habitat area of vulnerable fauna. The fauna habitat quality is indicated by the water level range and velocity range in a timestep of 60 seconds. Without ship passing the L-shaped groynes improve the habitat in the groyne field substantially. With ship passing (both upstream and downstream) the water level range and velocity range increase and behave in an out of phase pattern where the primary wave reflects near the closed end of the L-shaped groyne. This has a negative impact on the water level range for all branch lengths. The velocity range is negatively impacted by the L-shaped groynes for all branch lengths except for branch lengths which close off the groyne field by more than 85%, also for both upstream and downstream sailing vessels, see Figure 39 on Page 46. Additionally, no local improvements of water level range and velocity range occur at the same location. These statements make the L-shaped groyne modification unsuitable for improving the fauna habitat quality.

5. *Which flow dynamics occur in a side channel when a ship sails by and how can the optimized damping structure dampen the ship-induced waves in side channels?*

The general flow dynamics caused by ship-induced waves in groyne fields behave similarly with and without side channel. The ship-induced waves propagate into the side channel where its water level range decreases with increasing distance from the entrance and the velocity range increases with increasing distance from the entrance. The magnitude of the water level range and velocity range developing in the side channel are determined by the initial parameters at the entrance of the side channel. Notches reduce the magnitude of these parameters at the entrance of the side channel, resulting in an initially lower water level range and velocity range. This improves the fauna habitat quality.

7.2 Recommendations

The topic of this study has received little attention in scientific communities. As such limited information about the subject is available. Additionally, during this study several choices have been made to limit the study and focus on the main objective. Based on the limitations of this study and the known knowledge gaps, several recommendations are made to continue this research and enrich the subject knowledge. Additionally, an advice is given on whether an L-shaped groyne or notched groynes are a good solution to dampen ship-induced waves in groyne fields and side channels to increase the fauna habitat quality.

Optimal groyne modification to improve fauna habitat quality and its applicability
Based on the conclusions we can state that the L-shaped groyne is unsuitable for improving the fauna habitat quality, and the notched groyne does have the potential to dampen primary ship-induced waves in both the groyne field and side channel and improve the fauna habitat quality. The optimal notch design is based on the location; which depends on the jet through the notch and the area of interest, and the discharge through the notch (or flow area notch). The optimal groyne design results in an increase in fish density in the area of interest of 8% (rough estimation). The construction process of notches is relatively simple and cheap, as only a small notch has to be created in a groyne. No new construction material is needed and the entire work can be performed from a pontoon boat, furthermore the excavated groyne material can be re-used for other projects. If further ecological data becomes available the notch design can be optimized further, and when using a series of modified groynes, the fish density might increase even more. While this study has focussed on the specified area of interest (fauna habitat close to the river banks), we note that fauna habitat quality outside this area also increases, and the groyne fields on either side of the modified groyne field also experience an increase in fauna habitat quality.

Study the effect of a series of modified groynes
In this study, we chose to only modify two groynes for the optimisation study instead of a series of groynes. We concluded that the modification of two groynes has the same effect on the change in ecological parameters as a series of modified groynes. However, results also showed that more modified groynes resulted in a larger reduction of water level range and velocity range and thus an overall greater improvement for the groyne field and area of interest. To potentially further improve the fauna habitat, we advise expanding this study by modelling a series of modified groynes.

Study the effect of a side channel
In Section 5.5.4 a single model run was performed to gain insight in the potential of damping ship-induced waves in side channels using notched groynes. We found that the water level range and velocity range decreased in both the groyne field and the side channel. The flow pattern in the groyne field appeared similar to that of a groyne field without a side channel, except locally at the entrance of the side channel. Further study should verify this and confirm whether the optimal groyne modification is also optimal for a groyne field with side channel. Additionally, we recommend study on varied side channel geometries in order to better quantify the effect of notched groynes.

Quantify the fish density
The objective of this study was to improve the quality of the fauna habitat between groynes. Ecological research stated that two ecological parameters, water level range and velocity range, could be used to predict the fish density and thus habitat quality. However, research about the correlation between the parameters and the fish density is still in progress. Consequently, we are unable to provide a final answer on the optimal notch geometry. In Section 5.5.1 a conceptual optimal design was determined which was based on the notion that the water level range and velocity range are of equal importance. However, given this might not be the case, we advise that the optimal design is reconsidered when new ecological conditions become available.

Study the morphological effect of the notched groynes
In this study morphologic activity is not taken into account. However, groyne modifications will affect the flow patterns. These changes might result in different erosion and sedimentation processes, which over time could re-shape the local morphology surrounding the groyne field. These morphological changes could directly impact the fauna habitat, and they could change the effectiveness of the modified groynes. Thus, we advise further research on the morphological effects of notched groynes.

References

Adams, S. R., Keevin, T. M., Killgore, K. J., & Hoover, J. J. (1999). Stranding Potential of Young Fishes Subjected to Simulated Vessel-Induced Drawdown. *Transactions of the American Fisheries Society*, *128*(6), 1230–1234. https://doi.org/10.1577/1548-8659(1999)128<1230:spoyfs>2.0.co;2

Barret, J. C. (1992). Turbidity-Induced Reactive Distance of Rainbow Trout. *Transactions of the American Fisheries Society*, *4*(121), 437–443.

Blom, A. (2016). *Bed degradation in the Rhine river*. Flowsplatform. https://flowsplatform.nl/#/bed-degradation-in-the-rhine-river-1479821439344________

Brett, J. R. (1964). The respiratory metabolism and swimming performance of young sockeye salmon. *Journal of the Fisheries Research Board of Canada*, *21*(5), 1183–1226.

Brunke, M., Sukhodolov, A., Fischer, H., Wilczek, S., Engelhardt, C., & Pusch, M. (2002). Benthic and hyporheic habitats of a large lowland river (Elbe, Germany): influence of river engineering. *SIL Proceedings, 1922-2010*, *28*(1), 153–156. https://doi.org/10.1080/03680770.2001.11902565

Collas, F. P. L., Buijse, A. D., van den Heuvel, L., van Kessel, N., Schoor, M. M., Eerden, H., & Leuven, R. S. E. W. (2018). Longitudinal training dams mitigate effects of shipping on environmental conditions and fish density in the littoral zones of the river Rhine. *Science of the Total Environment*, *619–620*, 1183–1193. https://doi.org/10.1016/j.scitotenv.2017.10.299

de Jong, M. P. C., Roelvink, D., Reijmerink, S. P., & Breederveld, C. (2013). Numerical modelling of passing-ship effects in complex geometries and on shallow water. *Smart Rivers 2013*, *September*, 95.1-95.7.

de Jong, M., Roelvink, D. J., Breederveld, C., & Reijmerink, S. (2013). Numerical modelling of passing-ship effects in complex geometries and on shallow water SKIM : the Sea surface KInematics Multiscale monitoring satellite mission View project [AWA] Ecosystem Approach to the management of fisheries and the marine environmen. *Liege (BE)*, *June 2014*, 95. https://doi.org/10.13140/RG.2.1.1776.3049

DEL SIGNORE, A., LENDERS, H. J. R., Hendriks, A. J., VONK, A., MULDER, C., & Leuven, R. S. E. W. (2016). SIZE-MEDIATED EFFECTS OF WATER-FLOW VELOCITY ON RIVERINE FISH SPECIES. *River Research and Applications*, *32*, 390–398.

EC. (2001). WHITE PAPER: European transport policy for 2010: time to decide. In *Commission of the European Communities* (Issue 2001). https://doi.org/9289403411

European Commission. (2001). RICHTLIJN 2000/60/EG van het Europees Parlement en de raad van 23 oktober 2000 tot vaststelling van een kader voor communautaire maatregelen betreffende het waterbeleid. *Publicatieblad van de Europese Gemeenschappen*, *12*, 1–38.

Gabel, F., Lorenz, S., & Stoll, S. (2017). Effects of ship-induced waves on aquatic ecosystems. *Science of the Total Environment*, *601–602*(April 2019), 926–939. https://doi.org/10.1016/j.scitotenv.2017.05.206

Hall, K. M., & Benham, B. L. (2007). *Comparing alternative Methods of Simulating Bacteria Concentrations*. *40*(October), 1–13.

Hammer, C. (1995). Fatigue and exercise tests with fish. *Comparative Biochemistry and Physiology Part A: Physiology*, *112*(1), 1–20.

Havinga, H., Slootweg, H., & Zeekant, J. (1984). *Directe waterhuishouding en waterbeweging Rijkswaterstaat district zuidoost*.

Holland, L. E. (1987). Effect of Brief Navigation-Related Dewaterings on Fish Eggs and Larvae. *North American Journal of Fisheries Management*, *7*(1), 145–147.

Jude, D. J. (1998). Spring Distribution and Abundance of Larval Fishes in the St. Marys River, With a Note on Potential Effects of Freighter Traffic on Survival of Eggs and Larvae. *Journal of Great Lakes Research*, *24*(3), 569–581.

Klingeman, P. C., Kehe, S. M., & Owusu, Y. A. (1984). Steambank erosion protection and channel scour manipulation using rockfill dikes and gabions. In *Water resources research institute*.

Krebs, M., Zanke, U., & Mewis, P. (1999). Hydro-Morphodynamic modelling of groin fields. *IAHR*, *28*.
MarineTraffic. (2007). *MarineTraffic: Global Ship Tracking Intelligence | AIS Marine Traffic*. https://www.marinetraffic.com/en/ais/home/centerx:-12.0/centery:25.0/zoom:4
Mueller, G. (1980). Effects of Recreational River Traffic on Nest Defense by Longear Sunfish. *Transactions of the American Fisheries Society*, *109*(2), 248–251.
Pauli, G. (2010). Sustainable transport: A case study of Rhine navigation. *Natural Resources Forum*, *34*(4), 236–254. https://doi.org/10.1111/j.1477-8947.2010.01309.x
Przedwojski, B., Blazejewski, R., & Pilarczyk, K. W. (1994). *River training techniques fundamentals, techniques and applications*.
Rijkswaterstaat. (2008). *Scheepvaartinformatie Hoofdvaarwegen*.
Rijkswaterstaat PDR. (2012). *Vraagspecificatie Eisen (VSE) Kribverlaging Waal fase 3 en Langsdammen Wamel-Ophemert Contractnummer : 31051429*.
Roelvink, D., van Dongeren, A., Mccall, R., Hoonhout, B., van Rooijen, A., van Geer, P., de Vet, L., & Nederhoff, K. (2015). *Xbeach Manual*. 138.
Roo, S. De, & Troch, P. (2010). Analysis of Ship-Wave Loading on Alternative Bank Protection of a Non-Tidal Waterway – First Results. *Dept. of Civil Engineering, Ghent University, Belgium*.
Schans, H. (1998). Representativiteit van kribvakmetingen uit 1996 en 1997 ten opzichte van de hele Waal. *ICG*, *15*.
Shields Douglas Jr., F. (1988). Biological and Physical Effects of Missouri River Spur Dike Notching. *Miscellaneous Paper EL8811 US Army Corps of Engineers*, *September*.
Sorensen, R. M. (1997). *Prediction of Vessel-Generated Waves with Reference to Vessels Common to the Upper Mississippi River System*. *December 1997*, 50. http://ntl.bts.gov/lib/17000/17300/17398/PB2001101346.pdf
Tavakkol, S., & Lynett, P. (2017). Celeris: A GPU-accelerated open source software with a Boussinesq-type wave solver for real-time interactive simulation and visualization. *Computer Physics Communications*, *217*(April), 117–127. https://doi.org/10.1016/j.cpc.2017.03.002
Ten Brinke, W. B. M., Kruyt, N. M., Kroon, A., & Van Den Berg, J. H. (1999). Erosion of sediments between groynes in the River Waal as a result of navigation traffic. *Spec. Publs Int. Ass. Sediment*, *28*, 147–160.
Ten Brinke, W. B. M., Schulze, F. H., & Veer, P. van der. (2004). Sand exchange between groyne-field beaches and the navigation channel of the Dutch Rhine: The impact of navigation versus river flow. *River Research and Applications*, *20*(8), 899–928.
Termes, A. P. ., Wal, M. van der, & Verheij, H. J. (1991). *Waterbeweging door scheepvaart op rivieren en in kribvakken, WL Delft Hydraulics*.
Uijttewaal, B. W. S. J., Lehmann, D., & Mazijk, A. Van. (2001b). EXCHANGE PROCESSES BETWEEN A RIVER AND MODEL EXPERIMENTS ITS GROYNE FIELDS : *Journal of Hydraulic Engineering*, *127*(November), 928–936.
van der Hout, A. J., & de Jong, M. P. C. (2014). Passing ship effects in complex geometries and currents. *PIANC World Congress*, *31*(0), 17.
Verheij, H. J. (2008). *Inland waterways*.
Verheij, H. J., & Vermeer, K. (1987). *Groyne field erosion due to push tow navigation (six and four barges) on the River Waal (Kribvakerosie door zes- en vierbanksduwvaart op de Waal).*
Webb, P. W. (1975). Hydrodynamics and energetics of fish propulsion. *Bulletin - Fisheries Research Board of Canada*, *190*, 1–159.
Wolter, C., & Arlinghaus, R. (2003). Navigation impacts on freshwater fish assemblages: The ecological relevance of swimming performance. *Reviews in Fish Biology and Fisheries*, *13*(1), 63–89. https://doi.org/10.1023/A:1026350223459
Yossef, M. F. M. (2015). Morphodynamics of rivers with groynes. In *PhD thesis Delft, University of Technology Delf*.
Zawischa, D. (2020). *Kelvin wakes*. https://www.itp.uni-hannover.de/fileadmin/arbeitsgruppen/zawischa/static_html/KWake.html
Zhou, M., Roelvink, D., Verheij, H., & Ligteringen, H. (2013). Study of Passing Ship Effects along a Bank

by Delft3D-FLOW and XBeach. *International Workshop on Next Generation Nautical Traffic Models*, *1998*, 71–80.

Zhou, M., Roelvink, D., Zou, Z., & Van Wijhe, H. J. (2014). Effects of passing ship with a drift angle on a moored ship. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, *8B*, 1–7. https://doi.org/10.1115/OMAE2014-24515

Zijlema, M. (2015). *Computational Modelling of Flow and Transport*. 176.

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Appendices

A Calculations

This appendix consists of three sections. The first section shows the methodology and calculation for the vessel speed and accompanying ship-induced waves characteristics, both primary and secondary waves. Section A.2 shows the water level plots of various points and grid sizes for the grid dependency study. Section A.3 shows two plots visualizing the water levels and velocities in a stationary point for various grid sizes, also used for the grid dependency study.

A.1 Characteristic values of primary and secondary waves

In this appendix the vessel speed and corresponding primary and secondary waves are calculated. The statements below result in the parameters depicted in Table A-1 and used for this calculation:

- The cross section of the river has been simplified to a rectangular shape;
- The normative vessel a CEMT class VIc is based on the maximum allowed vessel on the Waal;
- The river characteristics are based on the mean values of the Waal as specified in Table 1 of the main report;
- The main channel depth is based on mean values from the Waal;
- For the calculations no current is assumed;
- Calculations and equations are based on theory from (Verheij, 2008).

Parameter	**Value**
Ship draft [D]	4 [m]
Ship width [B]	22,8 [m]
Ship length [L]	270 [m]
Main channel depth [h_0]	5,8 [m]
Main channel width [W]	279,5 [m]
Ship shape coefficient [α]	0,85 [-]
Distance to side of ship [y_s]	125 [m]

Table A-1: Parameters used for the calculation

Primary wave

The maximum velocity of the vessel (V_{lim}), maximum velocity of the wave (U_{lim}) and maximum drawdown (Z_{lim}) are based on the ratio between cross section vessel (A_s) and cross section channel (A_c). The cross section of the vessel is calculated by multiplying vessel width *(B)* by vessel draught *(D)*, and the cross section of the channel is calculated by multiplying channel width *(W)* by channel depth *(h_0)*. In channels with unrestricted width the vessel can sail with the velocity of a wave in shallow water, however the width restriction limits the velocities and additional parameters. Using the theory of Schijf these parameters can be determined, see figure A-1, based on the ratio of cross section between vessel and channel, see Equation A-1.

$$\frac{A_s}{A_c} = \frac{B \cdot D}{W \cdot h_0} = \frac{22{,}8 \cdot 4}{279{,}5 \cdot 5{,}8} = 0{,}06 \qquad \textit{eq. A-1}$$

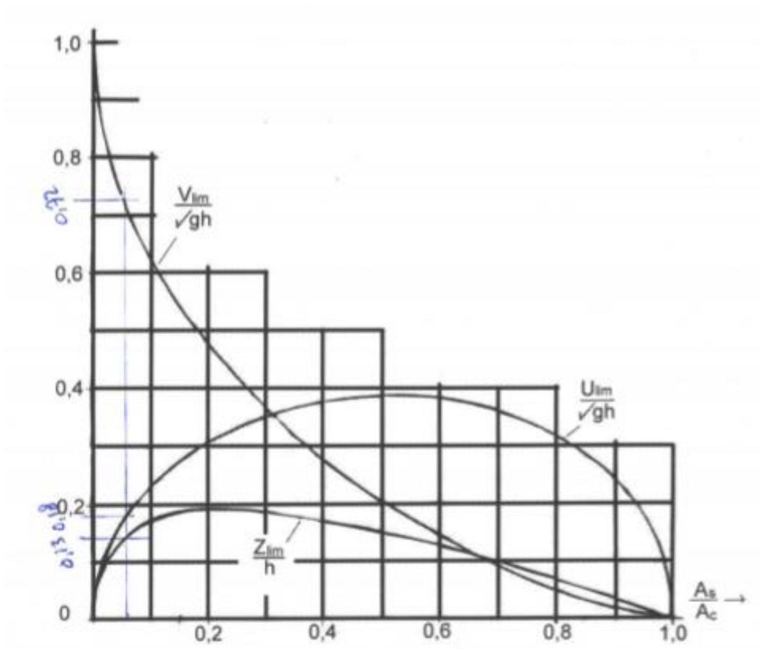


Figure A-1: Limiting values according to the theory of Schijf (Verheij, 2008)

Using the graph in Figure A-1 the maximum sailing velocity of the vessel is calculated. However, vessels mainly don't sail at limit velocity for economic and environmental reasons but mostly at around 80% of this speed, so the limit velocity will be adjusted to ship velocity (*V_s*).

$$\frac{V_{\lim}}{\sqrt{gh}} = \frac{V_{\lim}}{\sqrt{9{,}81 \cdot 5{,}8}} = 0{,}72 \qquad V_{\lim} = 5{,}43 \text{ m/s} \qquad V_s = 4.34 \text{ m/s} \qquad \textit{eq. A-2}$$

Using Equation A-4 and A-5 defined in the theory from (Verheij, 2008) the return current (Ur) and water level depression (Z) can be calculated. The return current is iteratively determined. The alpha factor *(α)* is a correction for the non-uniform distribution of the return current, this can be calculated using Equation A-3

$$\alpha = 1.4 - 0.4 \cdot \frac{V_s}{V_{\lim}} \qquad \alpha = 1.4 - 0.4 \cdot \frac{4.34}{5.43} = 1.08 \text{ [-]} \qquad \textit{eq. A-3}$$

$$\frac{\alpha \cdot (V_s + U_r)^2 - V_s^2}{2 \cdot g \cdot h} - \frac{U_r}{V_s + U_r} + \frac{A_s}{A_c} = 0 \qquad \textit{eq. A-4}$$

$$U_r = 0.60 \text{ m/s}$$

$$Z = \alpha \frac{(V_s + U_r)^2}{2 \cdot g} - \frac{V_s^2}{2 \cdot g} \qquad Z = 1.1 \cdot \frac{(4.34 + 0.60)^2}{2 \cdot 9.81} - \frac{4.34^2}{2 \cdot 9.81} = 0.41 \text{ m} \qquad \textit{eq. A-5}$$

The additional parameters of the non-free primary wave are:

h = 5.8 [m]	The water depth in the main channel
L = 270 [m]	The wave length is equal to the length of the vessel
c = 4.34 [m/s]	The wave speed is equal to the speed of the vessel
T = 62 [s]	The wave period
k = 0.023 [m^{-1}]	The wave number is based on the wave length, see Equation A-8

The primary wave characteristics for a free wave are based on the dispersion theory. Using this theory, the wave parameters are calculated with the equations for arbitrary depth.

$$L = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi h}{L}\right) \qquad \textit{eq. A-6}$$

$$c = \sqrt{\frac{g}{k}\tanh(kh)} \qquad \textit{eq. A-7}$$

$$k = \frac{2\pi}{L} \qquad \textit{eq. A-8}$$

h = 5.8 [m]	The water depth in the main channel
T = 62 [s]	The wave period is equal to the wave period of a non-free wave
L = 474 [m]	Using the dispersion relationship and Equation A-6 the wave length for the free wave is calculated using iteration
c = 7.56 [m/s]	The wave speed is calculated using Equation A-7 of which the wave number is calculated using Equation A-8
k = 0.013 [m^{-1}]	The wave number is based on the wave length, see Equation A-8

Secondary wave

The height of the secondary wave depends on the vessel velocity (as determined above), cross section of the channel and shape of the ship. The secondary waves consist of two types; the diverging wave and the transverse wave. These waves meet at the so-called cusps line, the occurring wave height at this location can be determined with the empirical relation below.

$$H = 1{,}2 \cdot \alpha \cdot h_0 \cdot \left(\frac{\gamma_s}{h_0}\right)^{-0{,}33} \cdot \left(\frac{V_s}{\sqrt{gh}}\right)^4 \qquad \textit{eq. A-9}$$

$$H = 1{,}2 \cdot 0{,}85 \cdot 5{,}8 \cdot \left(\frac{125}{5{,}8}\right)^{-0{,}33} \cdot \left(\frac{4{,}34}{\sqrt{9{,}81 \cdot 5{,}8}}\right)^4 = 0{,}23 \text{ m}$$

The wave length is determined using empirical formulas from (WL | Delft Hydraulics, 1998):

$$L = \tfrac{2}{3} \cdot 2\pi \cdot \tfrac{V_s^2}{g} \qquad L = \tfrac{2}{3} \cdot 2\pi \cdot \tfrac{4.34^2}{9.81} = 8.04 \text{ m} \qquad \textit{eq. A-10}$$

$$c = \sqrt{\frac{g}{k}\tanh(kh)} \qquad c = \sqrt{\frac{9.81}{0.78}\tanh(0.78 \cdot 5.8)} = 3.54 \text{ m/s} \qquad \textit{eq. A-11}$$

$$T = \frac{L}{c} \qquad T = \frac{8.04}{3.54} = 2.27 \text{ s} \qquad \textit{eq. A-12}$$

T = 2.27 [s]	The wave period is calculated using the dispersion theory, see Equation A-12
k = 0.78 [m^{-1}]	The wave number is based on the wave length, see Equation A-8

A.2 Water level points of mesh dependency study

The part of the grid dependency study in Section 4.5.1 of the main report discusses the effect of grid size on a river flow with complex geometry. The water level fluctuations before and after spin-up time are and the effect on grid size are discussed partly using the figures displayed in this appendix. The water level of the measuring points displayed here are specified in Figure 10 of the main report. Figure A-2 shows point 1 (red), Figure A-3 shows point 2 (blue), and Figure A-4 shows point 3 (green). Each subplot in the figures containing the timeseries of the water level during the entire model run and a zoomed version visualizing the water level after spin-up time.

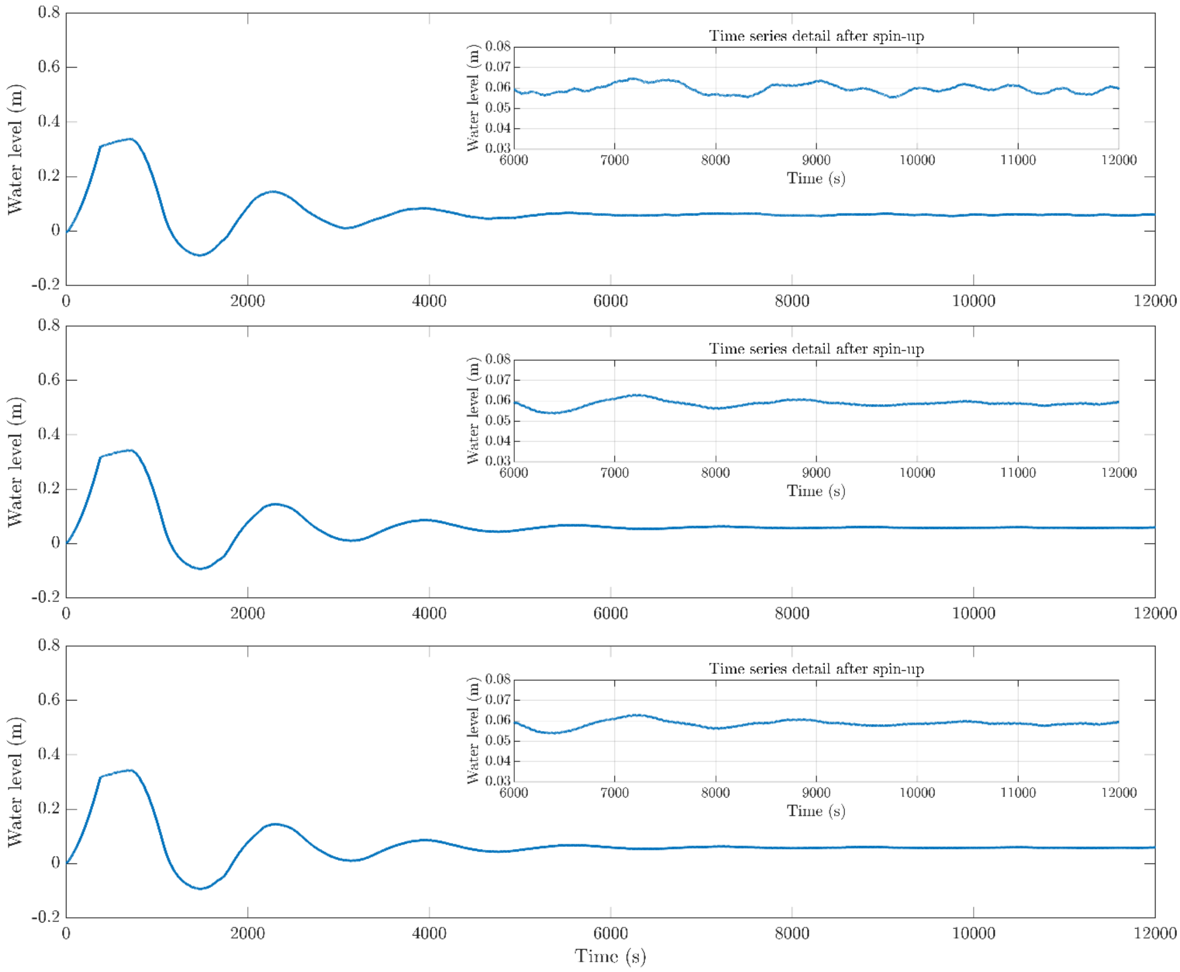


Figure A-2: Water level point 1 of grid dependency. Top is 2.5x2.5 grid size, middle is 5x5 grid size and bottom is 10x10 grid size.

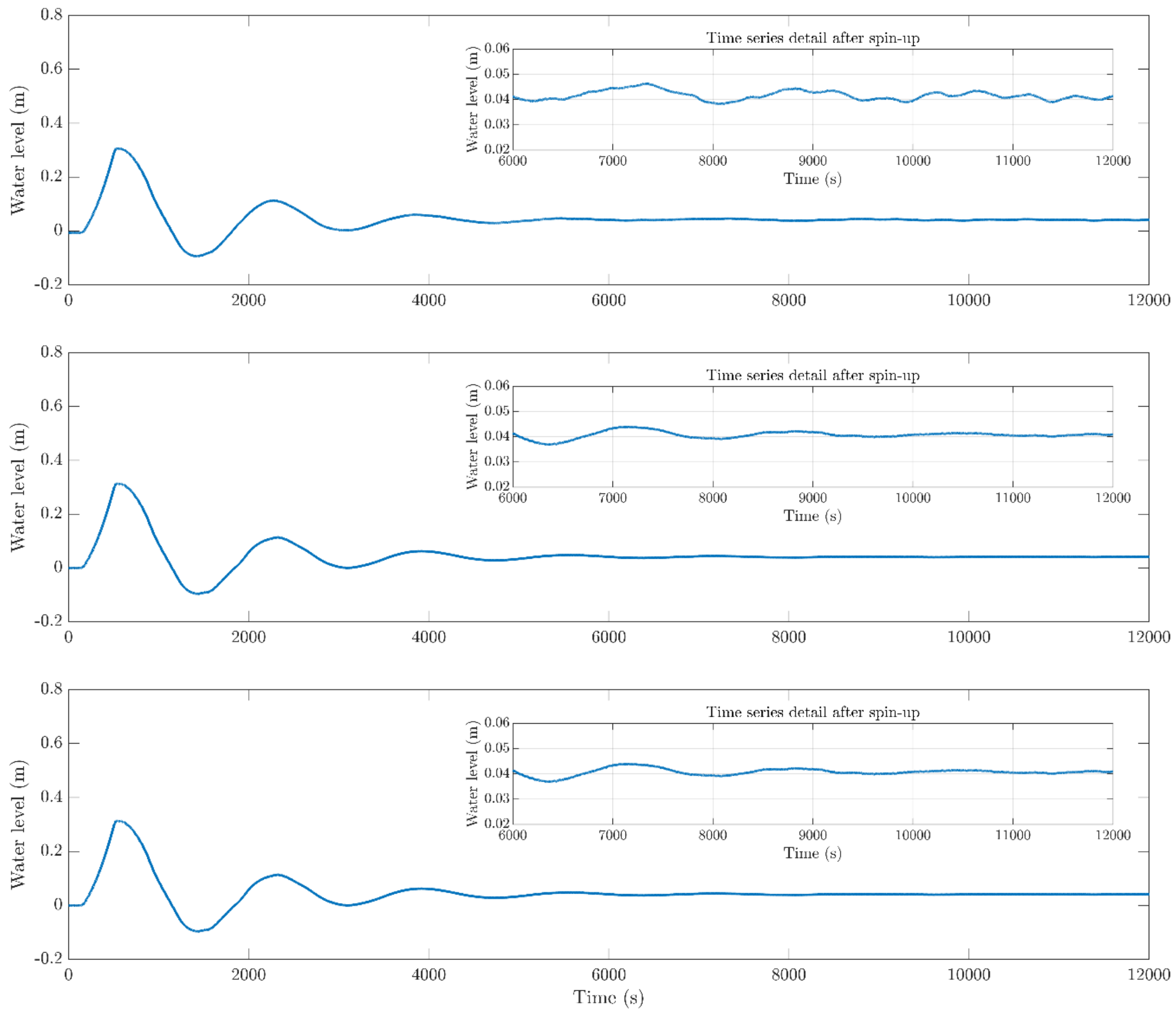


Figure A-3: Water level point 2 of grid dependency study. Top is 2.5x2.5 grid size, middle is 5x5 grid size and bottom is 10x10 grid size

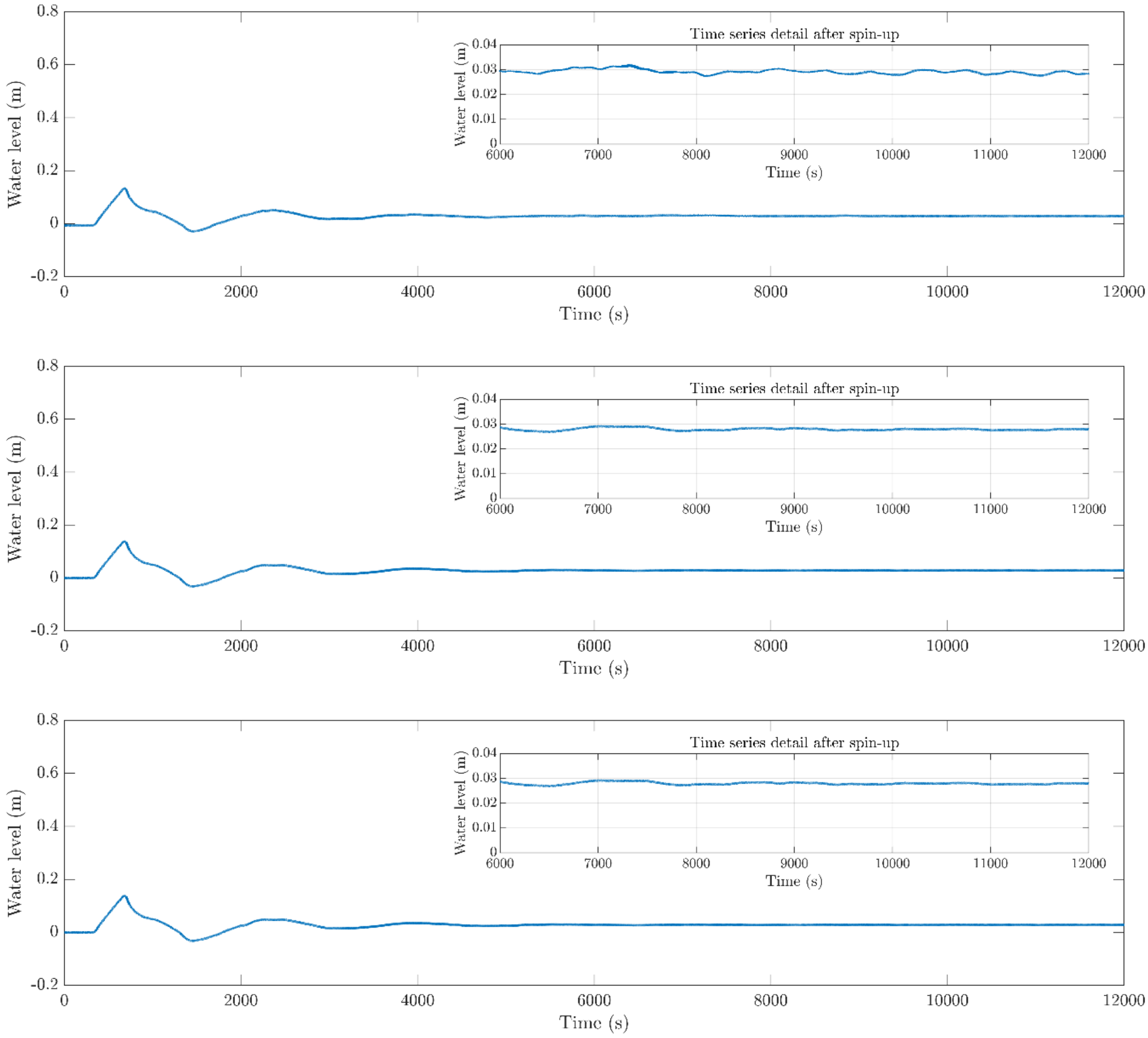


Figure A-4: Water level point 3 of grid dependency study. Top is 2.5x2.5 grid size, middle is 5x5 grid size and bottom is 10x10 grid size.

A.3 Grid points

The part of the grid dependency study in Section 4.5.2 of the main report discusses the effect of grid size on the ship-induced waves signals. Figure 14 in the main report displays the water level and velocity signals of point 1, a stationary point located in the main channel. Two other points mentioned in this section are stationary points located closer to the river banks and displayed below, point 2 (red) in Figure A-5 and point 3 (orange) in Figure A-6.

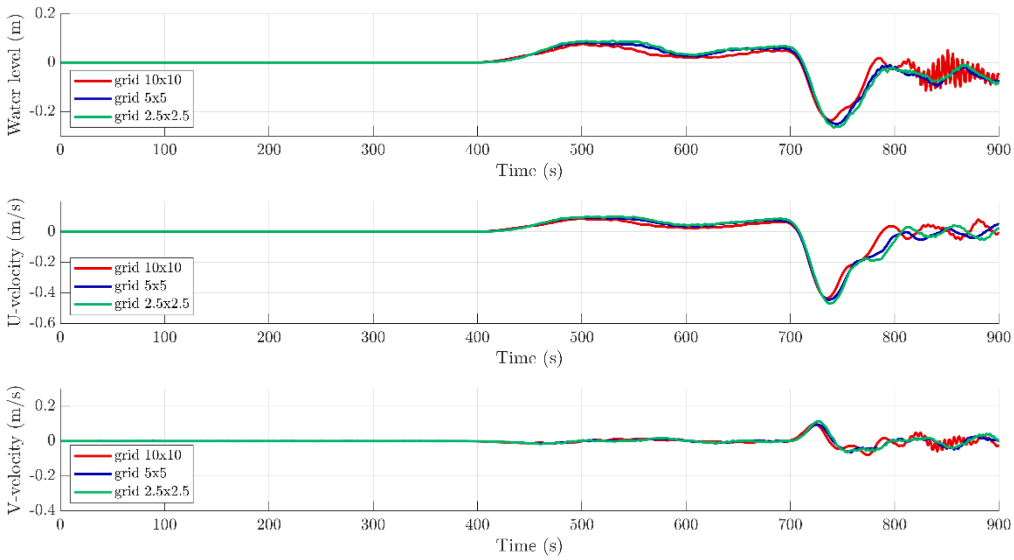


Figure A-5: Signals of ship passing in point 2 (red) for various grid sizes. Top plot shows the water level signal, the middle plot shows the longitudinal velocity vector (u-velocity), and the bottom plot shows the lateral velocity vector (v-velocity).

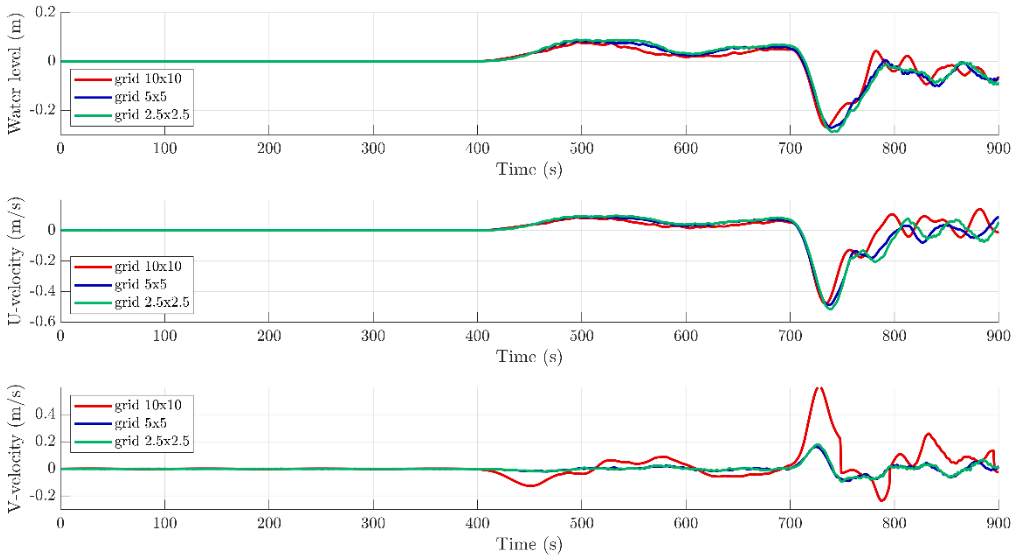


Figure A-6: Signals of ship passing in point 3 (orange) for various grid sizes. Top plot shows the water level signal, the middle plot shows the longitudinal velocity vector (u-velocity), and the bottom plot shows the lateral velocity vector (v-velocity).

B Boxplots

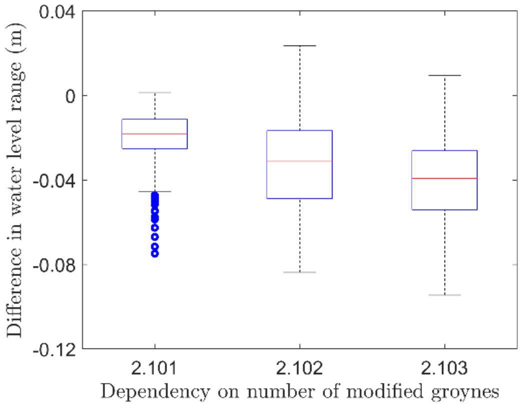
This appendix consists of 3 sections. Each section displays the boxplots for a different groyne modification. Section B.1 displays the boxplots for the optimisation study for the notched groynes. These consist out of the dependency on: number of modified groynes. Location, width, depth, shape, and number of notches. Section B.2 displays the boxplots for the optimisation study for the L-shaped groyne. Section B.3 shows the boxplots of different situations of the conceptual design which are: the optimal notch geometry layout, the optimal geometry layout with high water, the optimal geometry layout with a smaller vessel and the optimal geometry with a side channel.

A boxplot is a method to display a set of data using a five-number summery with outliers. The five numbers are the minimum, first quartile, median, third quartile and maximum of a data set. The outliers are extreme values which don't seem to fit in the distribution, they have a numerical value larger than 1.5 times the width of the "box" (distance between first and third quartile). A negative value of the difference in water level range and velocity range in the boxplot means a positive effect on the fauna habitat.

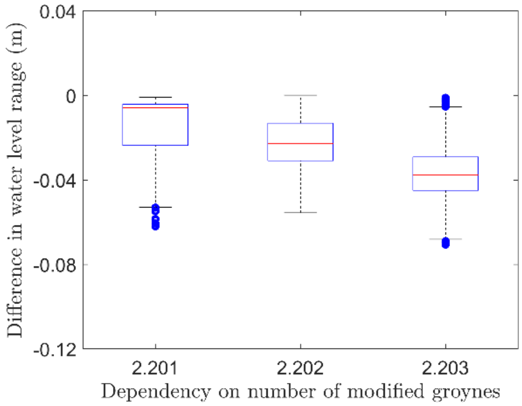
B.1 Results of the optimisation study for groynes with notches

Dependency on number of modified groynes				
Run number	**Number of modified groynes**	**Location of notch [m]**	**Width notch [m]**	**Depth notch [m]**
2.101 / 2.201	1	32.5	15	1.0
2.102 / 2.202	2	32.5	15	1.5
2.103 / 2.203	all	32.5	15	2.0

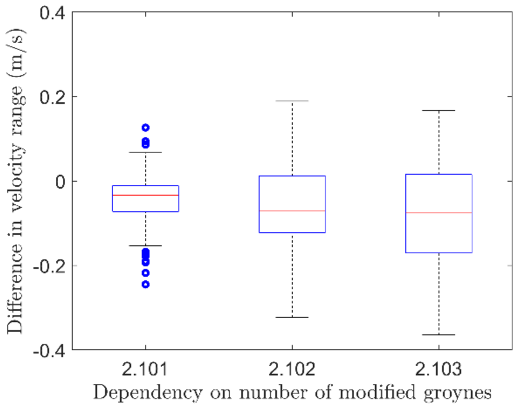
Water level range upstream sailing vessels



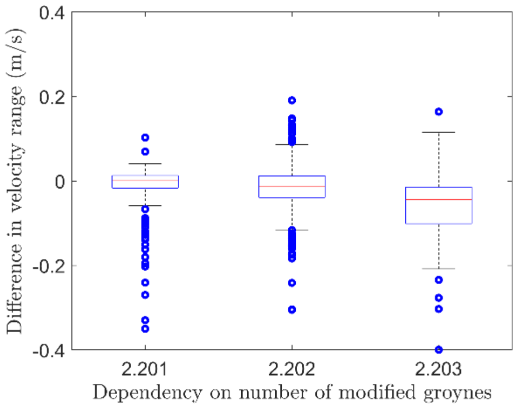
Water level range downstream sailing vessel



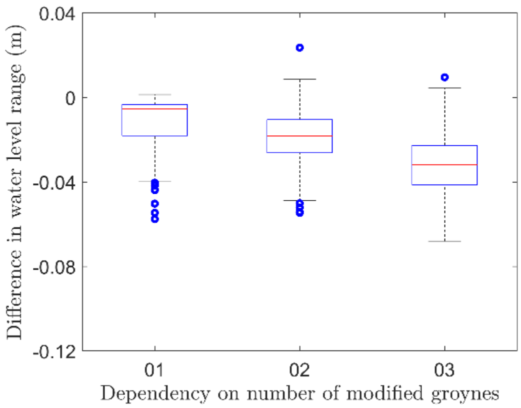
Velocity range upstream sailing vessels



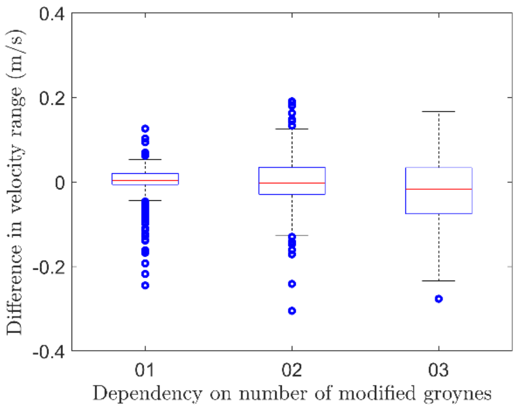
Velocity range downstream sailing vessels



Combined boxplot water level range

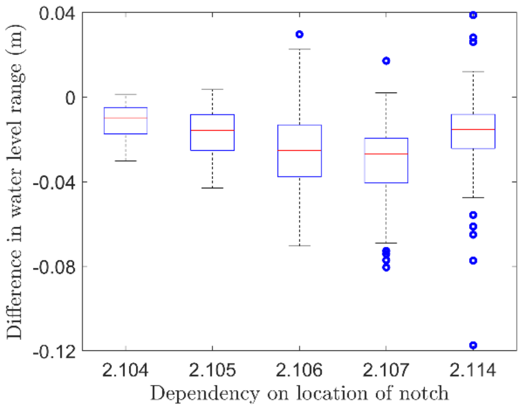


Combined boxplot velocity range

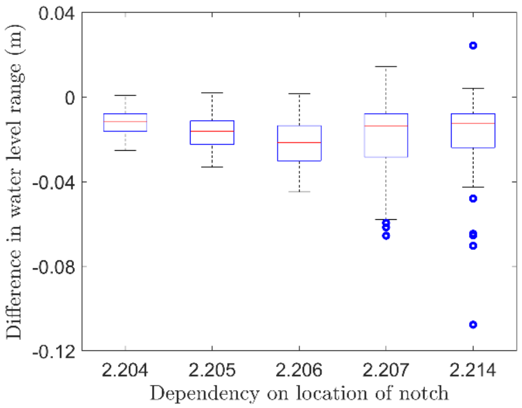


Location dependency				
Run number	**Number of notches**	**Location of notch [m]**	**Width notch [m]**	**Depth notch [m]**
2.104 / 2.204	1	15	10	1.0
2.105 / 2.205	1	25	10	1.0
2.106 / 2.206	1	35	10	1.0
2.107 / 2.207	1	45	10	1.0
2.114 / 2.214	1	55	10	1.0

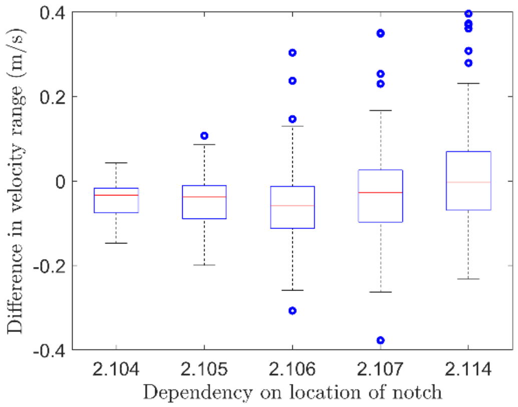
Water level range upstream sailing vessels



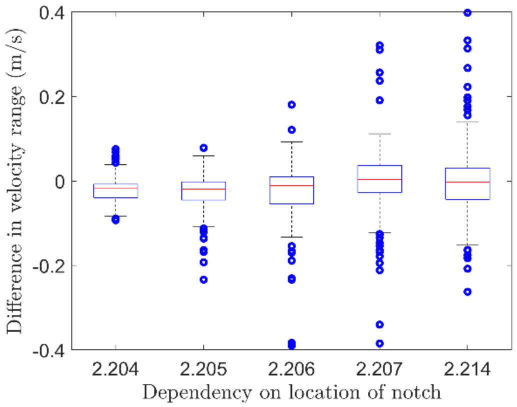
Water level range downstream sailing vessel



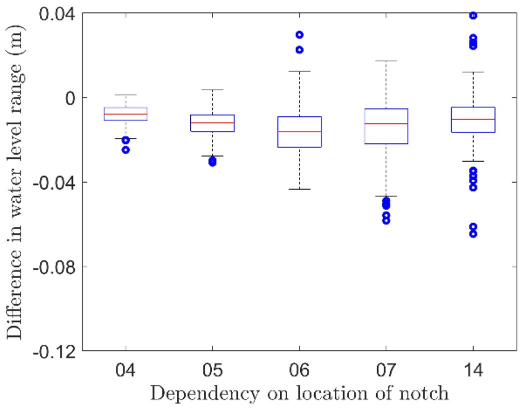
Velocity range upstream sailing vessels



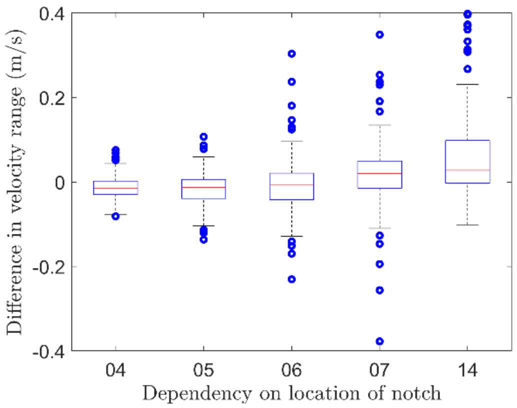
Velocity range downstream sailing vessels



Combined boxplot water level range

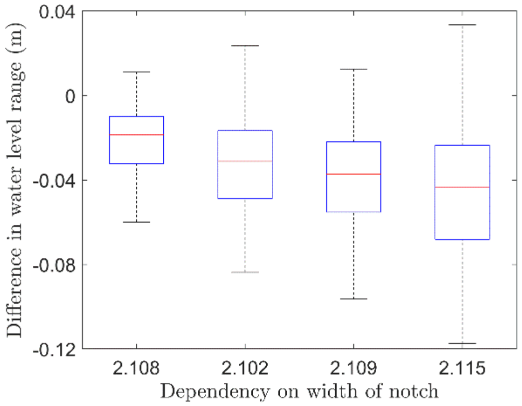


Combined boxplot velocity range

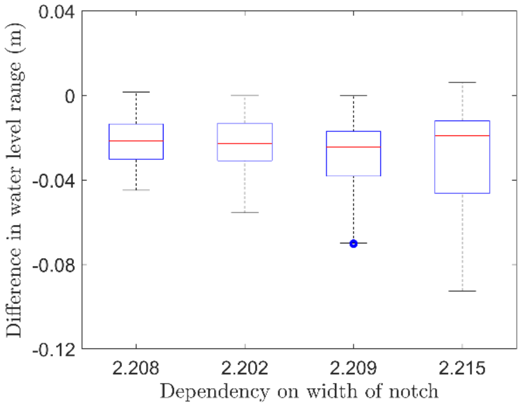


Width dependency				
Run number	**Number of notches**	**Location of notch [m]**	**Width notch [m]**	**Depth notch [m]**
2.108 / 2.208	1	30	10	1
2.102 / 2.202	1	30	15	1
2.109 / 2.209	1	30	20	1
2.115 / 2.215	1	30	30	1

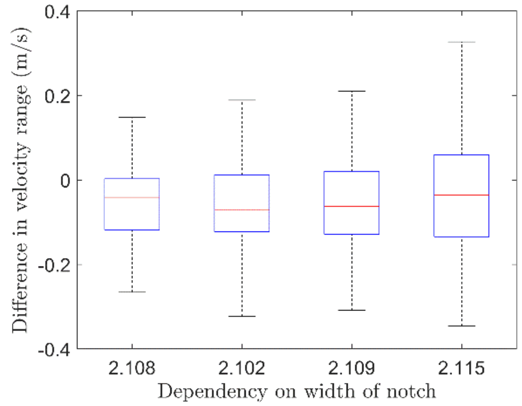
Water level range upstream sailing vessels



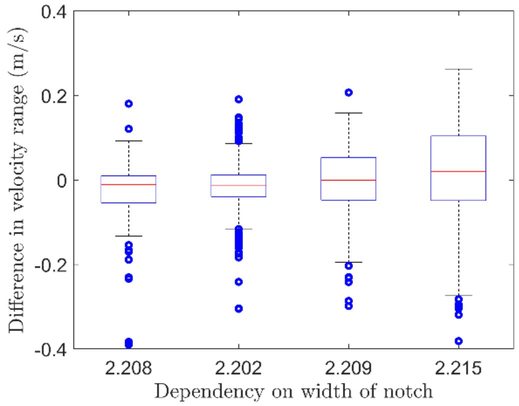
Water level range downstream sailing vessel



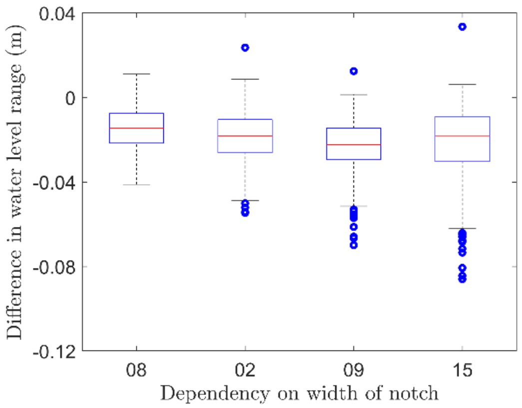
Velocity range upstream sailing vessels



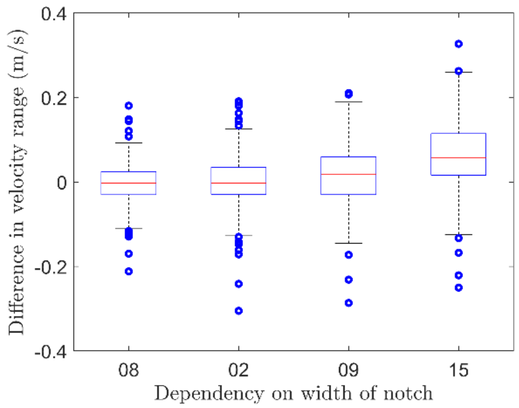
Velocity range downstream sailing vessels



Combined boxplot water level range

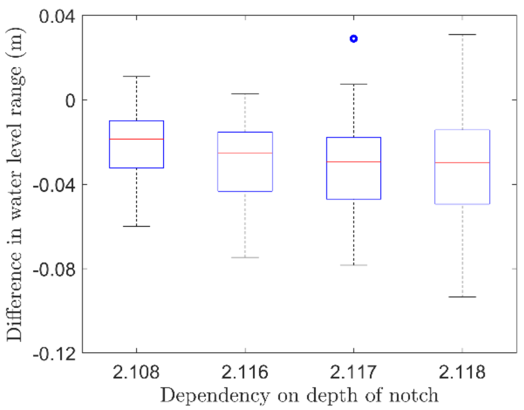


Combined boxplot velocity range

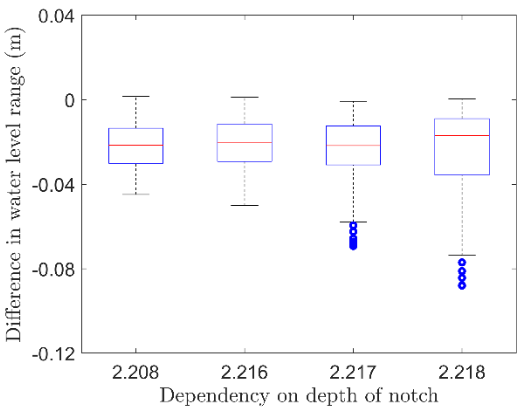


Depth dependency				
Run number	**Number of notches**	**Location of notch [m]**	**Width notch [m]**	**Depth notch [m]**
2.108 / 2.208	1	30	10	1.0
2.116 / 2.216	1	30	10	1.5
2.117 / 2.217	1	30	10	2.0
2.118 / 2.218	1	30	10	3.0

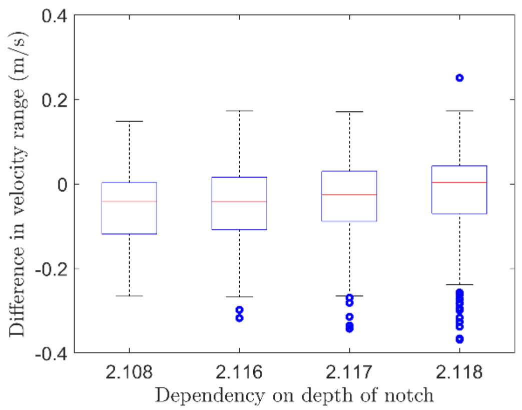
Water level range upstream sailing vessels



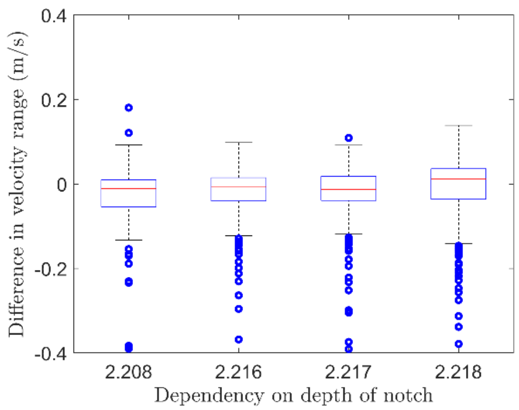
Water level range downstream sailing vessel



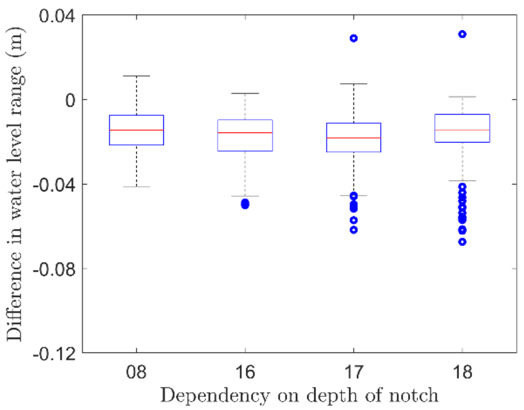
Velocity range upstream sailing vessels



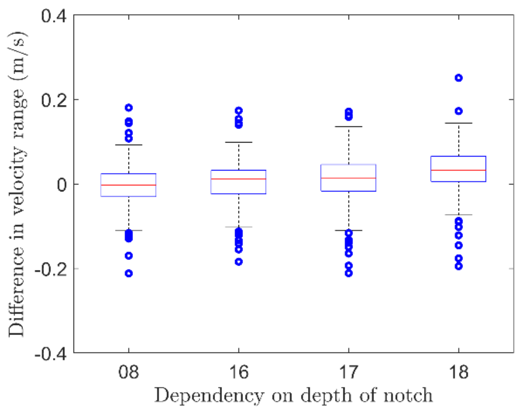
Velocity range downstream sailing vessels



Combined boxplot water level range

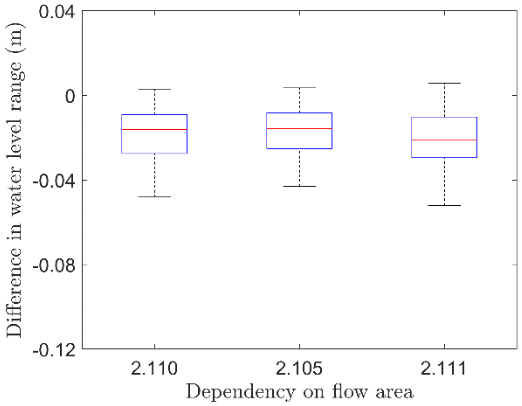


Combined boxplot velocity range

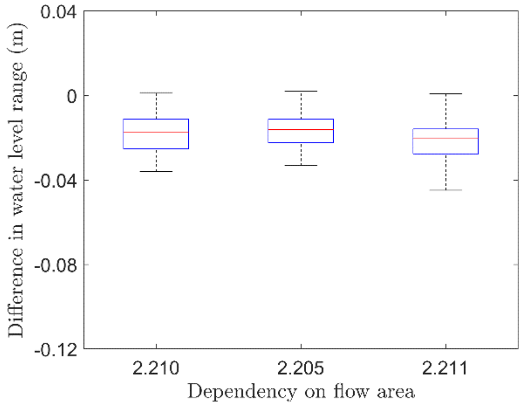


Shape dependency				
Run number	**Number of notches**	**Location of notch [m]**	**Width notch [m]**	**Depth notch [m]**
2.110 / 2.210	1	27.5	5	2.0
2.105 / 2.205	1	25	10	1.0
2.111 / 2.211	1	27.5	15	0.67

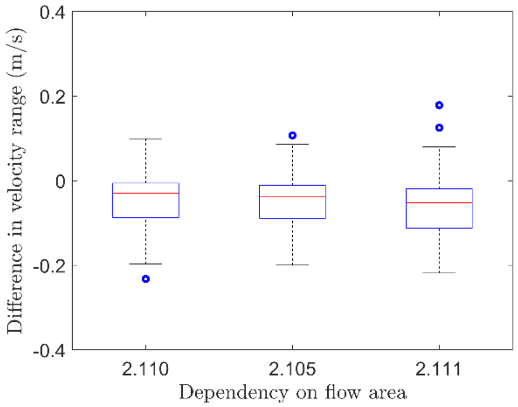
Water level range upstream sailing vessels



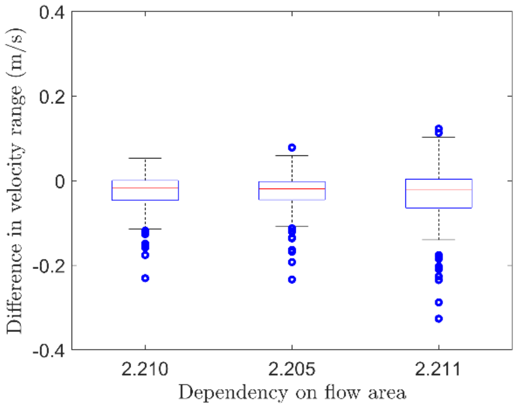
Water level range downstream sailing vessel



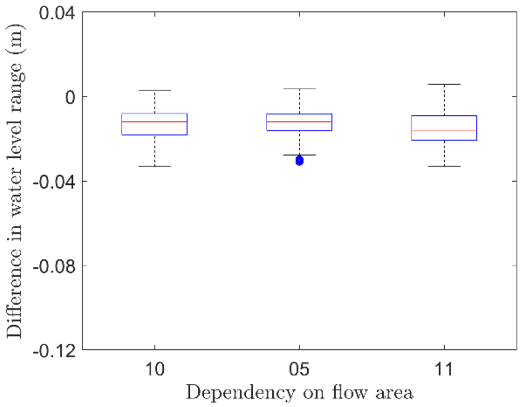
Velocity range upstream sailing vessels



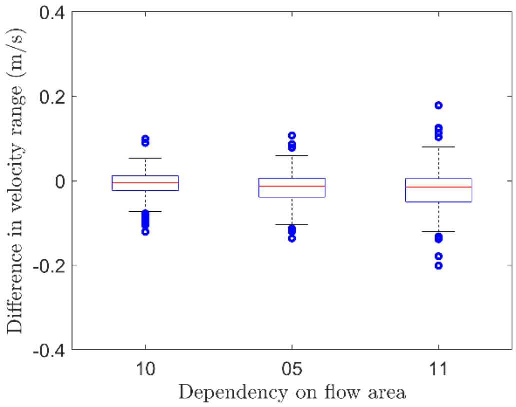
Velocity range downstream sailing vessels



Combined boxplot water level range

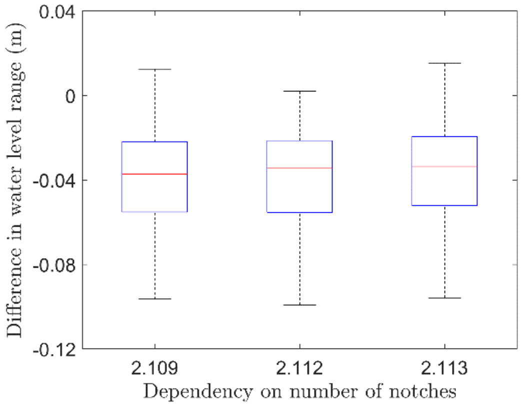


Combined boxplot velocity range

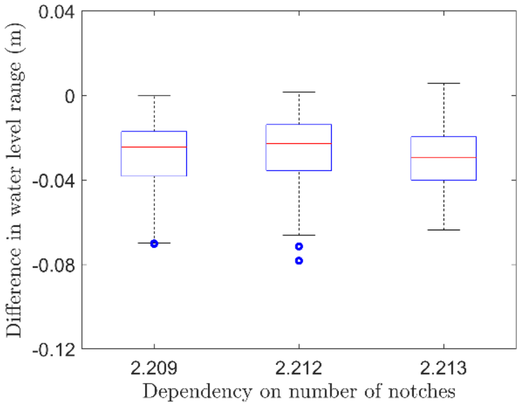


Dependency on number of notches				
Run number	**Number of notches**	**Location of notch [m]**	**Width notch [m]**	**Depth notch [m]**
2.109 / 2.209	1	30	20	1.0
2.112 / 2.212	2	15 / 35	10	1.0
2.113 / 2.213	4	15 / 25 / 35 / 45	5	1.0

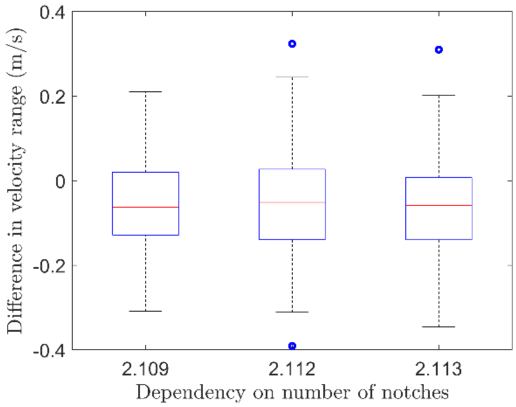
Water level range upstream sailing vessels



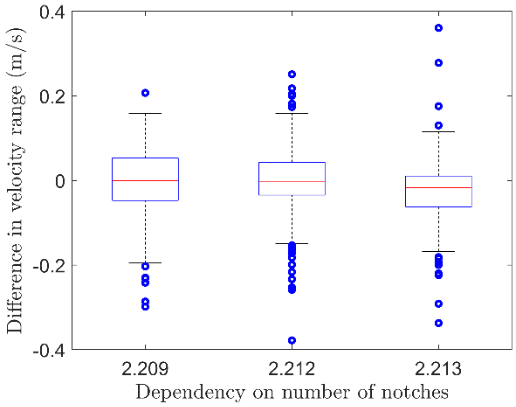
Water level range downstream sailing vessel



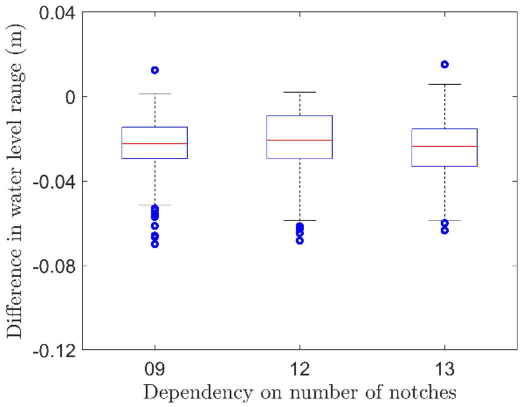
Velocity range upstream sailing vessels



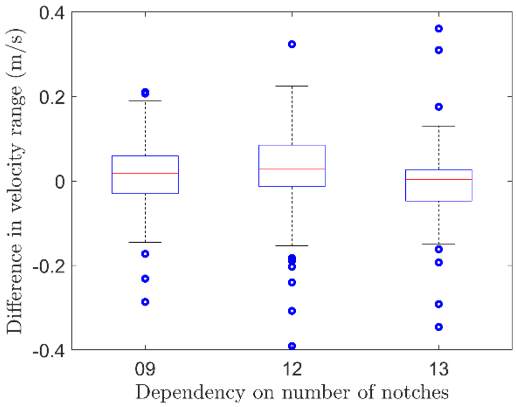
Velocity range downstream sailing vessels



Combined boxplot water level range



Combined boxplot velocity range

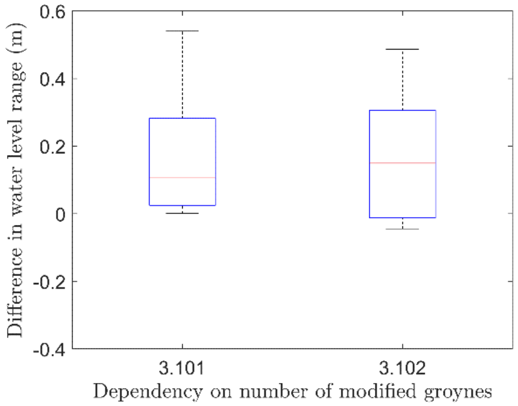


B.2 Results of the optimisation study for L-shaped groynes

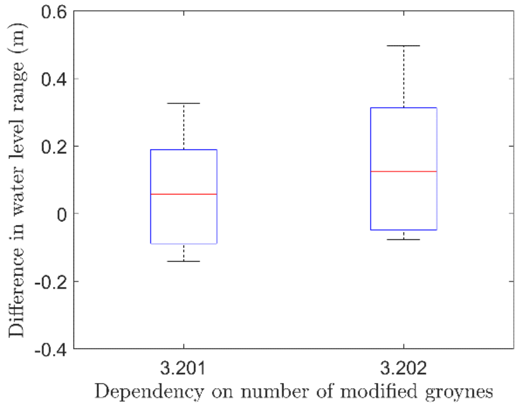
Dependency on number of L-shaped groynes

Run number	Number of L-shaped groynes	Length of branch L-groyne
3.101 / 3.201	1	100 m
3.102 / 3.202	2	100 m

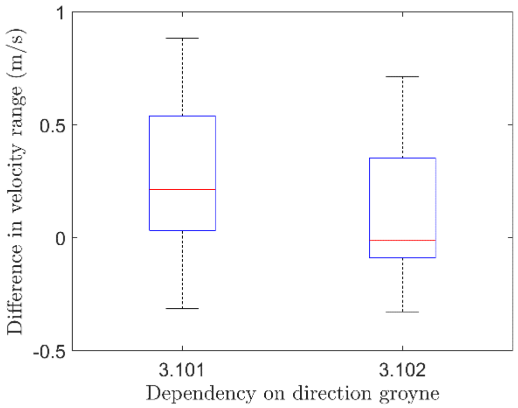
A) Water level range upstream sailing vessels



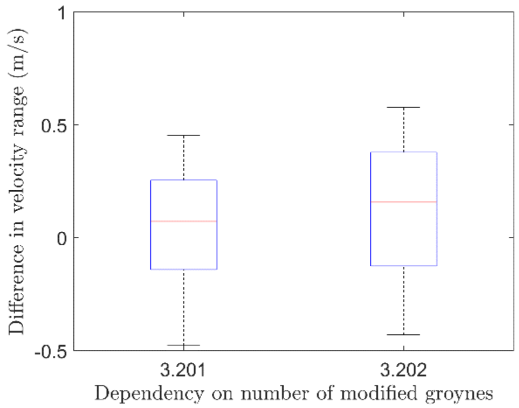
B) Water level range downstream sailing vessel



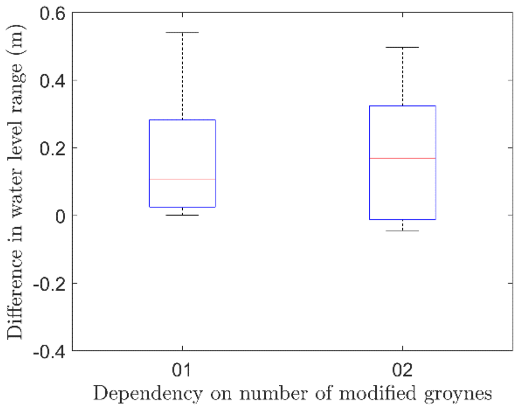
C) Velocity range upstream sailing vessels



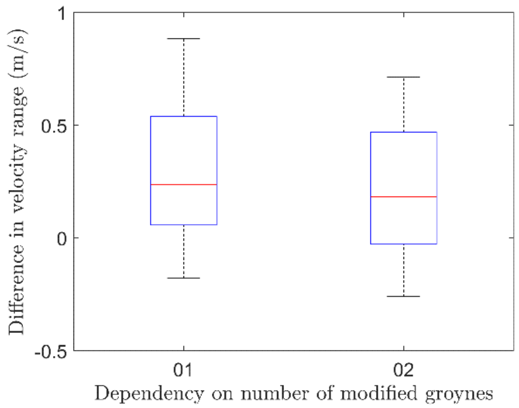
D) Velocity range downstream sailing vessels



E) Combined boxplot water level range

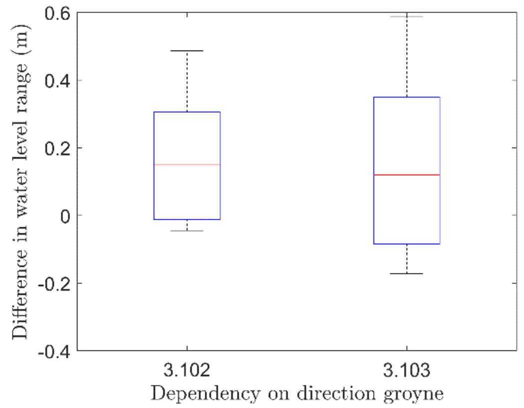


F) Combined boxplot velocity range

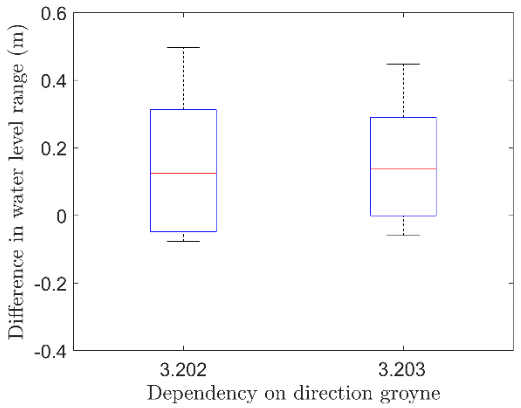


Dependency on direction of L-shaped groynes		
Run number	**Direction of L-shaped groynes**	**Length of branch L-groyne**
3.102 / 3.202	Downstream	100 m
3.103 / 3.203	Upstream	100 m

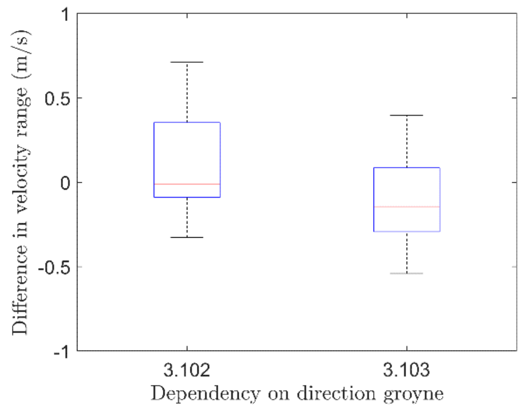
A) Water level range upstream sailing vessels



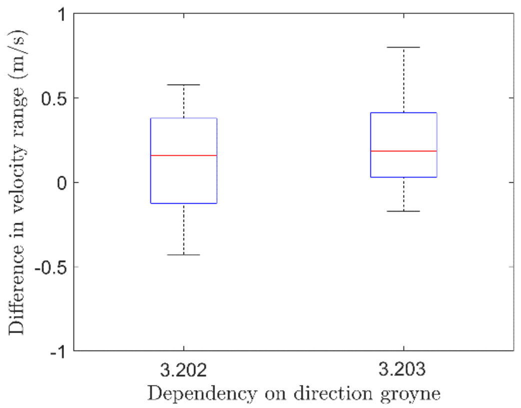
B) Water level range downstream sailing vessel



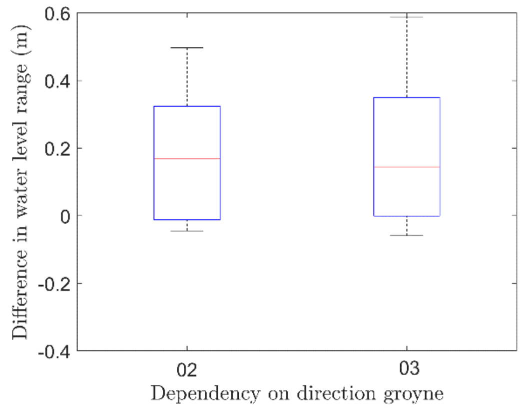
C) Velocity range upstream sailing vessels



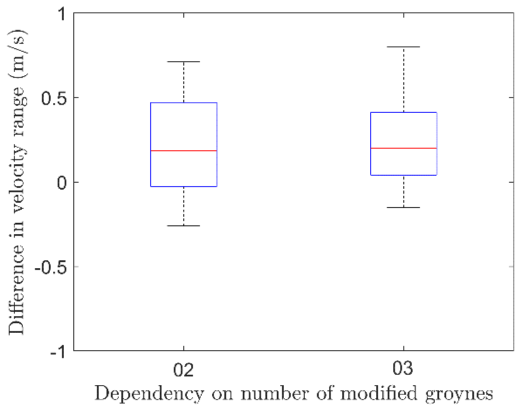
D) Velocity range downstream sailing vessels



E) Combined boxplot water level range

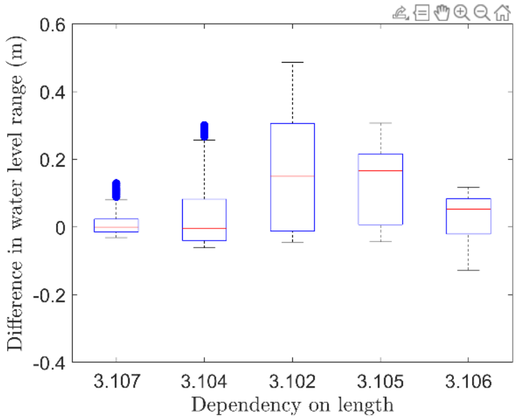


F) Combined boxplot velocity range

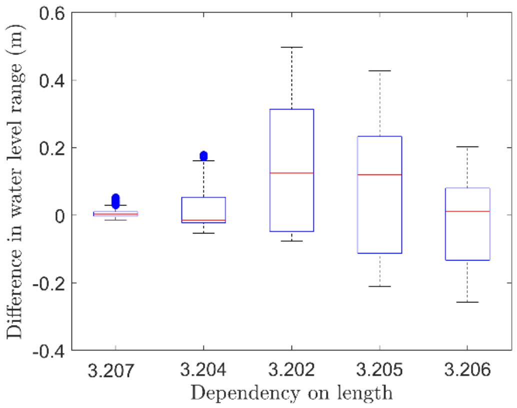


Dependency length of branch L-groyne	
Run number	**Length of branch L-groyne**
3.107 / 3.207	25 m
3.104 / 3.204	50 m
3.102 / 3.202	100 m
3.105 / 3.205	150 m
3.106 / 3.206	175 m

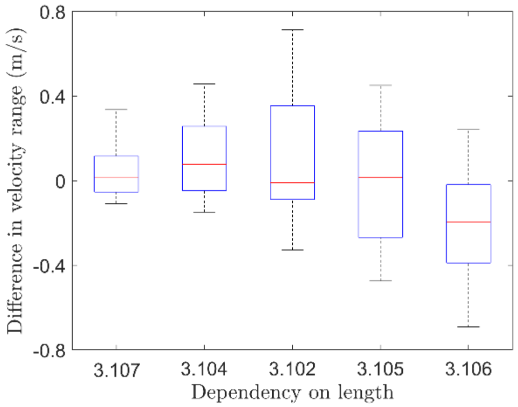
A) Water level range upstream sailing vessels



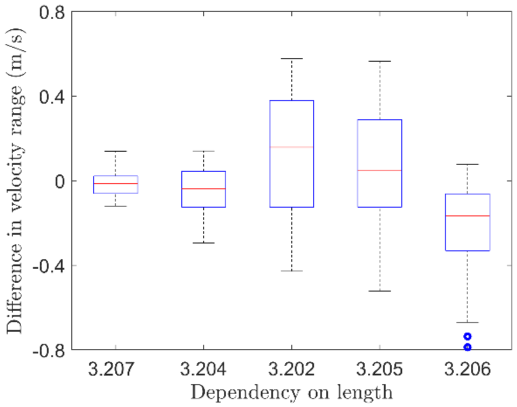
B) Water level range downstream sailing vessel



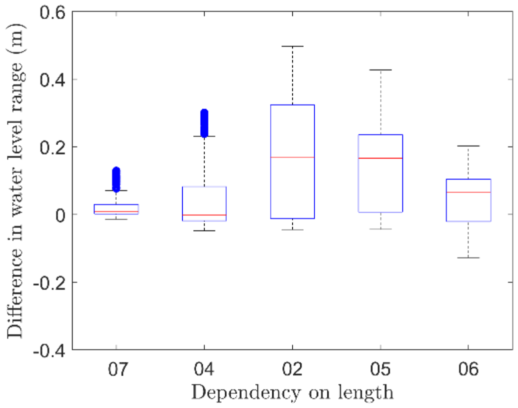
C) Velocity range upstream sailing vessels



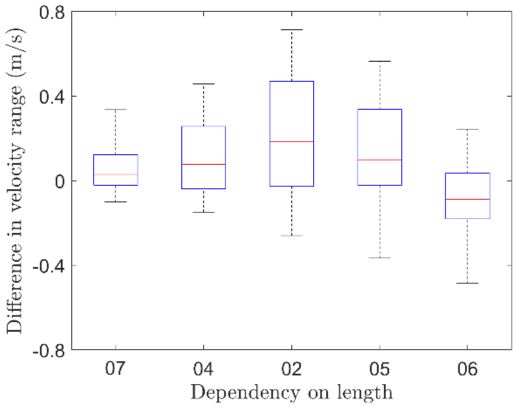
D) Velocity range downstream sailing vessels



E) Combined boxplot water level range



F) Combined boxplot velocity range

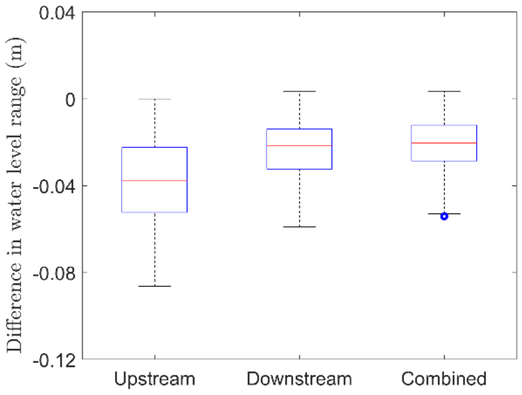


B.3 Results of the conceptual design study

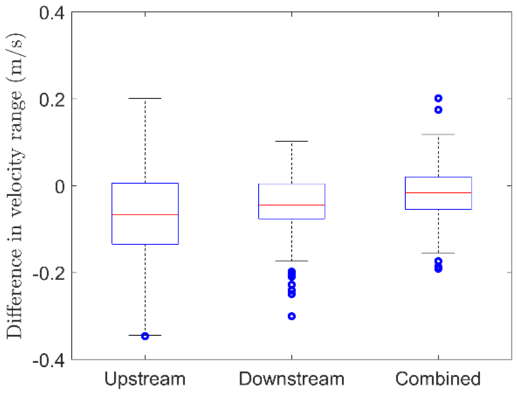
Additional study

Run number	**Alternative**
4.101 / 4.201	Optimal design
4.102 / 4.202	High water
4.104 / 4.204	Small vessel

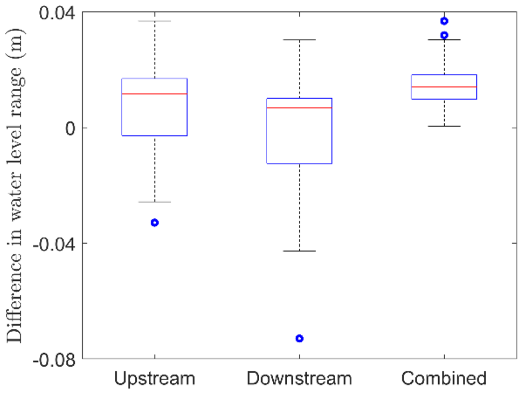
A) Water level range optimal design



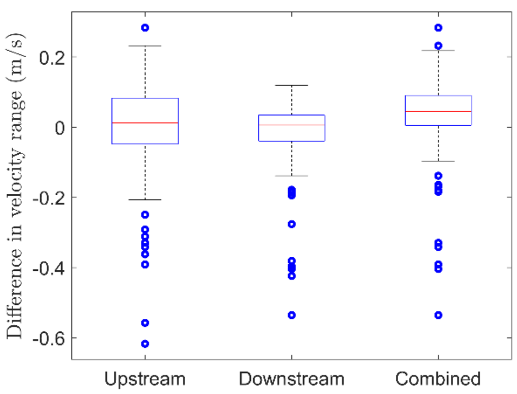
B) Velocity range optimal design



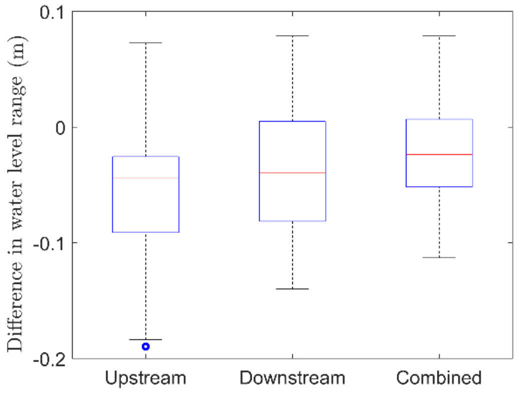
C) Water level range high water



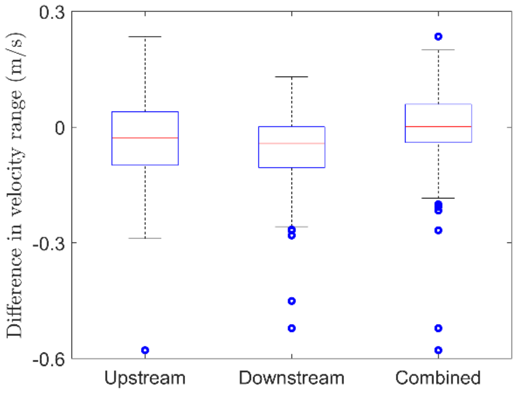
D) Velocity range high water



E) Water level range small vessel

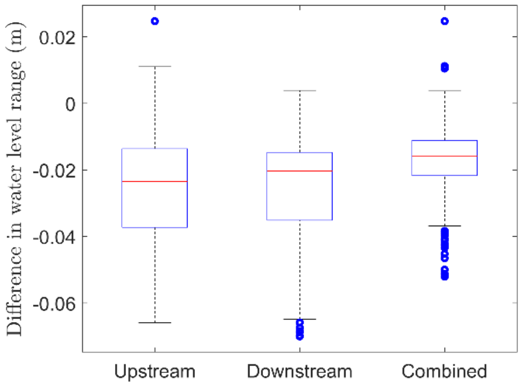


F) Velocity range small vessel

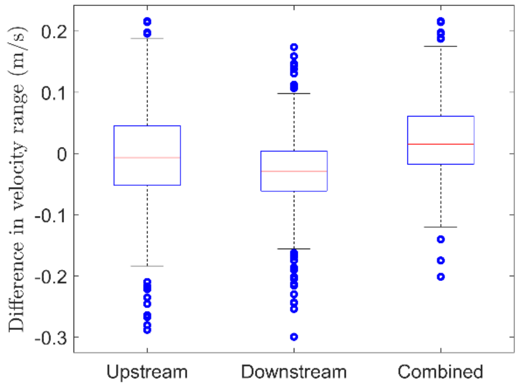


Additional study	
Run number	**Alternative**
4.106 / 4.206	Side channel

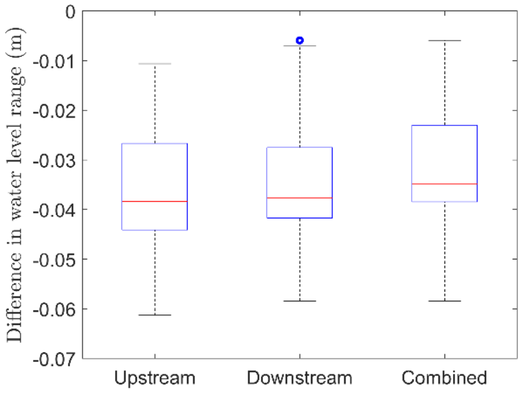
A) Water level range side channel area 1



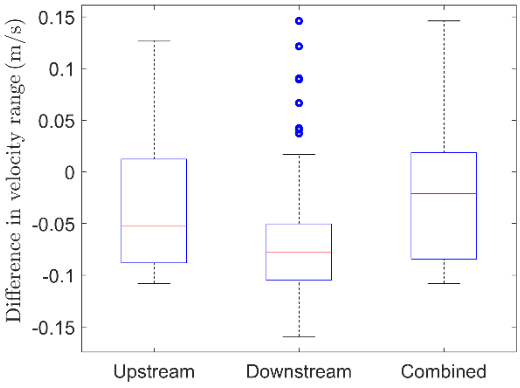
B) Velocity range side channel area 1



C) Water level range side channel area 2



D) Velocity range side channel area 2



C Results

This appendix consists of 3 Sections. Each section displays the results for a different groyne modification. Section C.1 displays the results for the groynes modified with notches, and Section C.2 shows the results for the L-shaped groynes. Section C.3 shows the results of the different situations of the conceptual design which are: the optimal notch geometry layout, the optimal geometry layout with high water, the optimal geometry layout with a smaller vessel, and the optimal geometry with a side channel. The results are displayed in a table as follows: at the top the run number and general groyne characteristics are depicted, below that information about the modification is given both textually and in figure. Further the table shows water level range plots and velocity range plots in the selected groyne field for upstream and downstream sailing vessels and a combination of both. These plots are structured as follows: the top plot shows the water level range or velocity range during ship passing for a normal design, called the reference model. The middle plot shows the water level range or velocity range during ship passing for a modified groyne and the plot at the bottom displays the difference in water level range or velocity range between the reference model and the modified model. The negative value in the difference plot (blue) has a positive influence on the quality of the fauna habitat.

Section C.1 starts below, section C.2 starts on page 172 and section C.3 starts on page 208.

C.1 Results of the groynes modified with notches

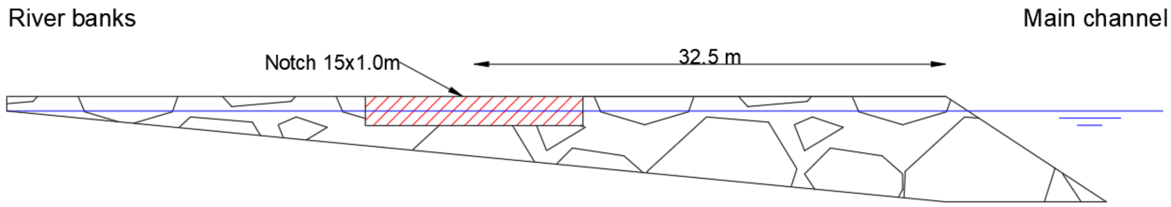
In the graph below an overview of the pages of the runs is given. The sixth cell called “used for dependency on” refers to the optimisation study, one run can be used for multiple dependency studies. In Section 5.3 the study is split up in 6 different notch characteristics to determine the dependency of the flow pattern in the groyne field on these characteristics. In this cell is displayed which run is used to determine the dependency on various characteristics.

Run number upstream / downstream	Number of notches	Location of notch from tip groyne [m]	Width notch [m]	Depth notch below water level [m]	Used for dependency on	Page number
2.101 / 2.201	1	32.5	15	1.0	Number of modified groynes	87
2.102 / 2.202	1	32.5	15	1.0	Number of modified groynes / Width	92
2.103 / 2.203	1	32.5	15	1.0	Number of modified groynes	97
2.104 / 2.204	1	15	10	1.0	Location	102
2.105 / 2.205	1	25	10	1.0	Location / Shape	107
2.106 / 2.206	1	35	10	1.0	Location	112
2.107 / 2.207	1	45	10	1.0	Location	117
2.108 / 2.208	1	30	10	1.0	Width / Depth	122
2.109 / 2.209	1	30	20	1.0	Width / Number of notches	127
2.110 / 2.210	1	27.5	5	2.0	Shape	132

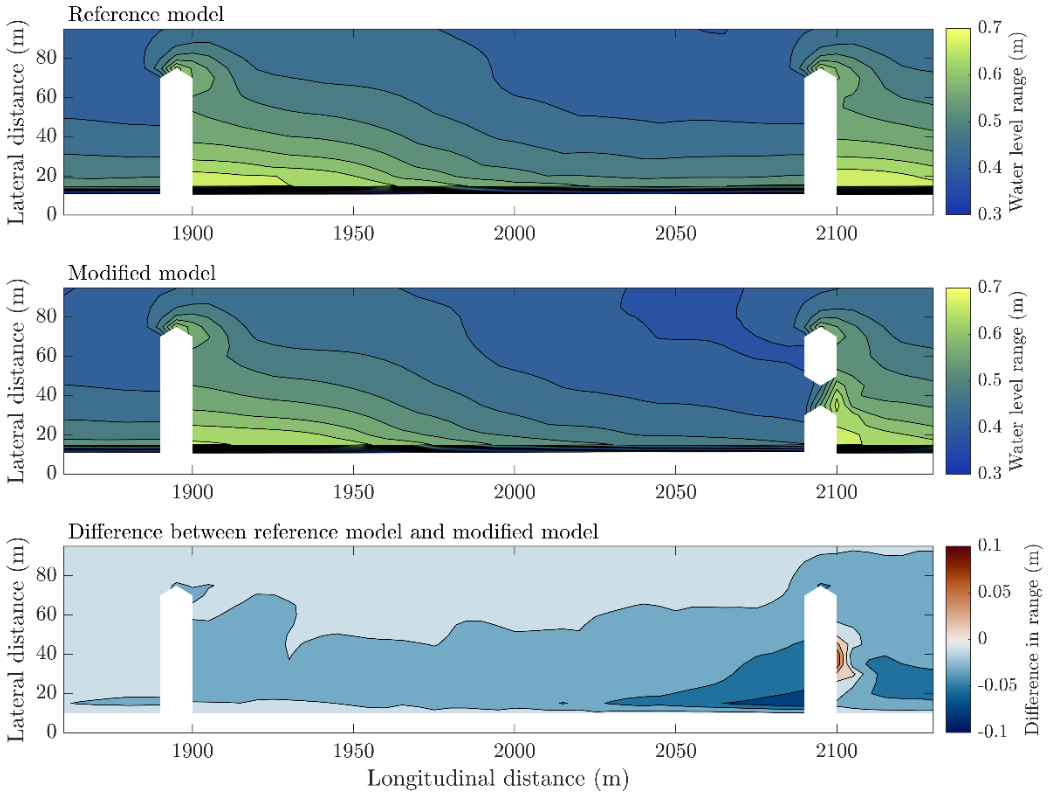
Run number upstream / downstream	Number of notches	Location of notch from tip groyne [m]	Width notch [m]	Depth notch below water level [m]	Used for dependency on	Page number
2.111 / 2.211	1	27.5	15	0.667	Shape	137
2.112 / 2.212	2	15/35	10	1.0	Number of notches	142
2.113 / 2.213	4	15/25/35/45	5	1.0	Number of notches	147
2.114 / 2.214	1	55	10	1.0	Location	152
2.115 / 2.215	1	30	30	1.0	Width	157
2.116 / 2.216	1	30	10	1.5	Depth	162
2.117 / 2.217	1	30	10	2.0	Depth	167
2.118 / 2.218	1	30	10	3.0	Depth	172

Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.101	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.201	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

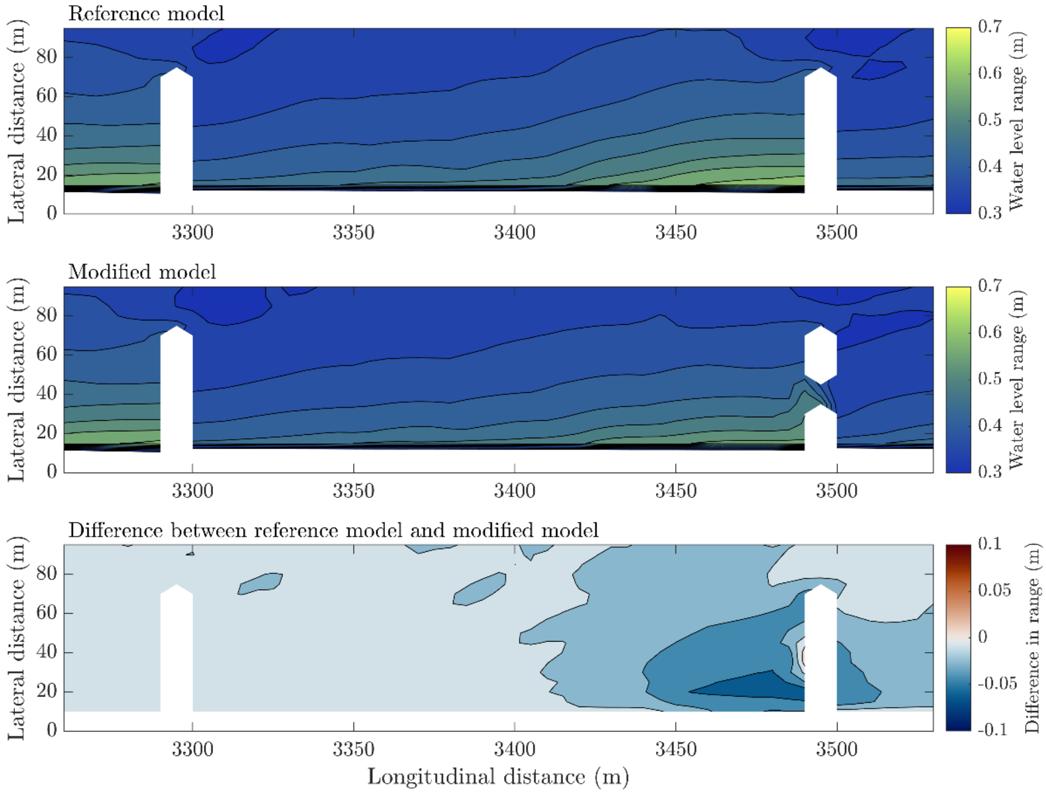
Number of notches	Location of notch	Width notch	Depth notch
1	32.5 m	15 m	1.0 m



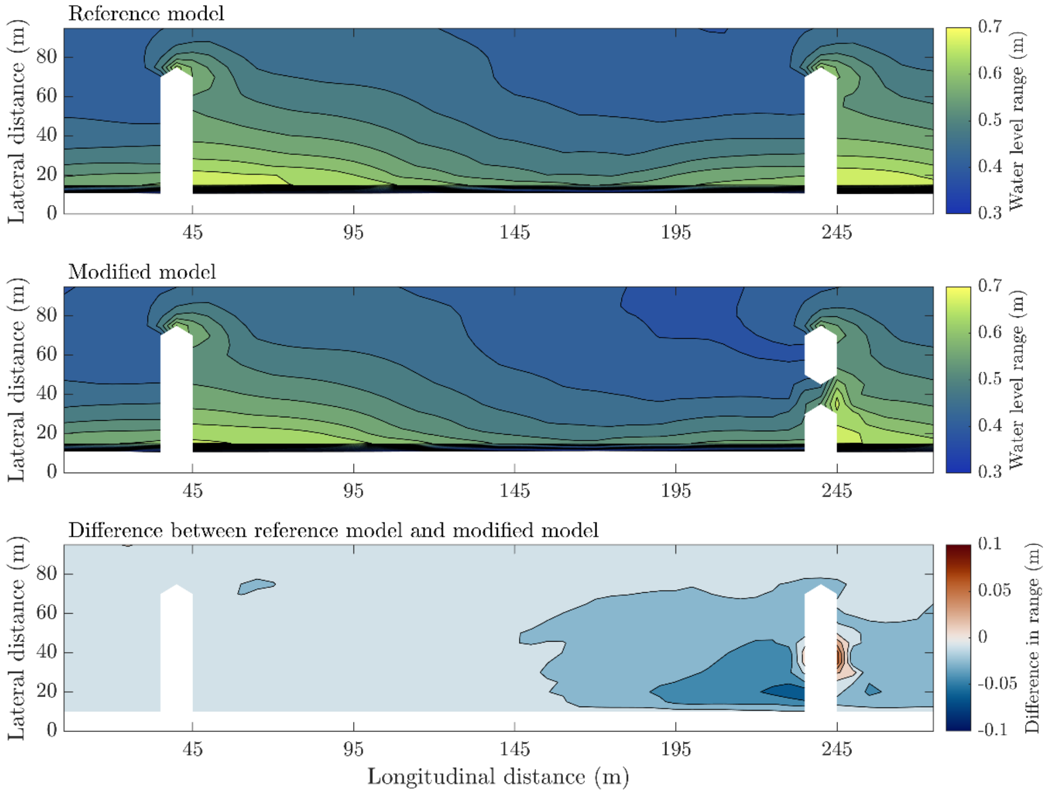
Water level range during upstream sailing



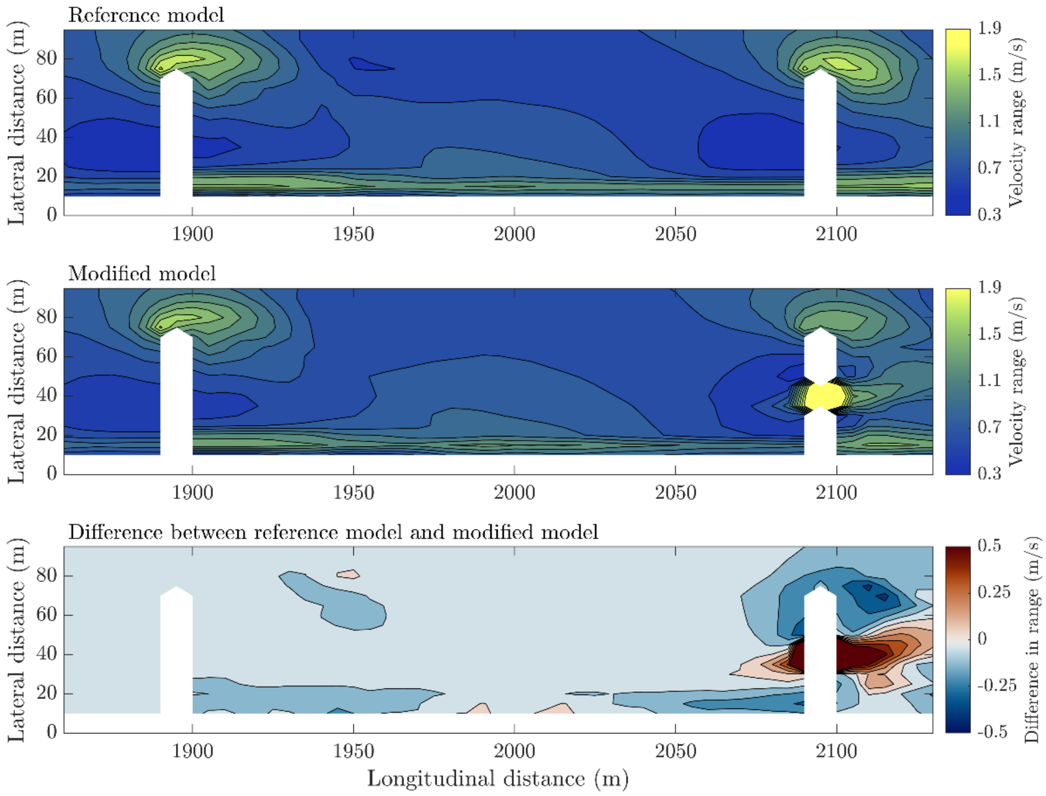
Water level range during downstream sailing



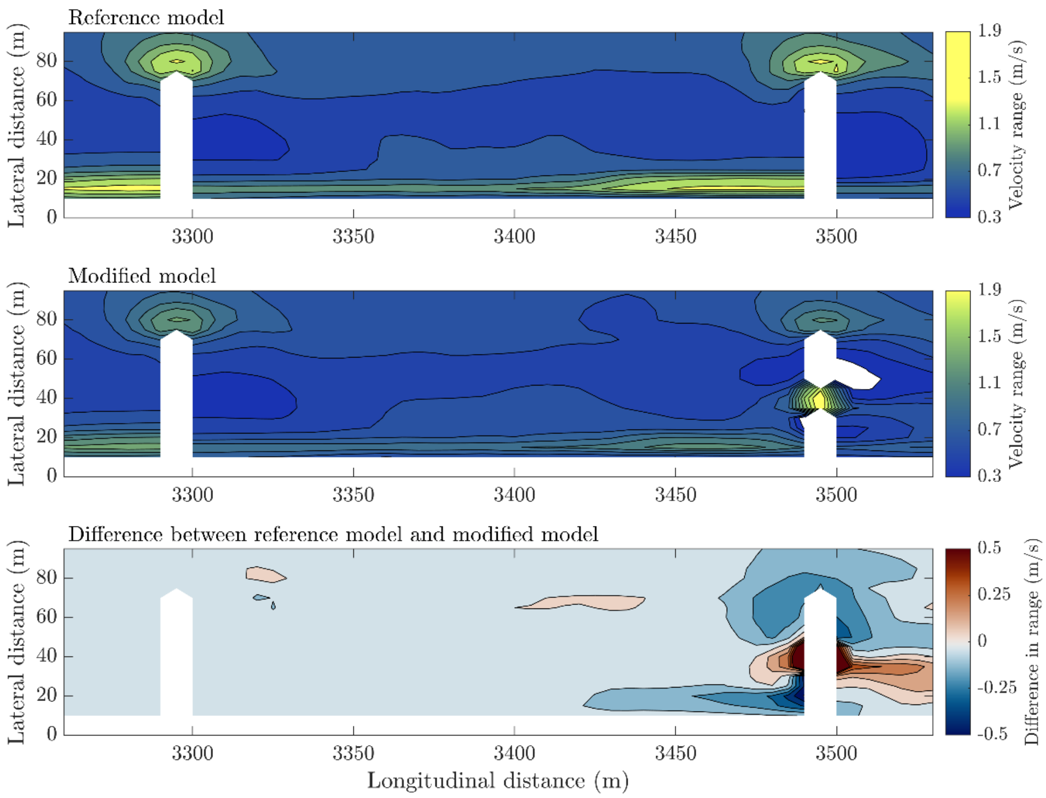
Combined water level range



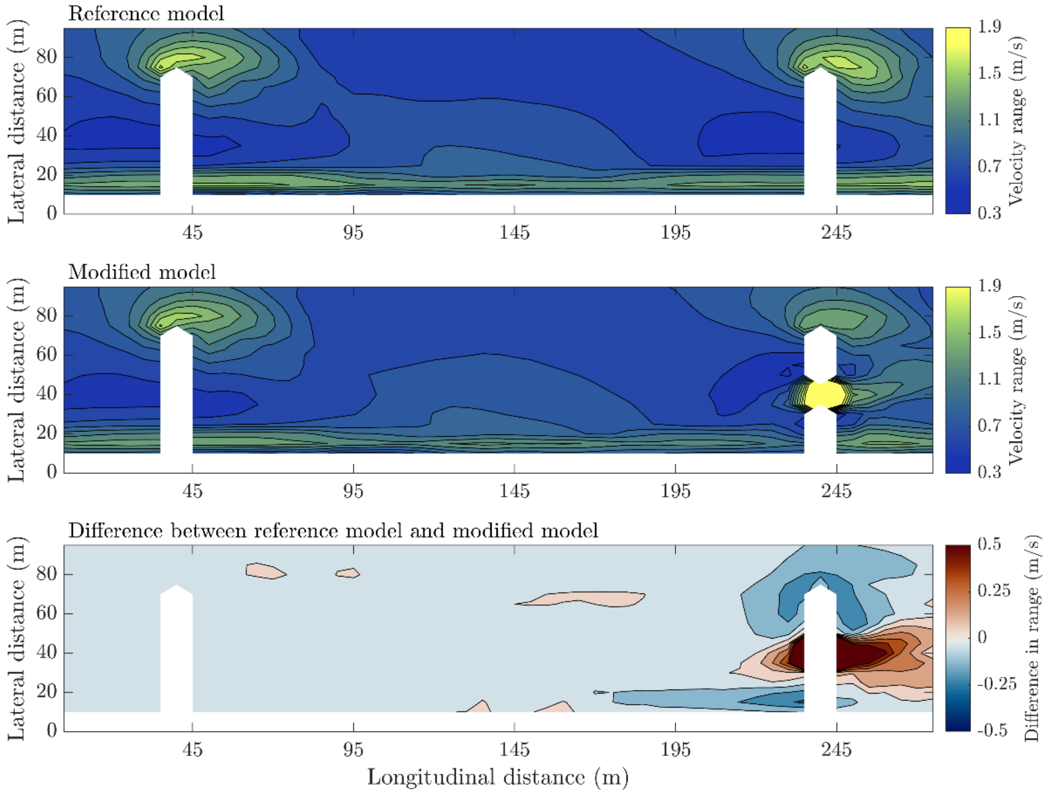
Velocity range upstream sailing



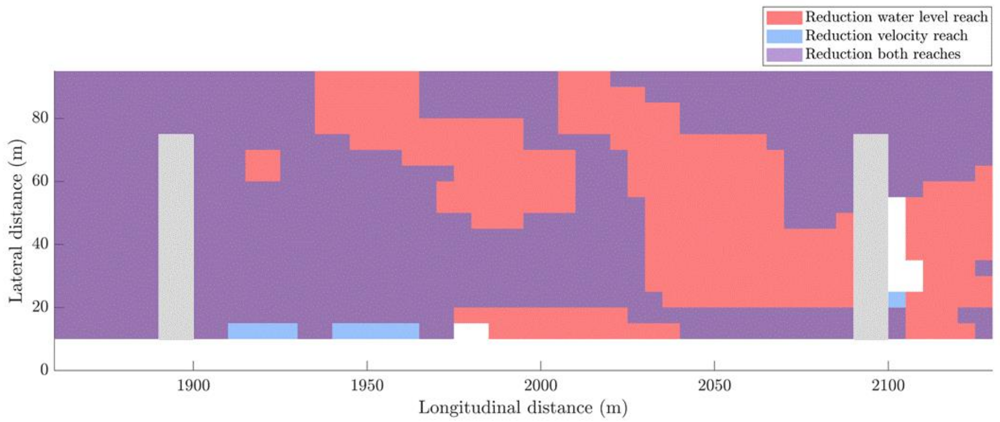
Velocity range downstream sailing



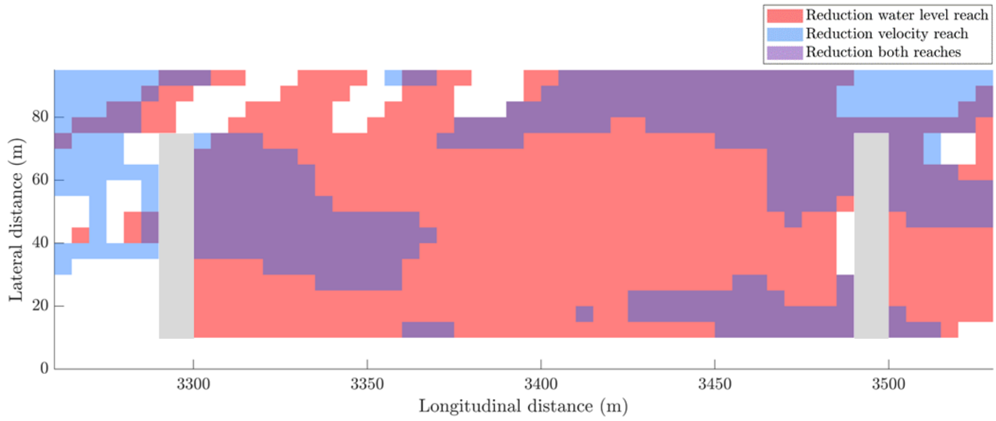
Combined velocity range



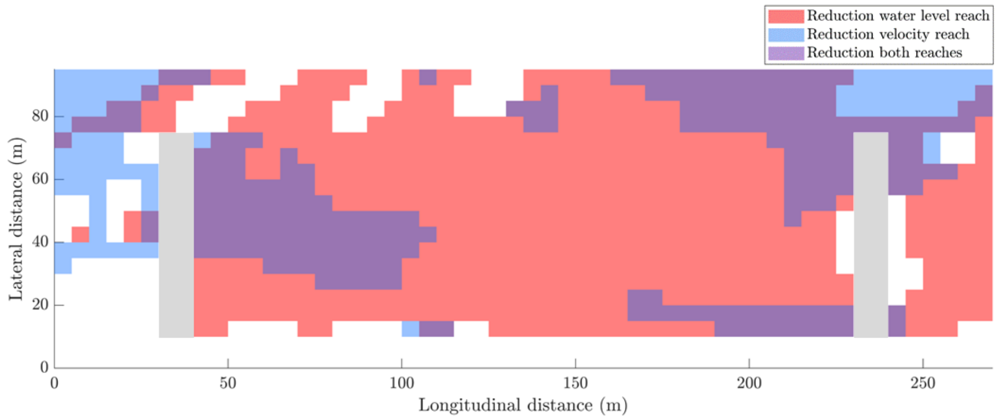
Overview plot upstream sailing



Overview plot dowstream sailing

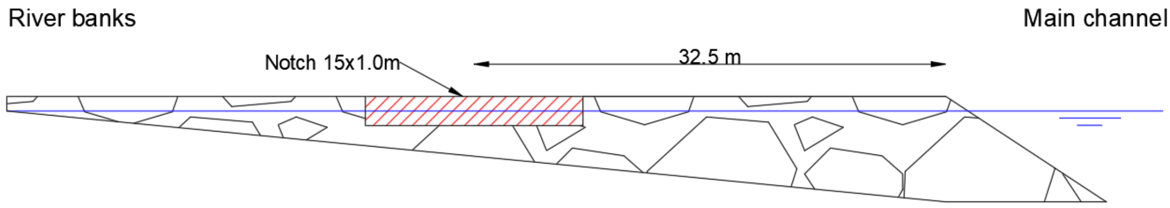


Combined overview plot

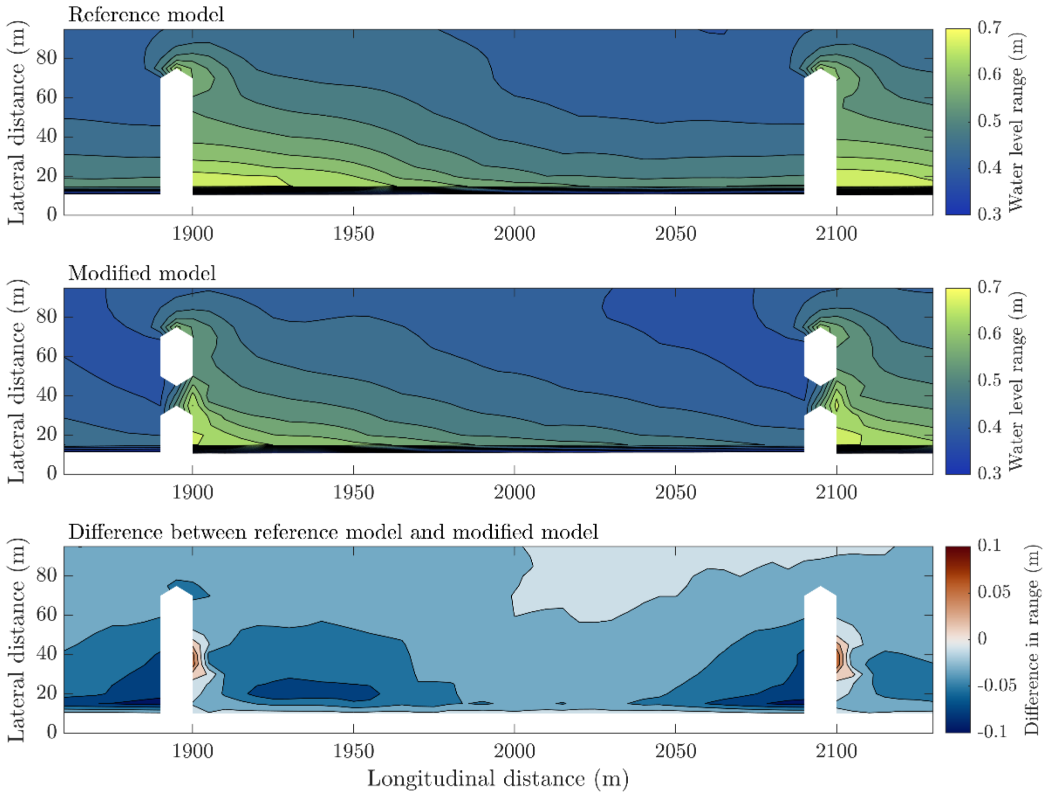


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.102	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.202	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

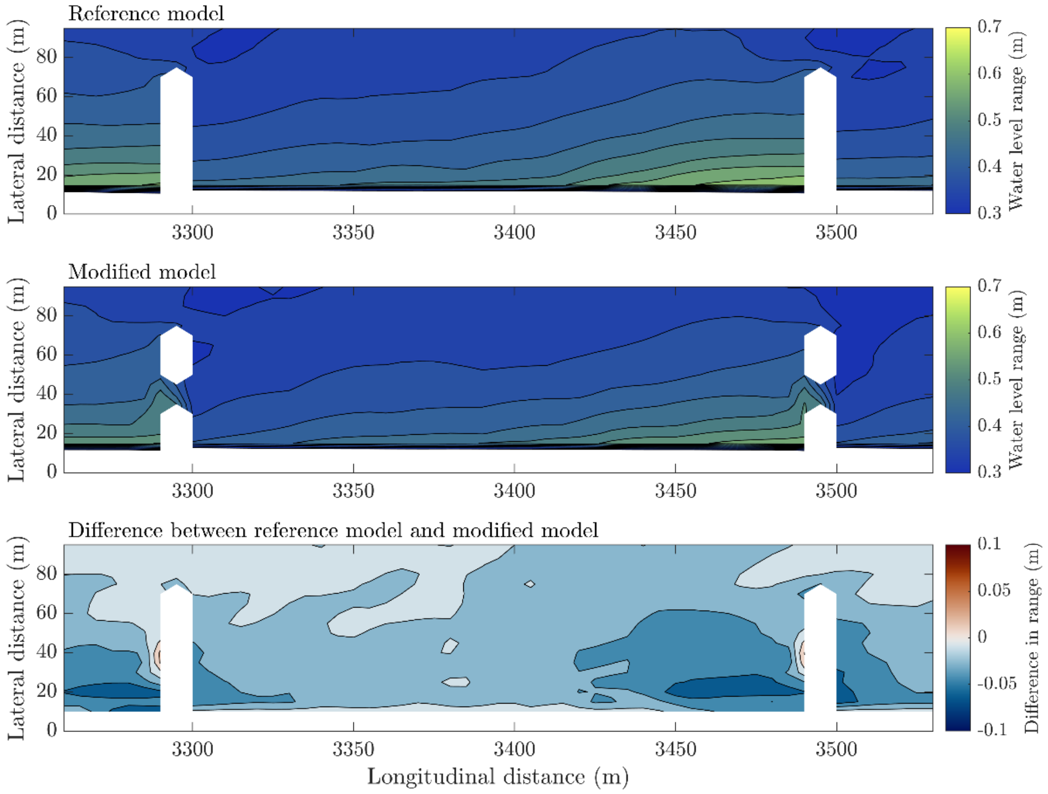
Number of notches	Location of notch	Width notch	Depth notch
1	32.5 m	15 m	1.0 m



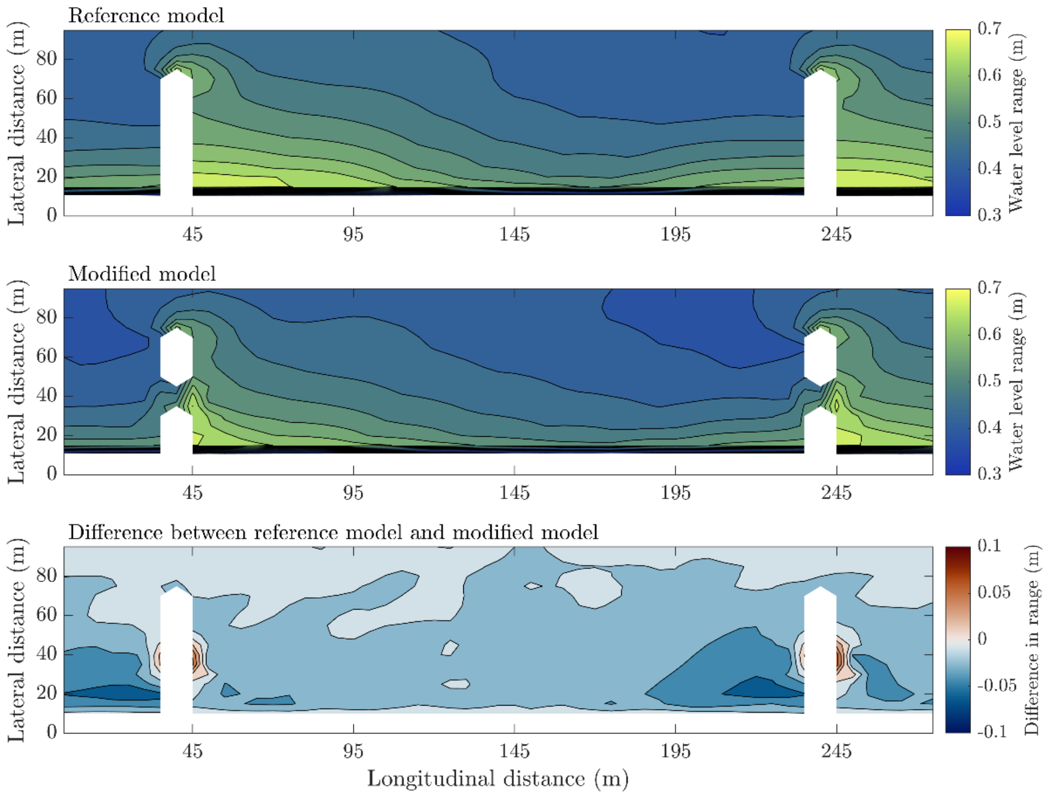
Water level range upstream sailing



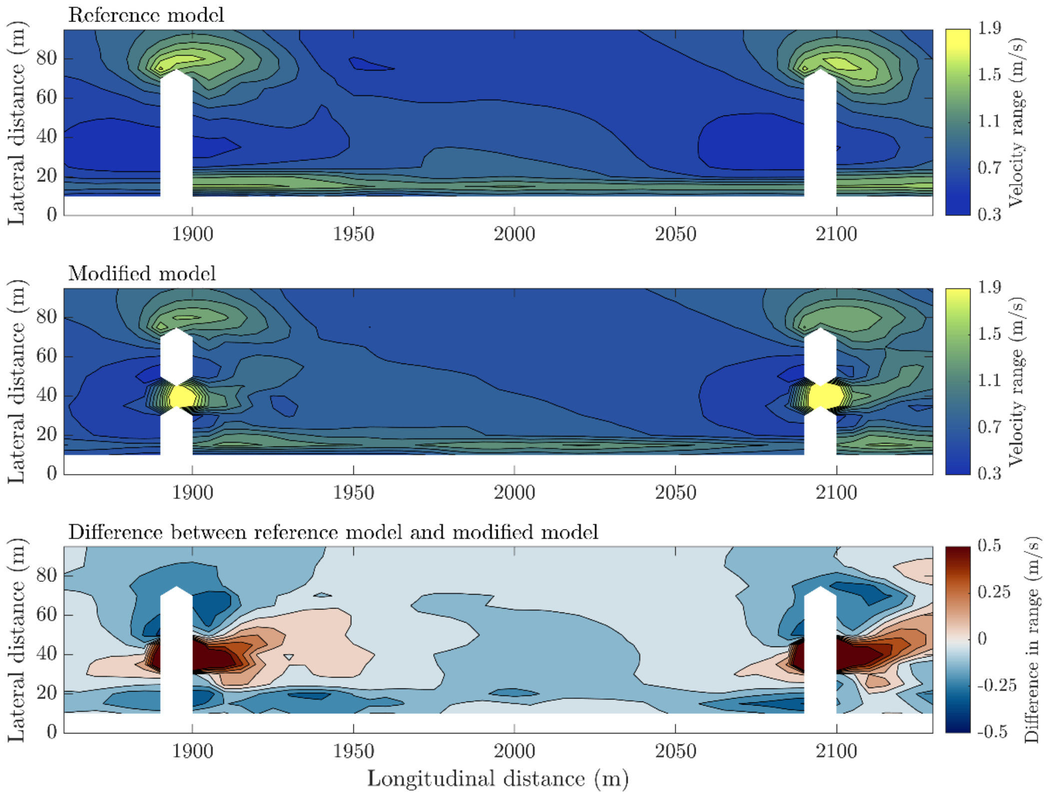
Water level range downstream sailing



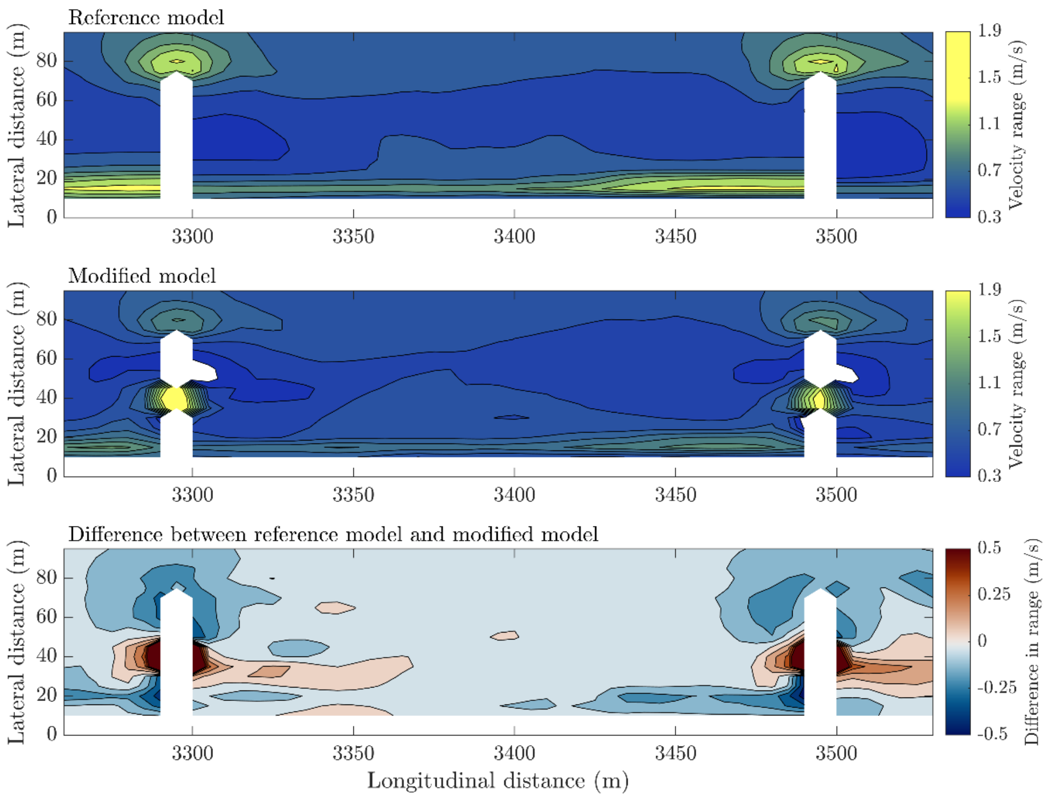
Combined water level range



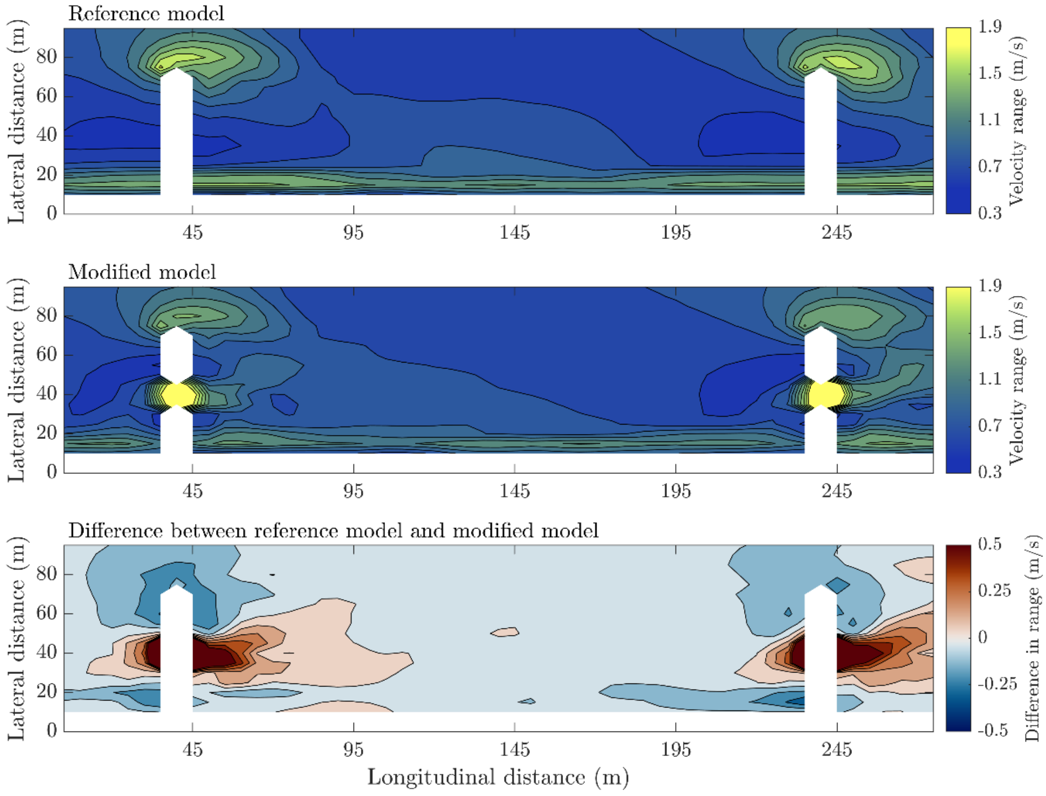
Velocity range upstream sailing



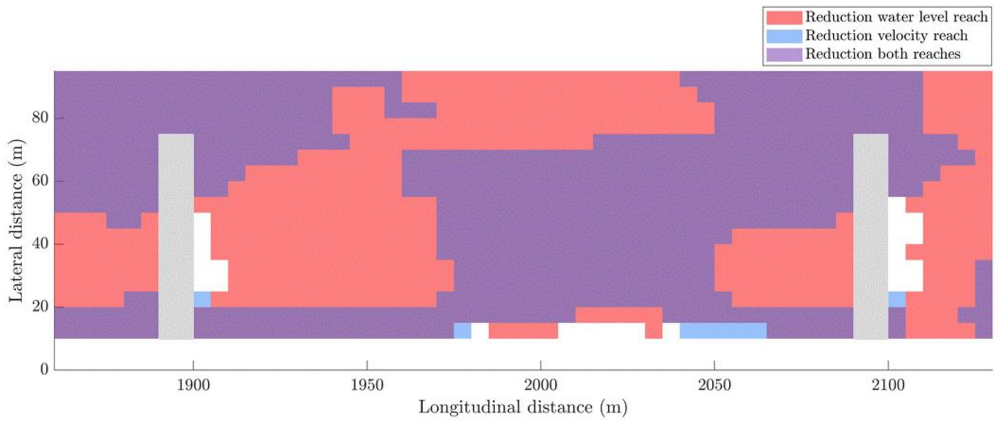
Velocity range downstream sailing



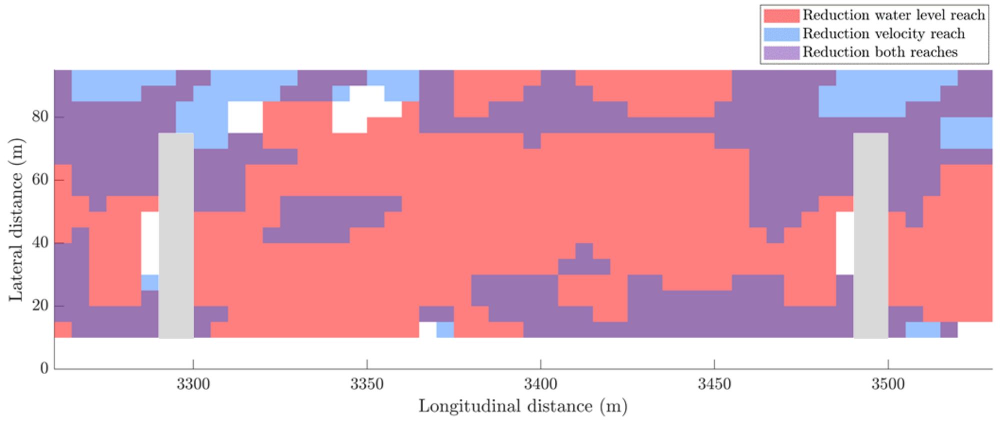
Combined velocity range



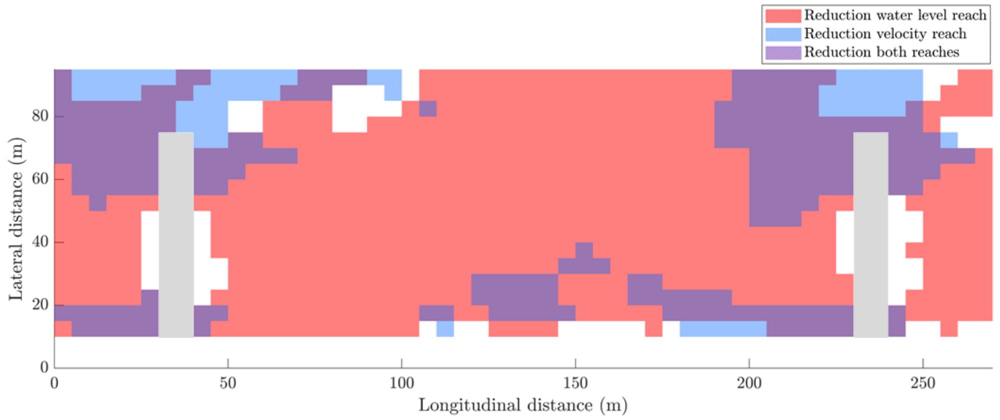
Overview plot upstream sailing



Overview plot dowstream sailing

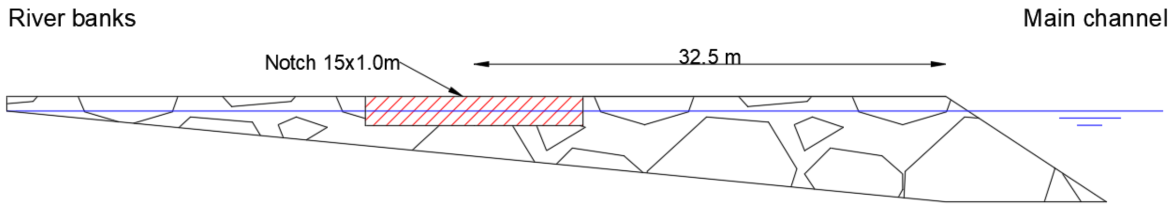


Combined overview plot

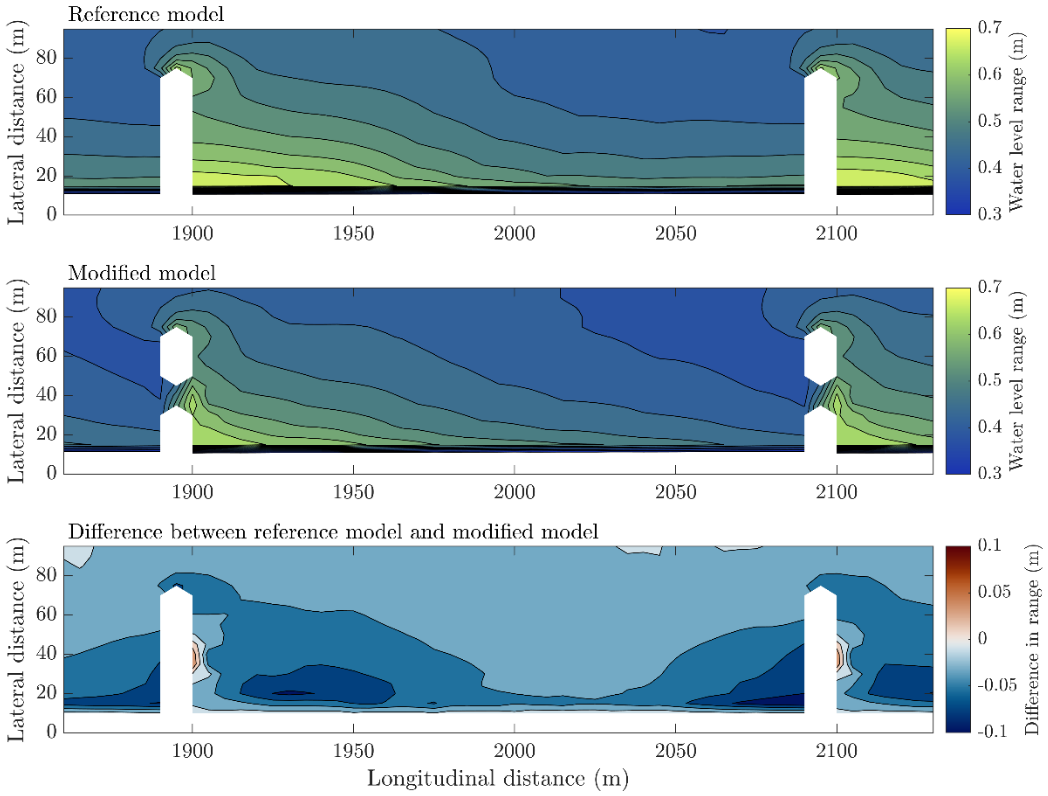


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.103	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.203	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

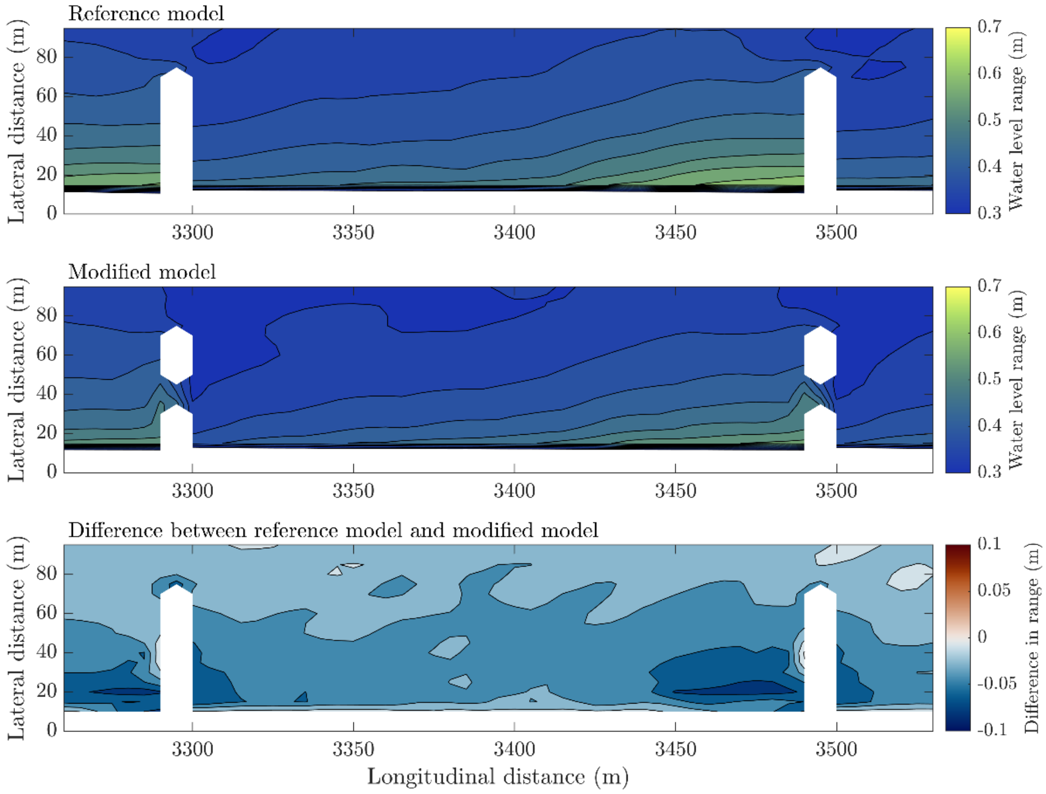
Number of notches	Location of notch	Width notch	Depth notch
1	32.5 m	15 m	1.0 m



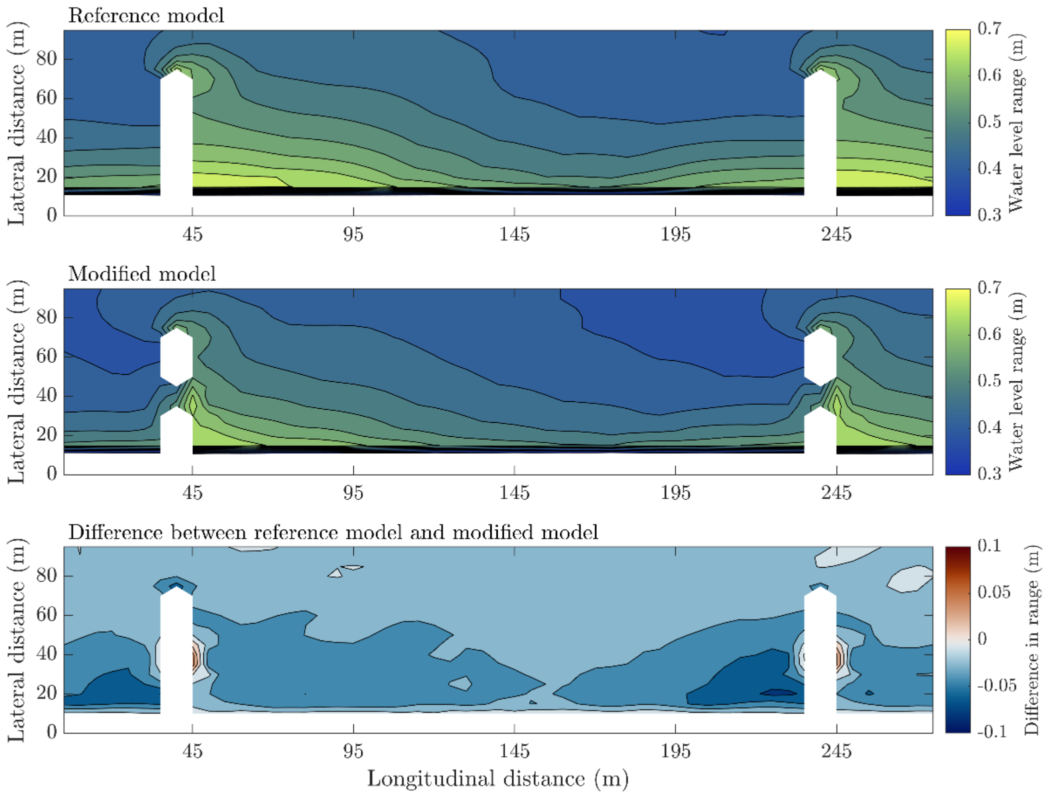
Water level range upstream sailing



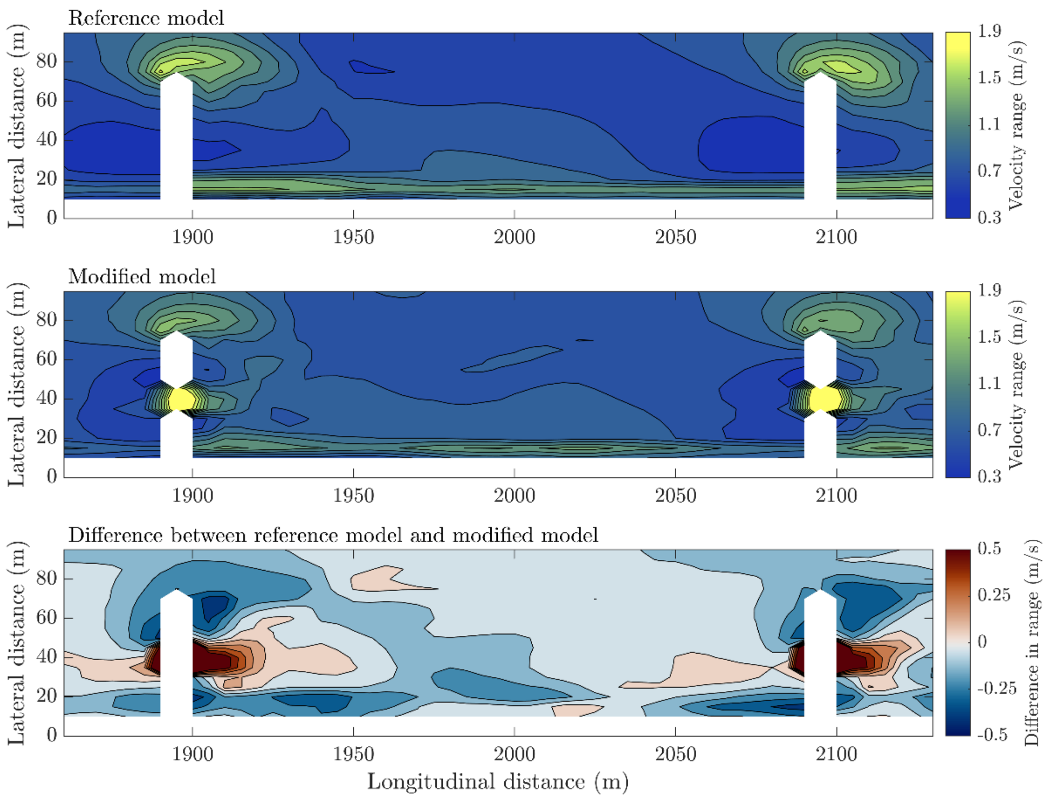
Water level range downstream sailing



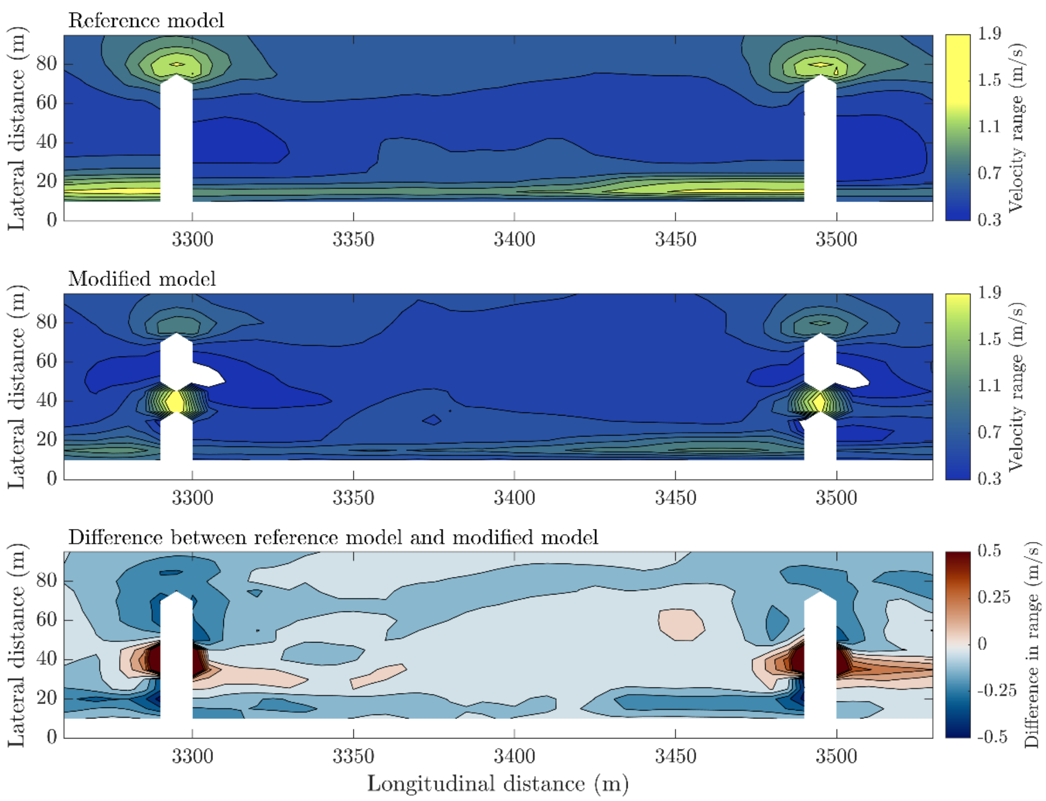
Combined water level range



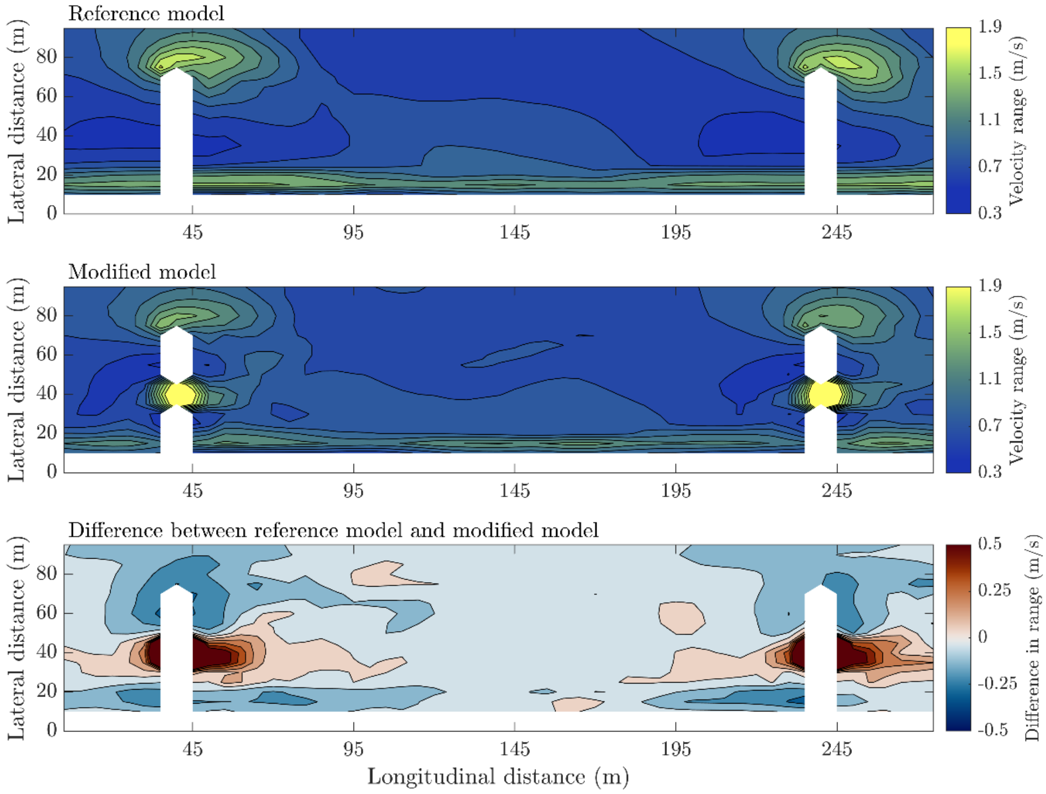
Velocity range upstream sailing



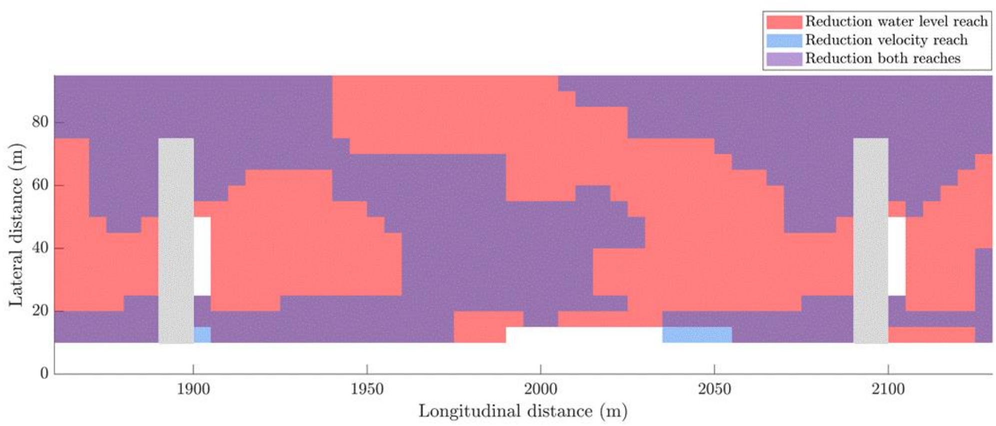
Velocity range downstream sailing



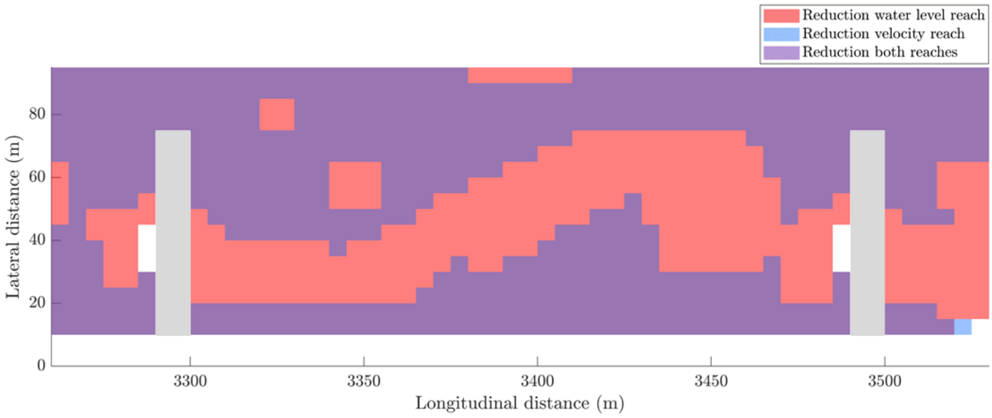
Combined velocity range



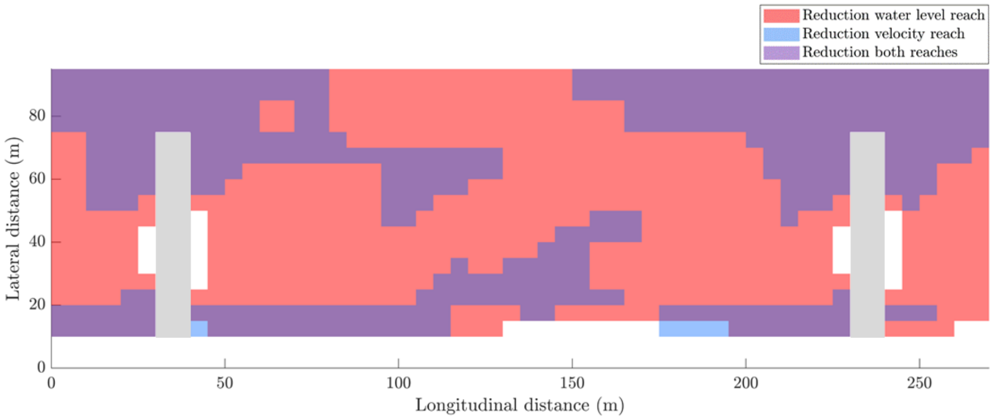
Overview plot upstream sailing



Overview plot dowstream sailing

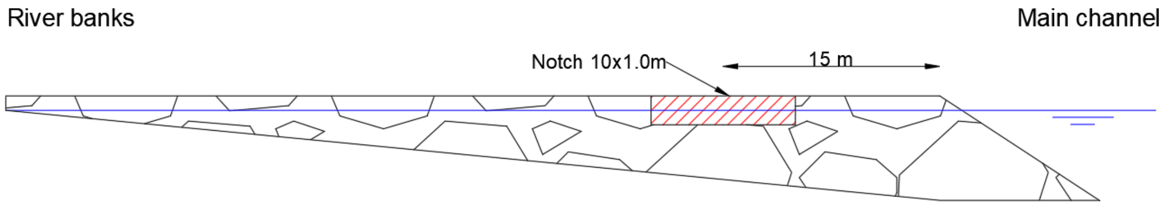


Combined overview plot

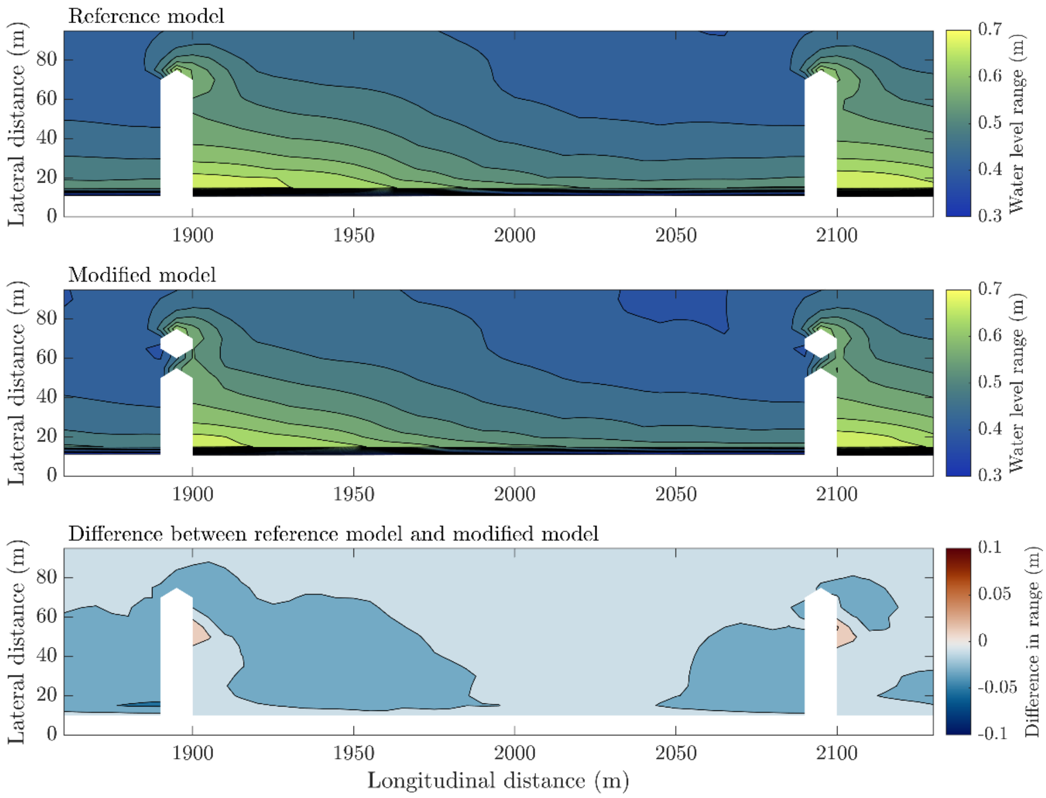


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.104	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.204	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

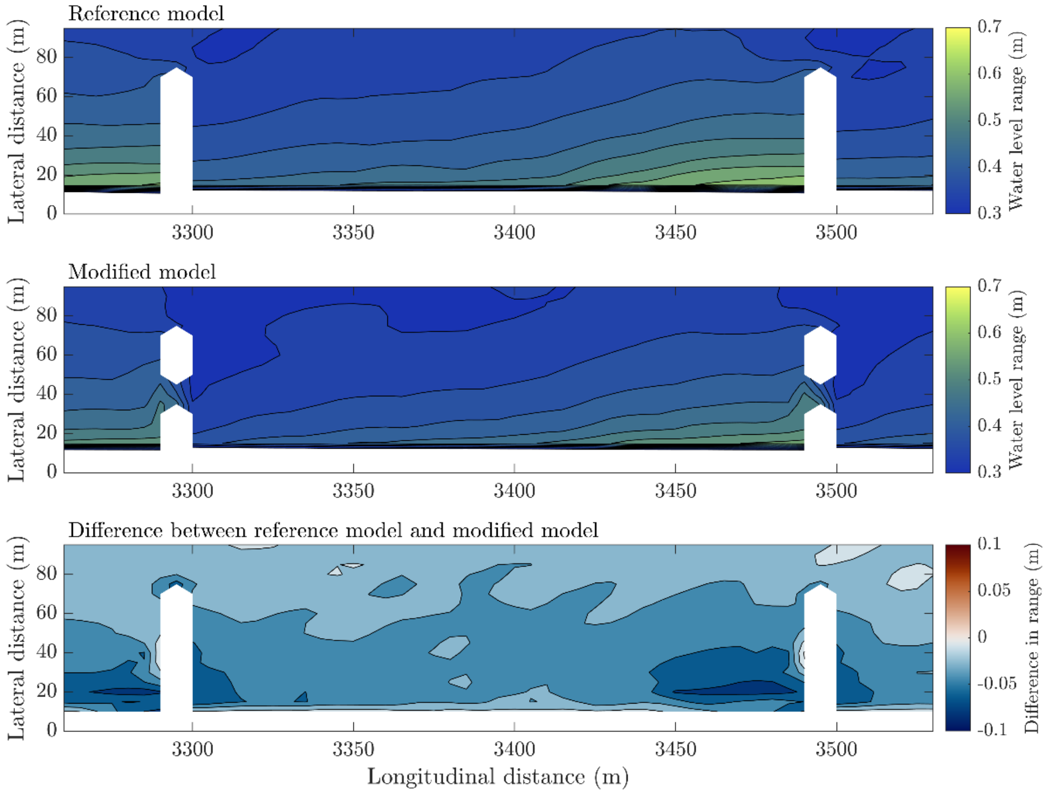
Number of notches	Location of notch	Width notch	Depth notch
1	15 m	10 m	1.0 m



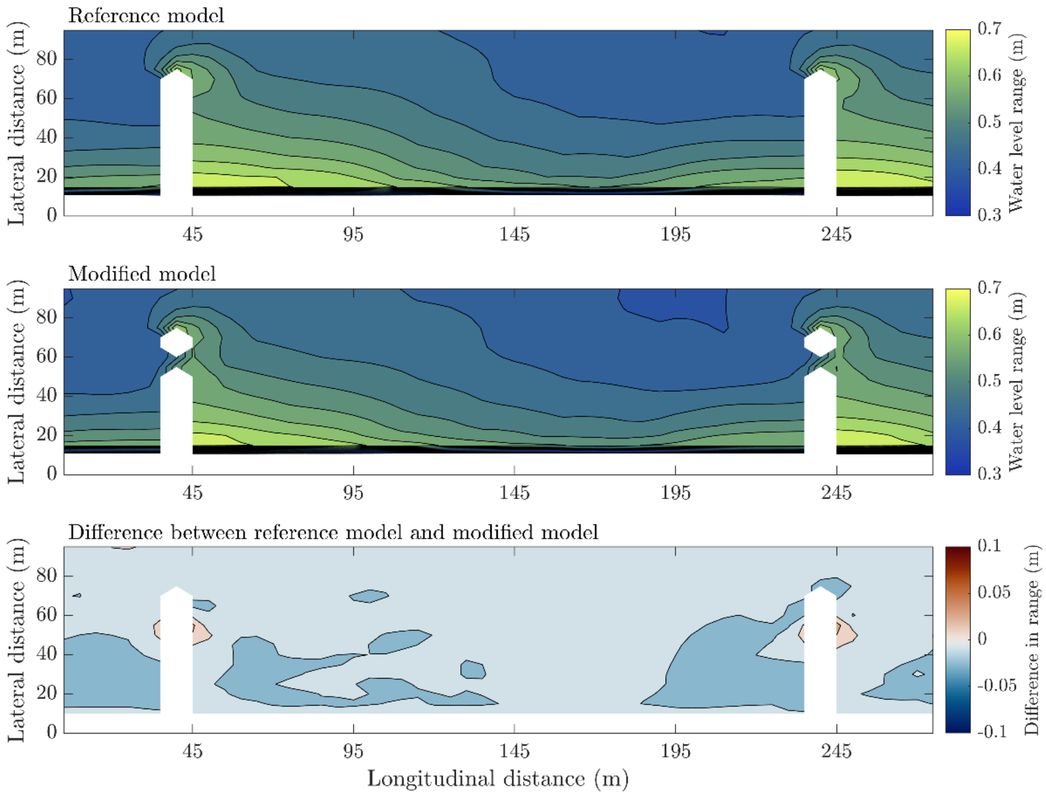
Water level range upstream sailing



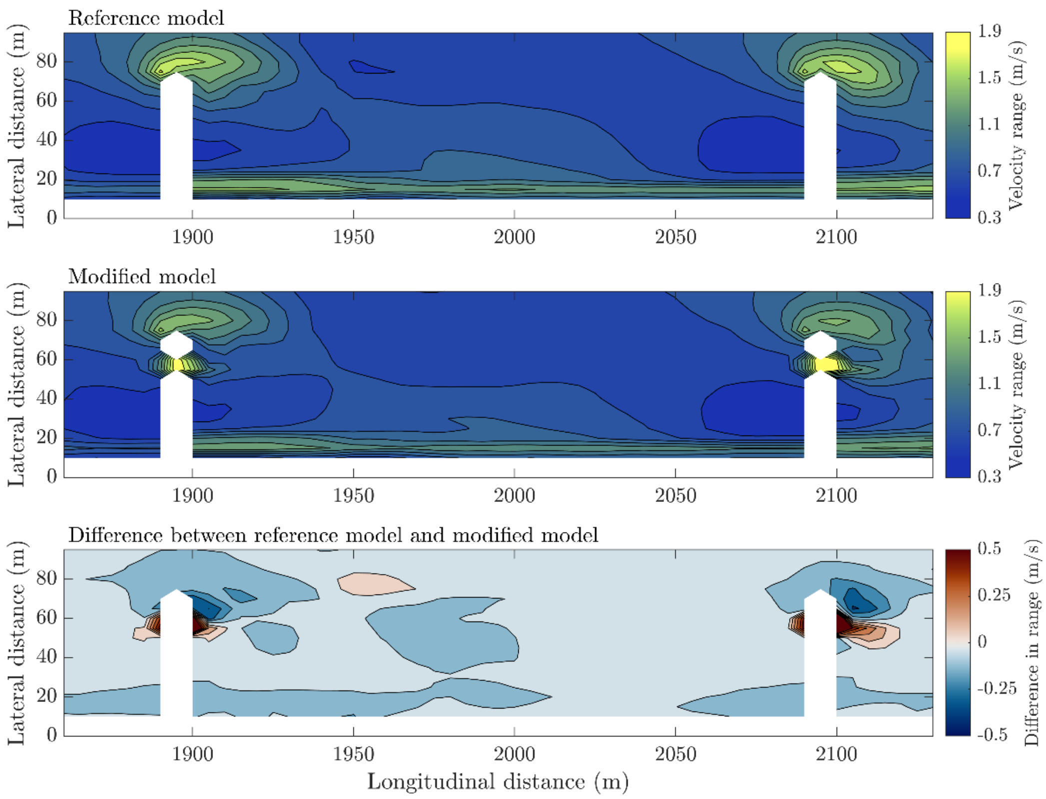
Water level range downstream sailing



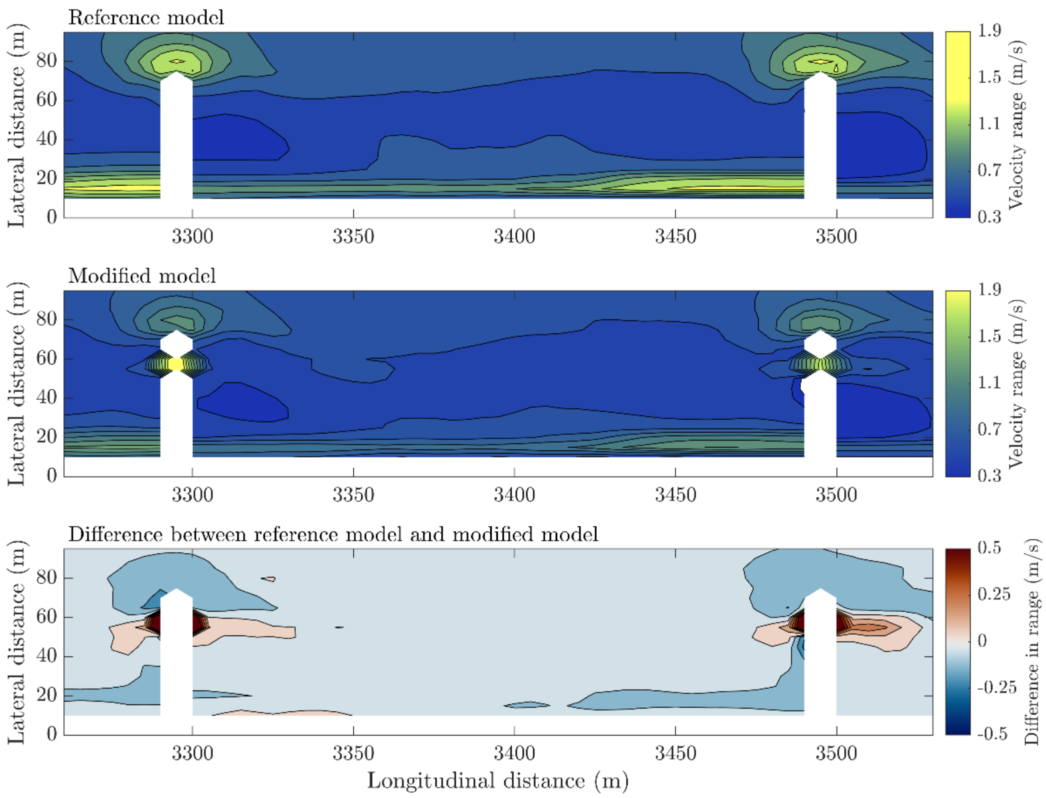
Combined water level range



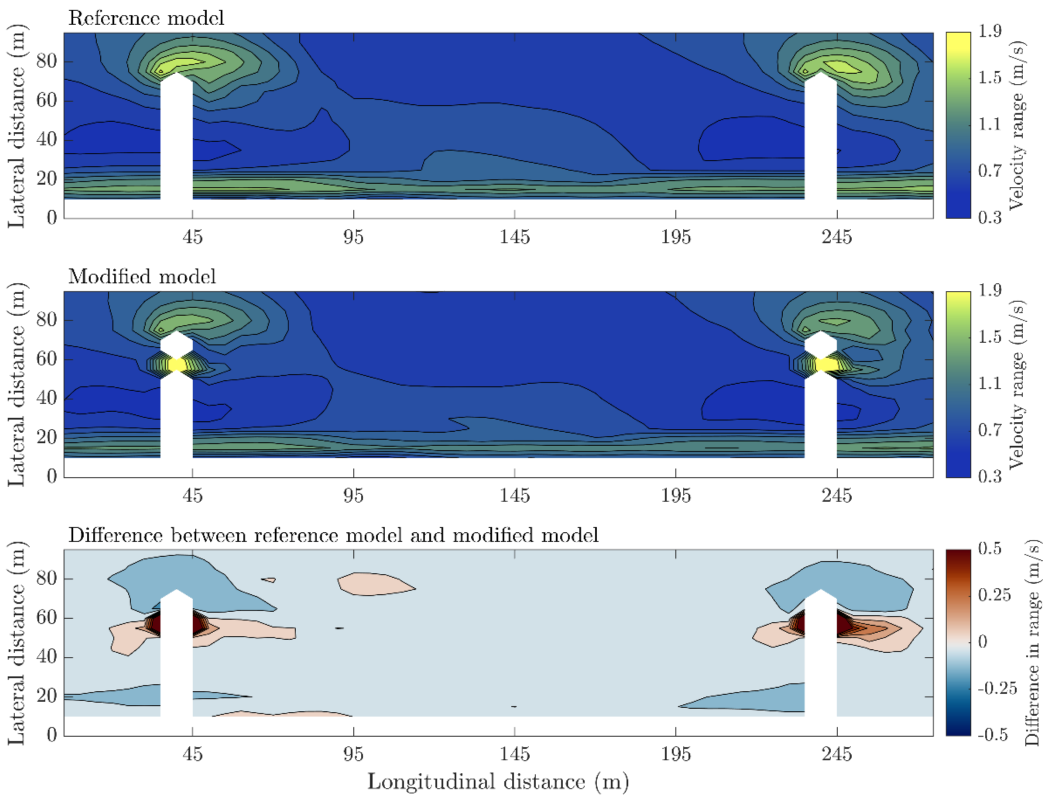
Velocity range upstream sailing



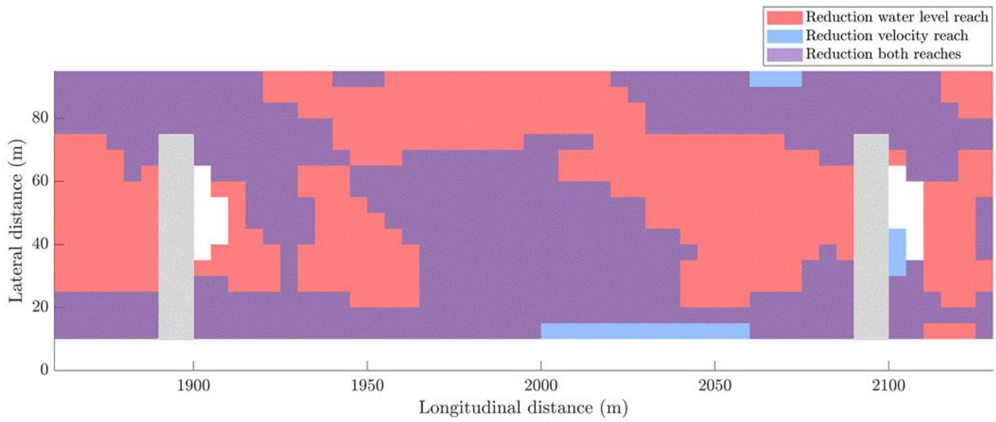
Velocity range downstream sailing



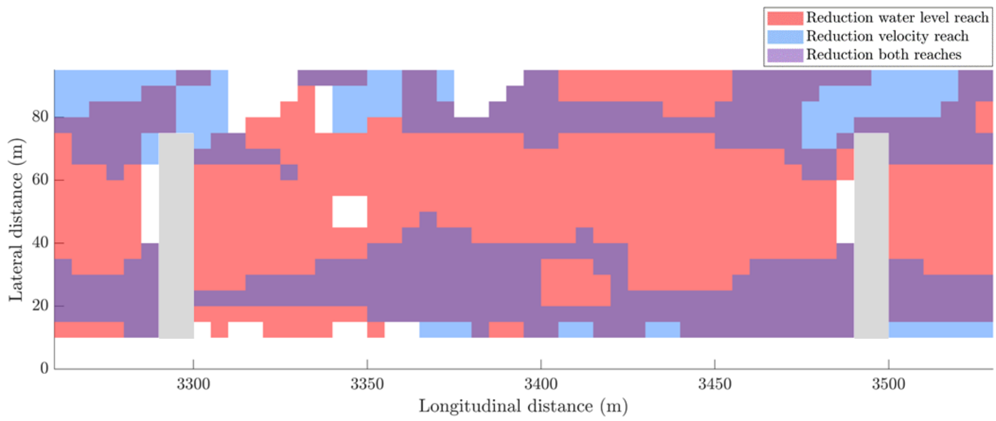
Combined velocity range



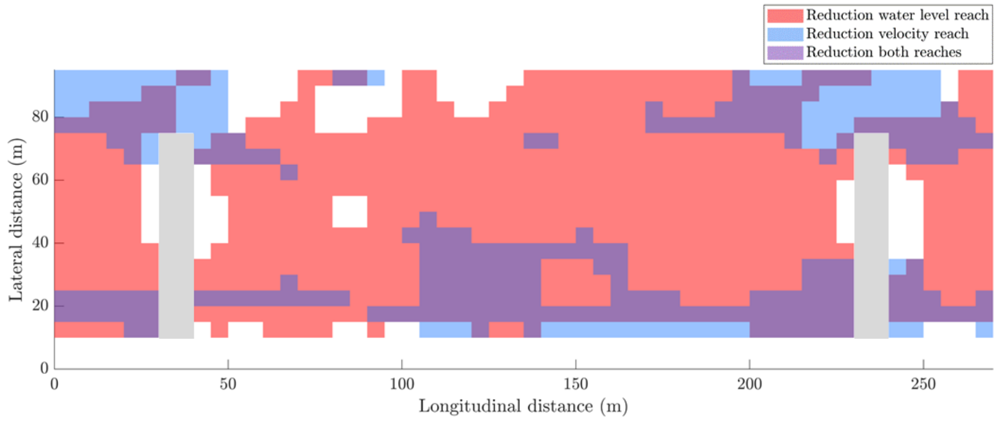
Overview plot upstream sailing



Overview plot dowstream sailing

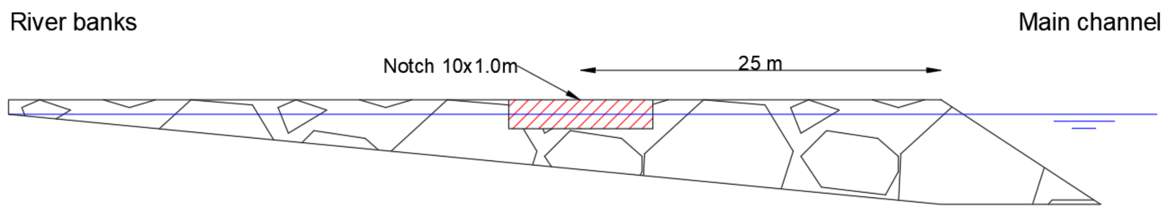


Combined overview plot

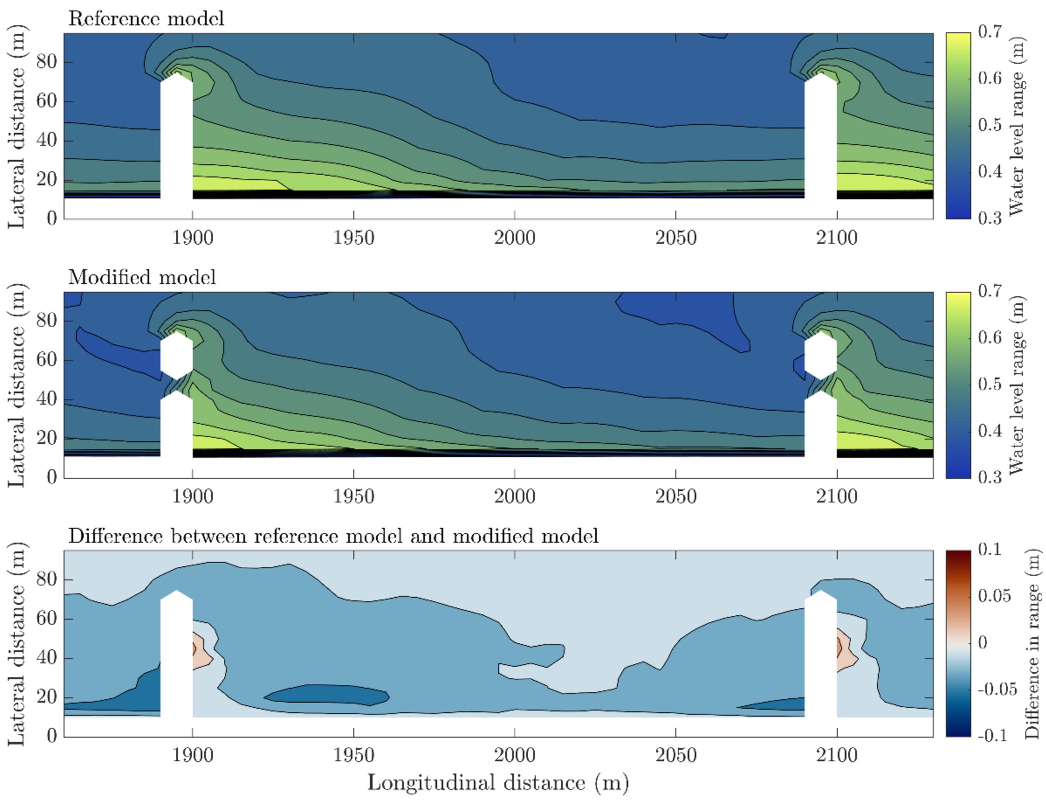


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.105	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.205	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

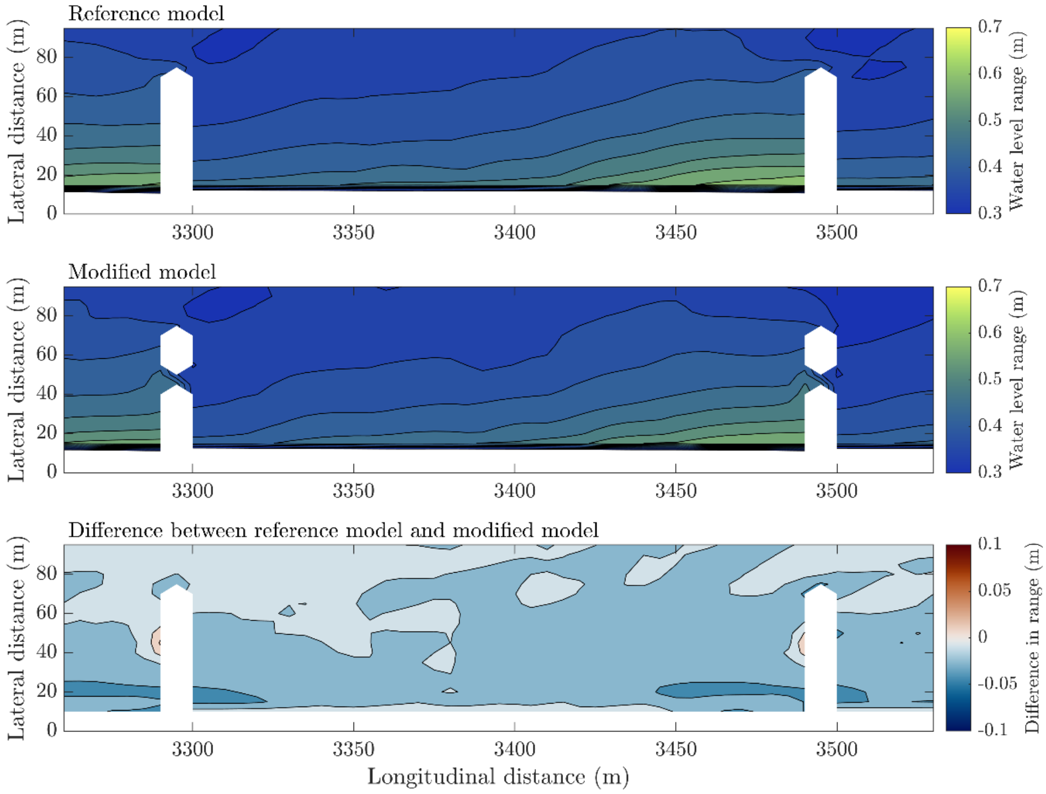
Number of notches	Location of notch	Width notch	Depth notch
1	25 m	10 m	1.0 m



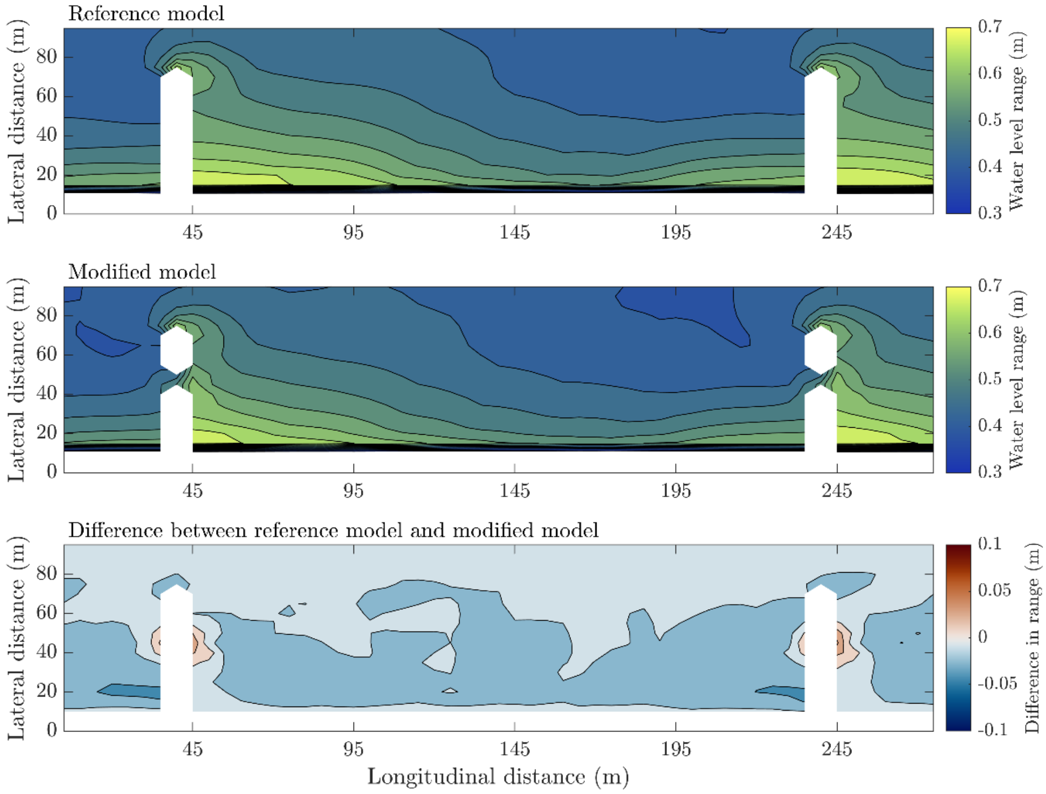
Water level range upstream sailing



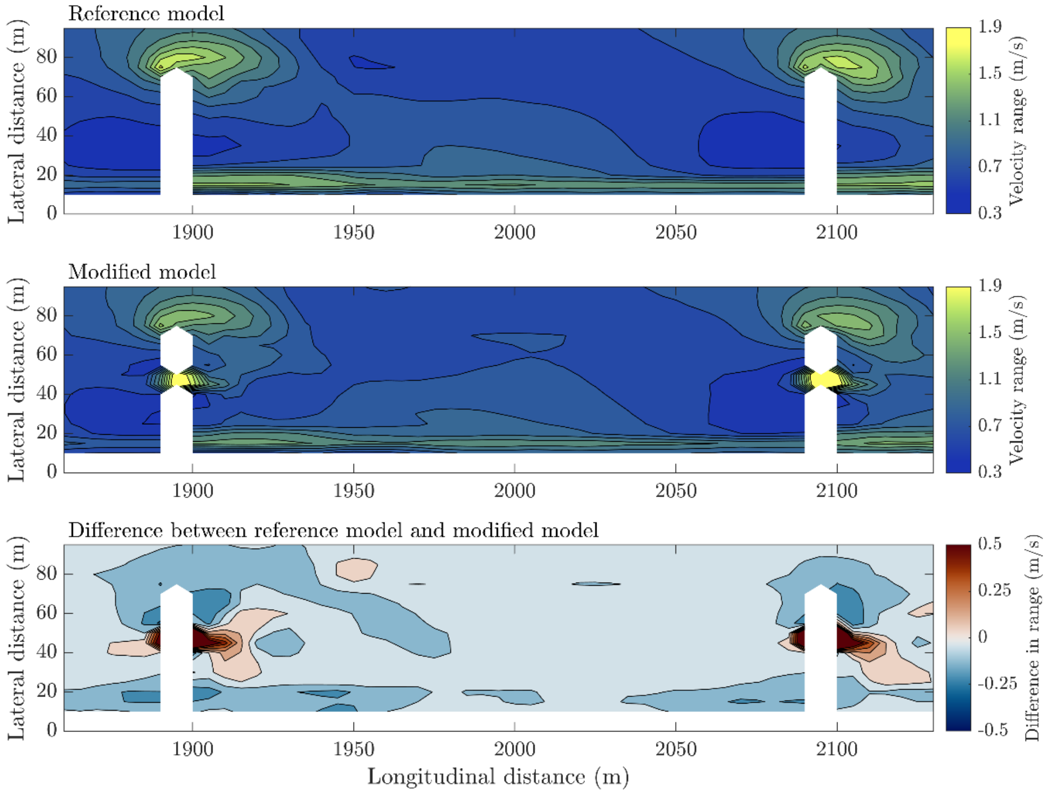
Water level range downstream sailing



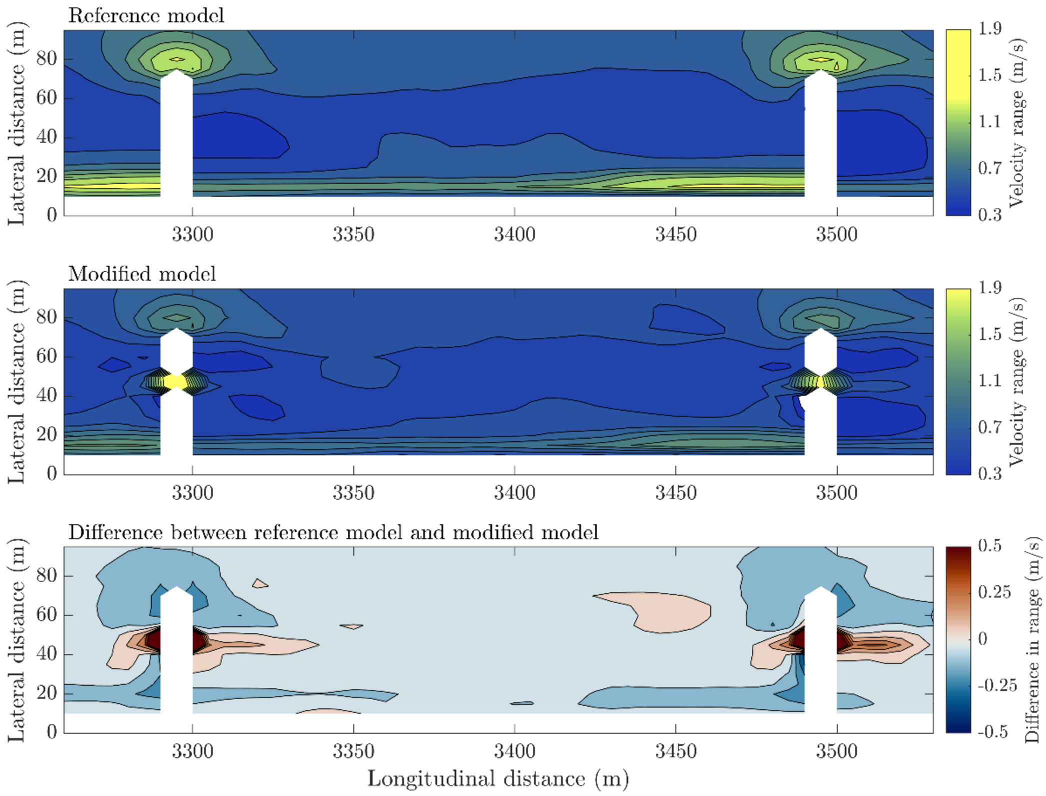
Combined water level range



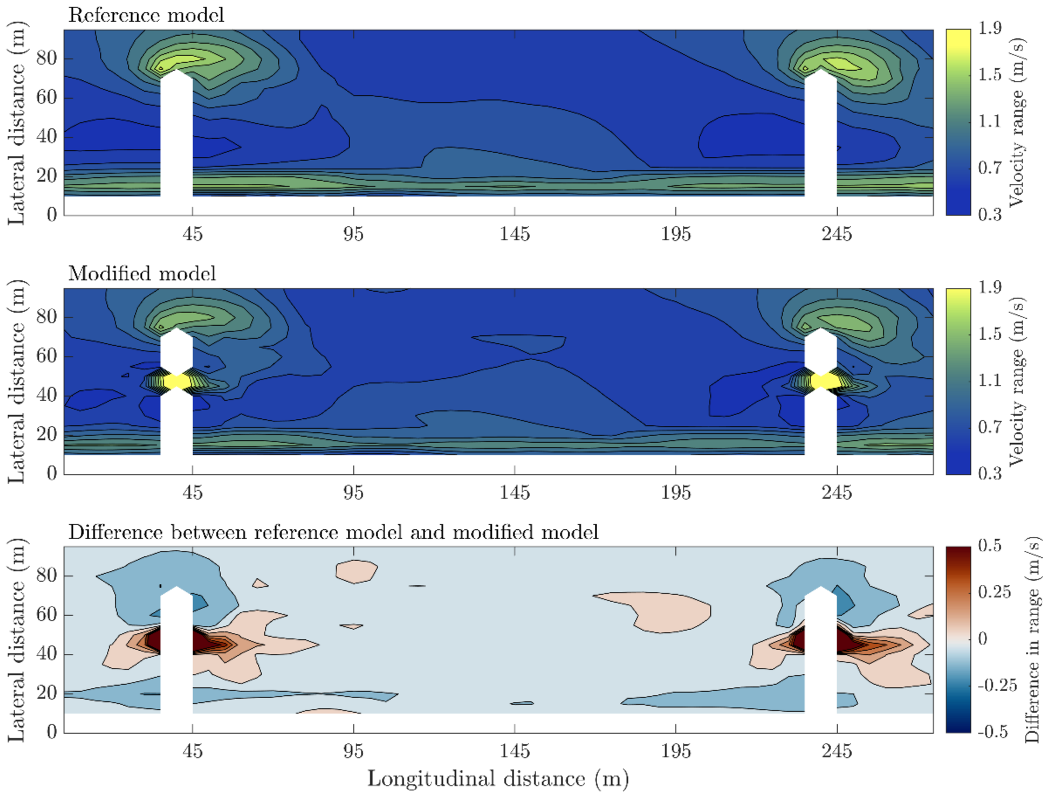
Velocity range upstream sailing



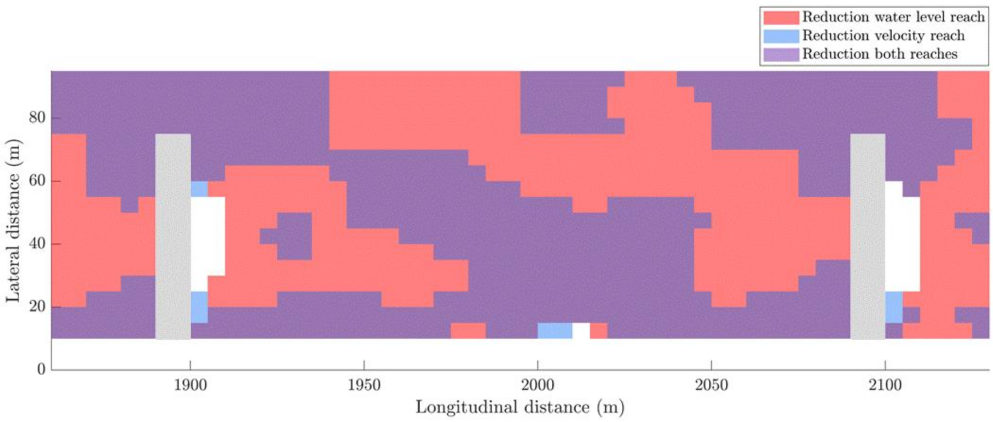
Velocity range downstream sailing



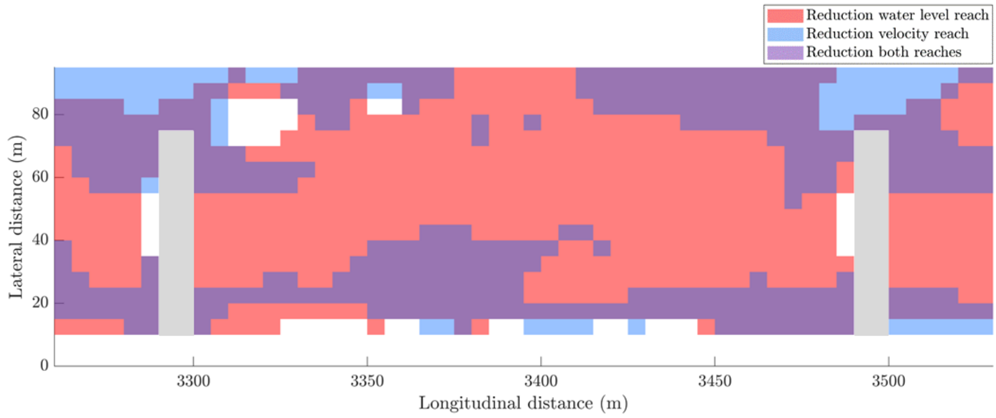
Combined velocity range



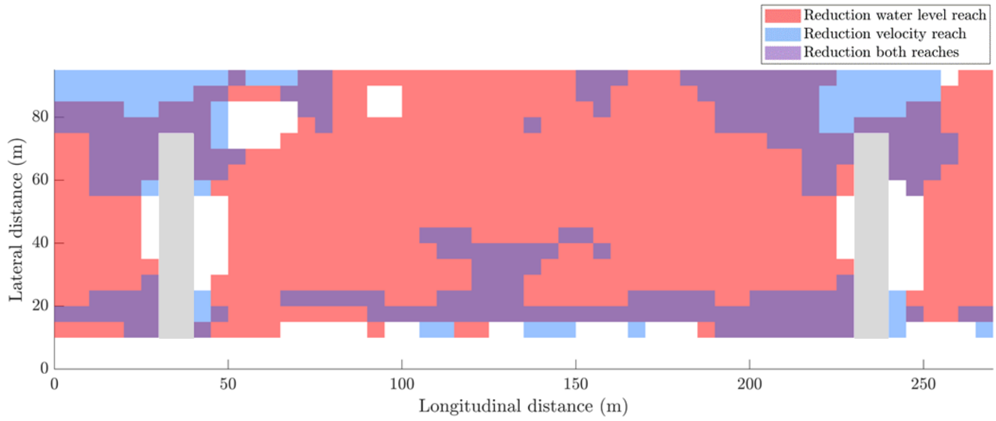
Overview plot upstream sailing



Overview plot dowstream sailing

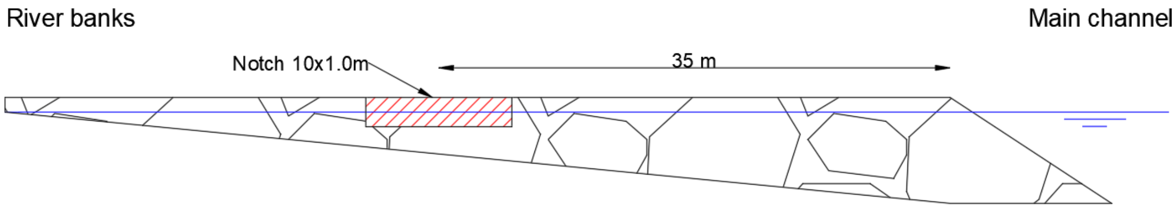


Combined overview plot

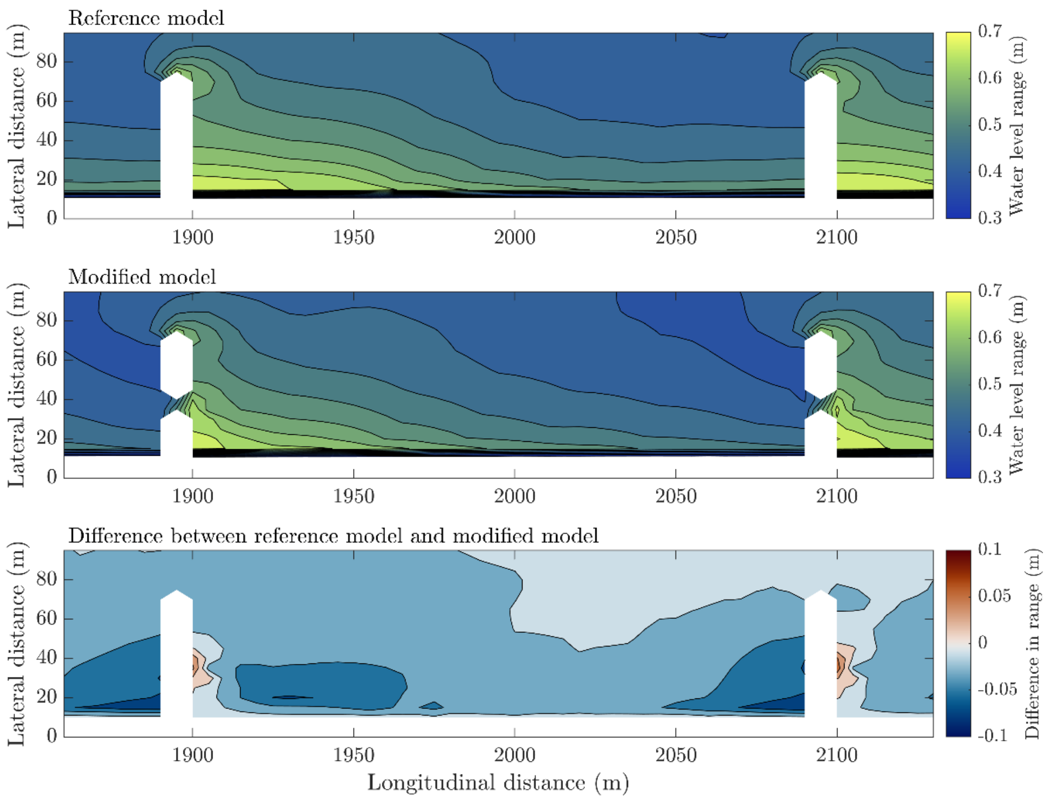


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.106	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.206	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

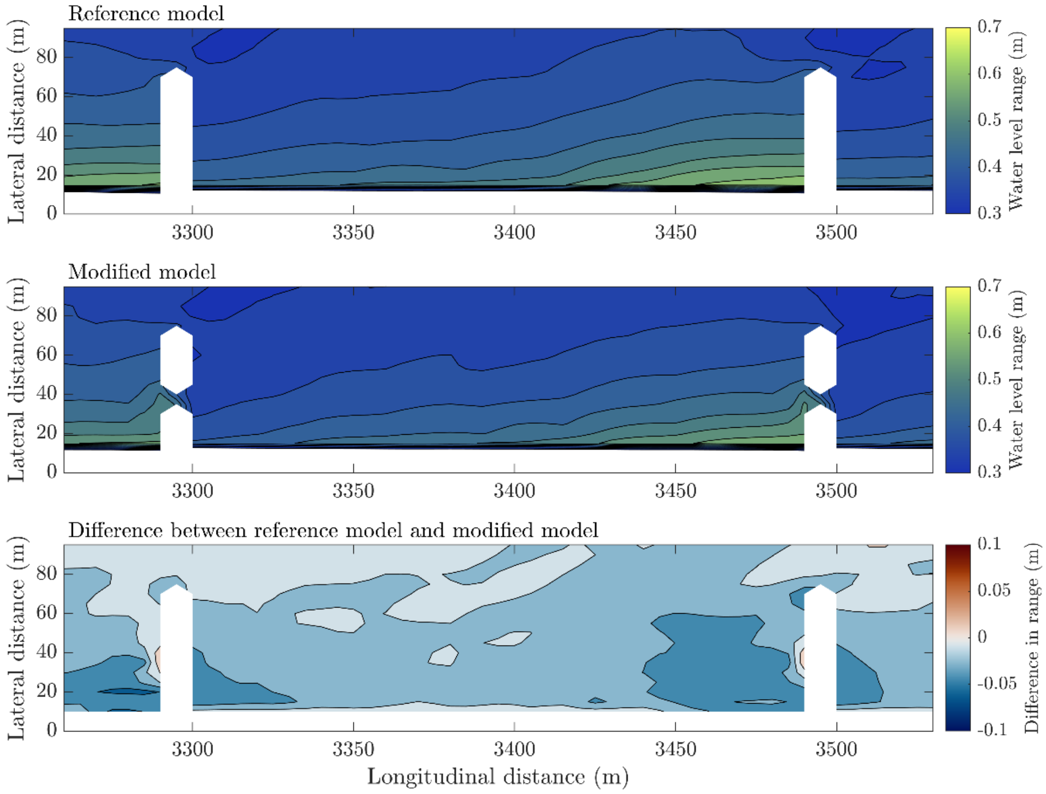
Number of notches	Location of notch	Width notch	Depth notch
1	35 m	10 m	1.0 m



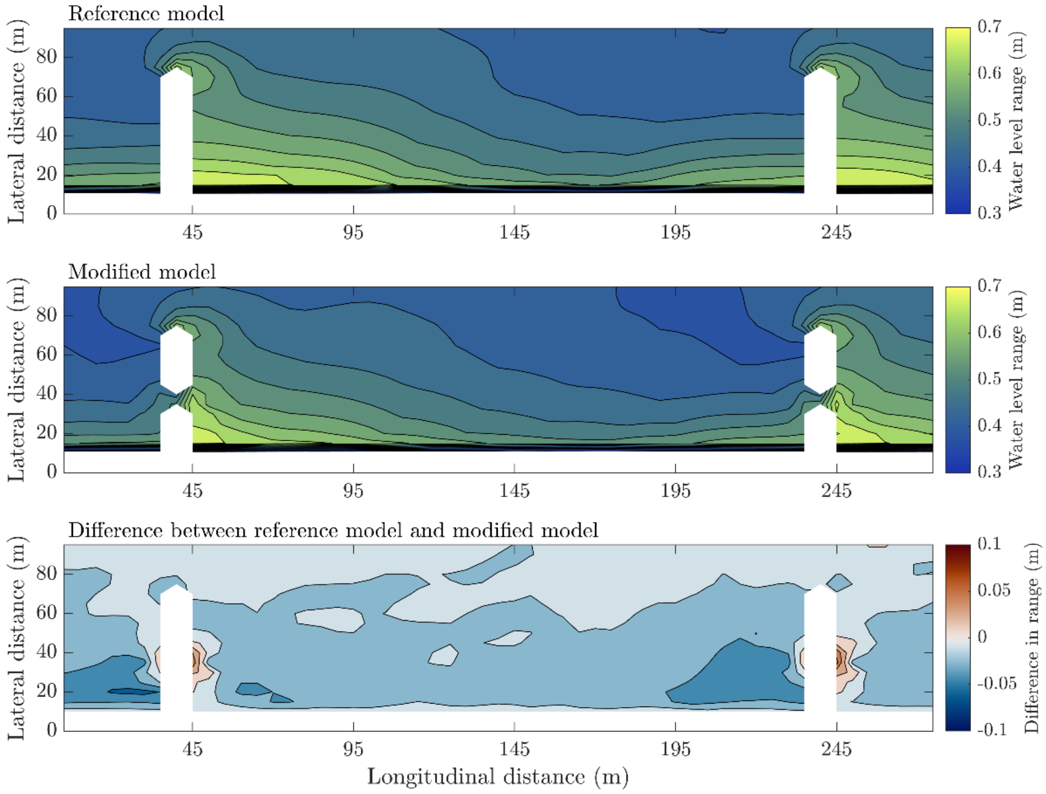
Water level range upstream sailing



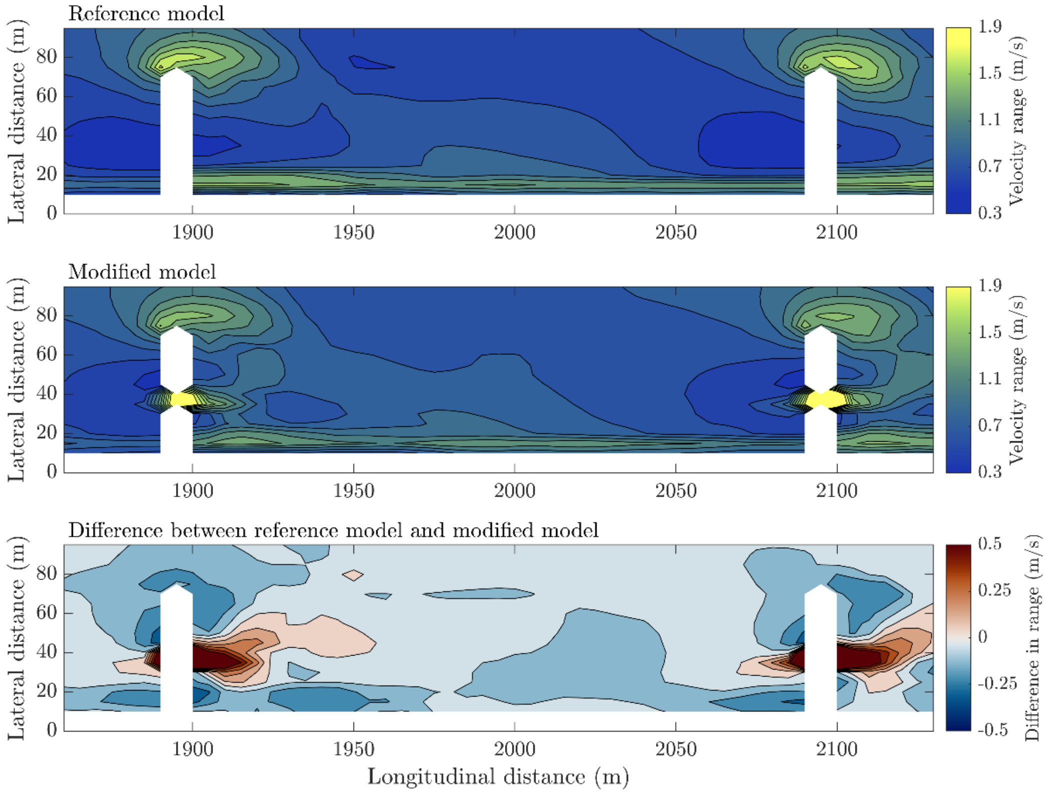
Water level range downstream sailing



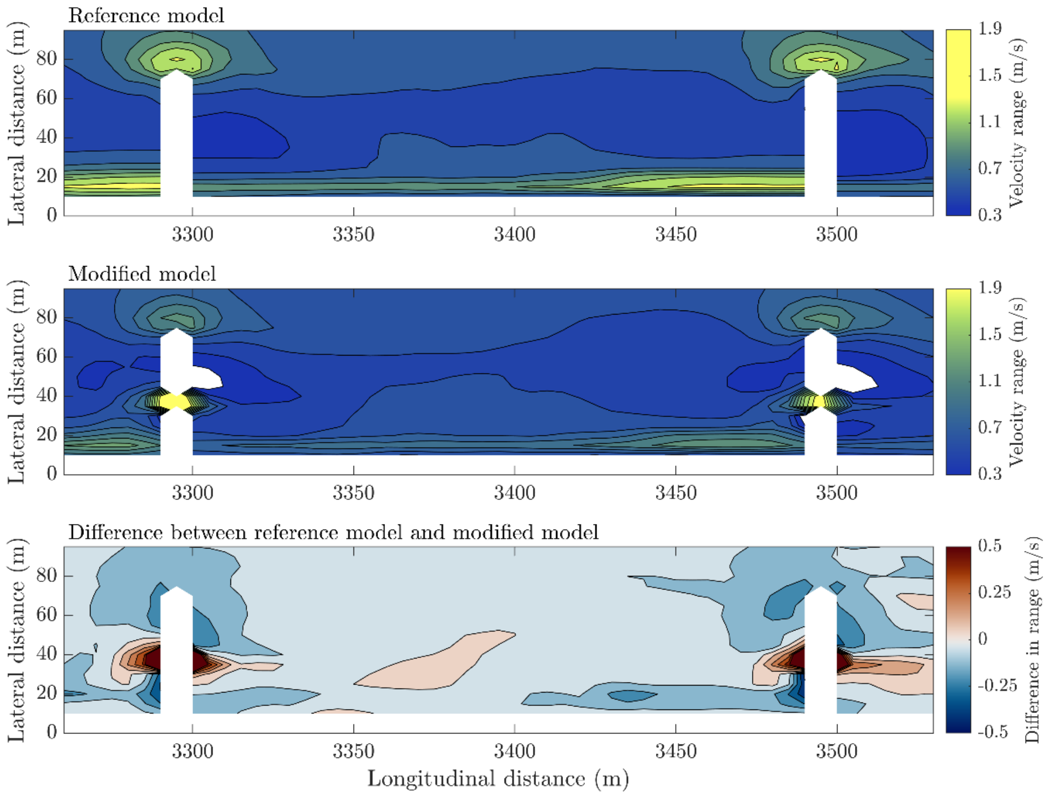
Combined water level range



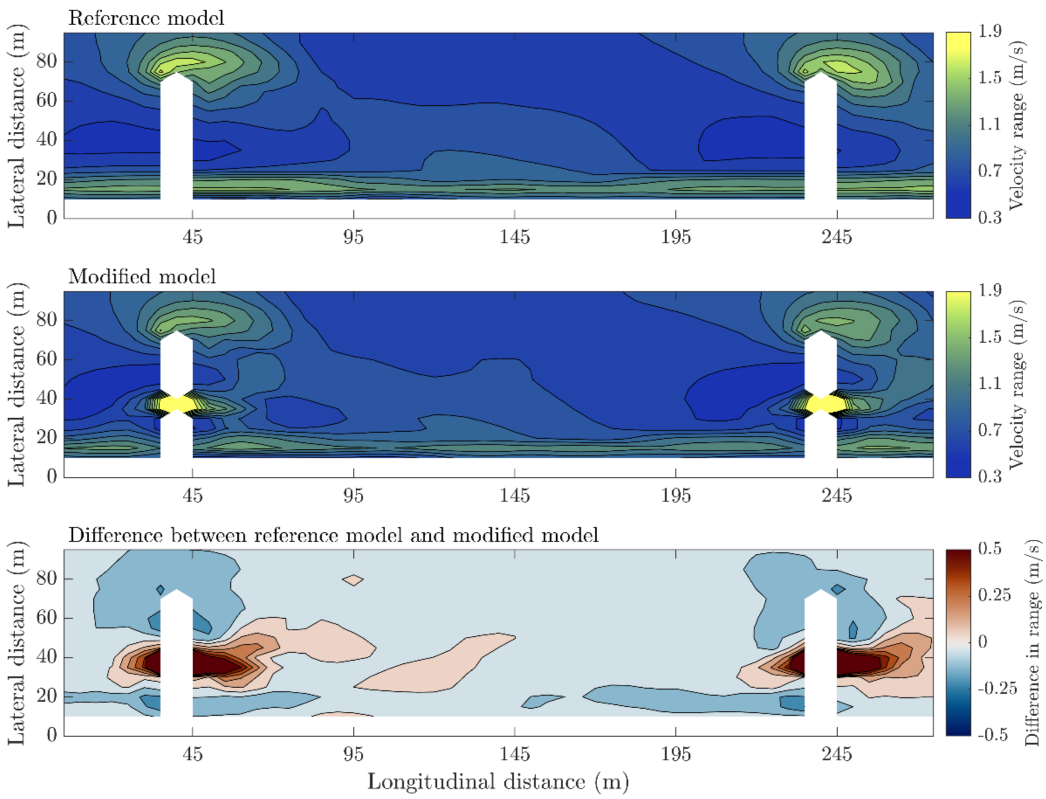
Velocity range upstream sailing



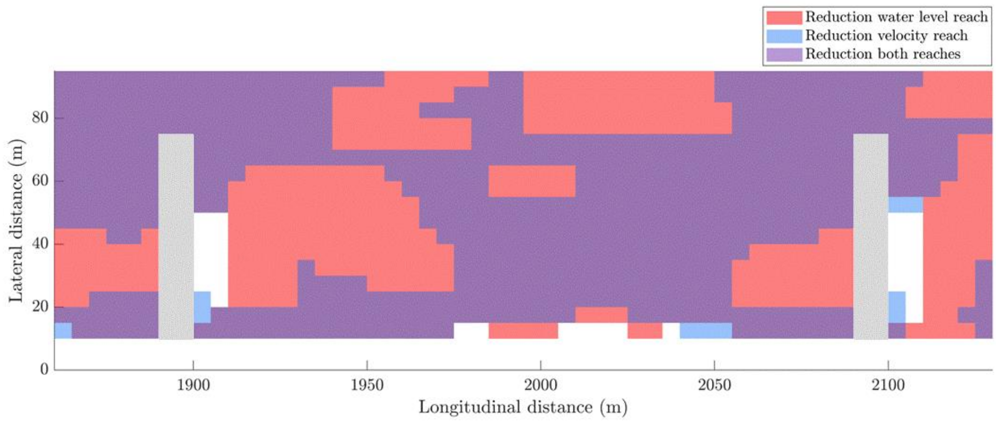
Velocity range downstream sailing



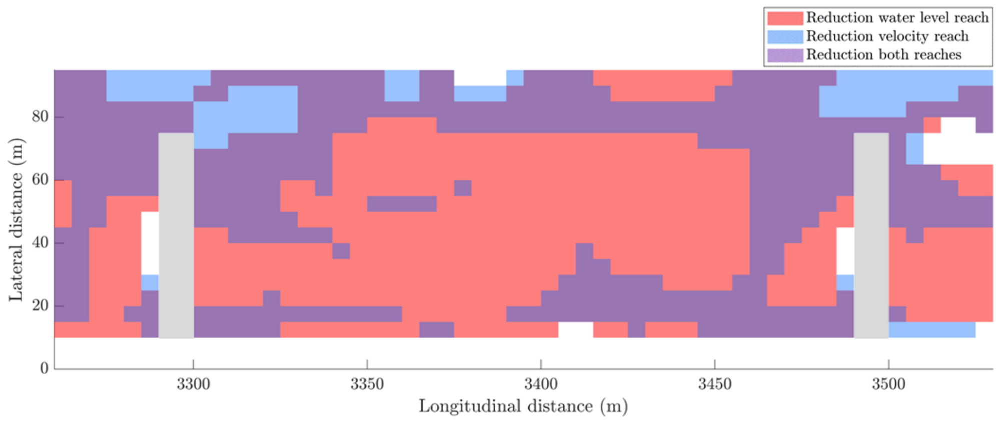
Combined velocity range



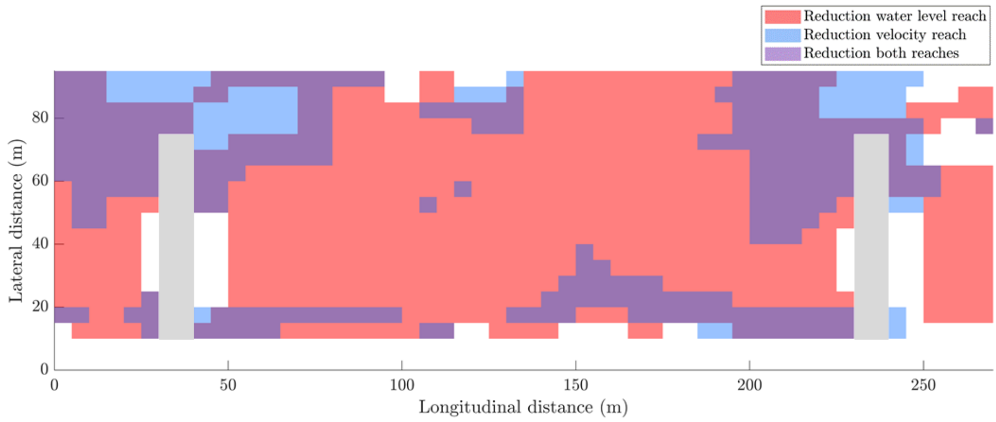
Overview plot upstream sailing



Overview plot dowstream sailing

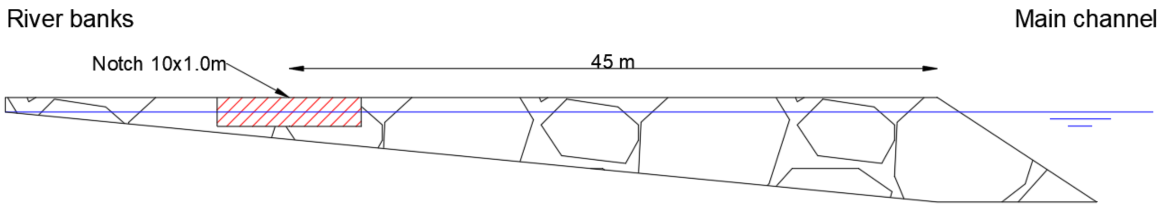


Combined overview plot

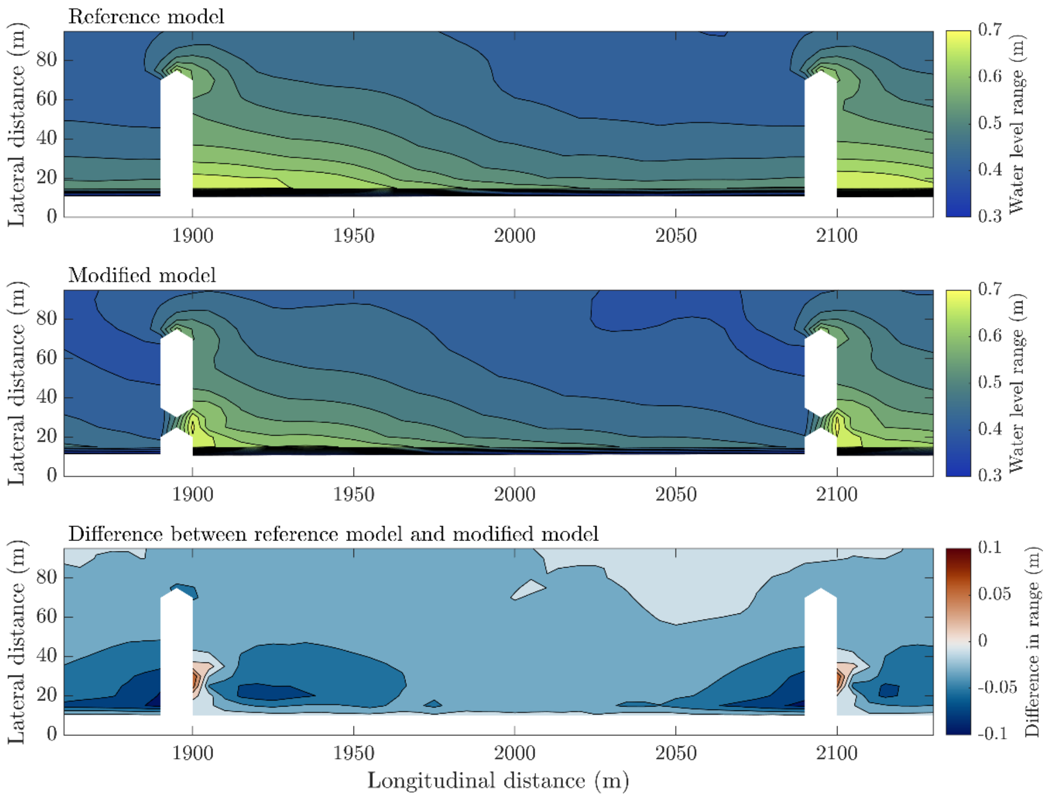


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.107	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.207	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

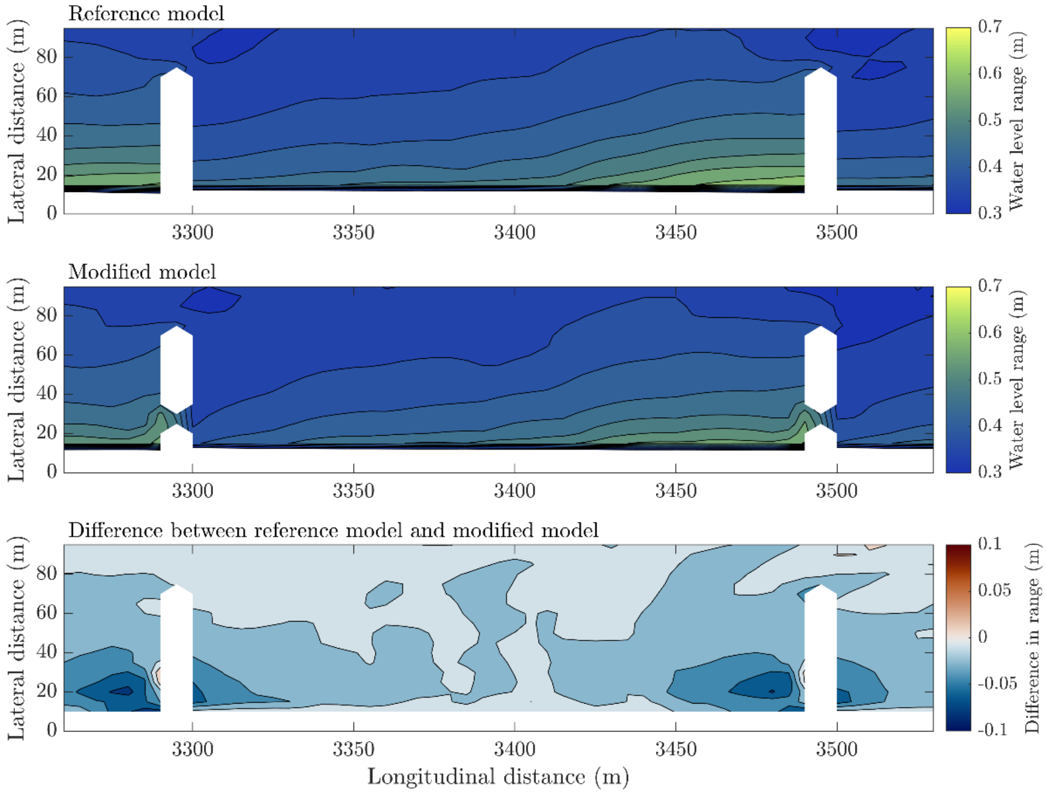
Number of notches	Location of notch	Width notch	Depth notch
1	45 m	10 m	1.0 m



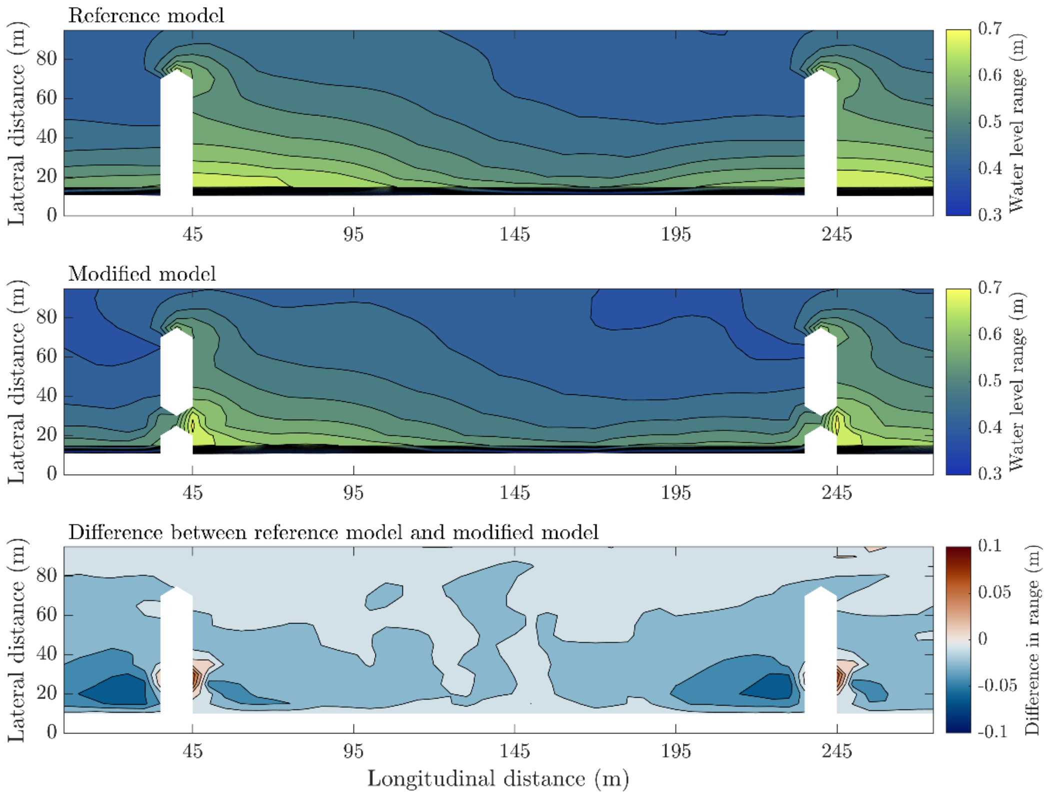
Water level range upstream sailing



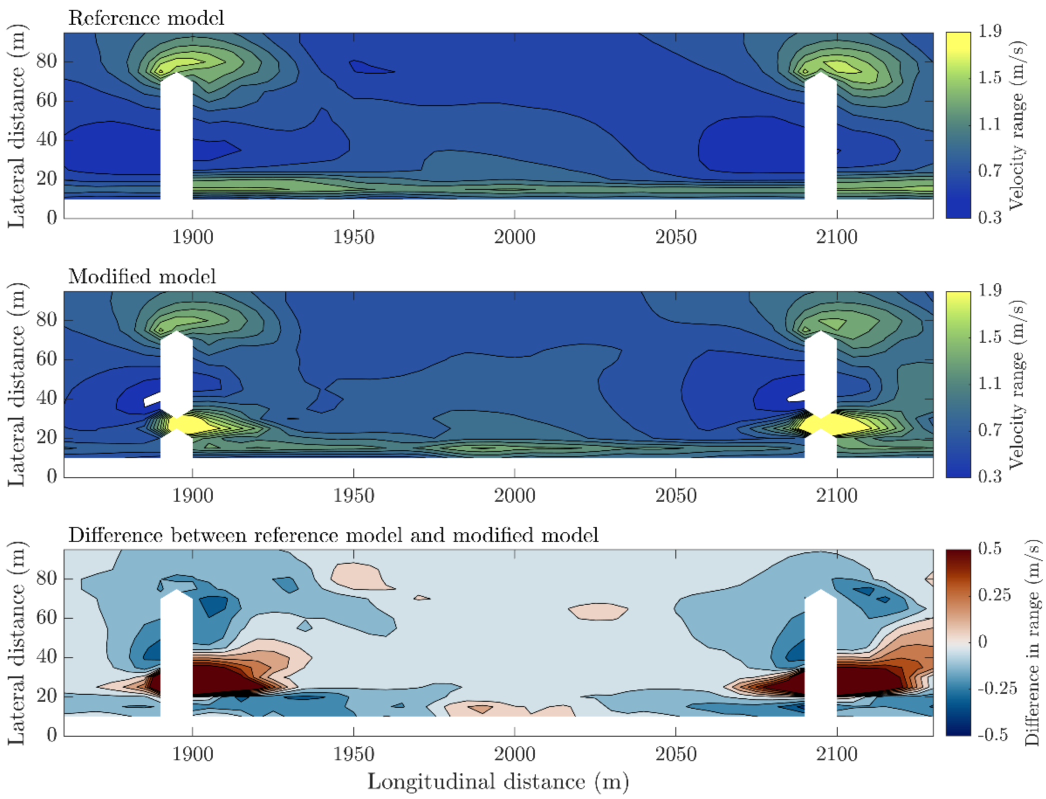
Water level range downstream sailing



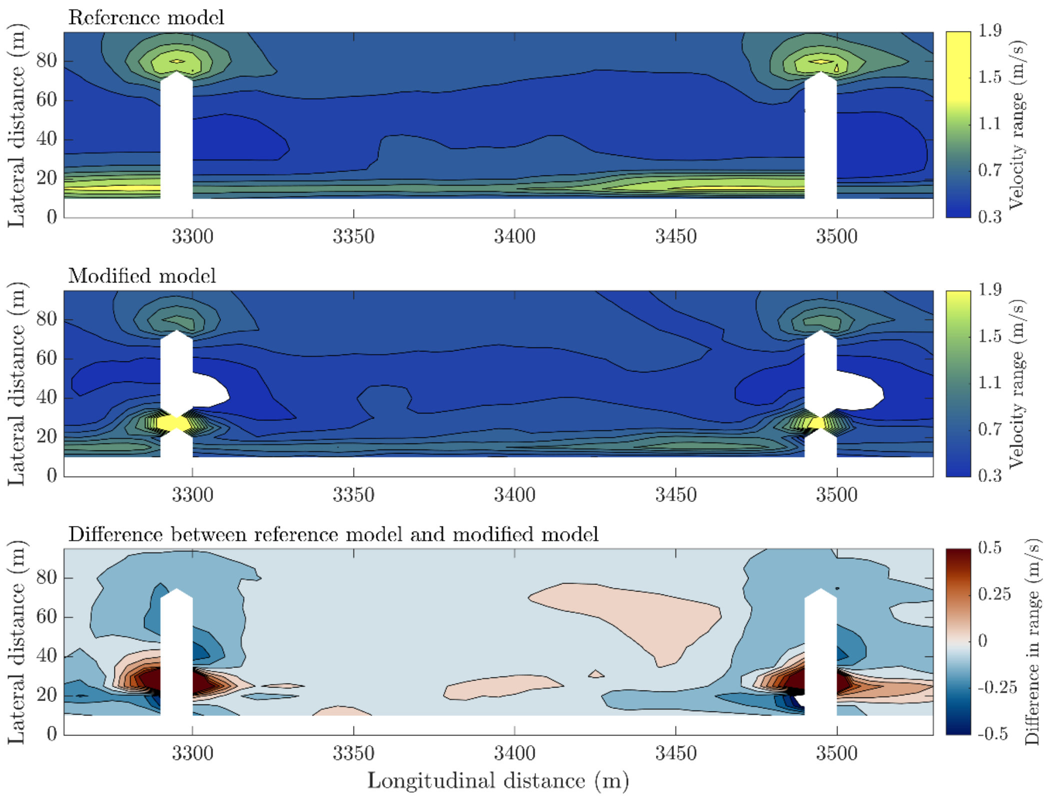
Combined water level range



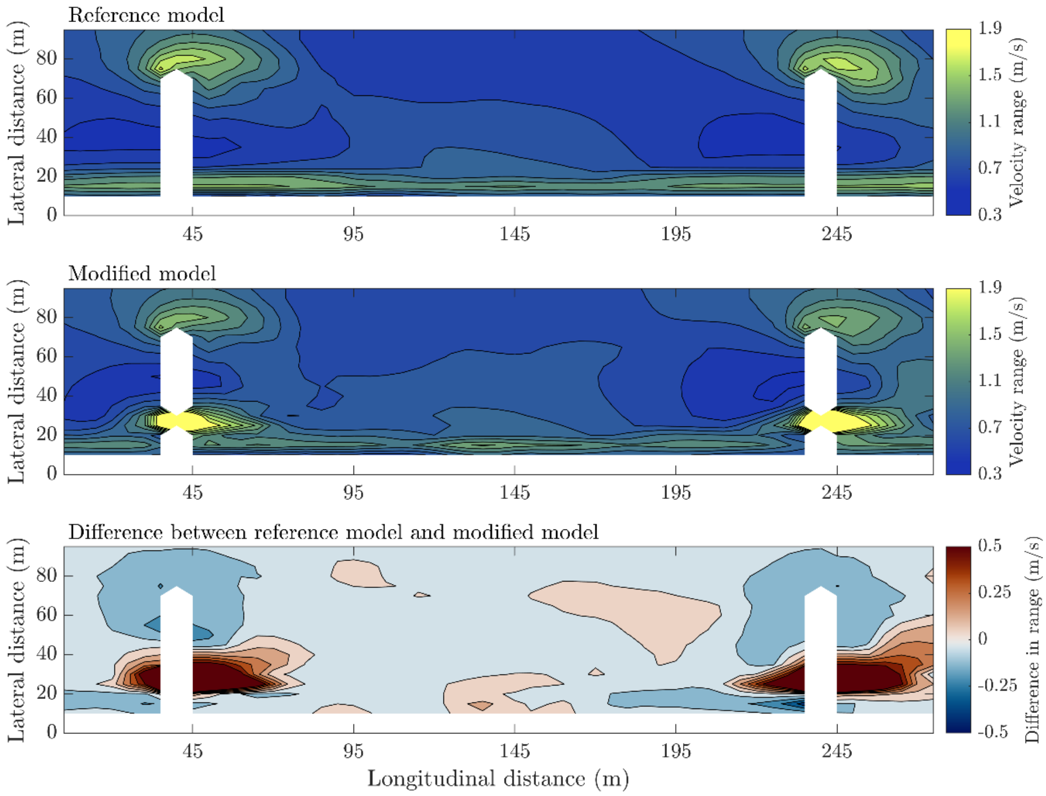
Velocity range upstream sailing



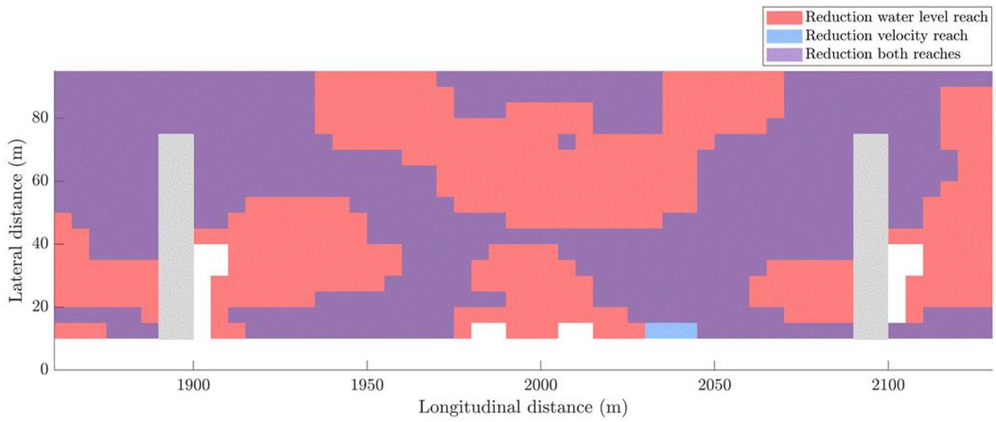
Velocity range downstream sailing



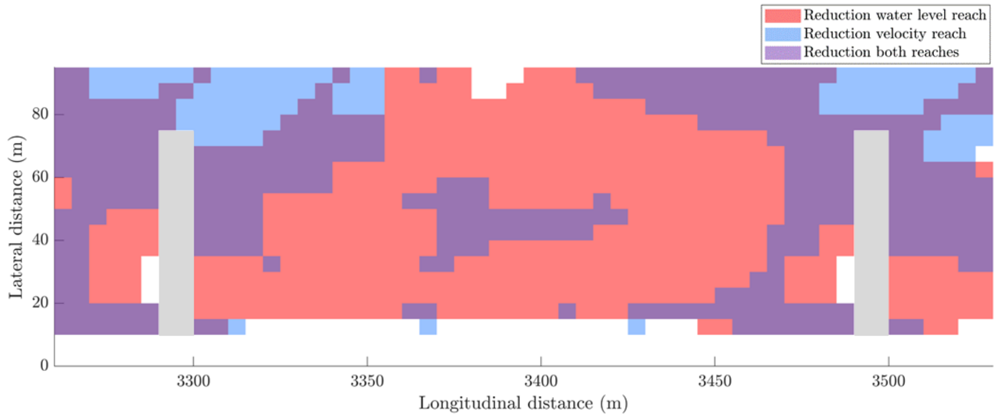
Combined velocity range



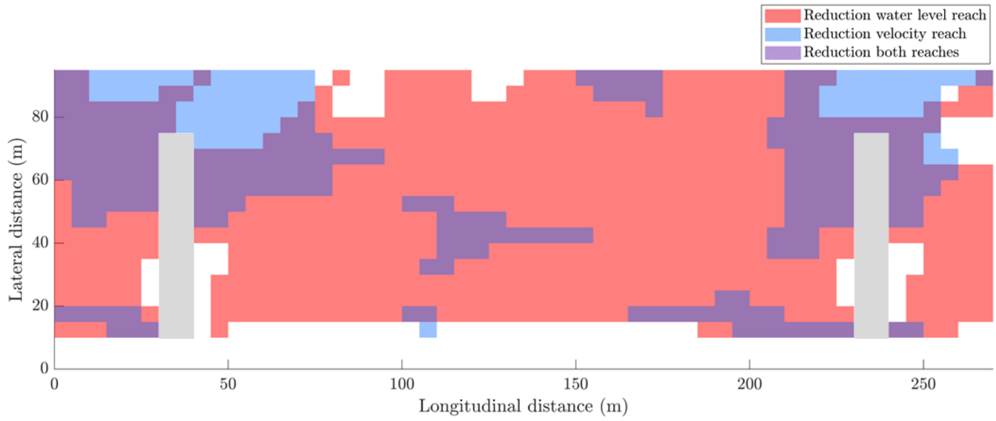
Overview plot upstream sailing



Overview plot dowstream sailing

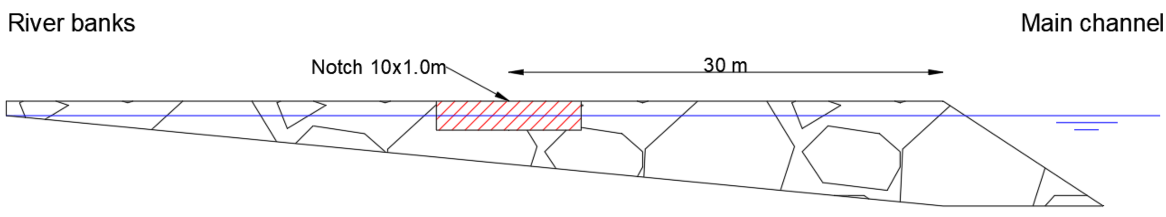


Combined overview plot

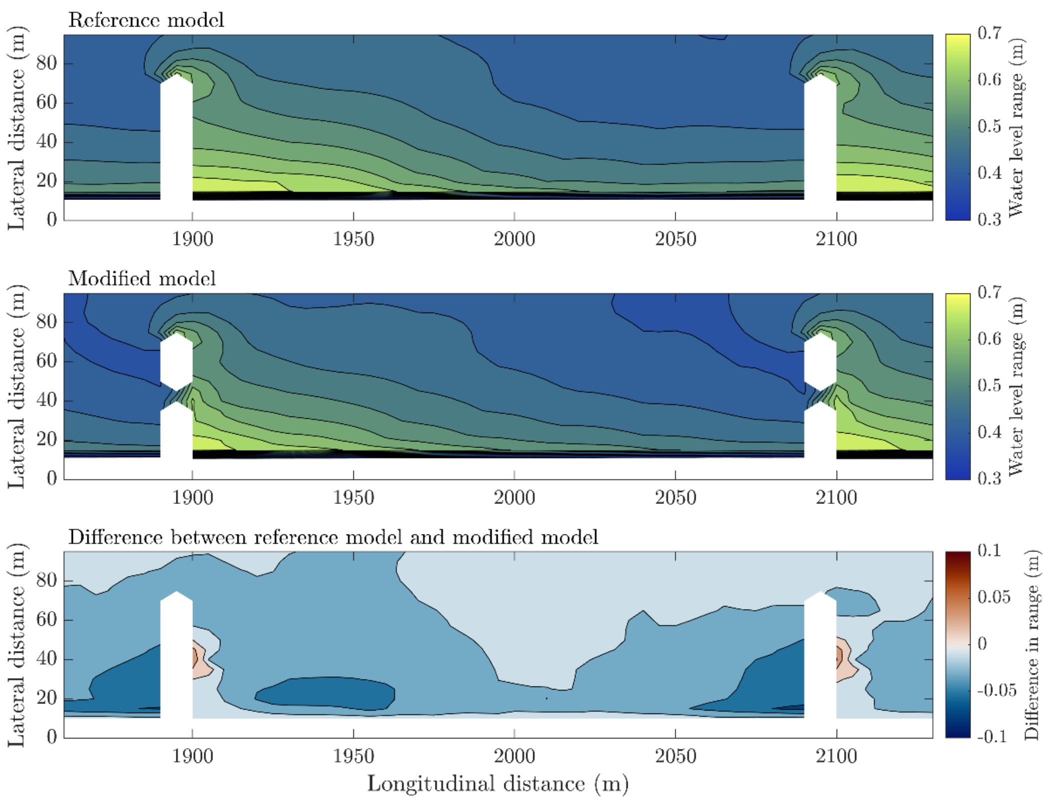


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.108	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.208	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

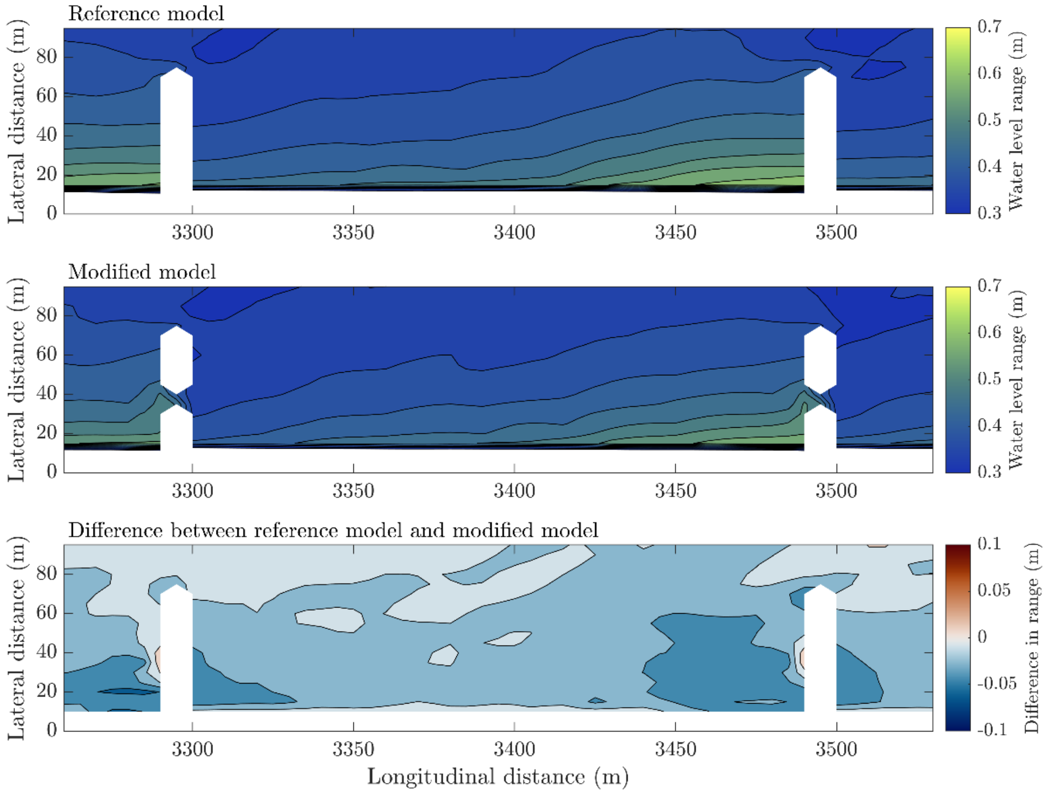
Number of notches	Location of notch	Width notch	Depth notch
1	30 m	10 m	1.0 m



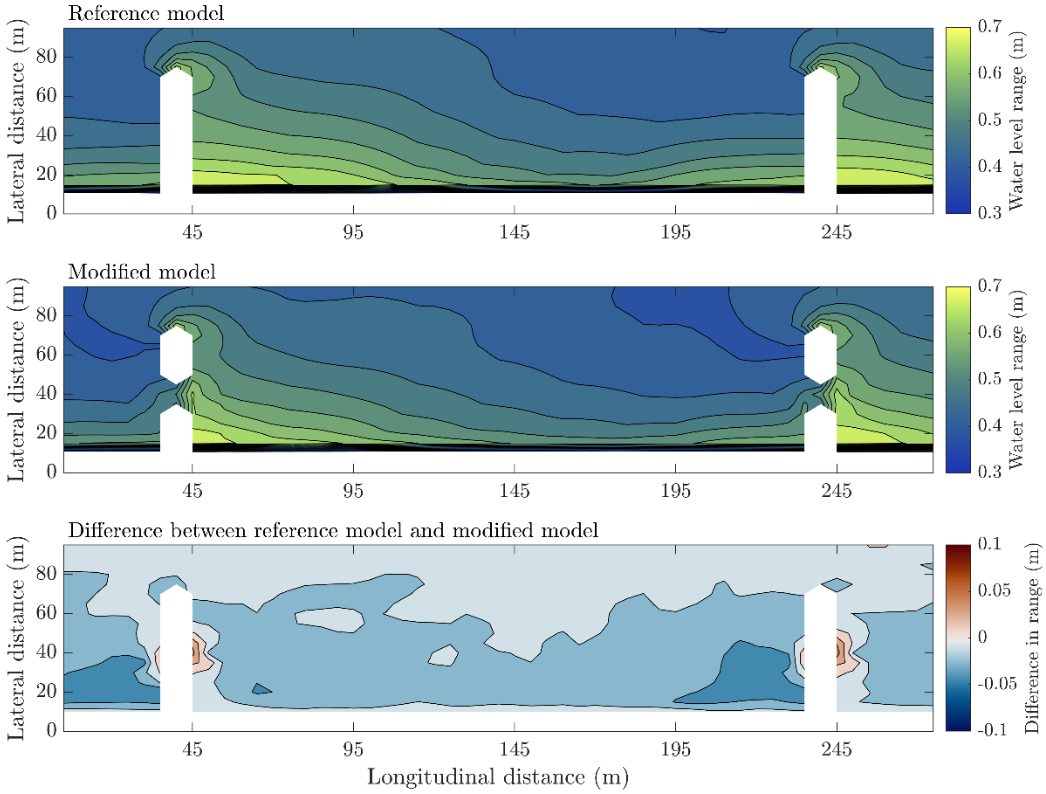
Water level range upstream sailing



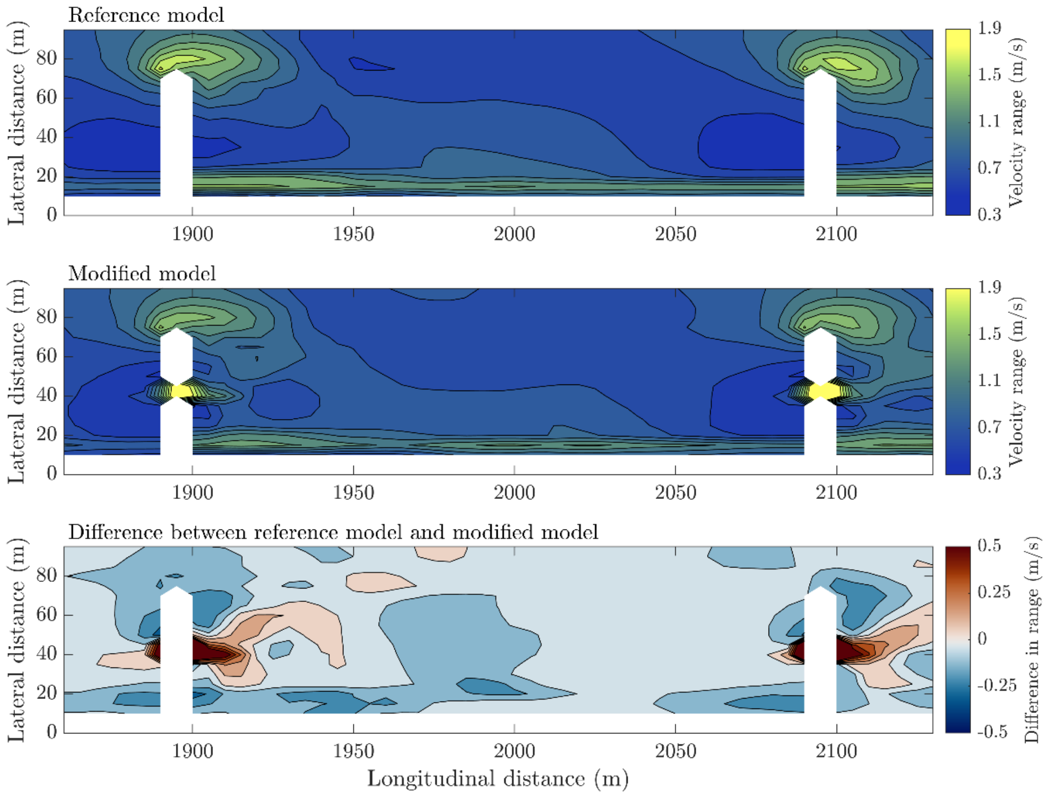
Water level range downstream sailing



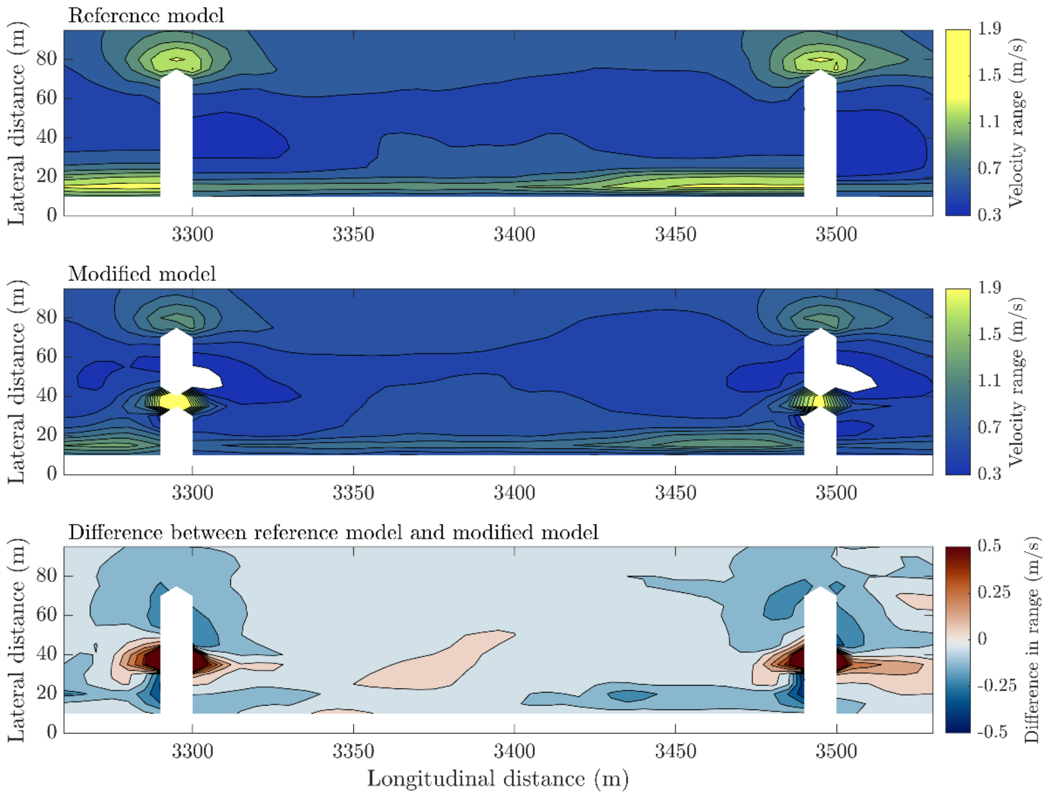
Combined water level range



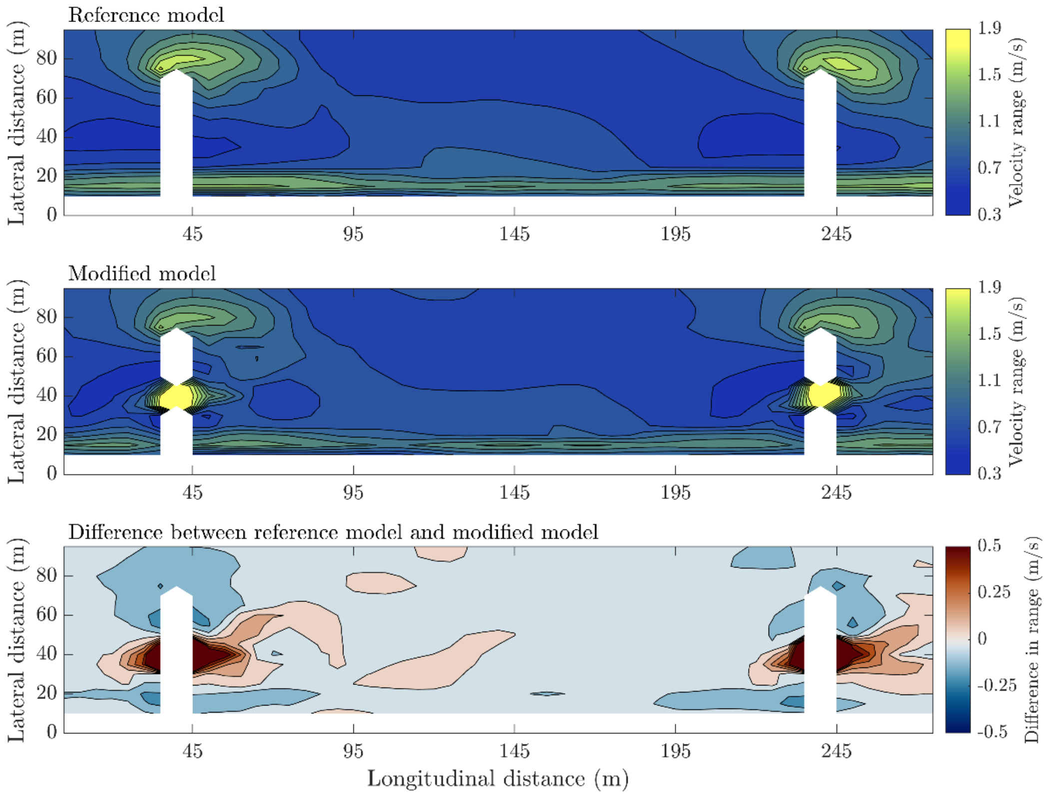
Velocity range upstream sailing



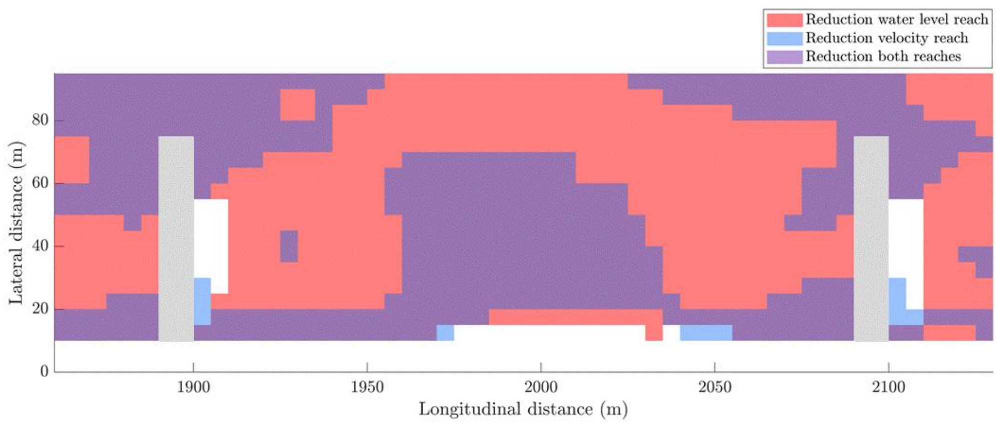
Velocity range downstream sailing



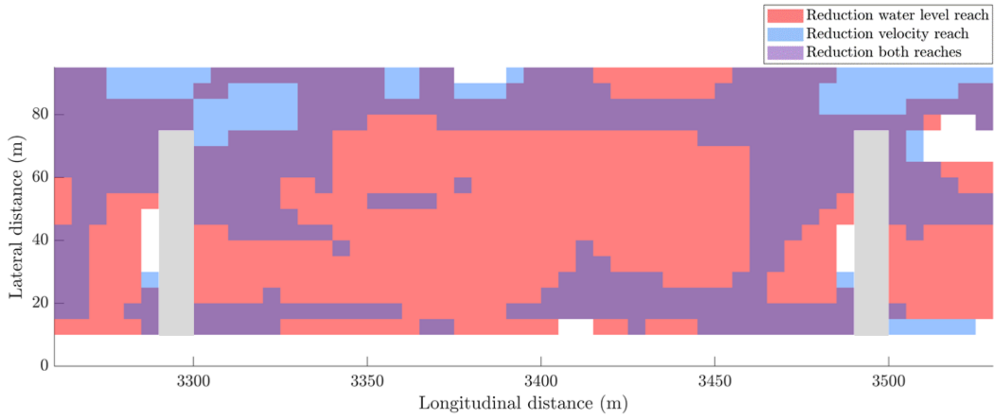
Combined velocity range



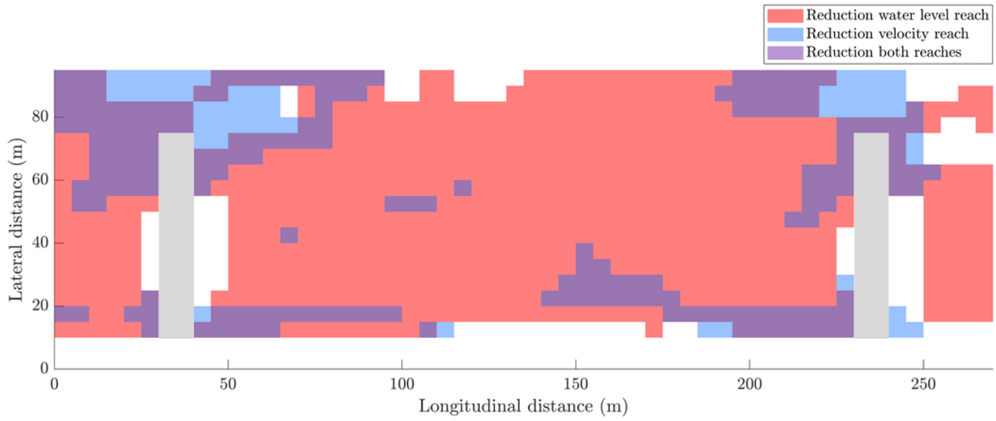
Overview plot upstream sailing



Overview plot dowstream sailing

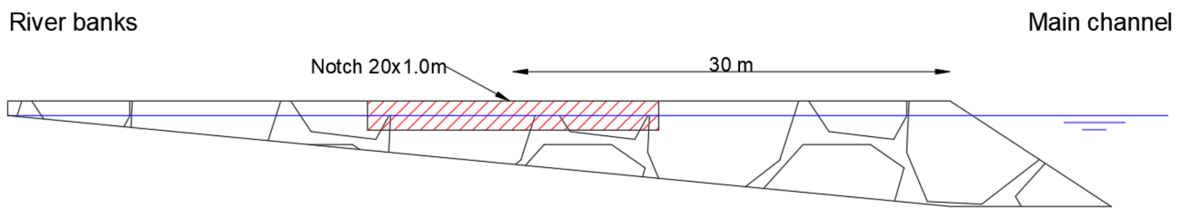


Combined overview plot

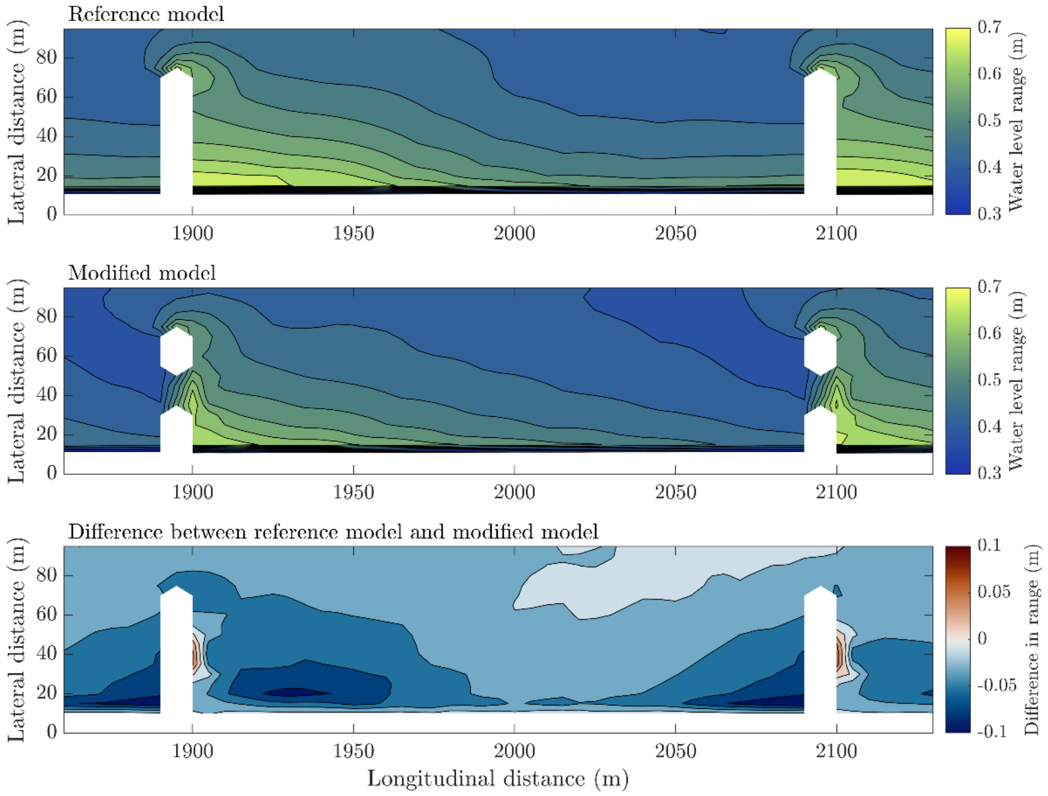


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.109	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.209	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

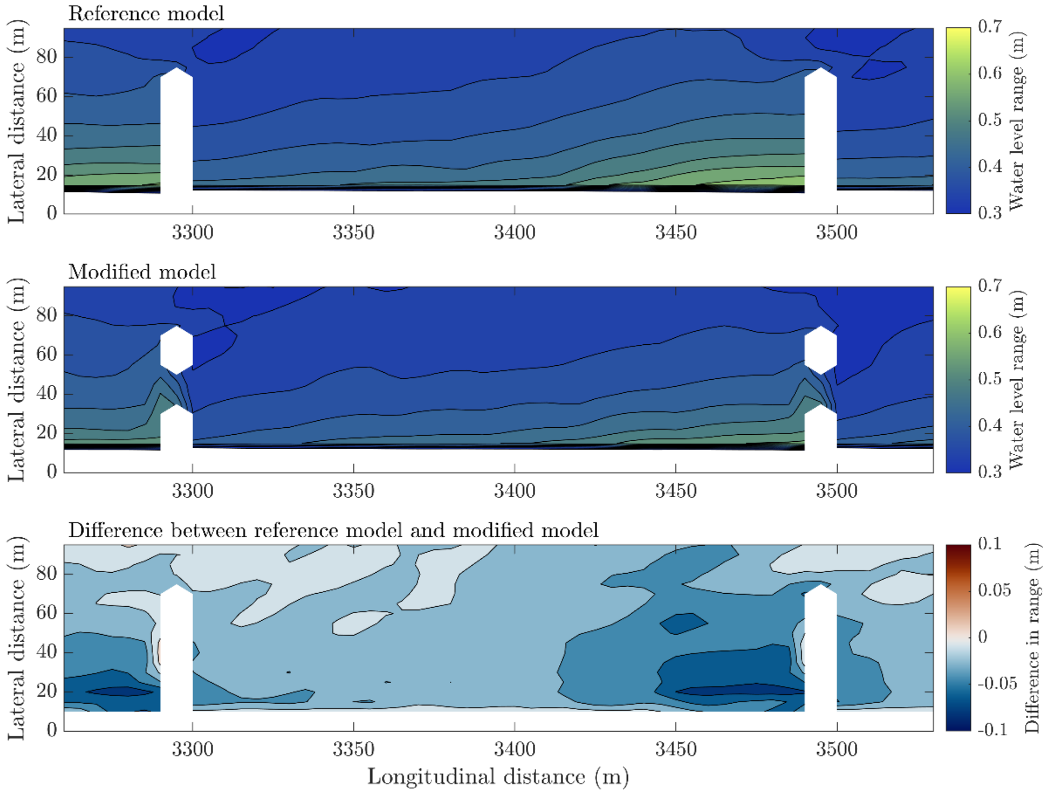
Number of notches	Location of notch	Width notch	Depth notch
1	30 m	20 m	1.0 m



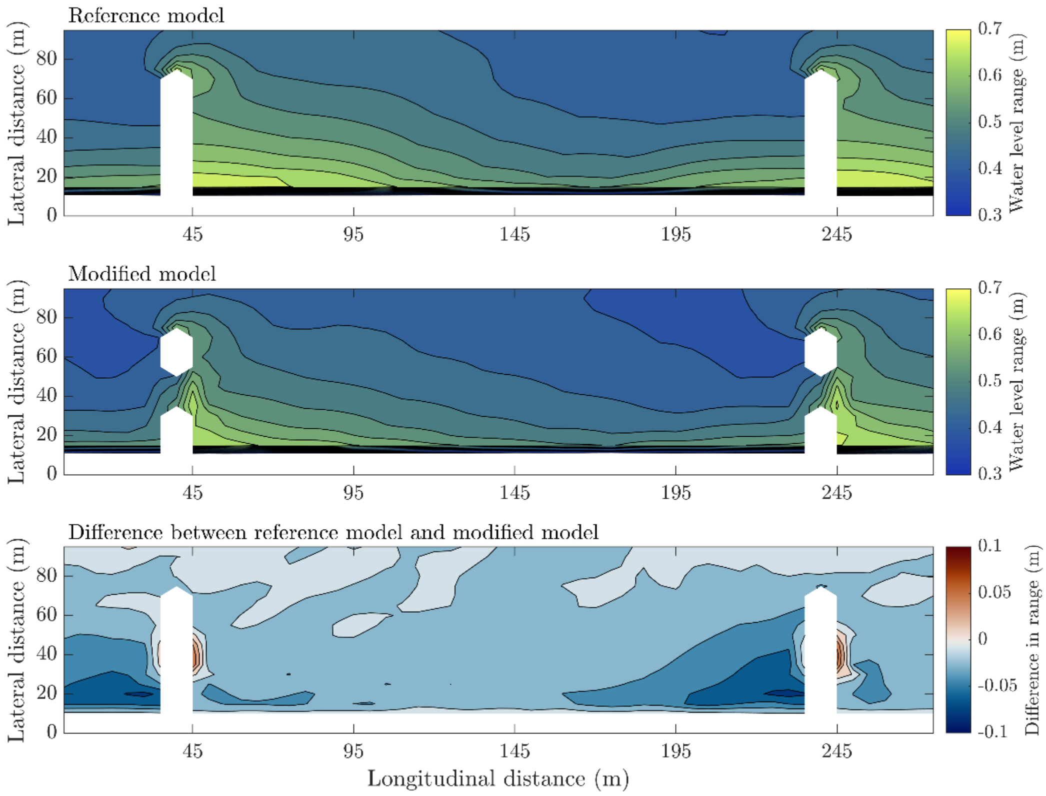
Water level range upstream sailing



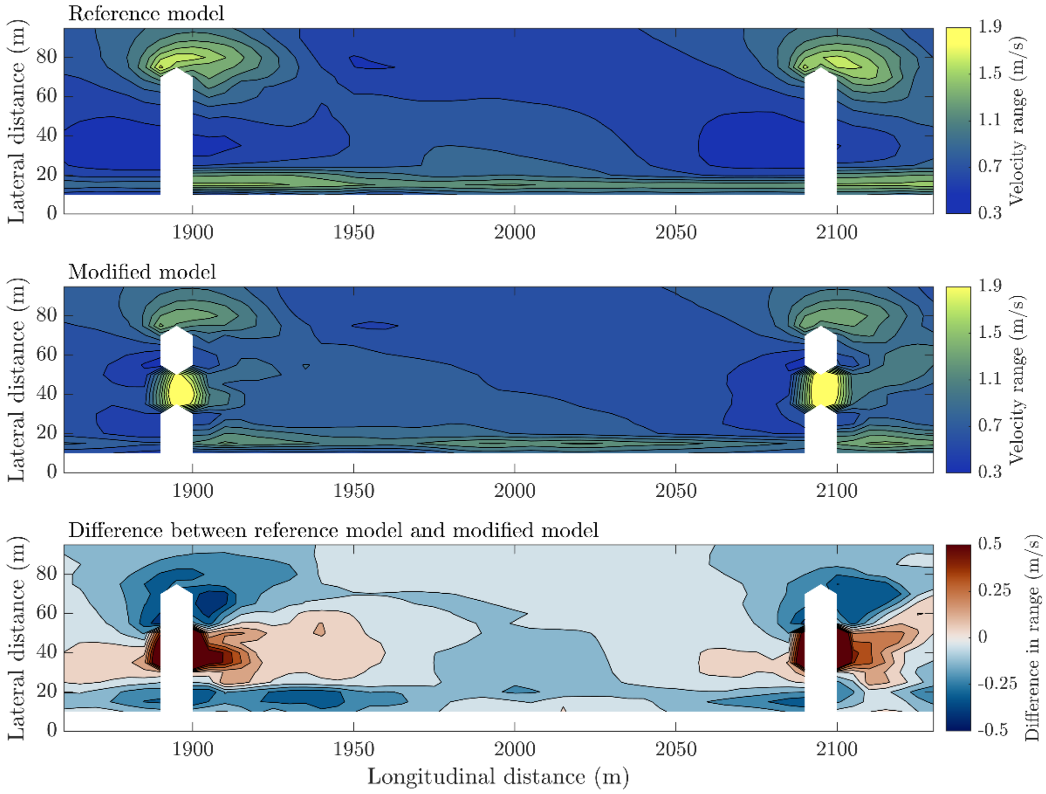
Water level range downstream sailing



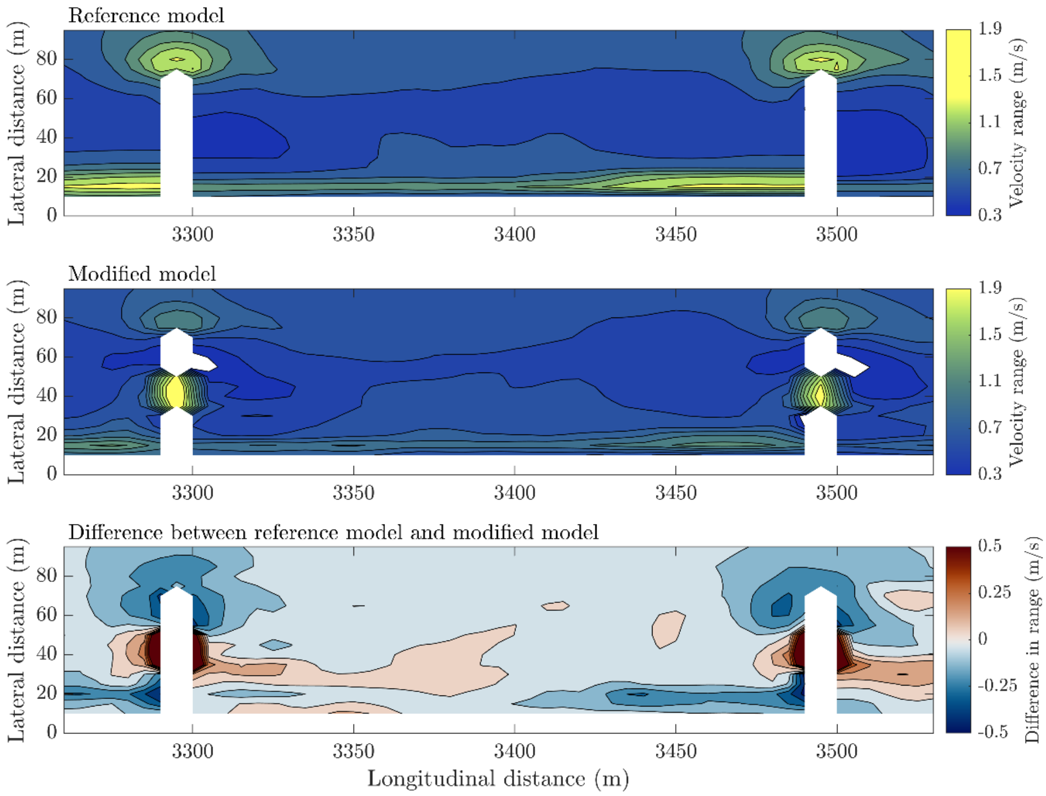
Combined water level range



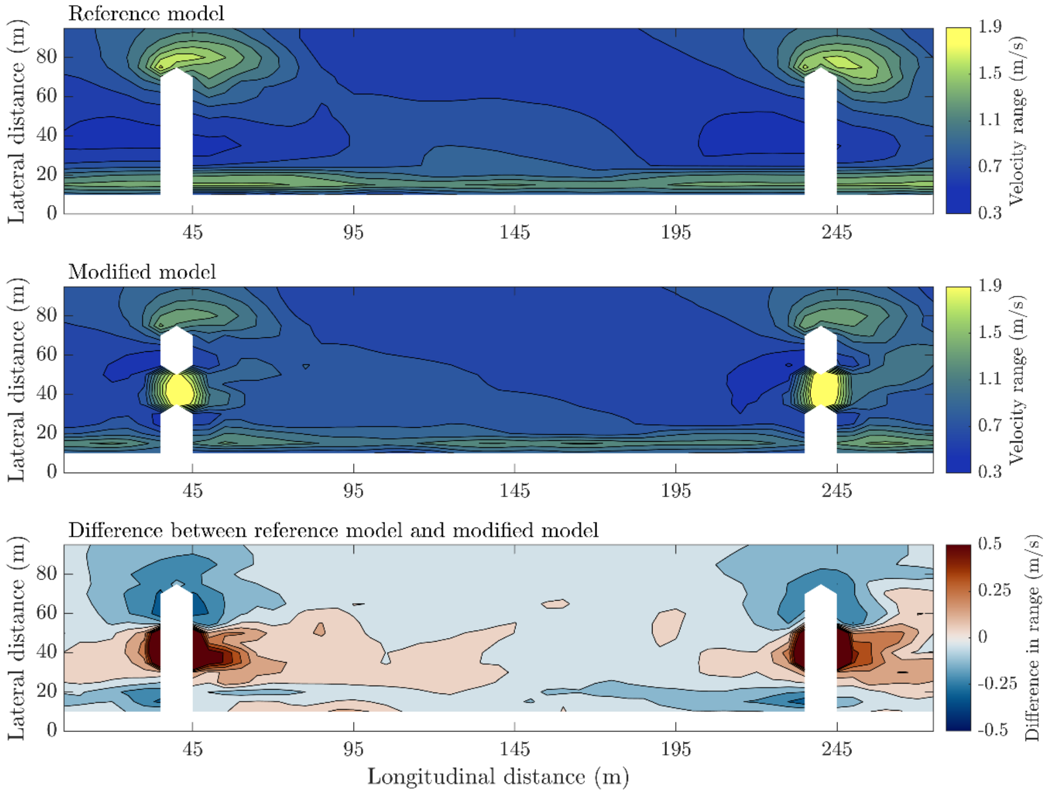
Velocity range upstream sailing



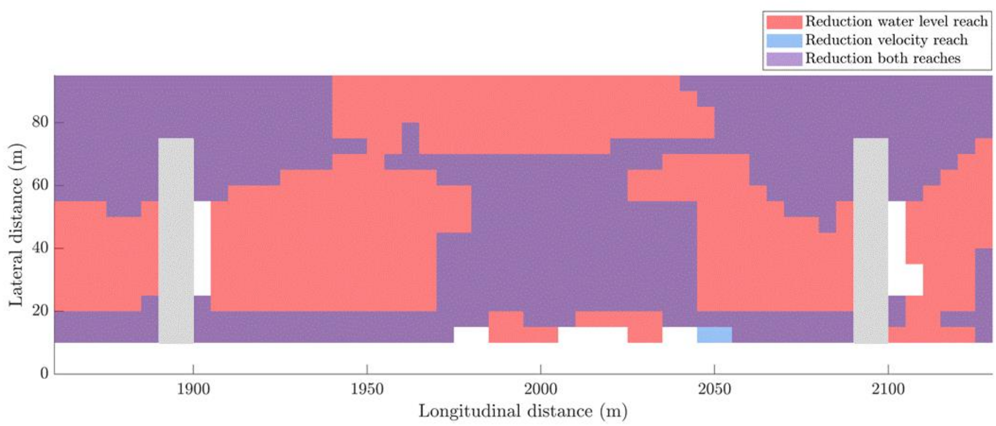
Velocity range downstream sailing



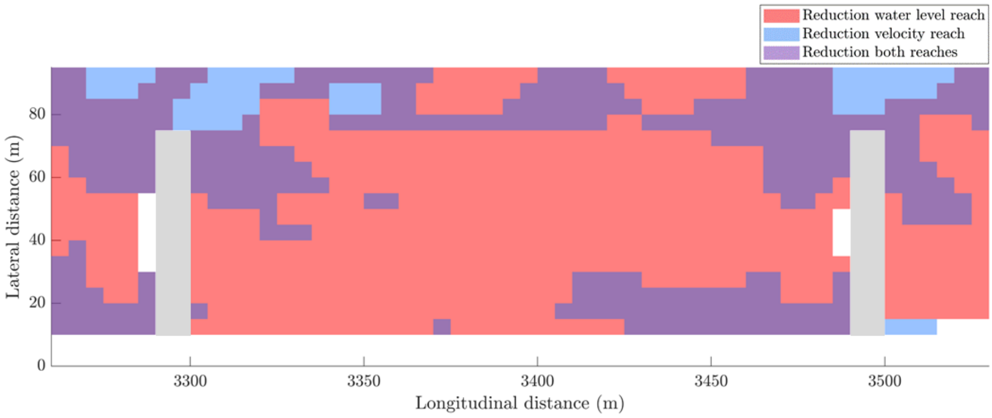
Combined velocity range



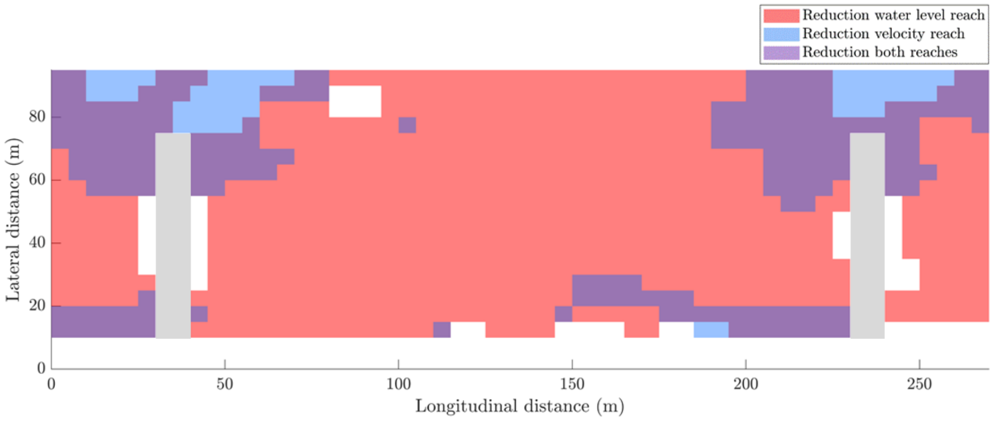
Overview plot upstream sailing



Overview plot dowstream sailing

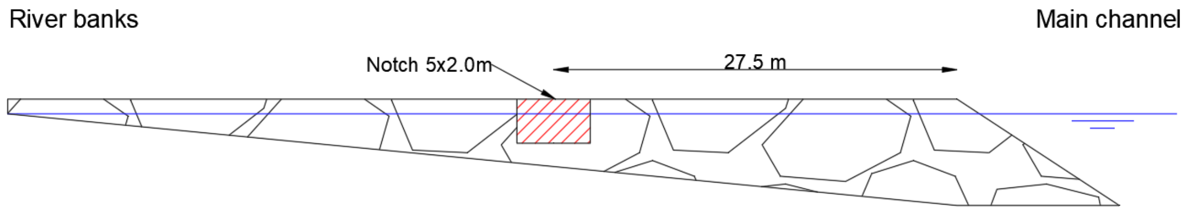


Combined overview plot

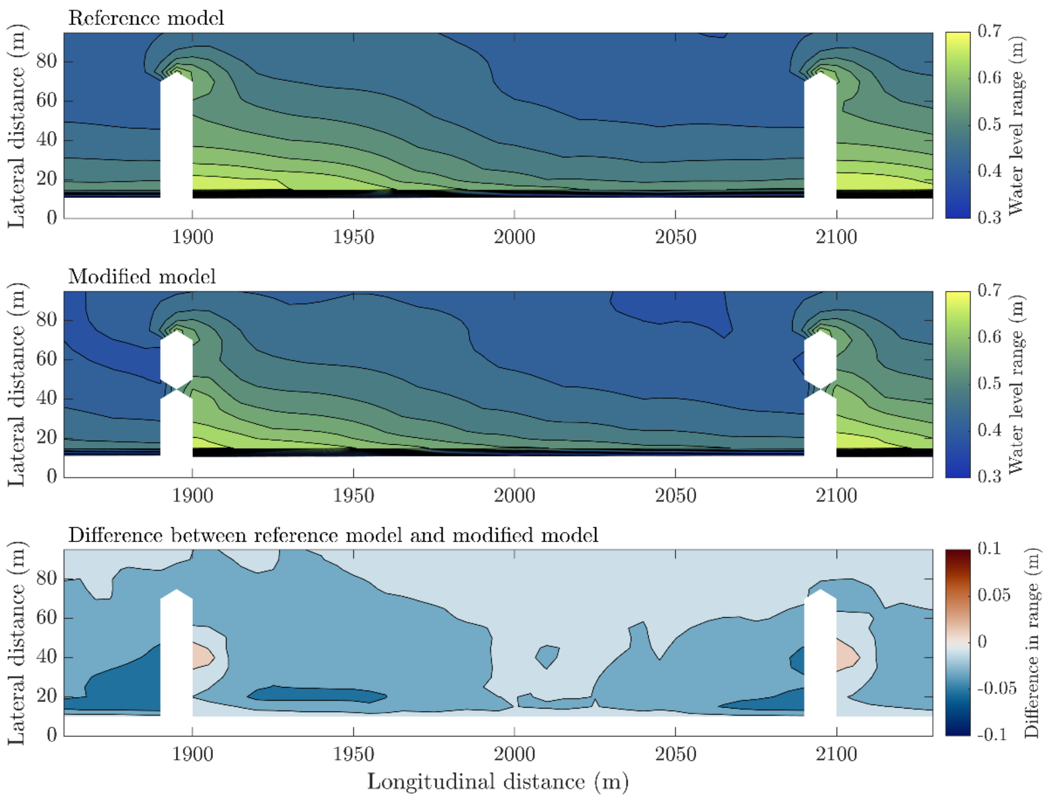


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.110	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.210	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

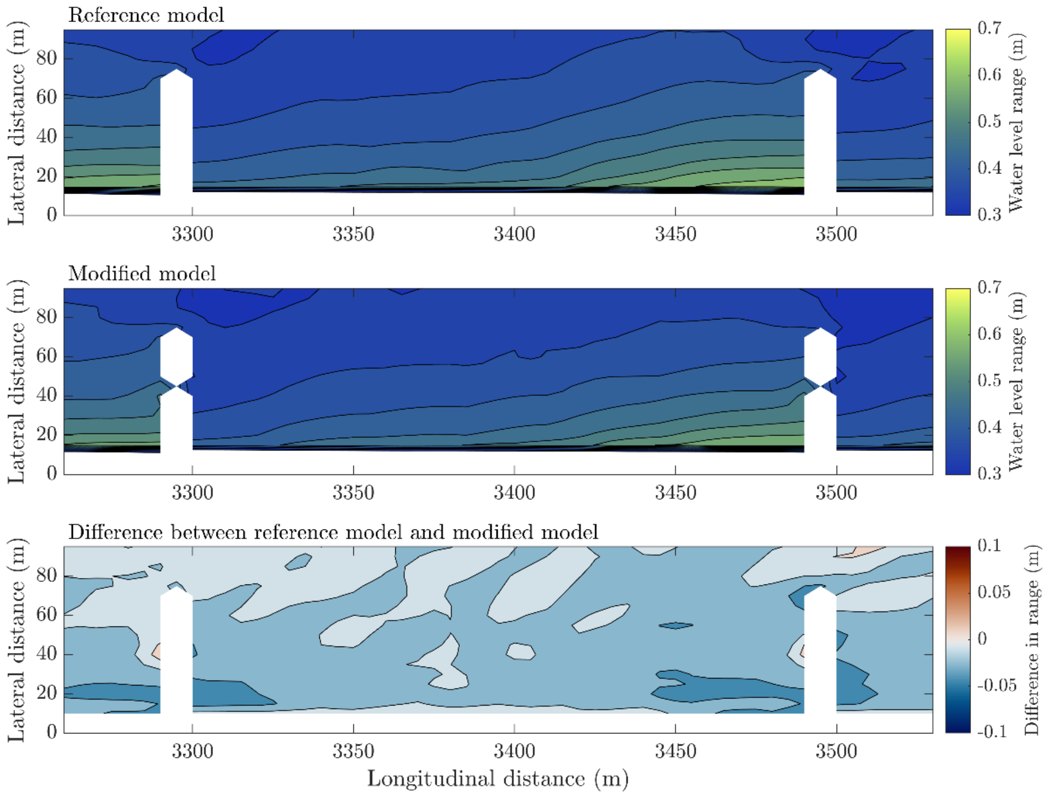
Number of notches	Location of notch	Width notch	Depth notch
1	27.5 m	5 m	2.0 m



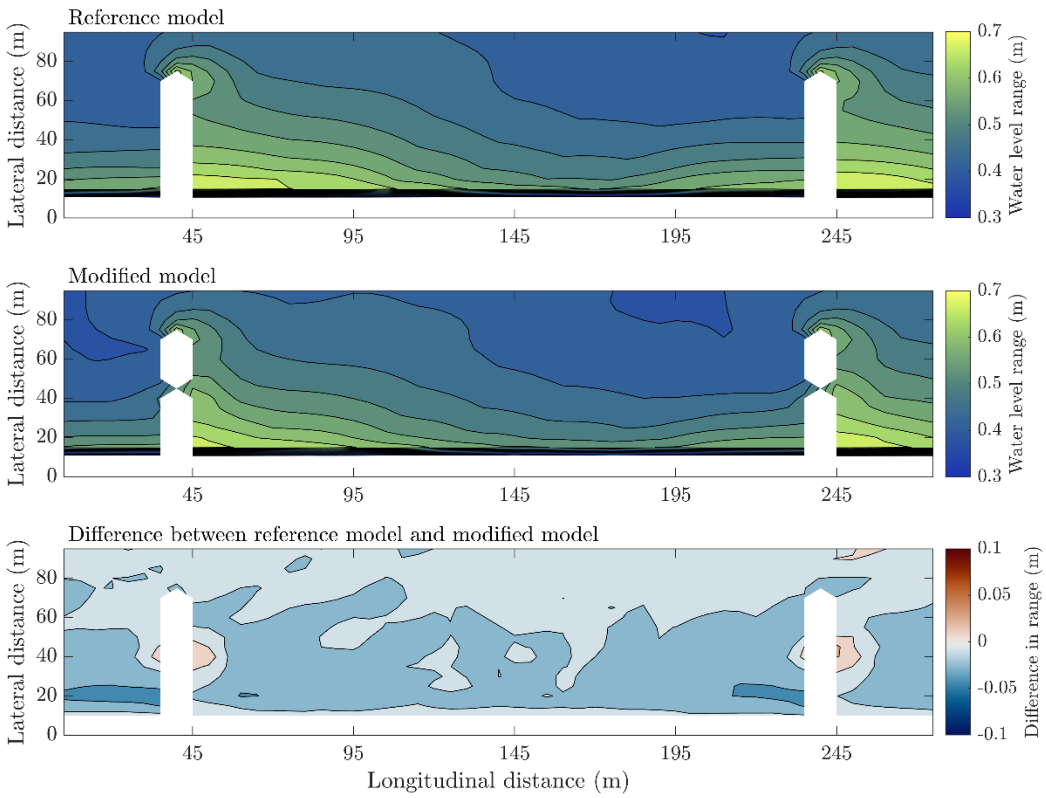
Water level range upstream sailing



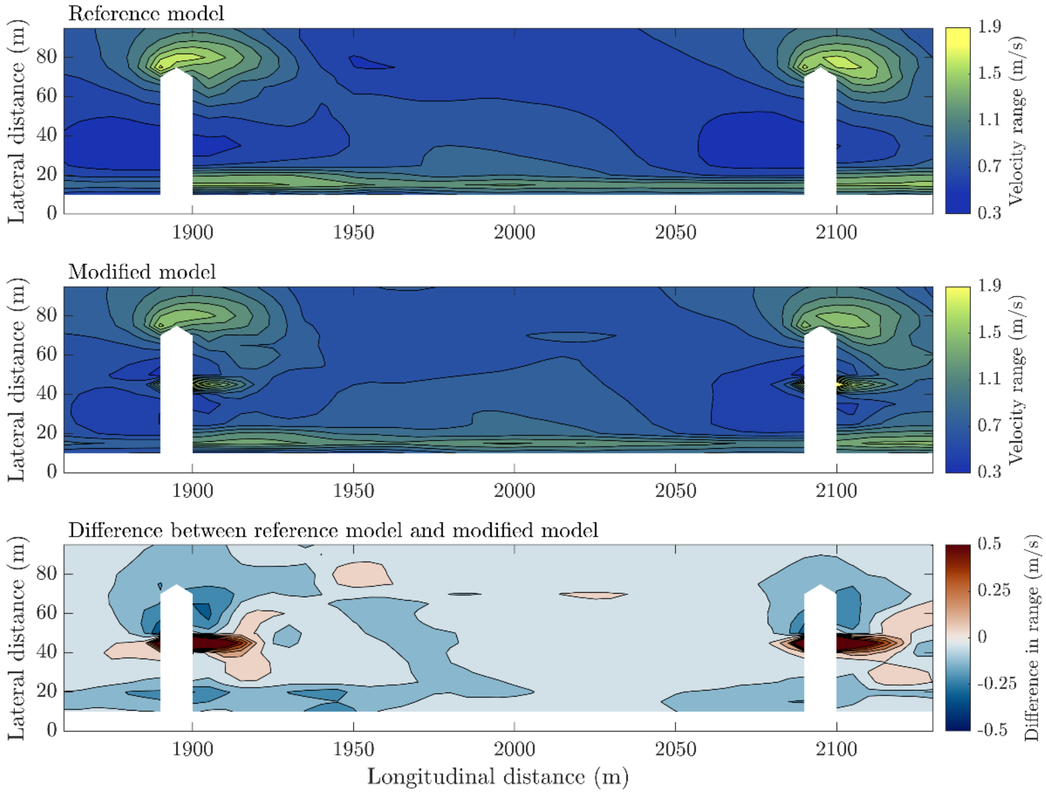
Water level range downstream sailing



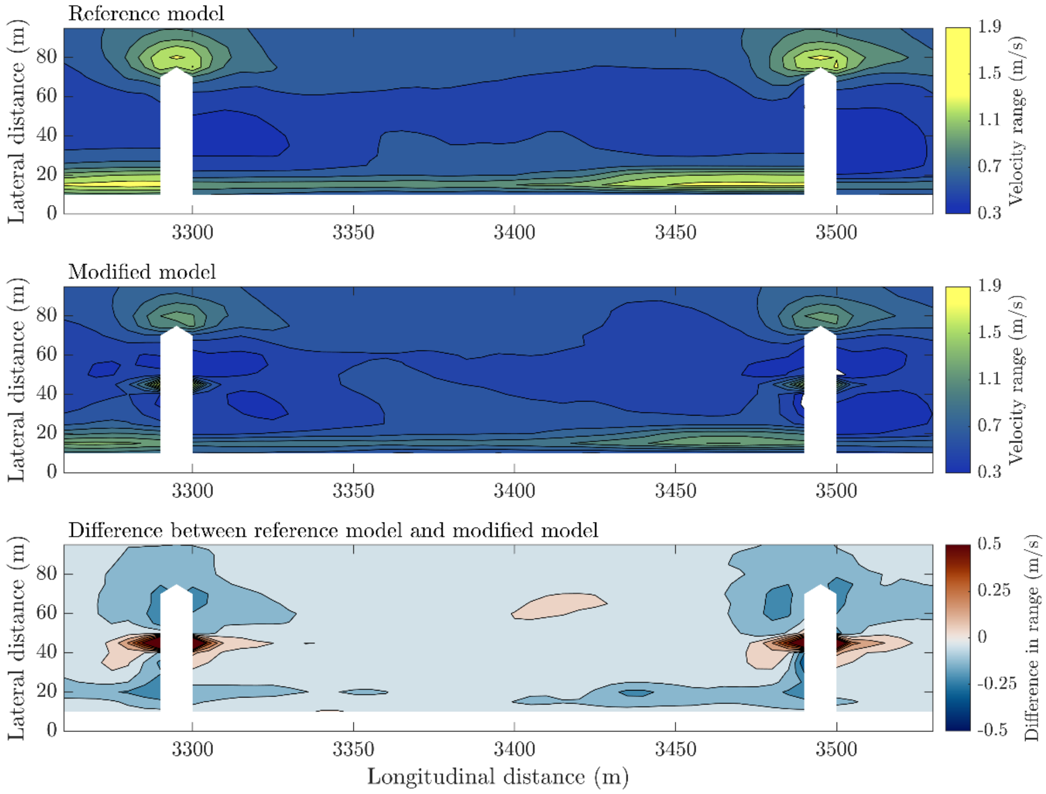
Combined water level range



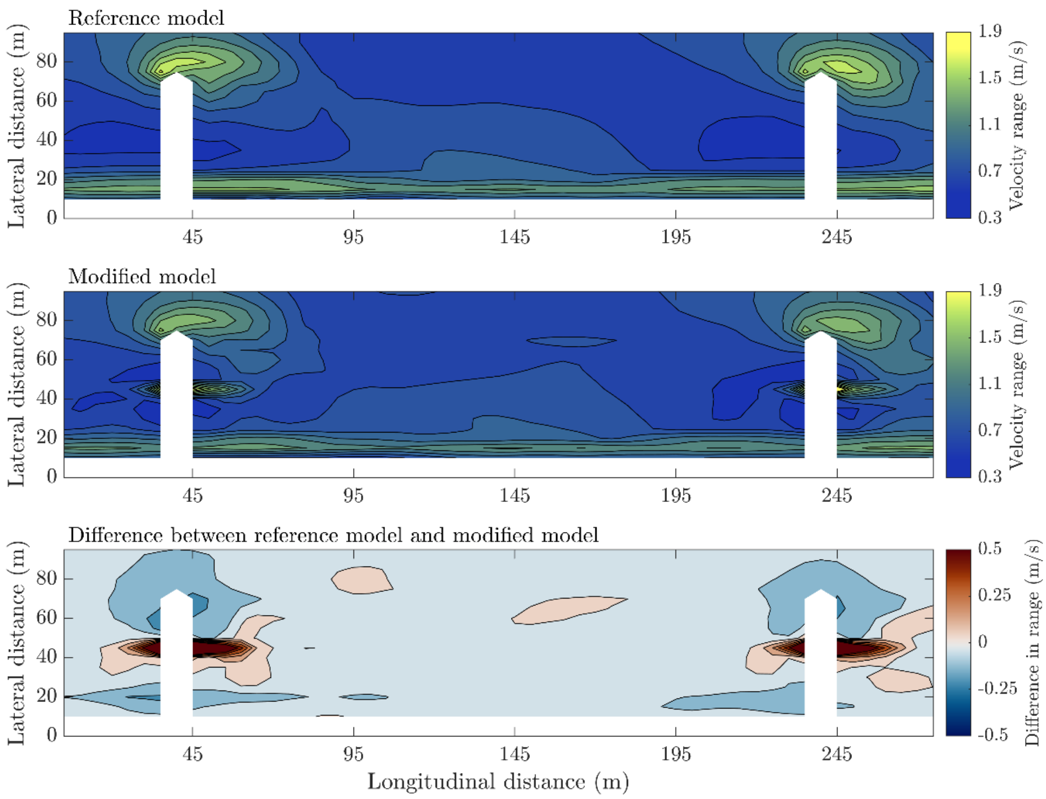
Velocity range upstream sailing



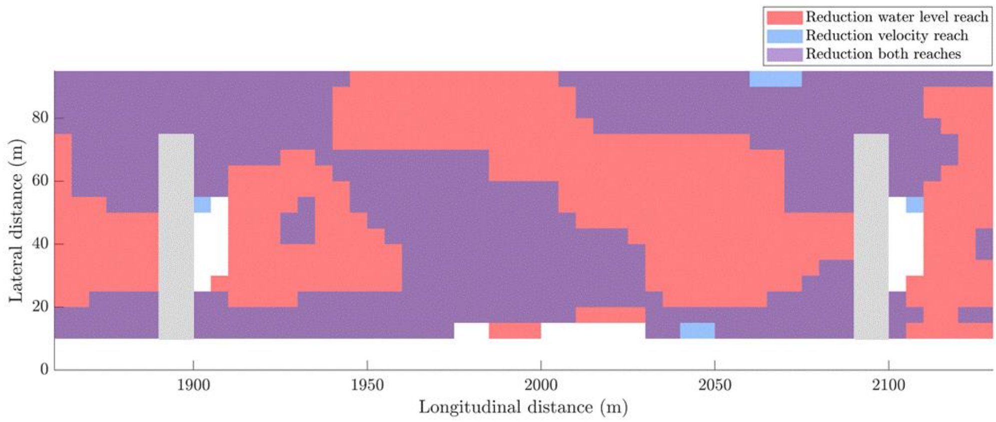
Velocity range downstream sailing



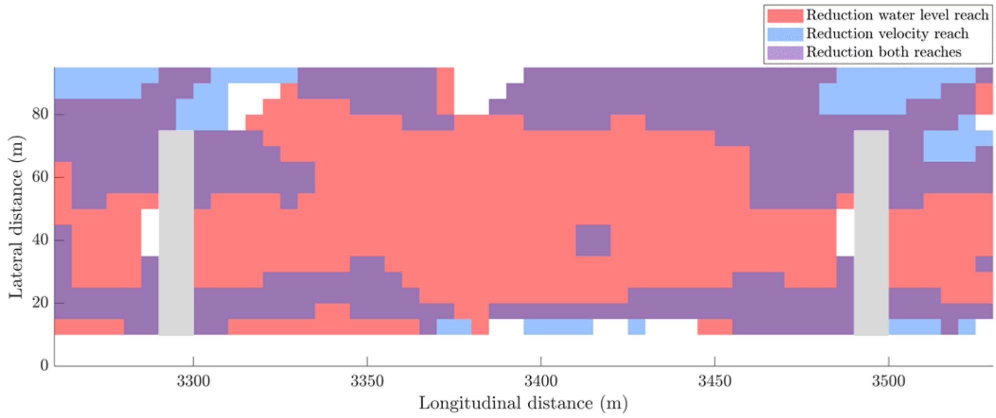
Combined velocity range



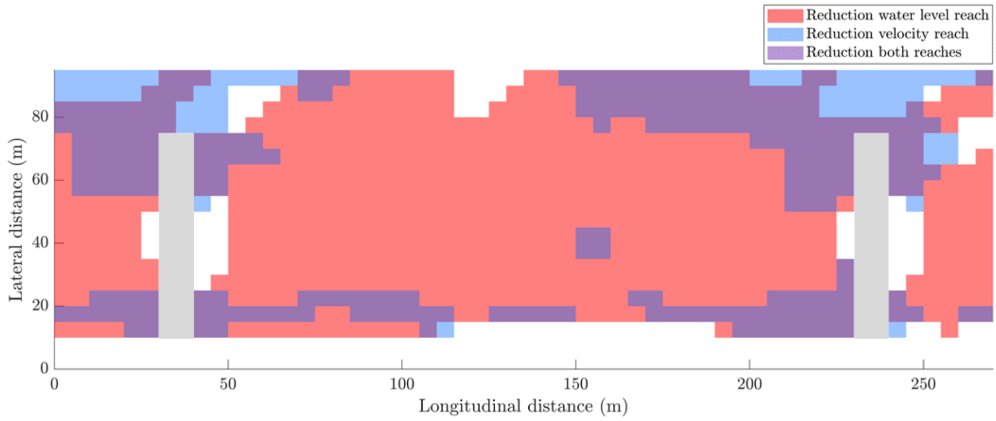
Overview plot upstream sailing



Overview plot dowstream sailing

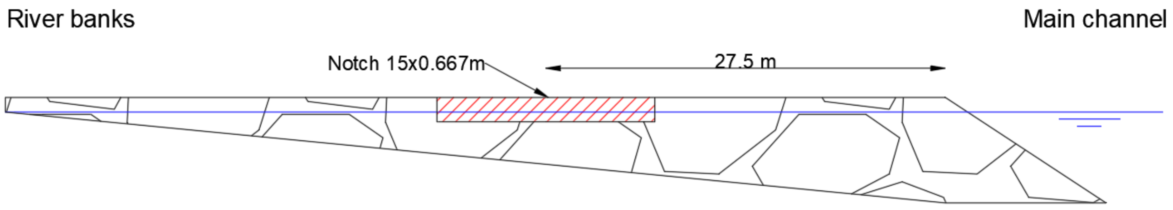


Combined overview plot

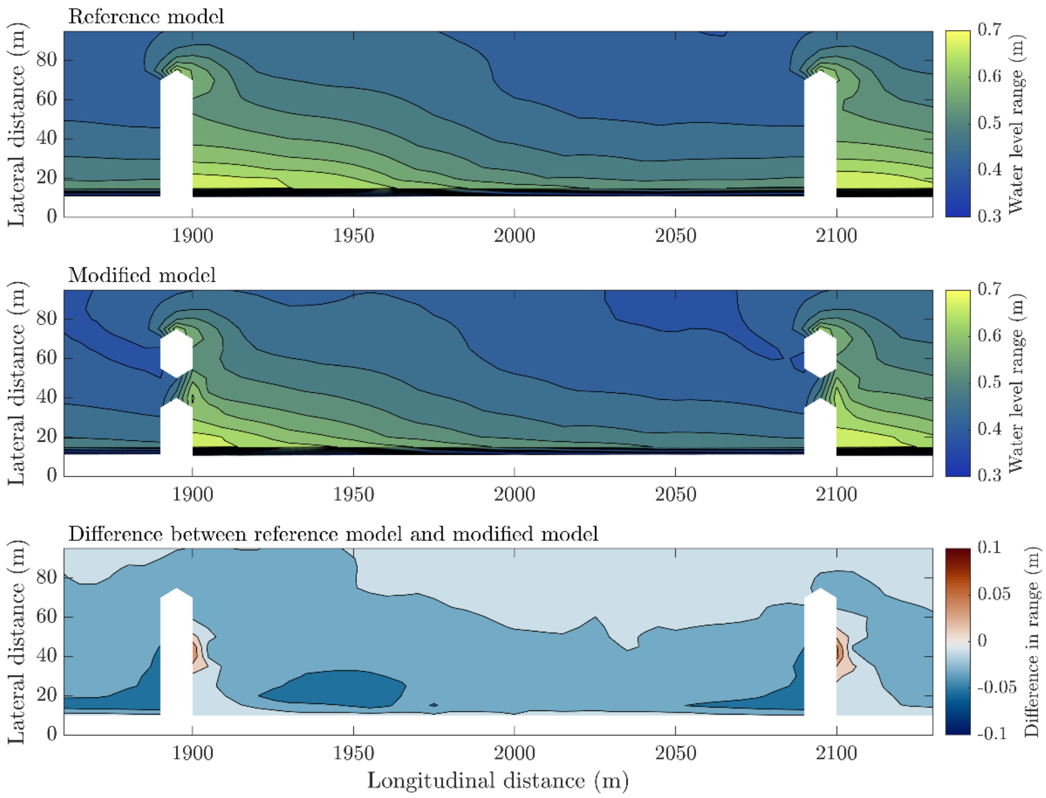


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.111	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.211	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

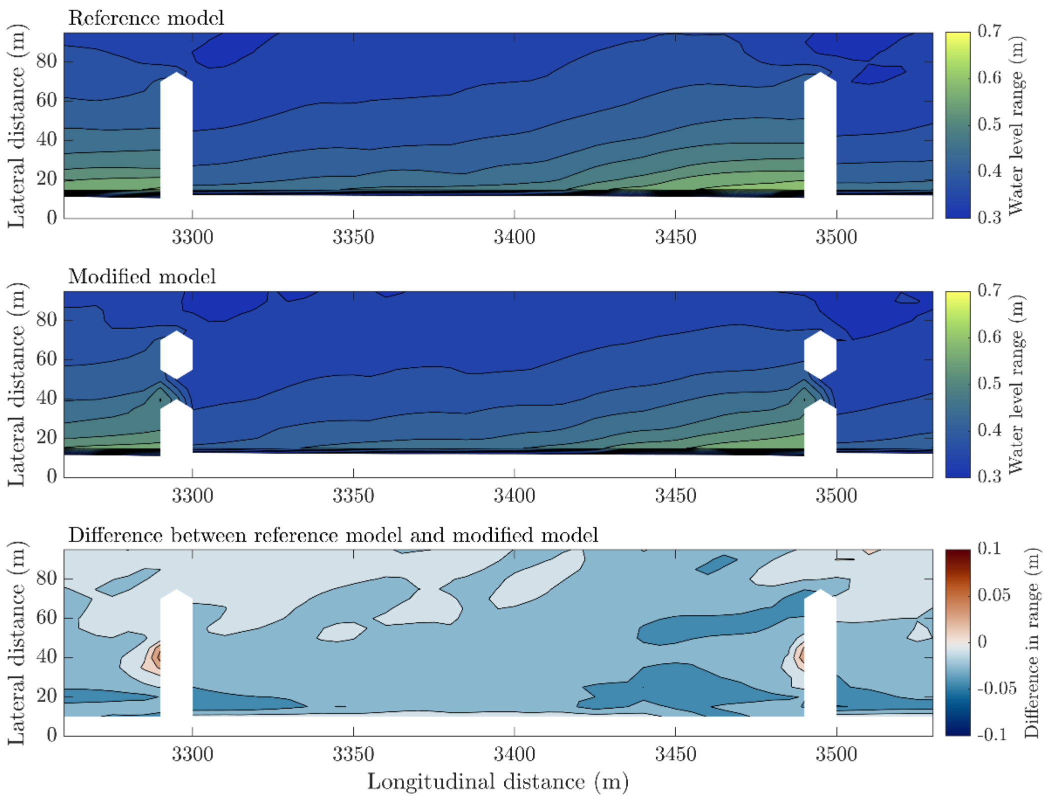
Number of notches	Location of notch	Width notch	Depth notch
1	27.5 m	15 m	0.667 m



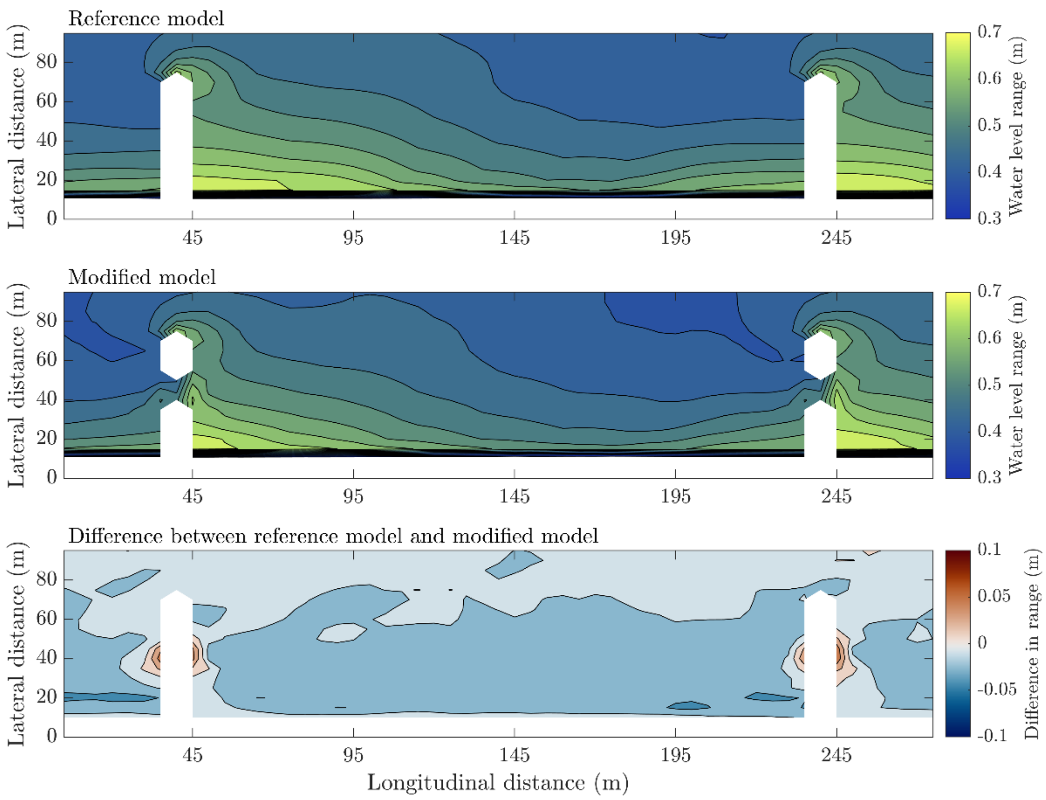
Water level range upstream sailing



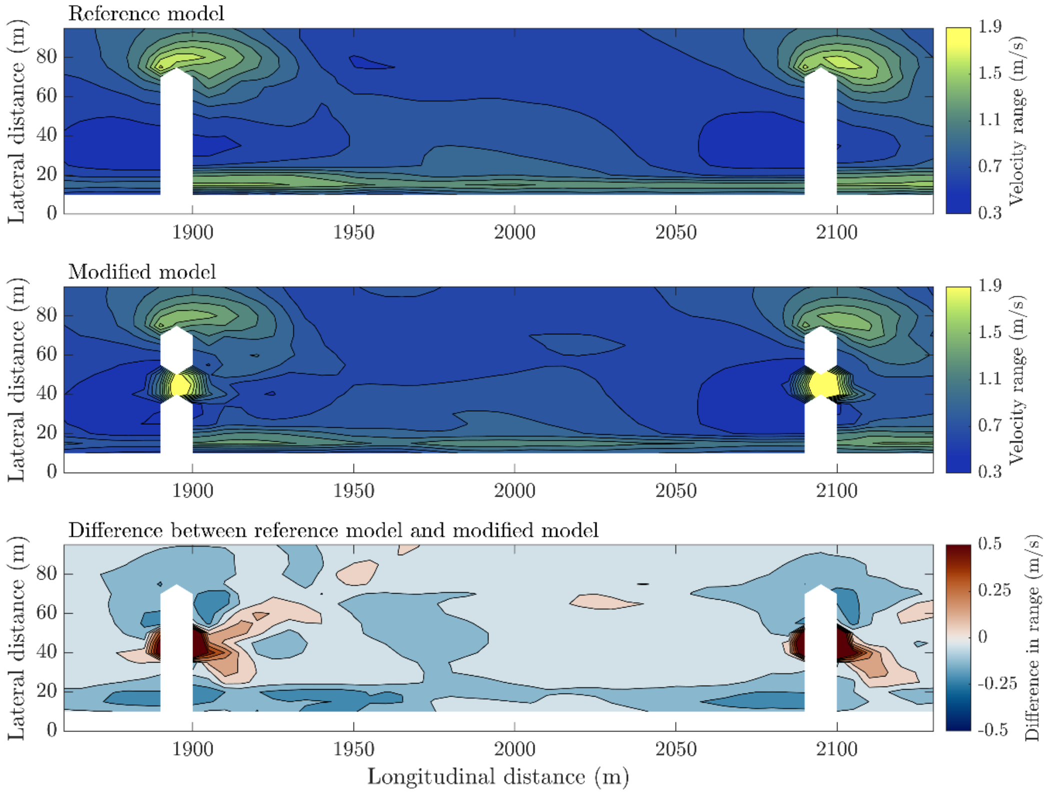
Water level range downstream sailing



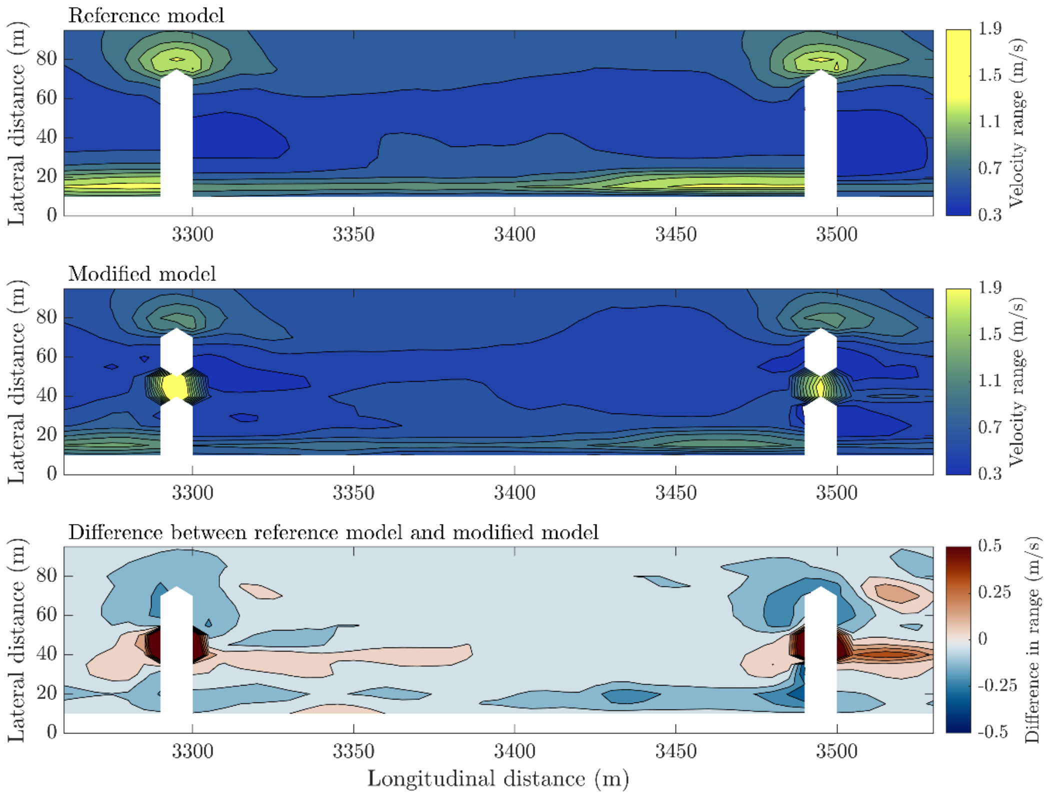
Combined water level range



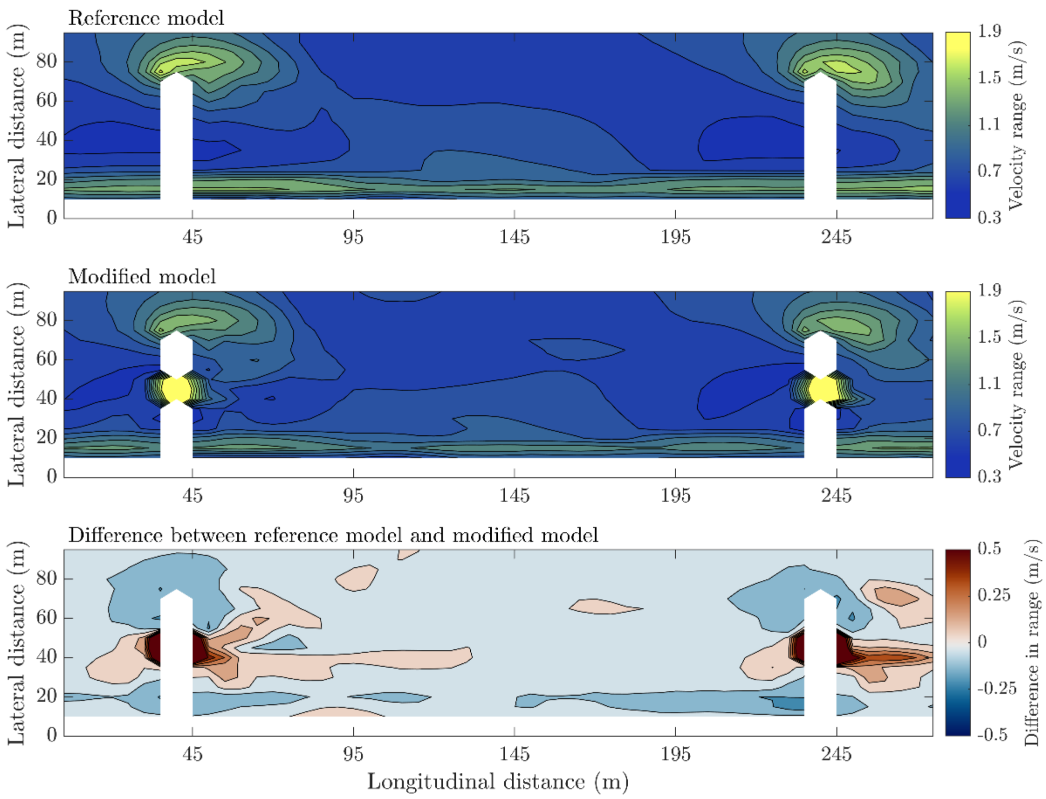
Velocity range upstream sailing



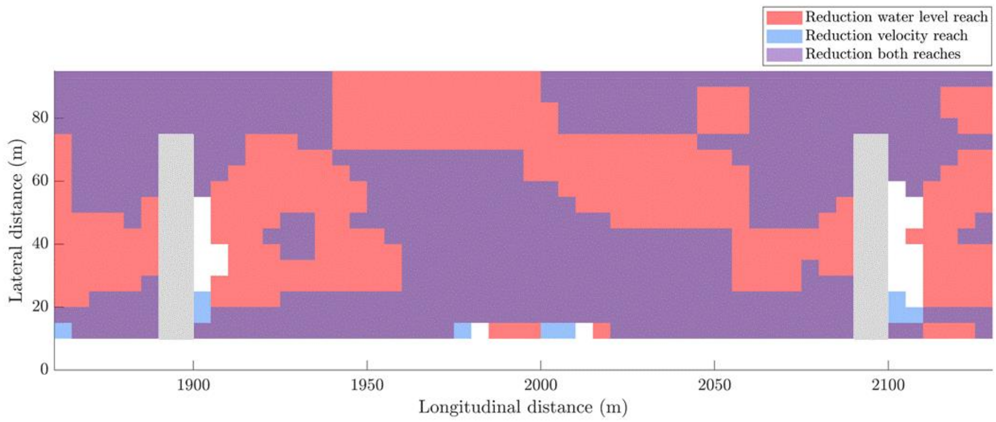
Velocity range downstream sailing



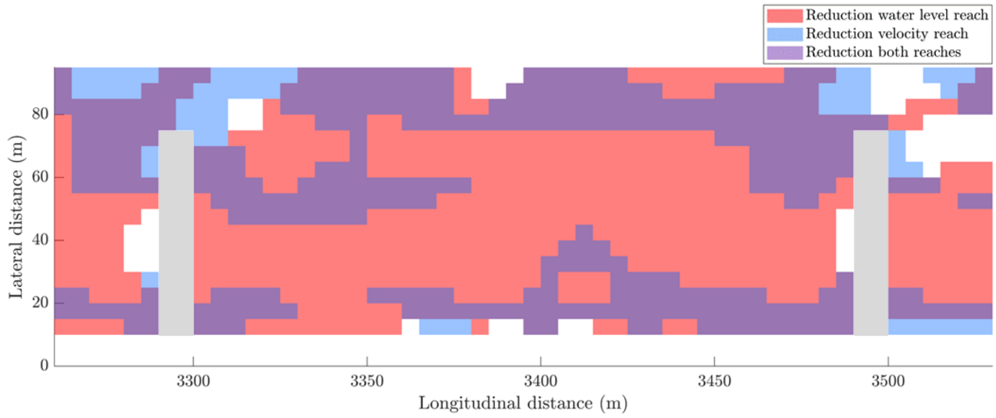
Combined velocity range



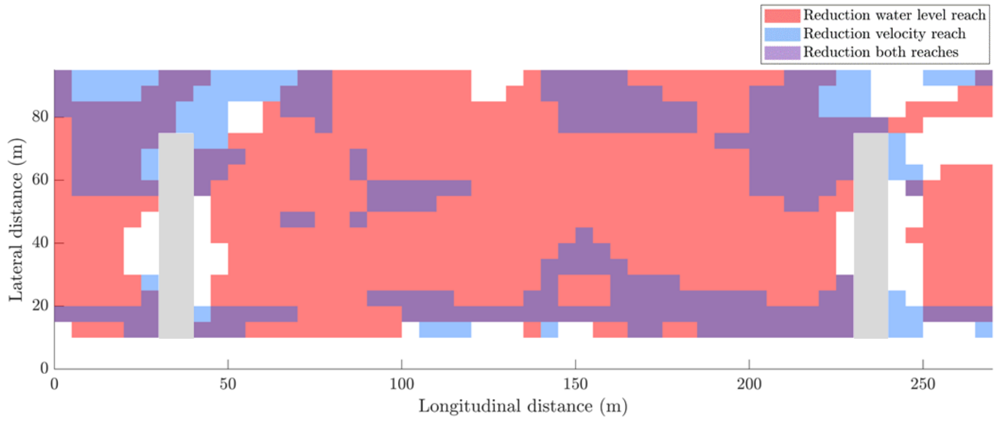
Overview plot upstream sailing



Overview plot dowstream sailing

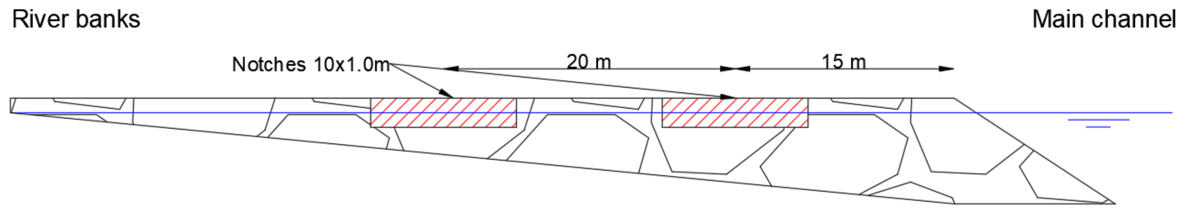


Combined overview plot

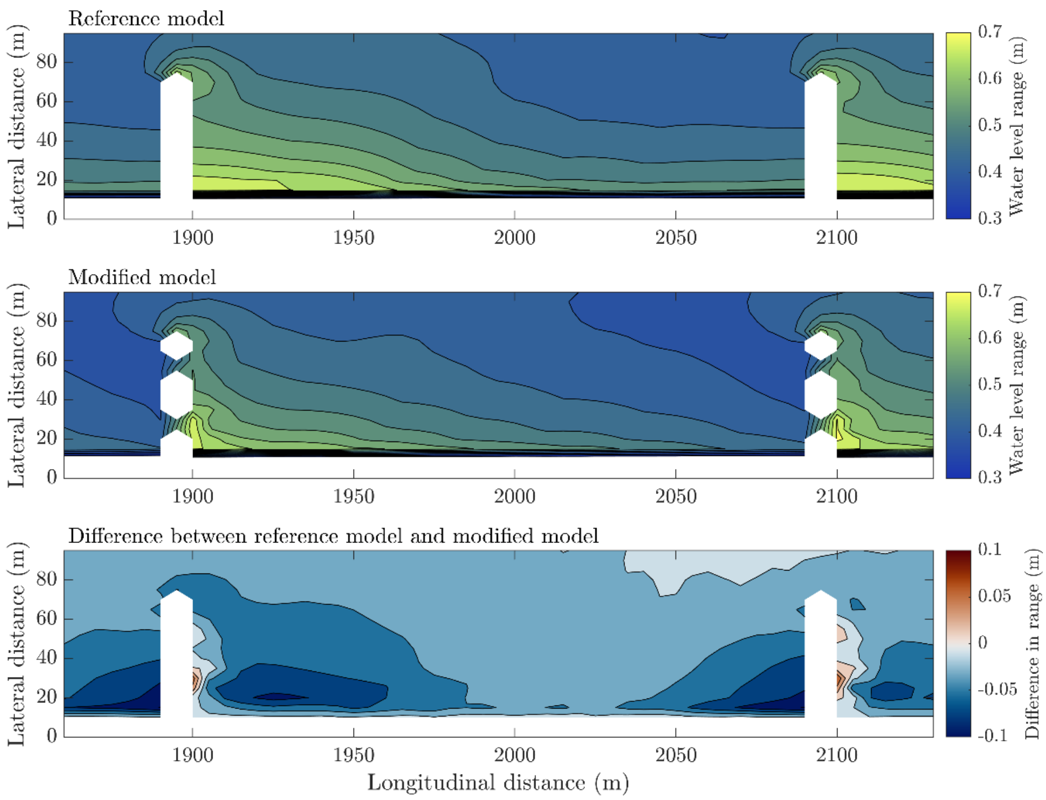


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.112	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.212	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

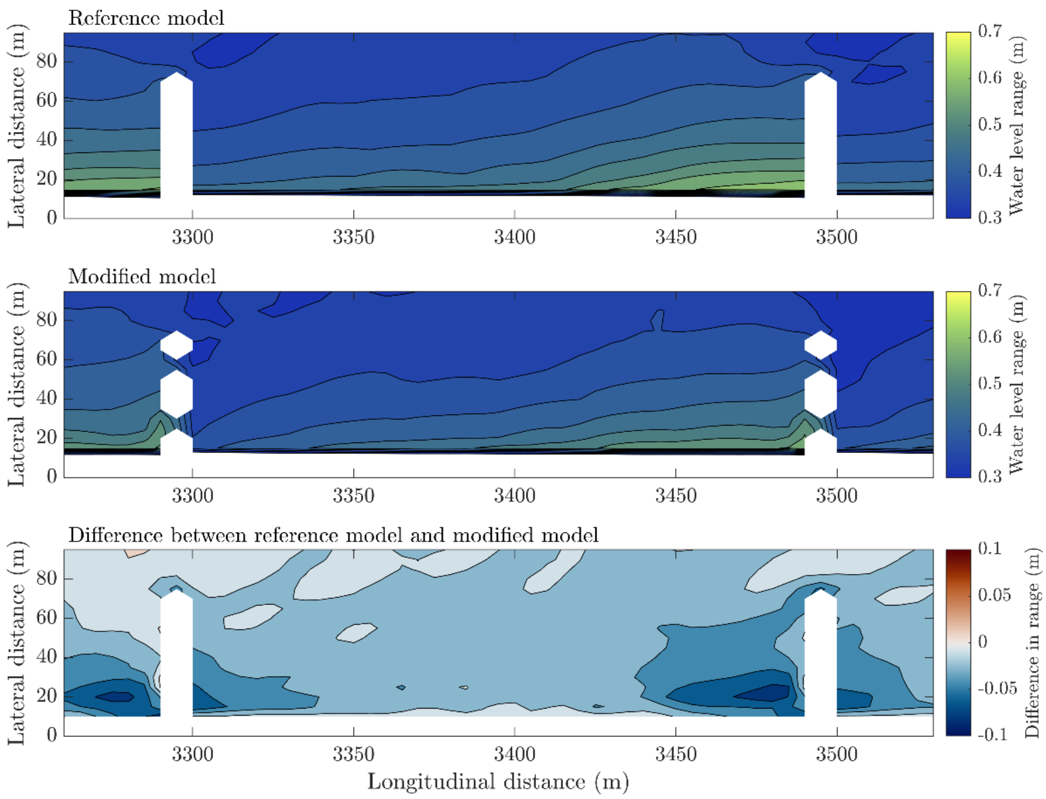
Number of notches	Location of notch	Width notch	Depth notch
2	15 & 35 m	10 m	1.0 m



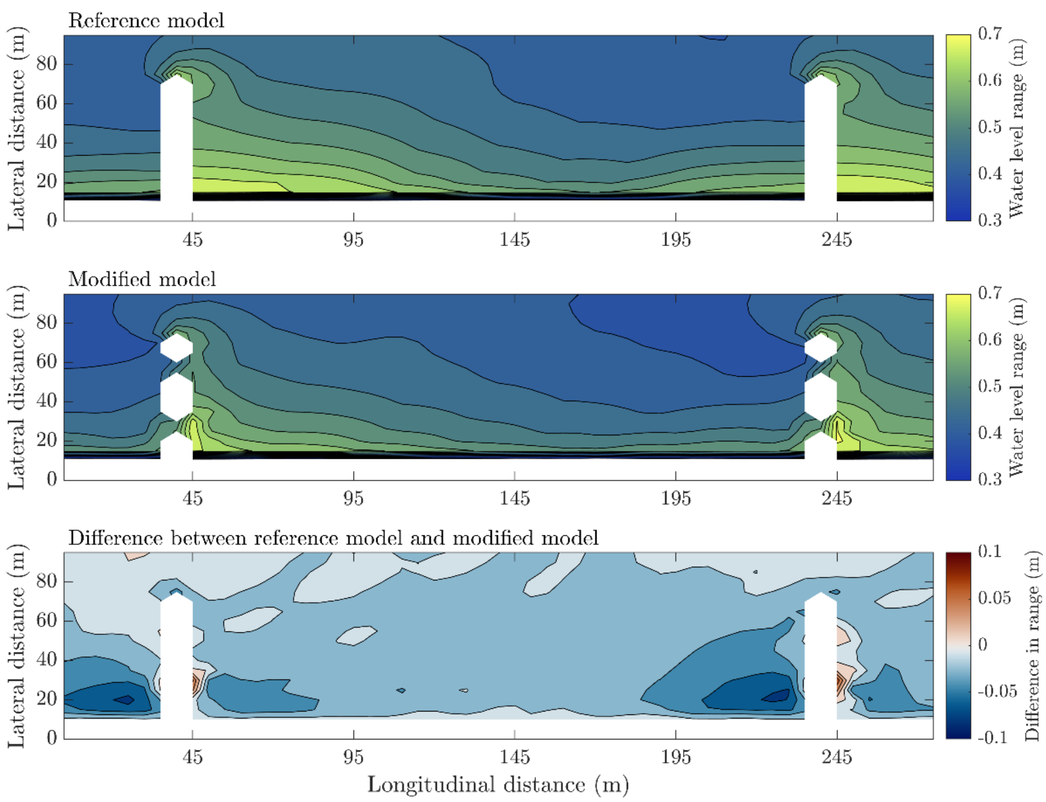
Water level range upstream sailing



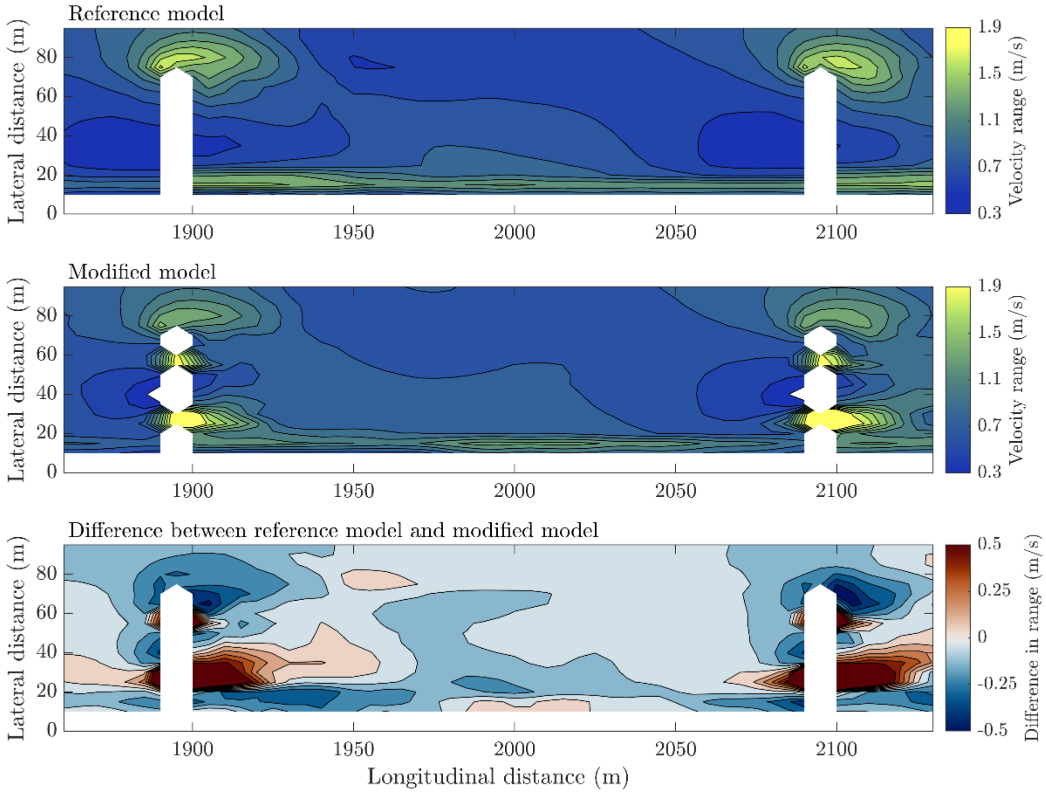
Water level range downstream sailing



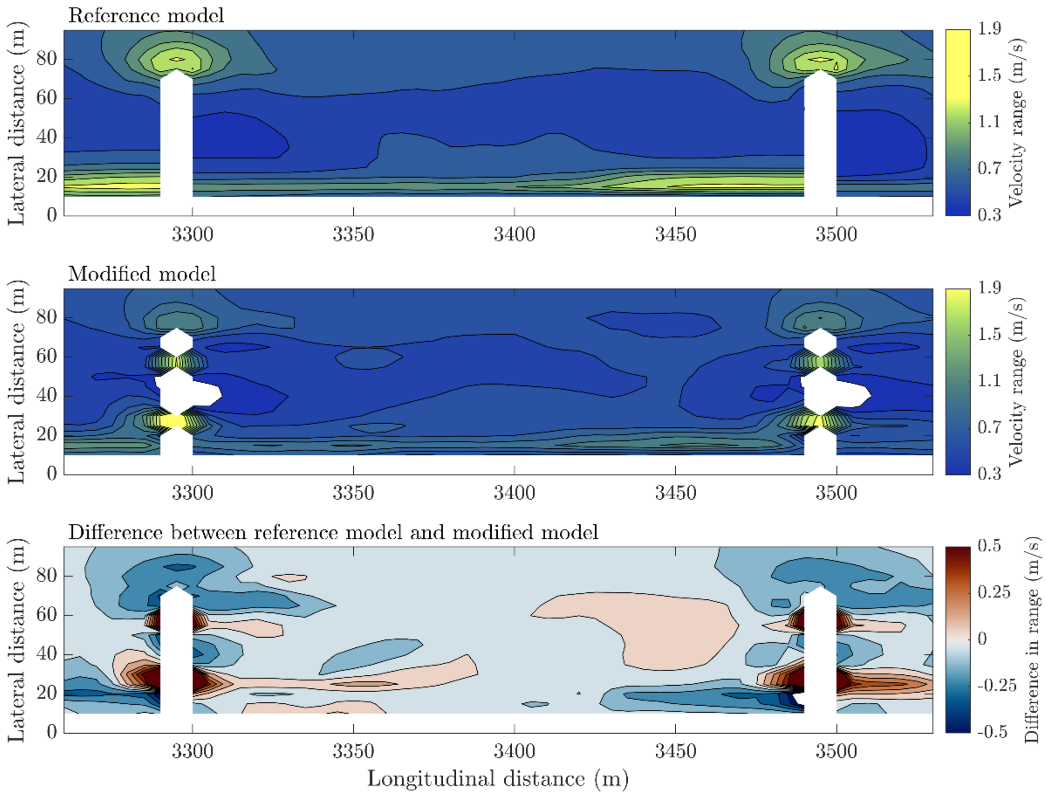
Combined water level range



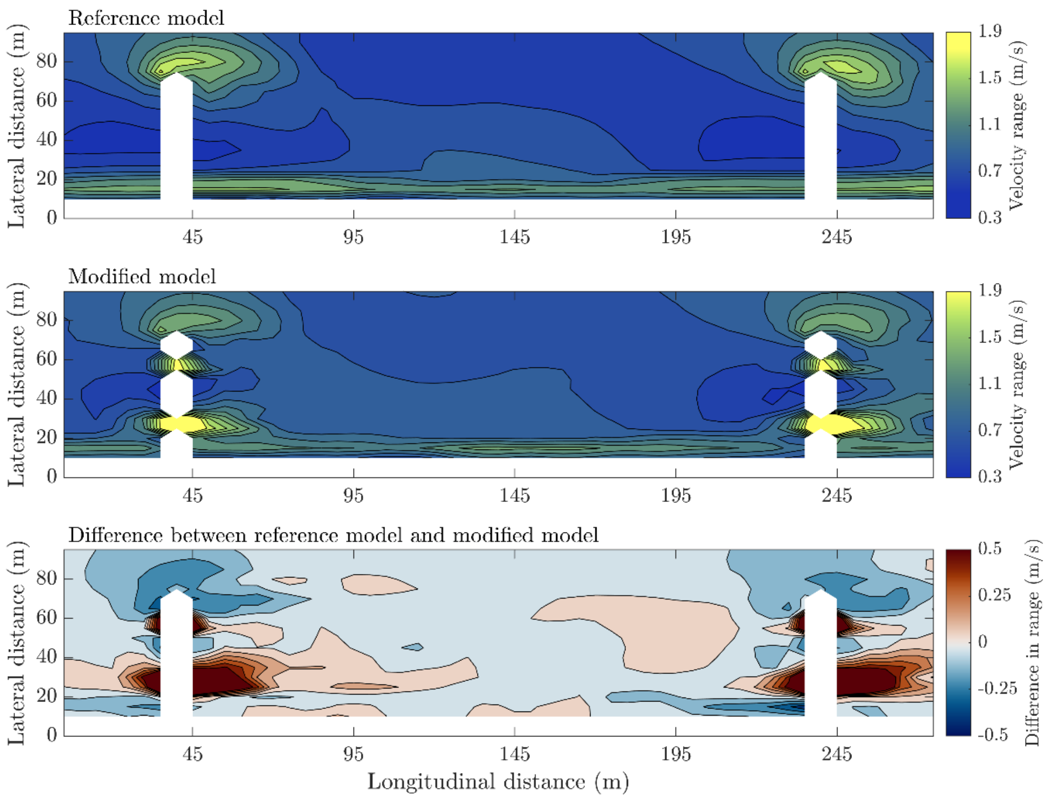
Velocity range upstream sailing



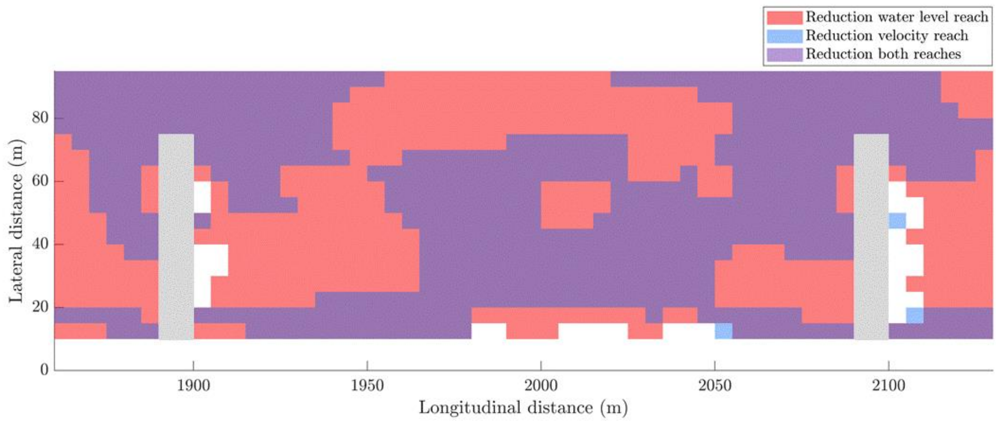
Velocity range downstream sailing



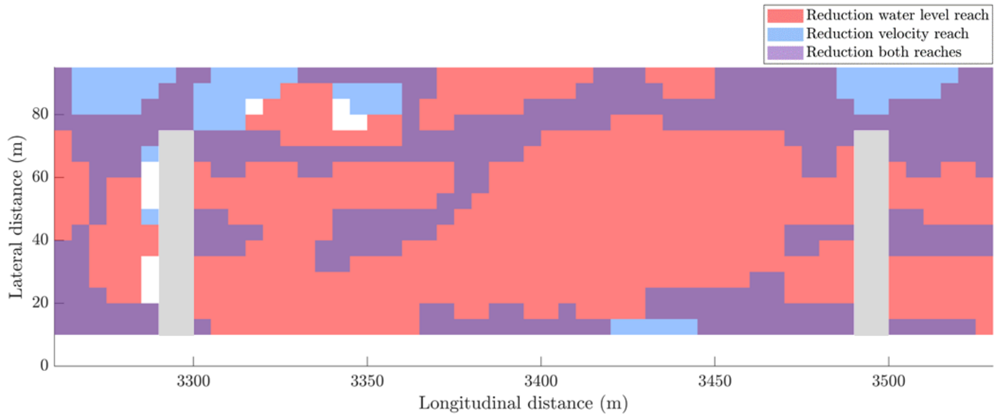
Combined velocity range



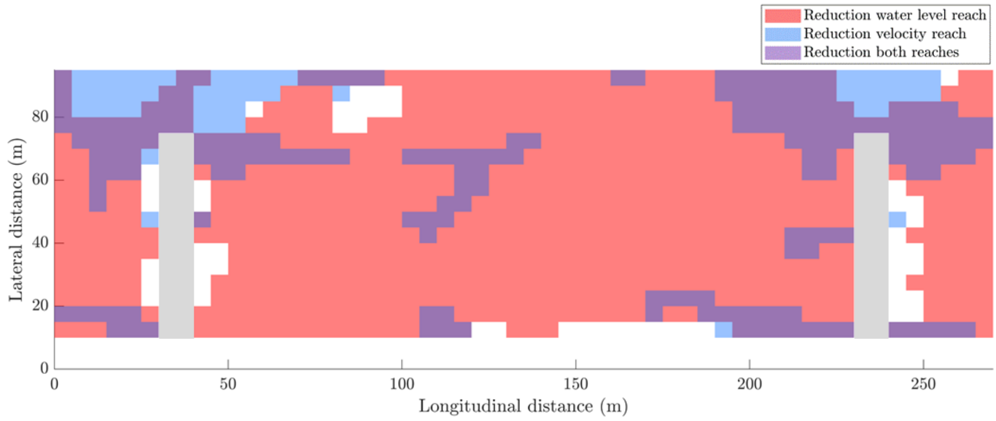
Overview plot upstream sailing



Overview plot dowstream sailing

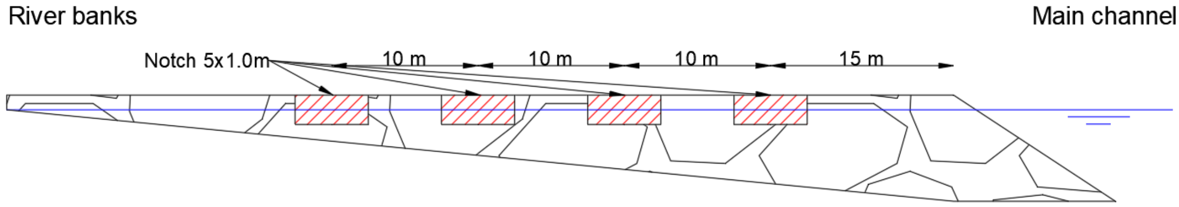


Combined overview plot

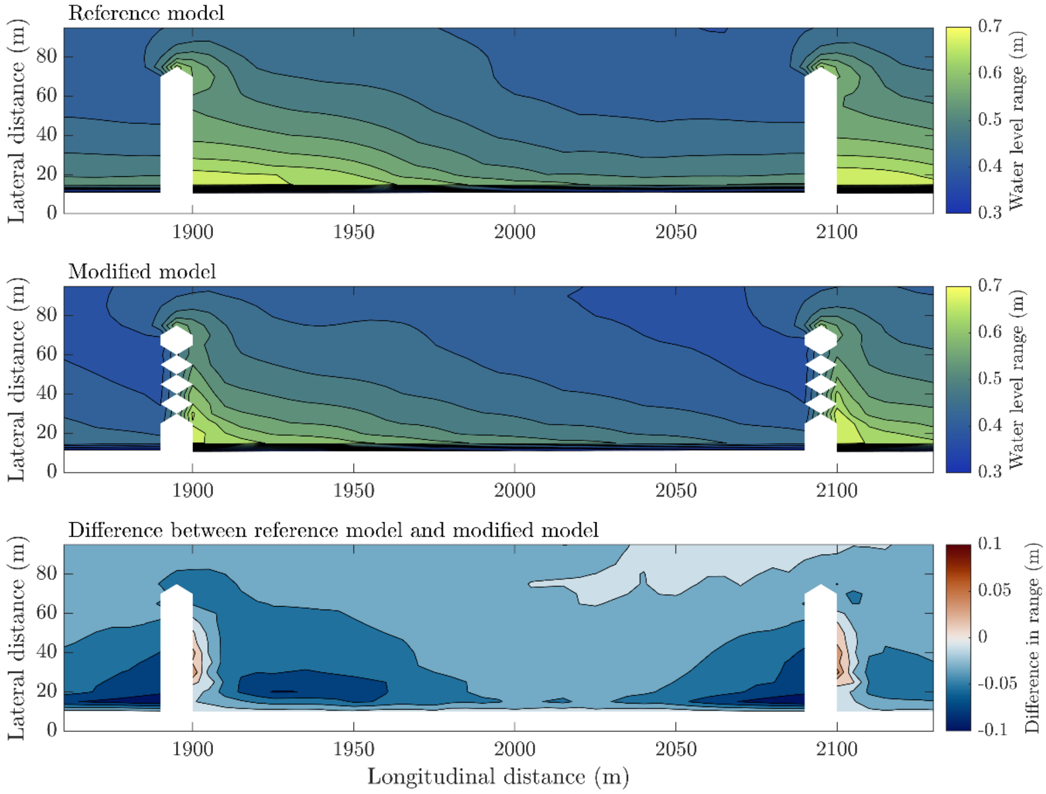


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.113	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.213	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

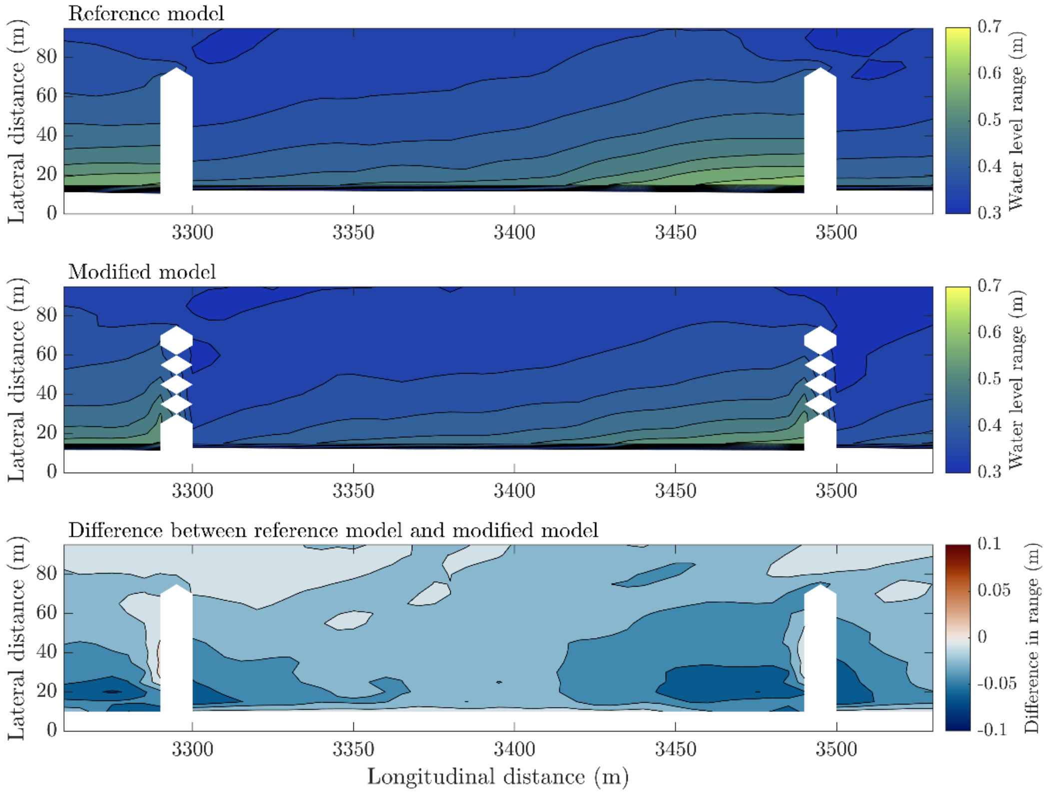
Number of notches	Location of notch	Width notch	Depth notch
4	15 m & 25 m & 35 m & 45 m	5 m	1.0 m



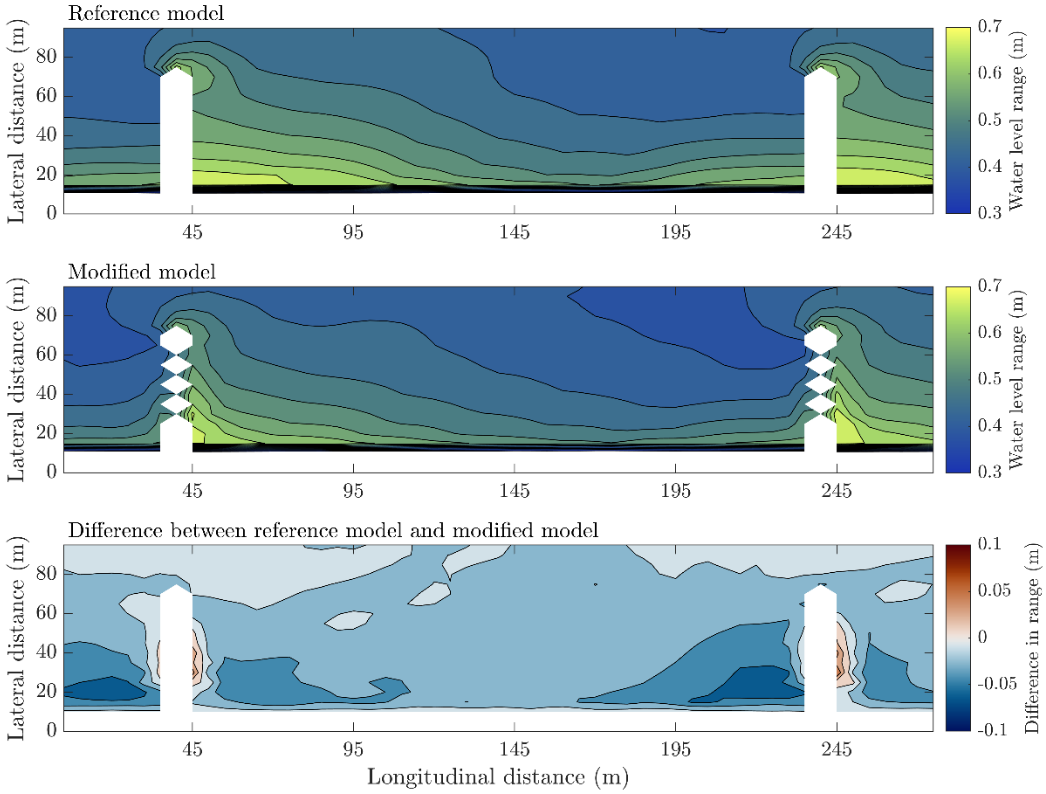
Water level range upstream sailing



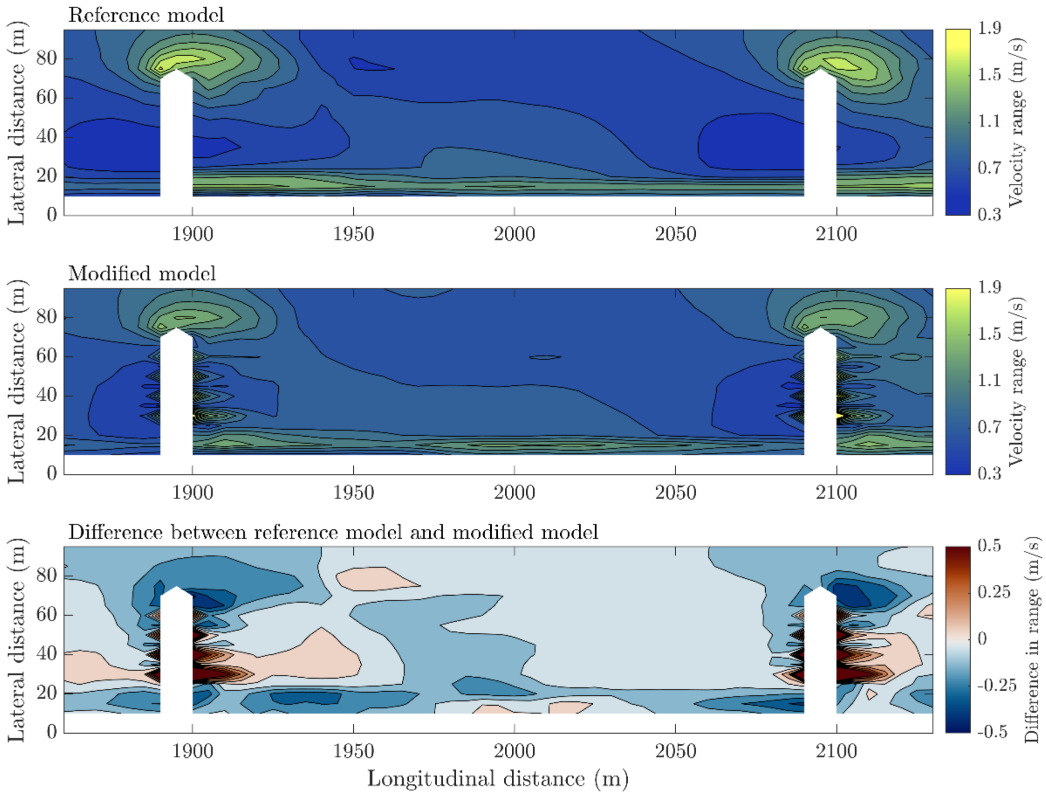
Water level range downstream sailing



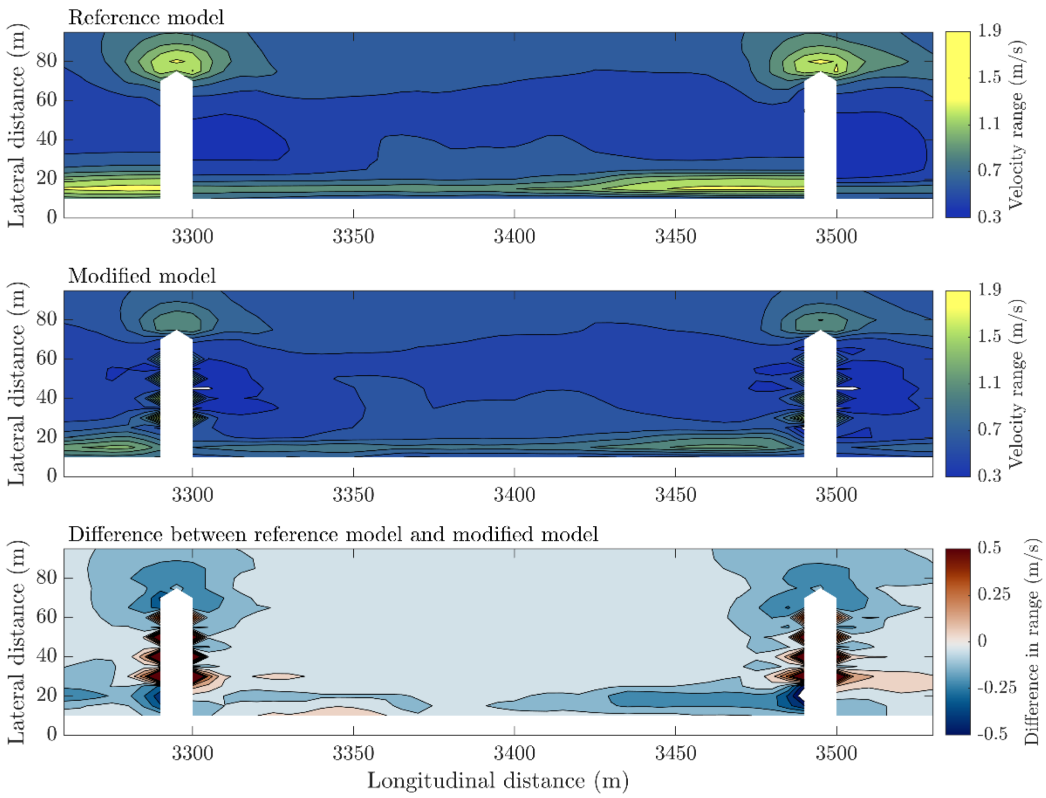
Combined water level range



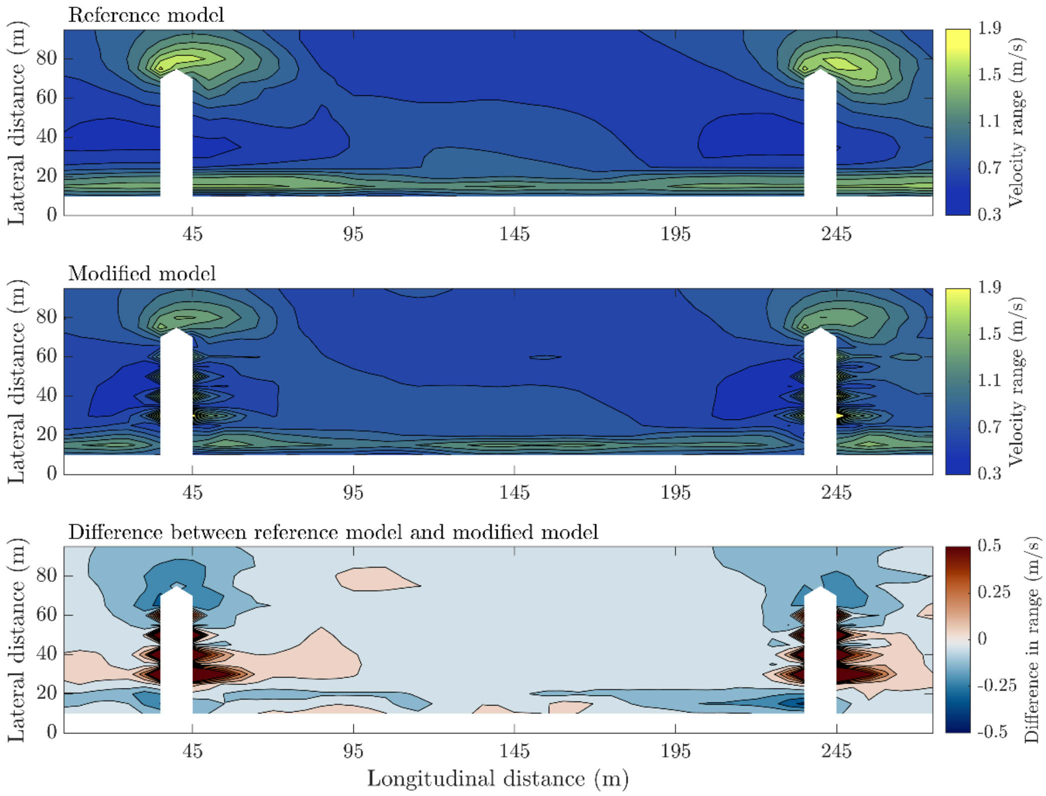
Velocity range upstream sailing



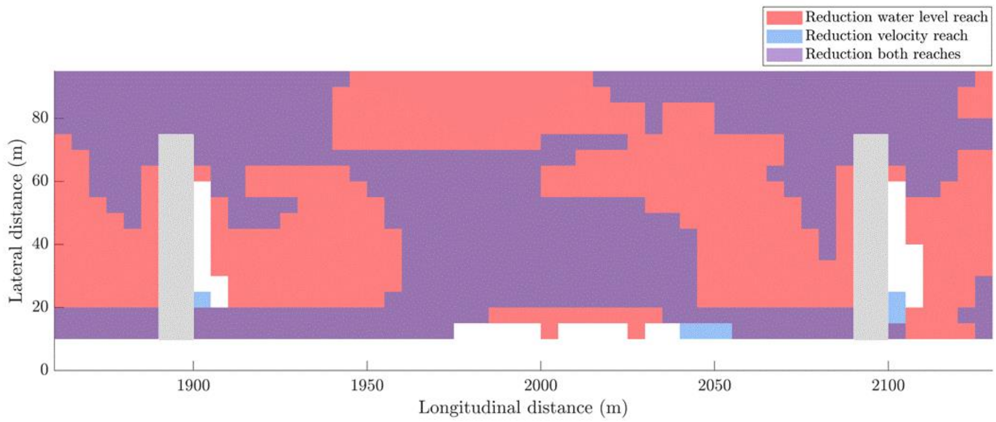
Velocity range downstream sailing



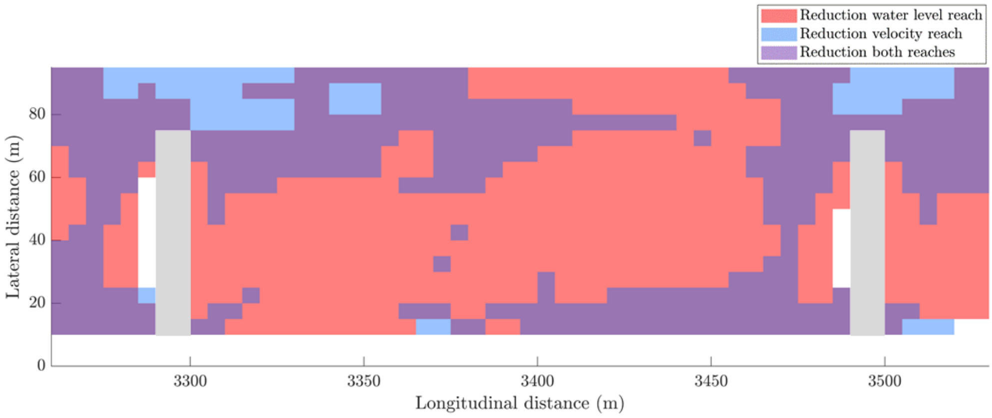
Combined velocity range



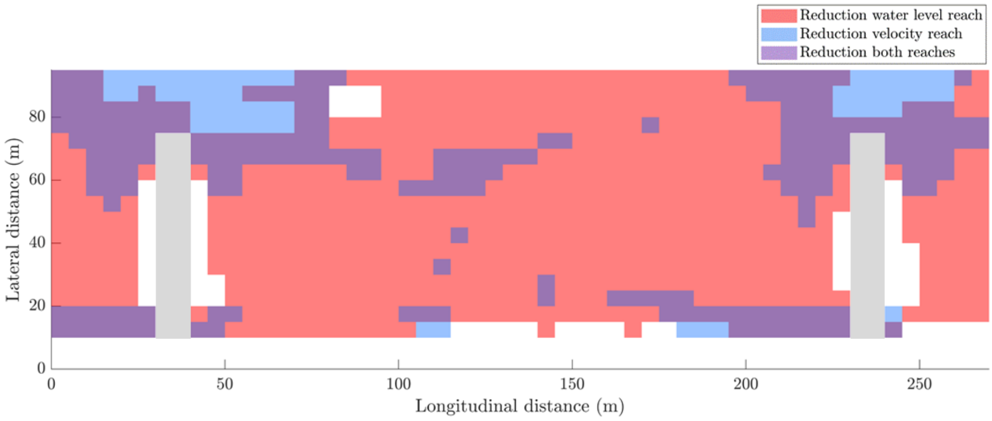
Overview plot upstream sailing



Overview plot dowstream sailing

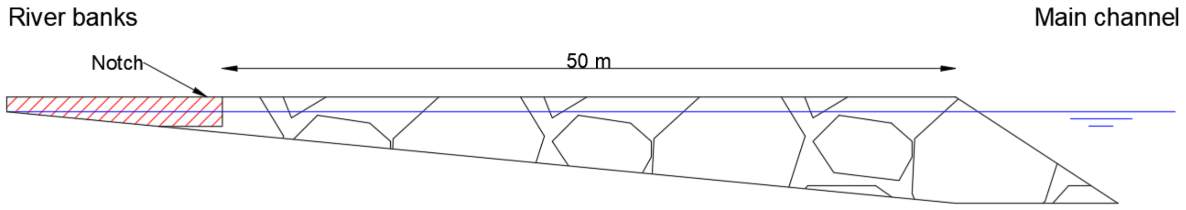


Combined overview plot

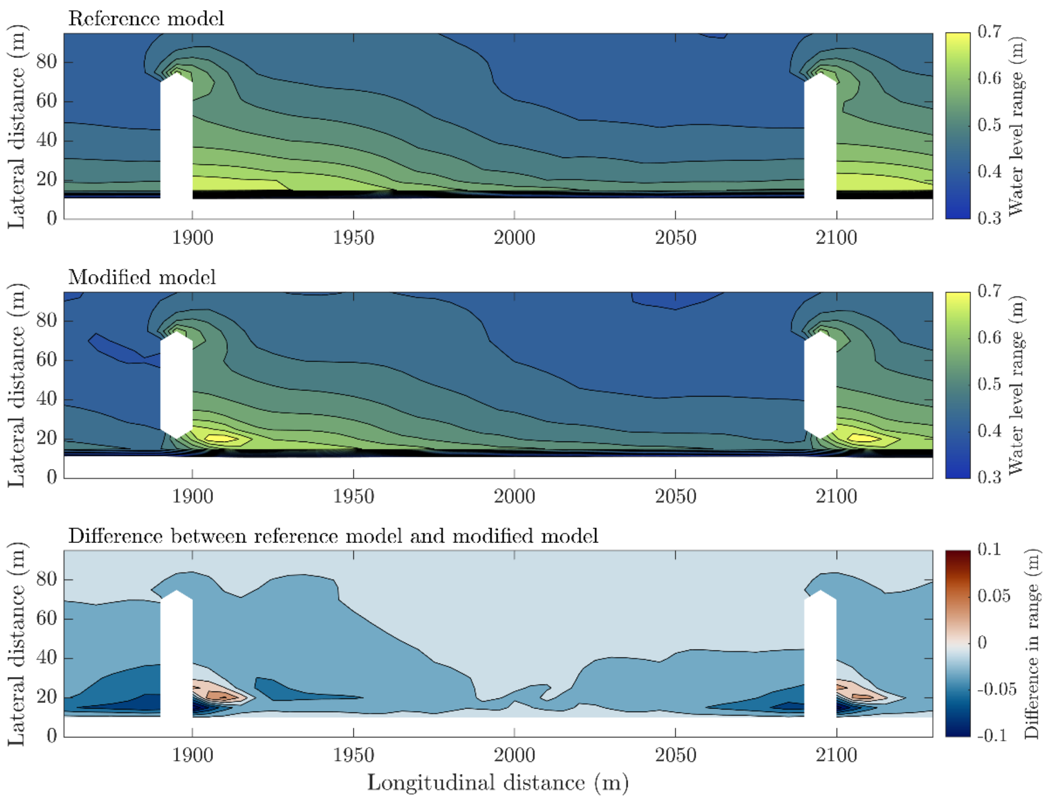


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.114	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.214	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

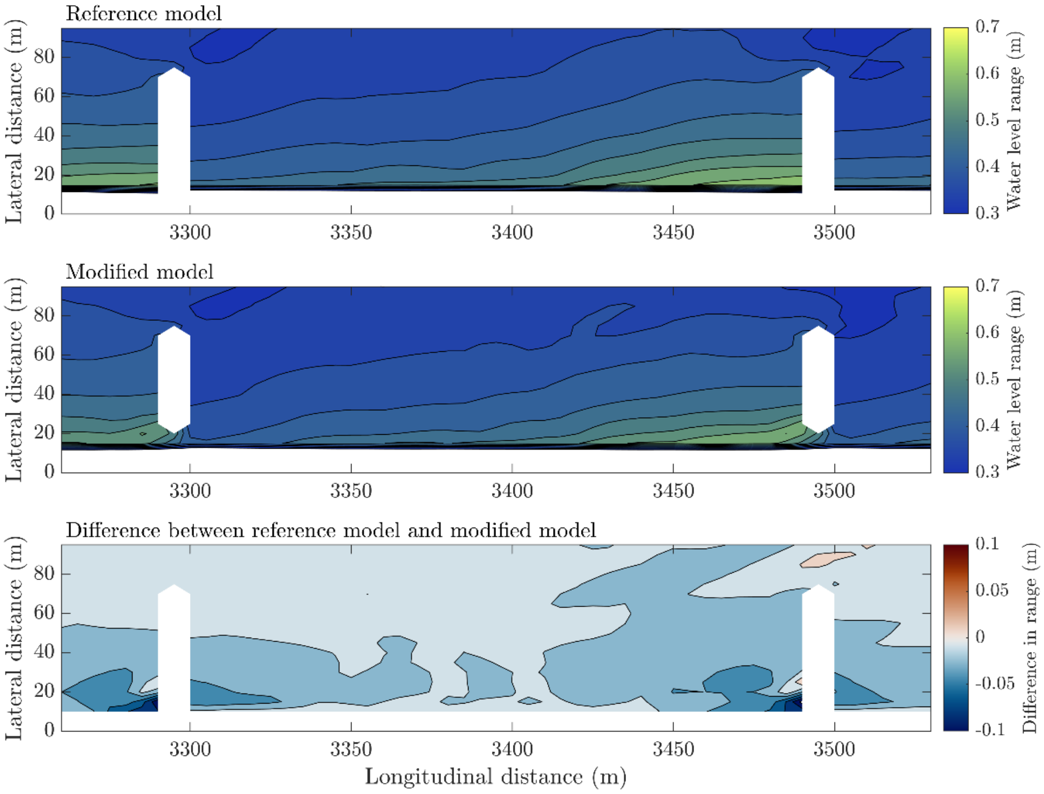
Number of notches	Location of notch	Width notch	Depth notch
1	50 m	15 m	0 - 1.0 m



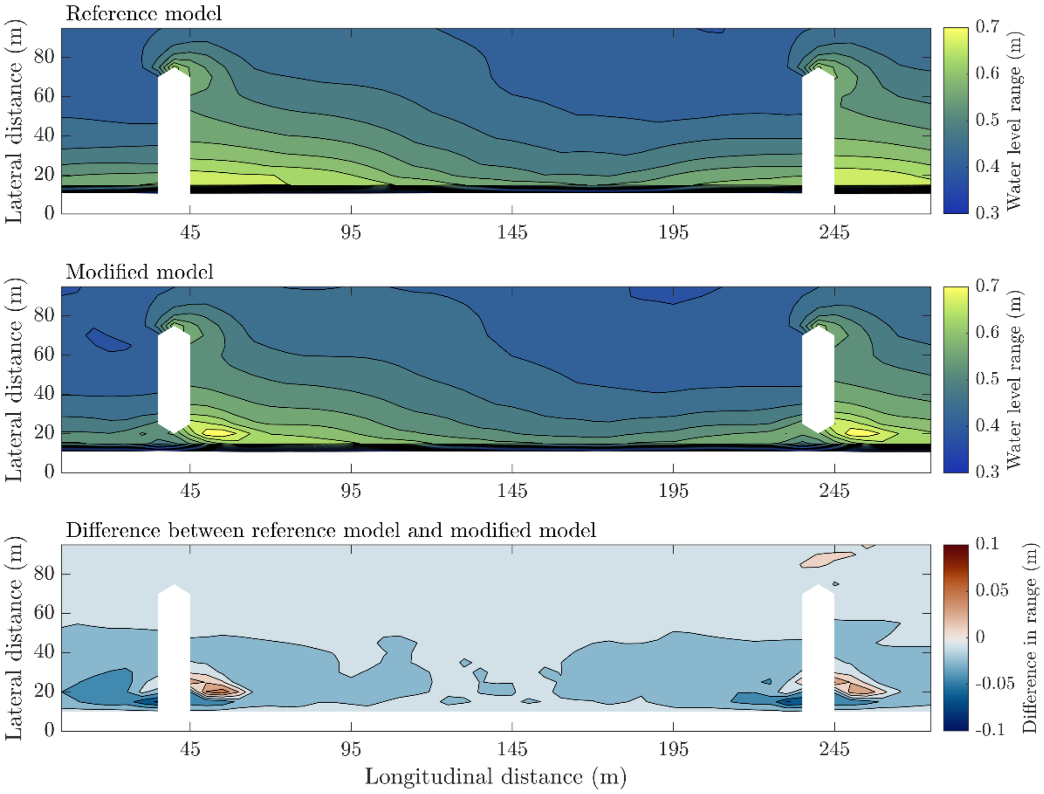
Water level range upstream sailing



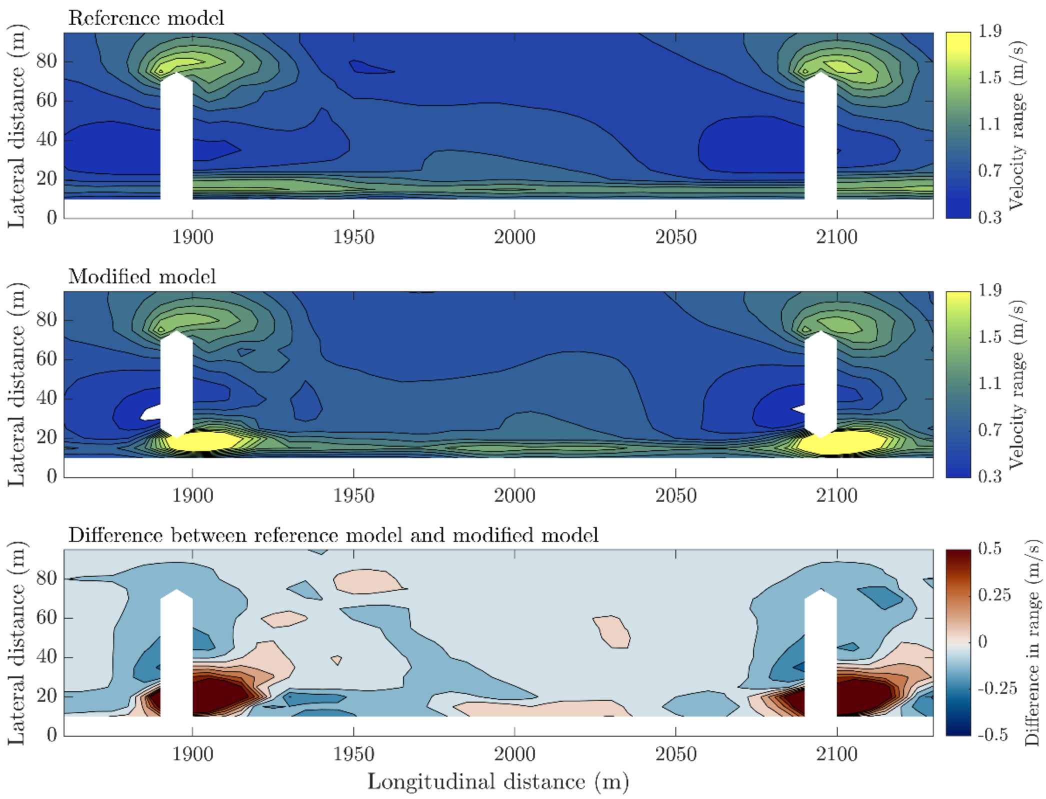
Water level range downstream sailing



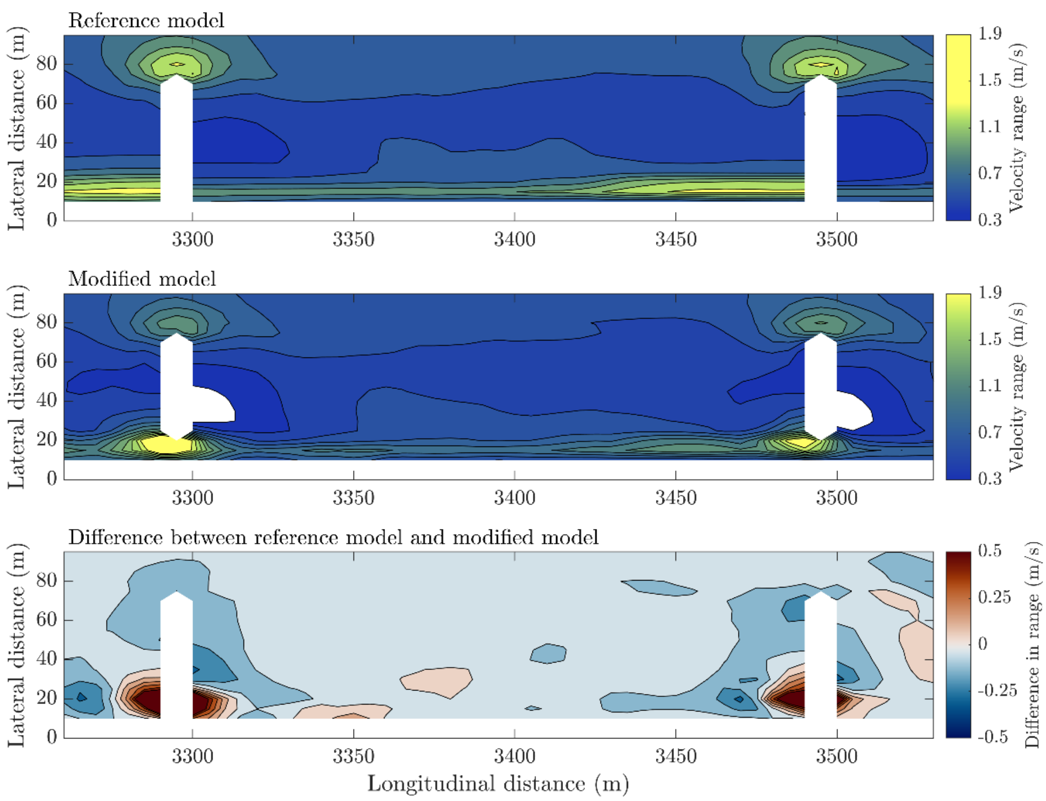
Combined water level range



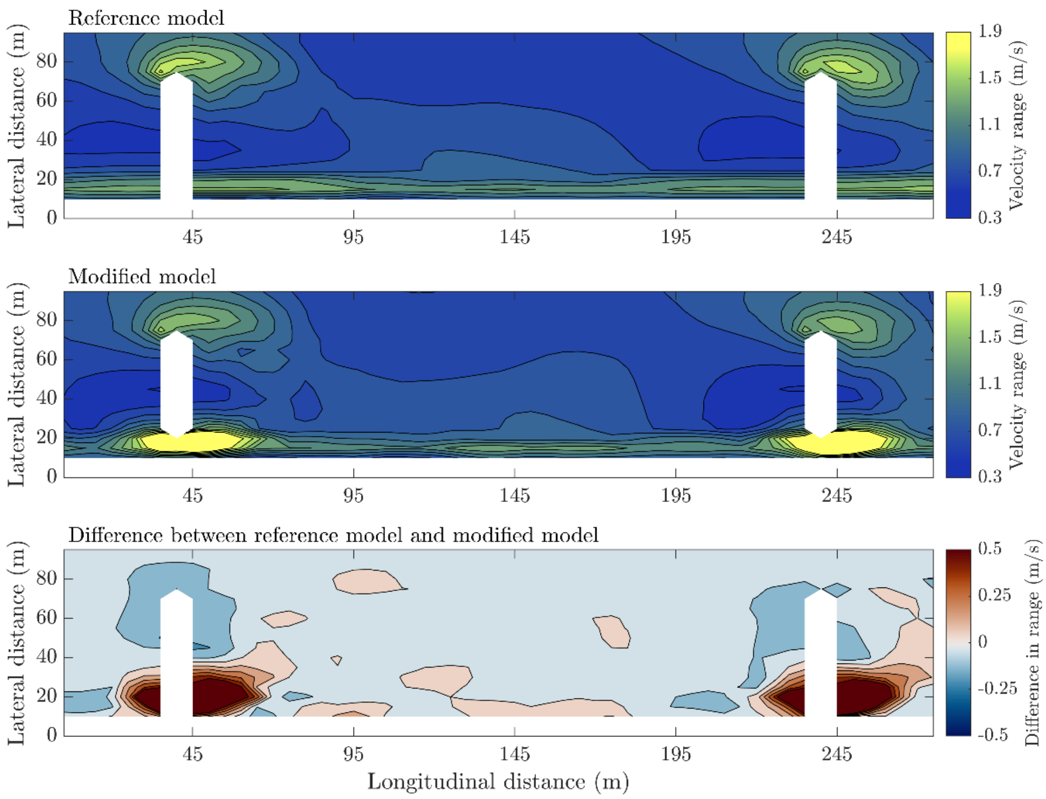
Velocity range upstream sailing



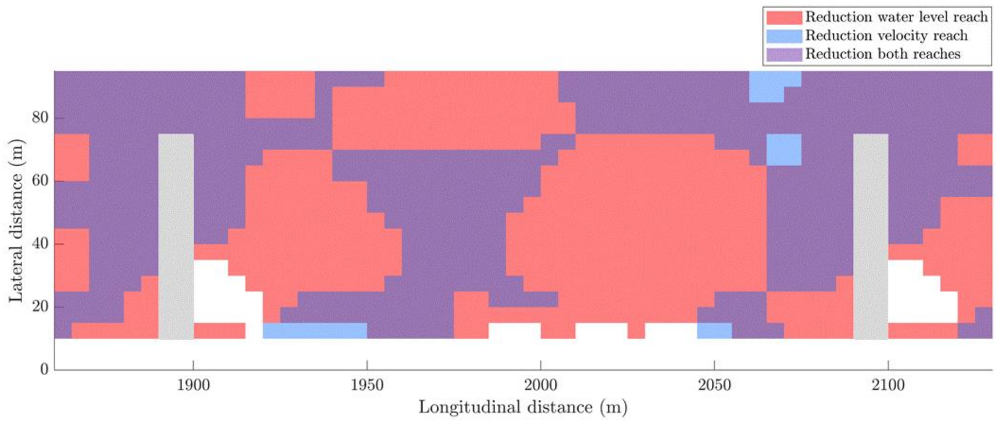
Velocity range downstream sailing



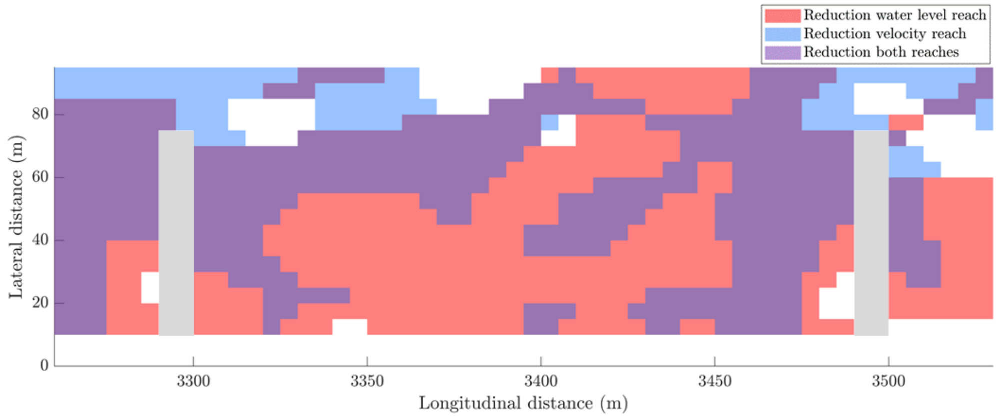
Combined velocity range



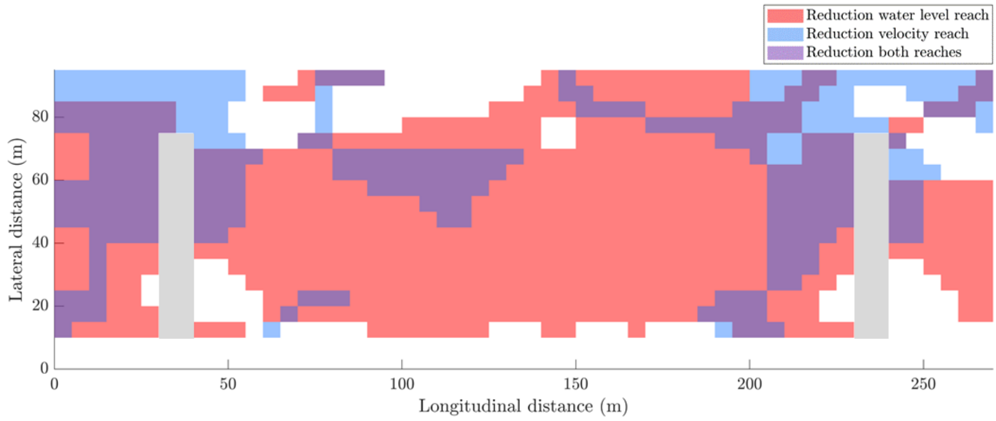
Overview plot upstream sailing



Overview plot dowstream sailing

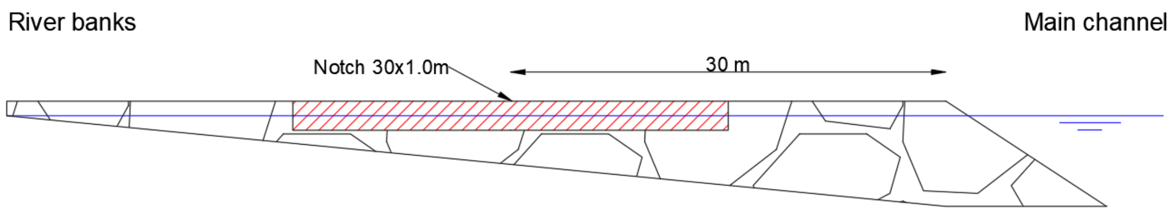


Combined overview plot

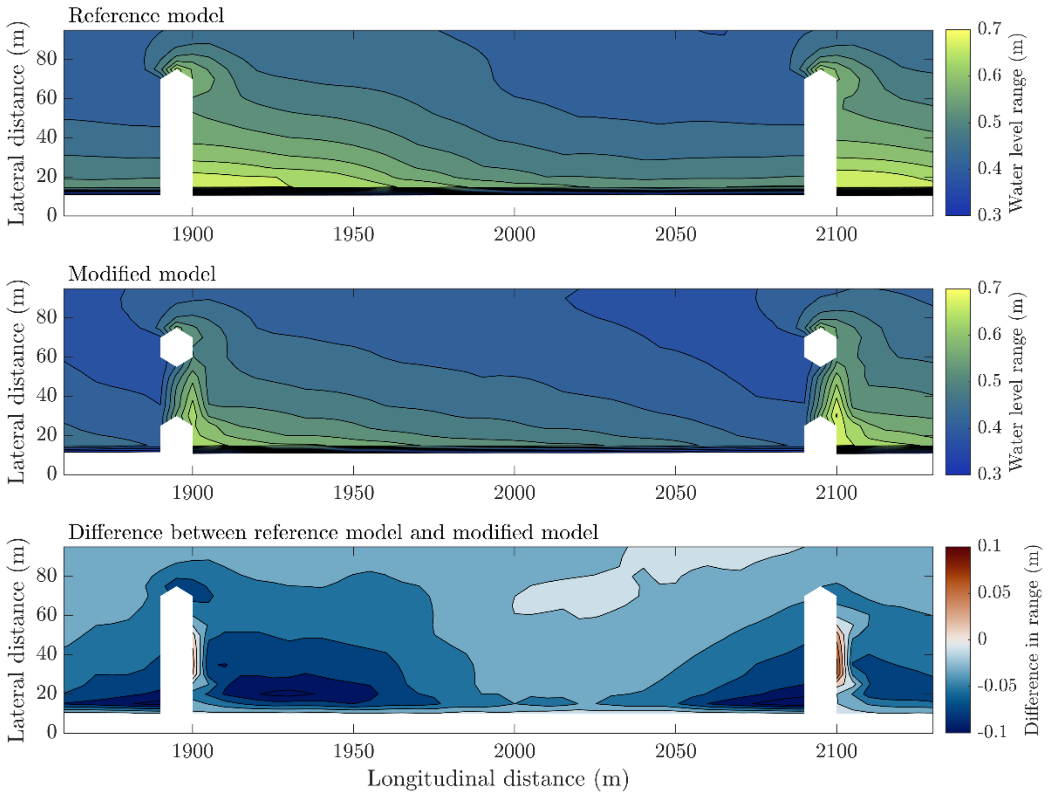


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.115	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.215	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

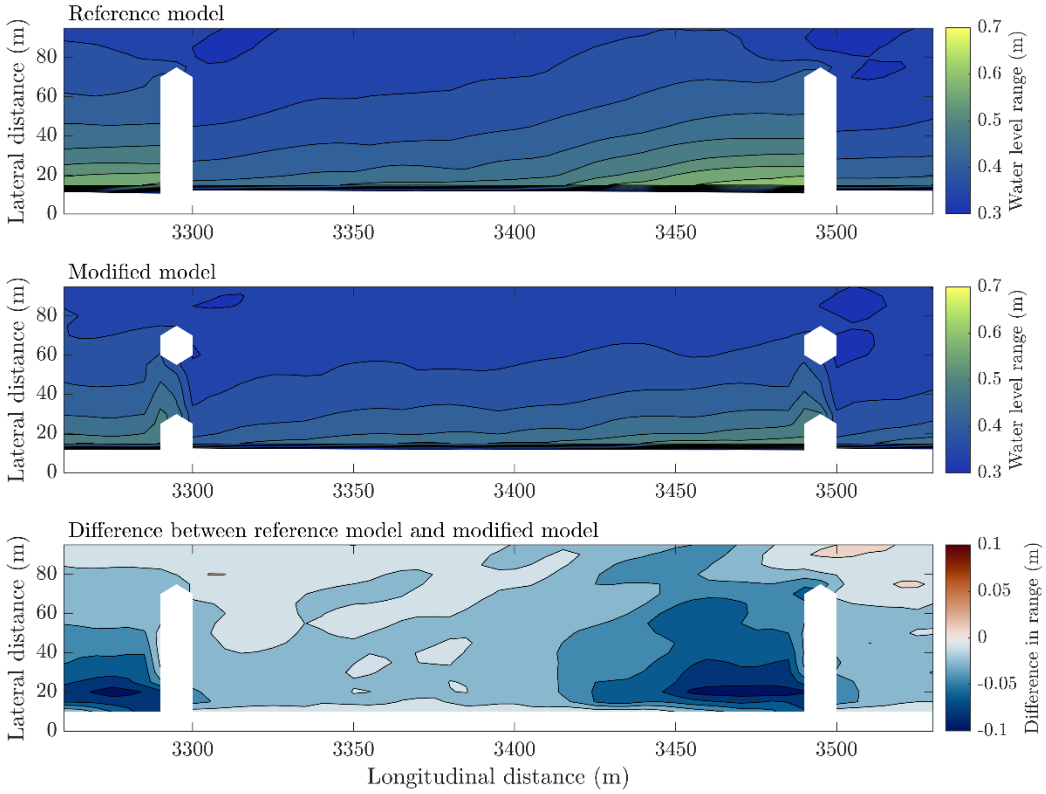
Number of notches	Location of notch	Width notch	Depth notch
1	30 m	30 m	1.0 m



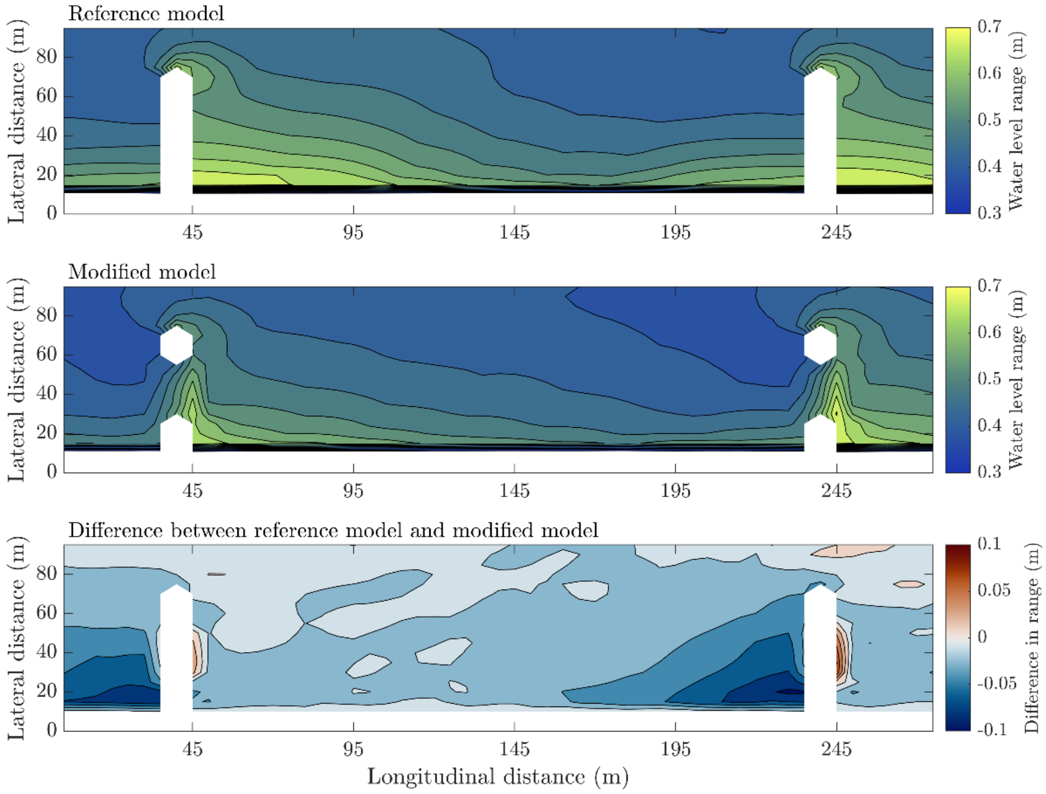
Water level range upstream sailing



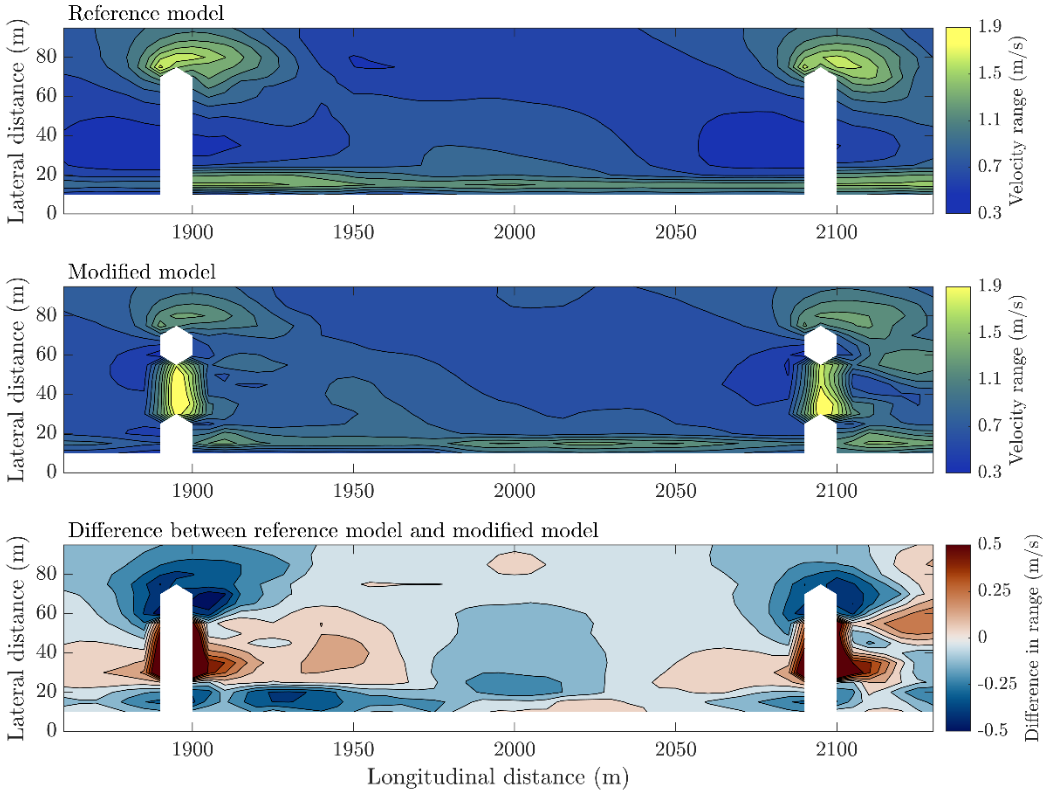
Water level range downstream sailing



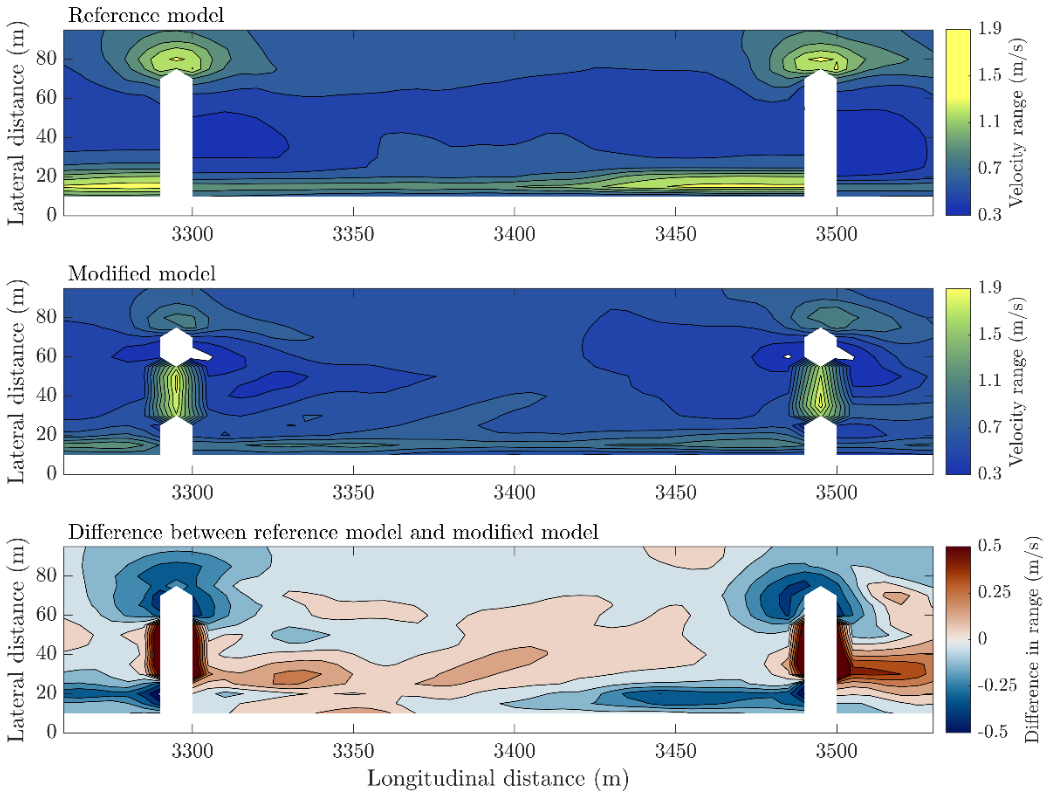
Combined water level range



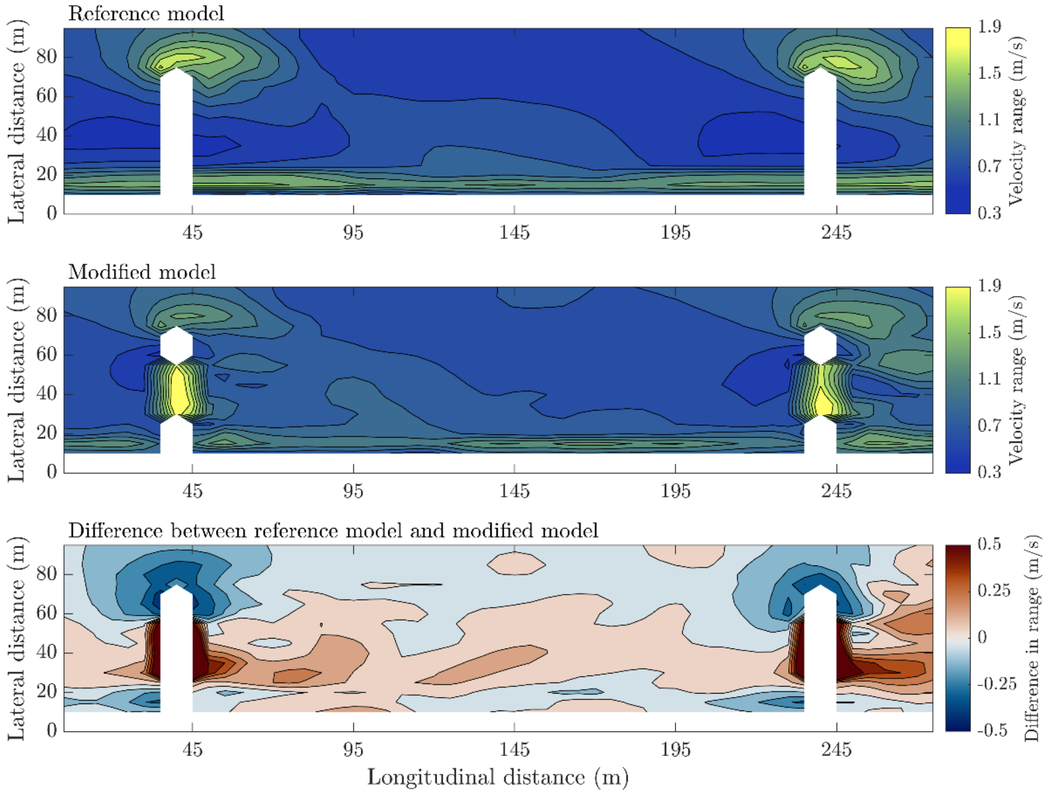
Velocity range upstream sailing



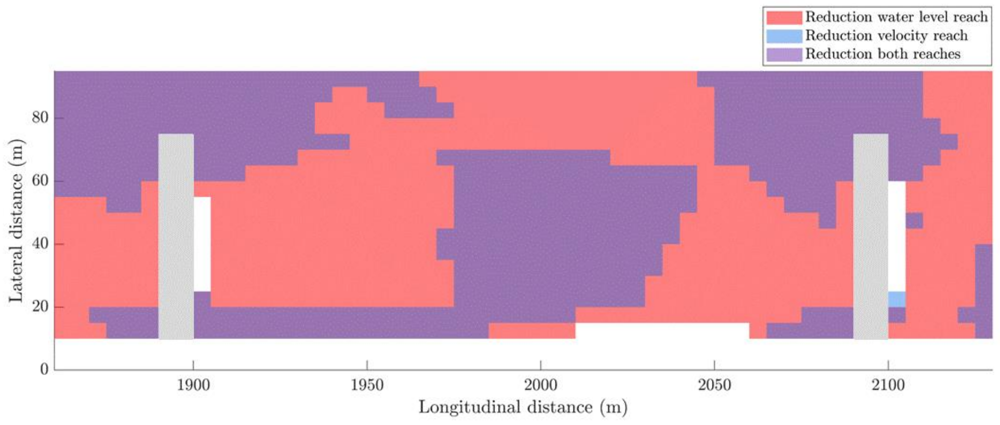
Velocity range downstream sailing



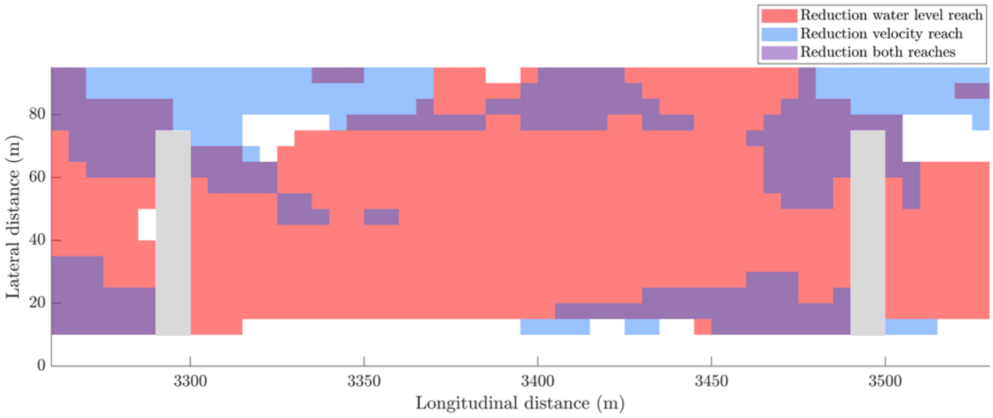
Combined velocity range



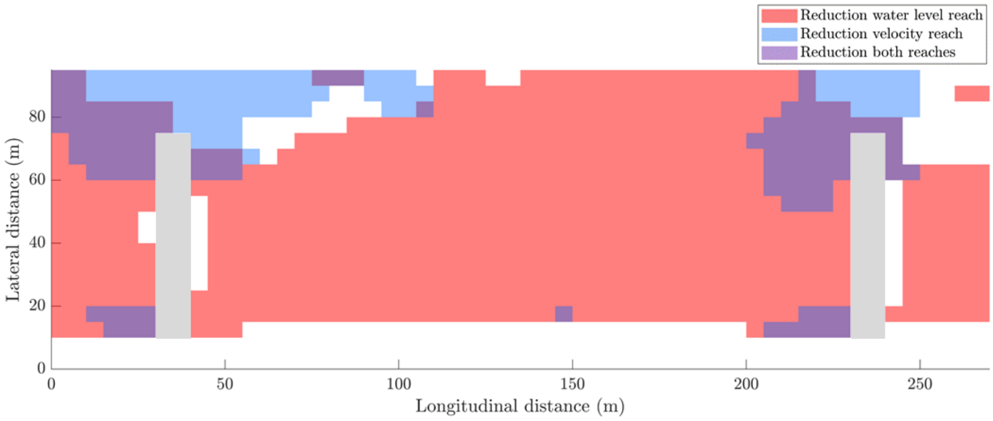
Overview plot upstream sailing



Overview plot dowstream sailing

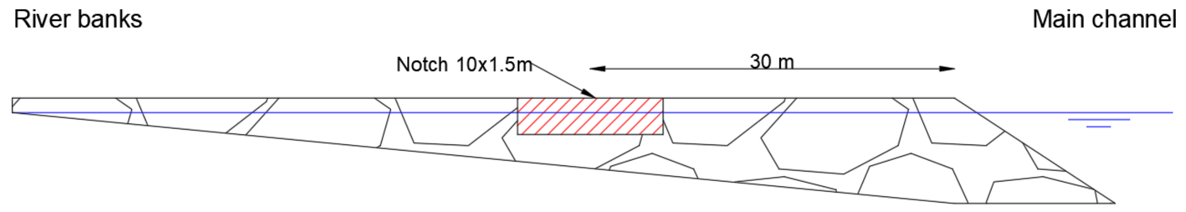


Combined overview plot

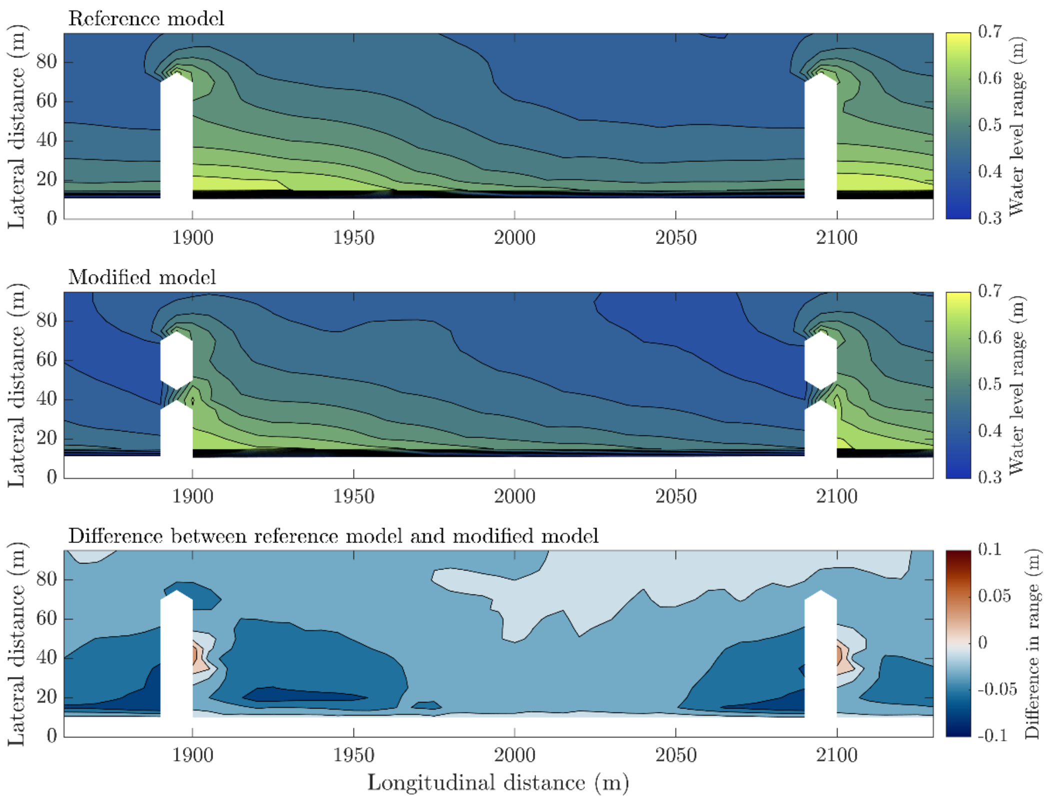


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.116	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.216	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

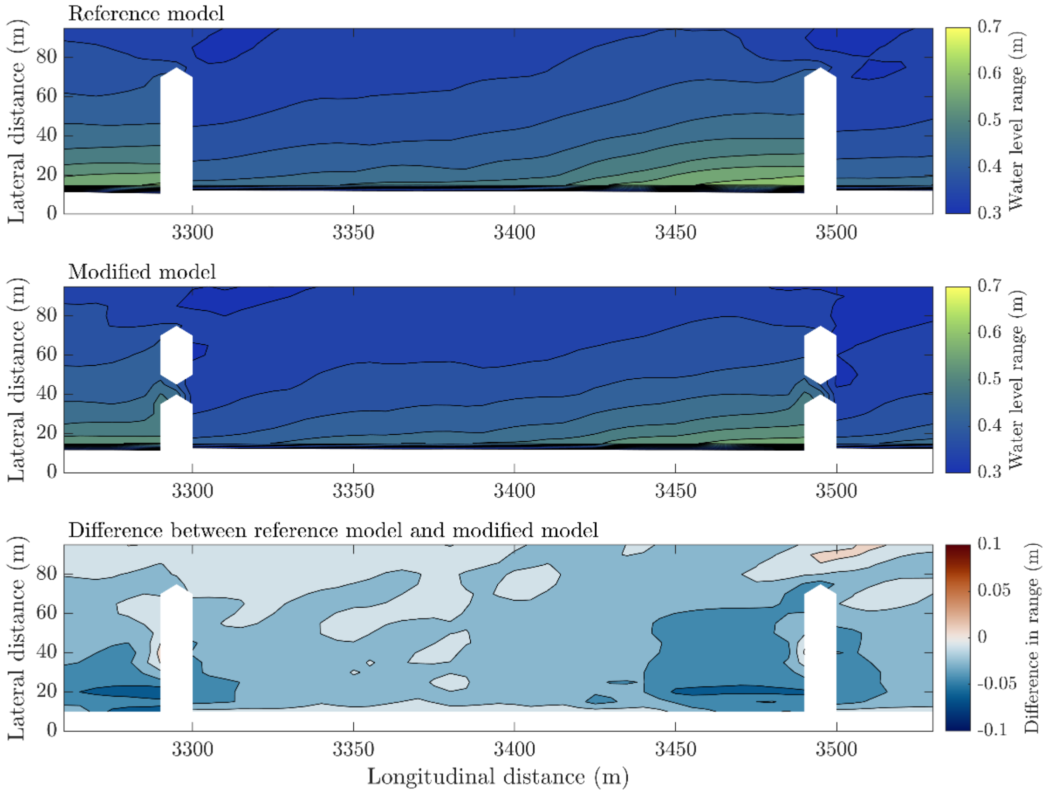
Number of notches	Location of notch	Width notch	Depth notch
1	30 m	10 m	1.5 m



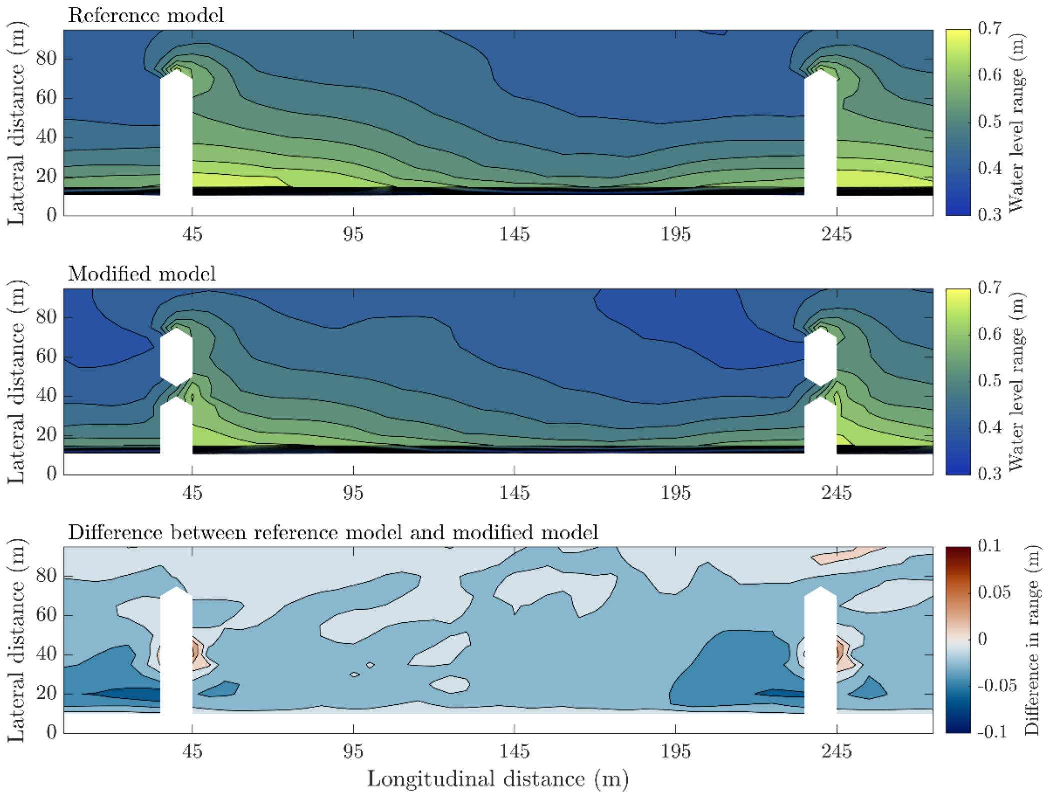
Water level range upstream sailing



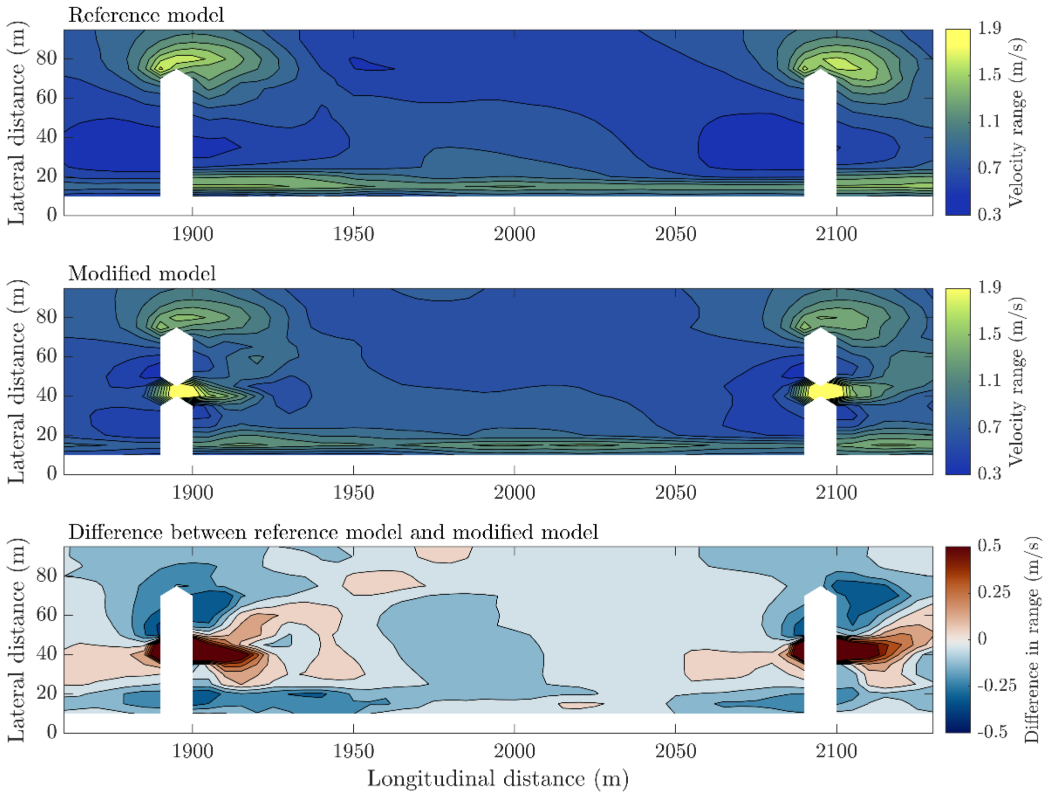
Water level range downstream sailing



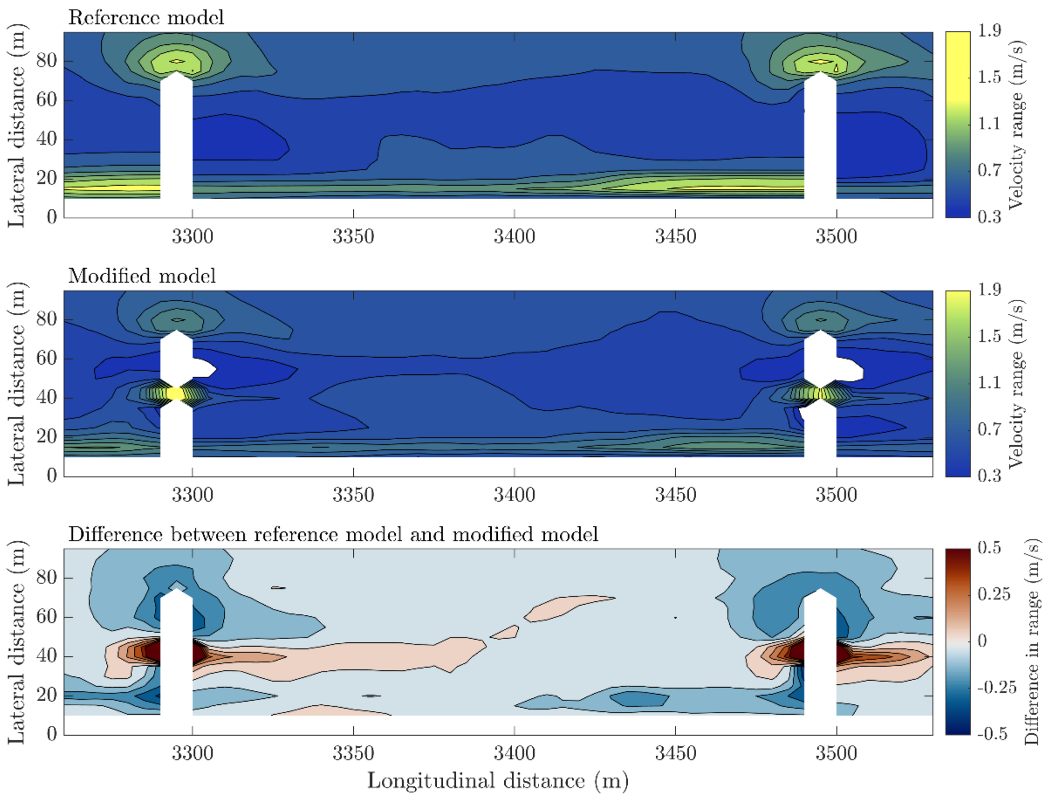
Combined water level range



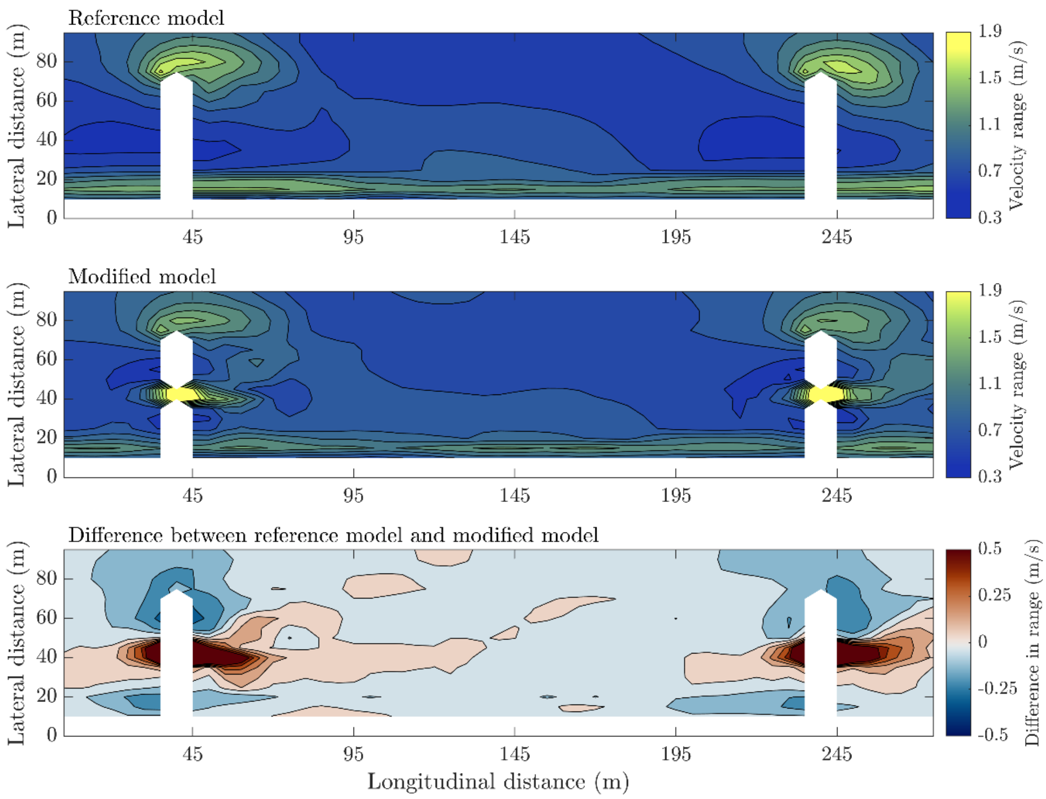
Velocity range upstream sailing



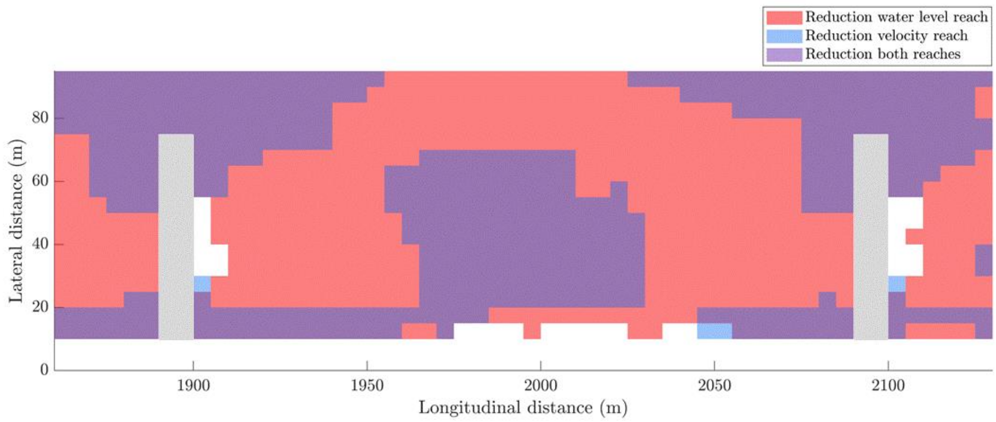
Velocity range downstream sailing



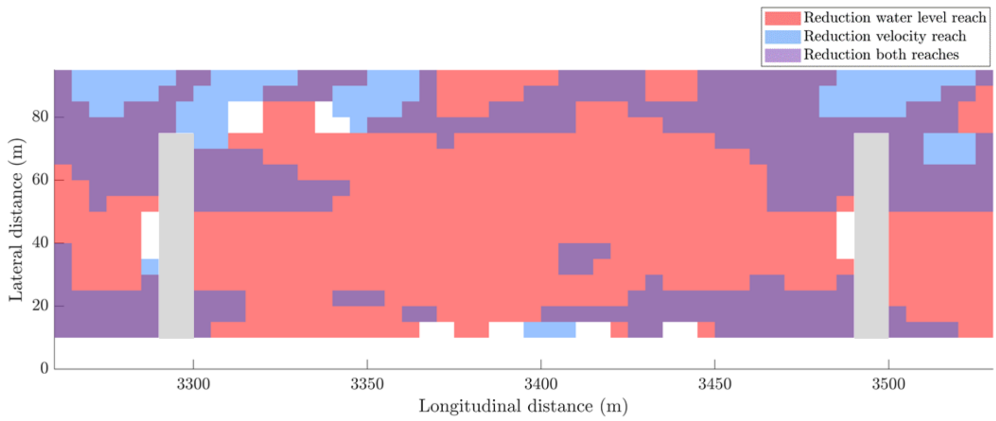
Combined velocity range



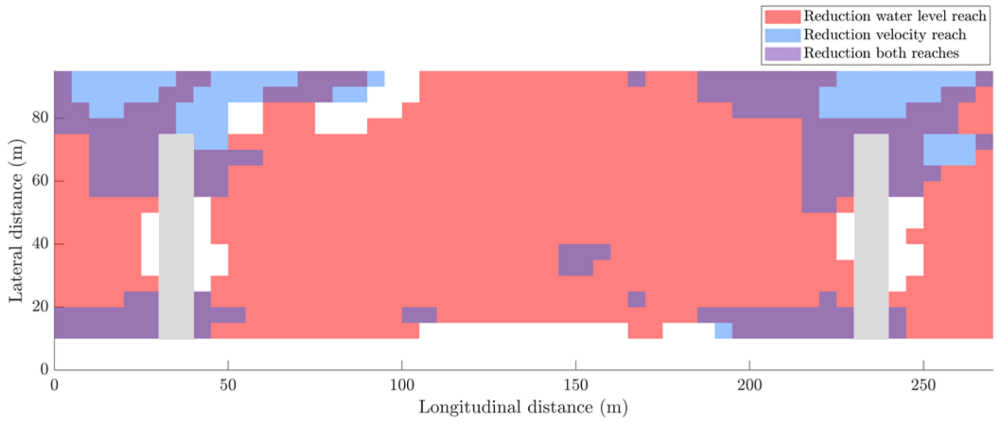
Overview plot upstream sailing



Overview plot dowstream sailing

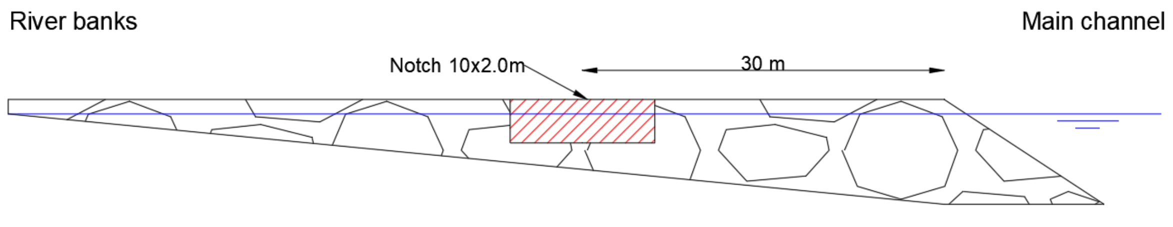


Combined overview plot

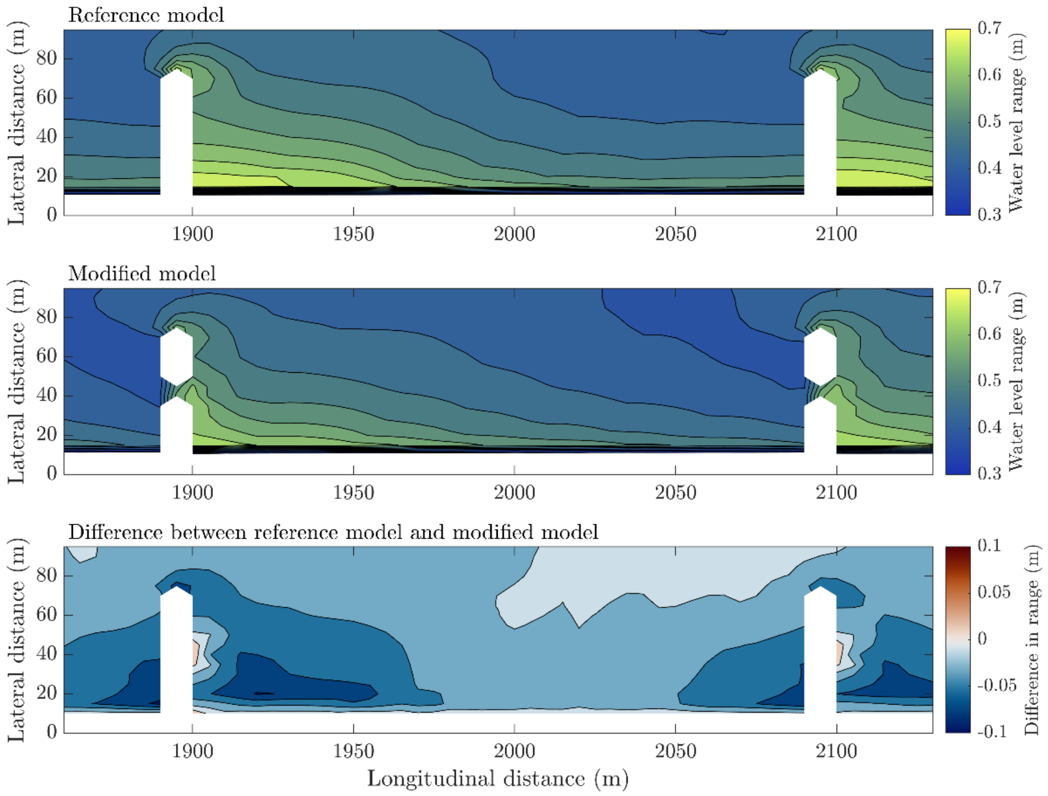


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.117	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.217	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

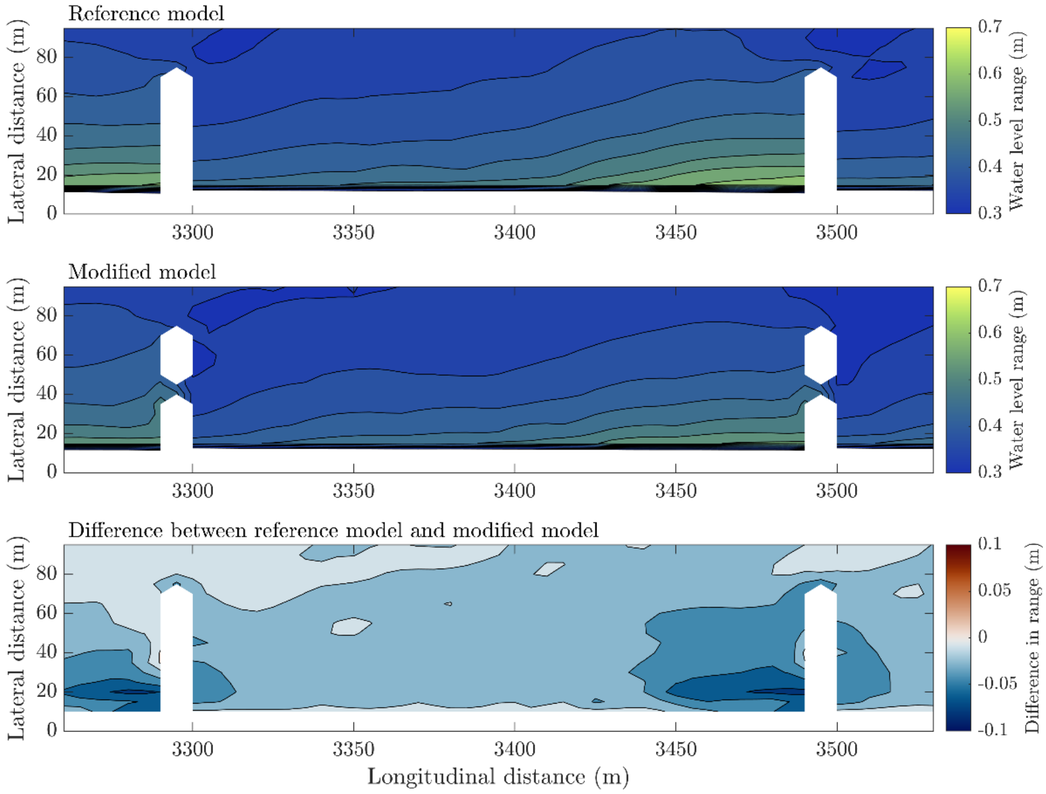
Number of notches	Location of notch	Width notch	Depth notch
1	30 m	10 m	2.0 m



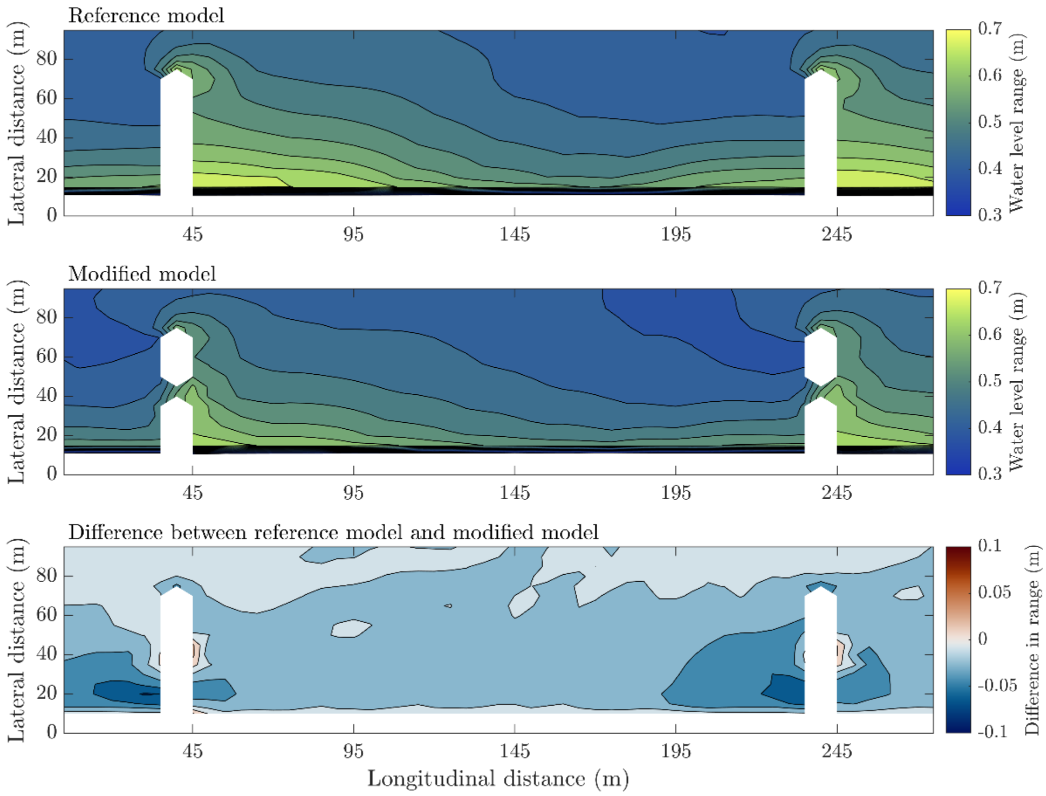
Water level range upstream sailing



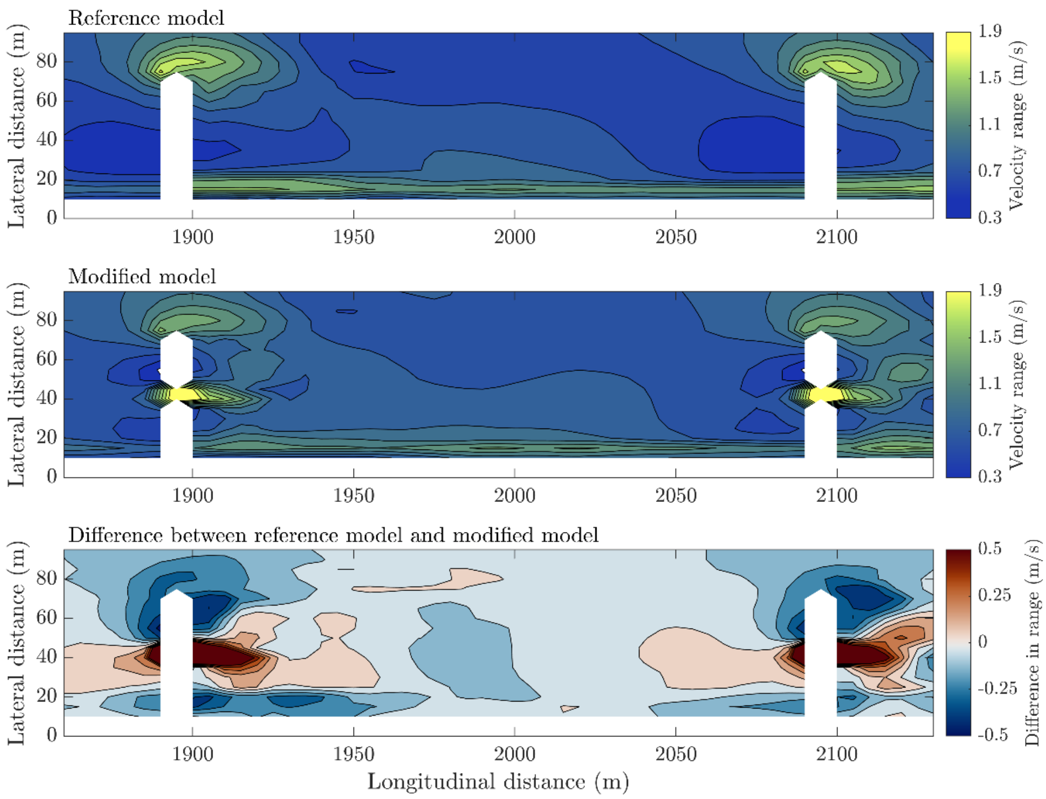
Water level range downstream sailing



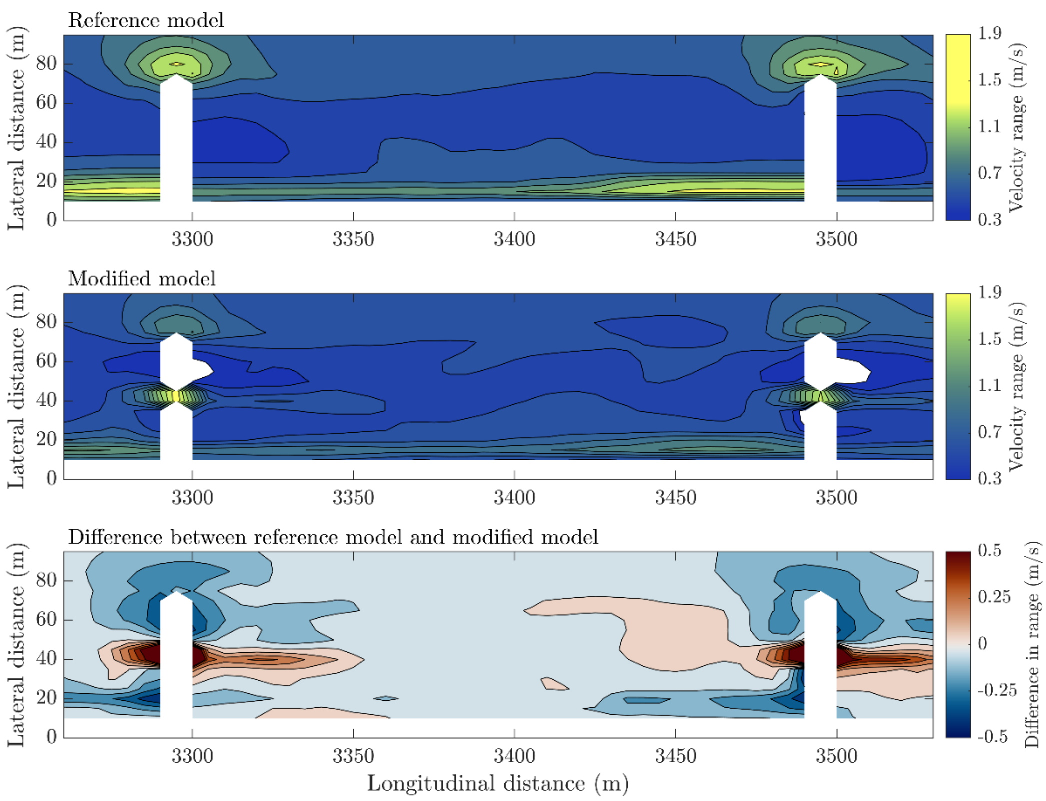
Combined water level range



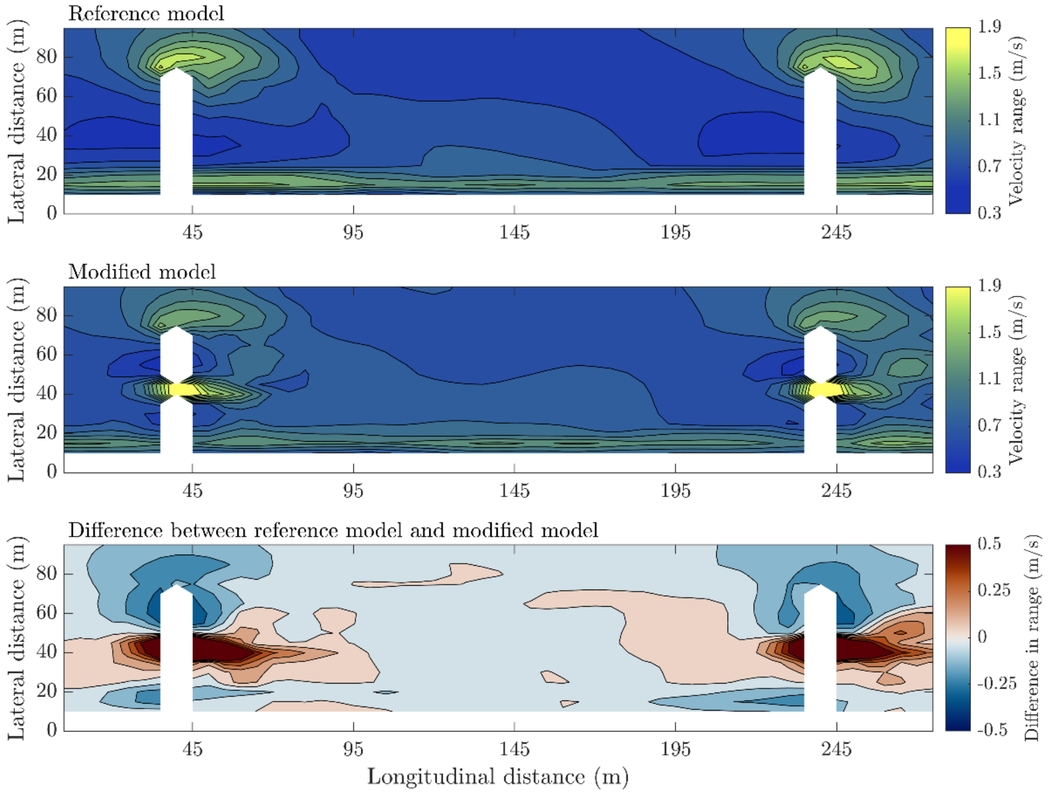
Velocity range upstream sailing



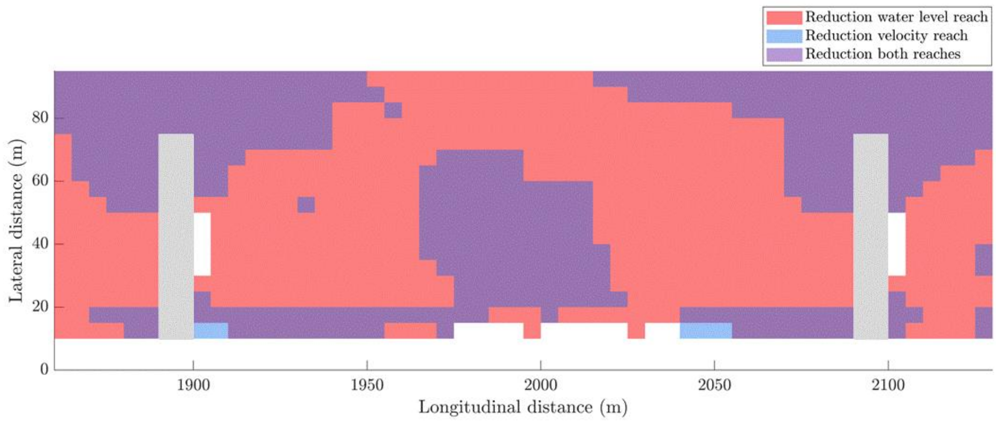
Velocity range downstream sailing



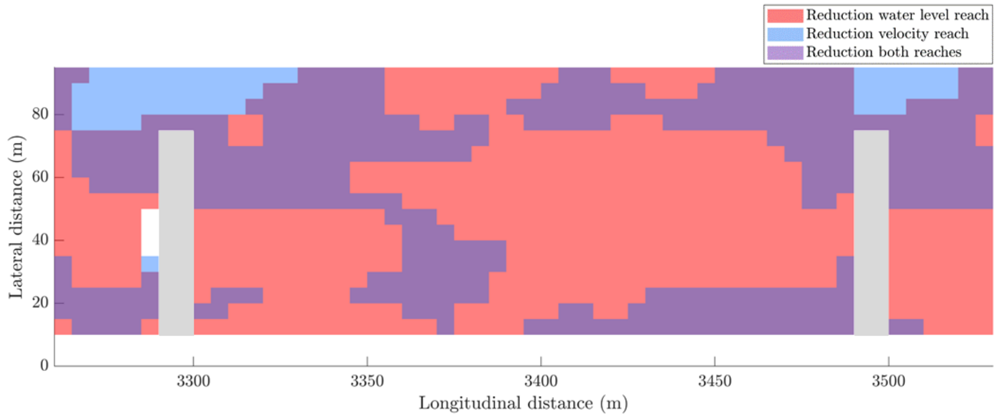
Combined velocity range



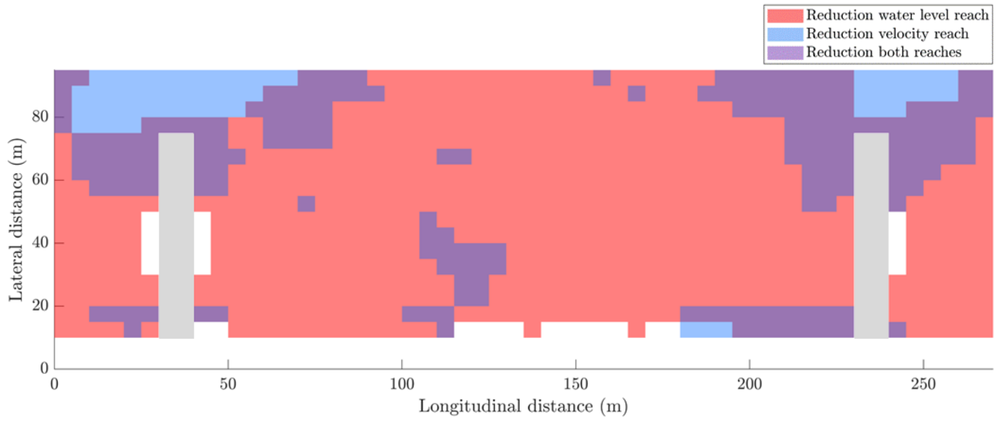
Overview plot upstream sailing



Overview plot dowstream sailing

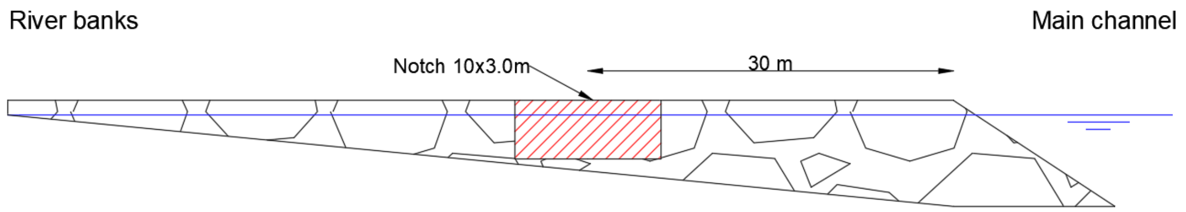


Combined overview plot

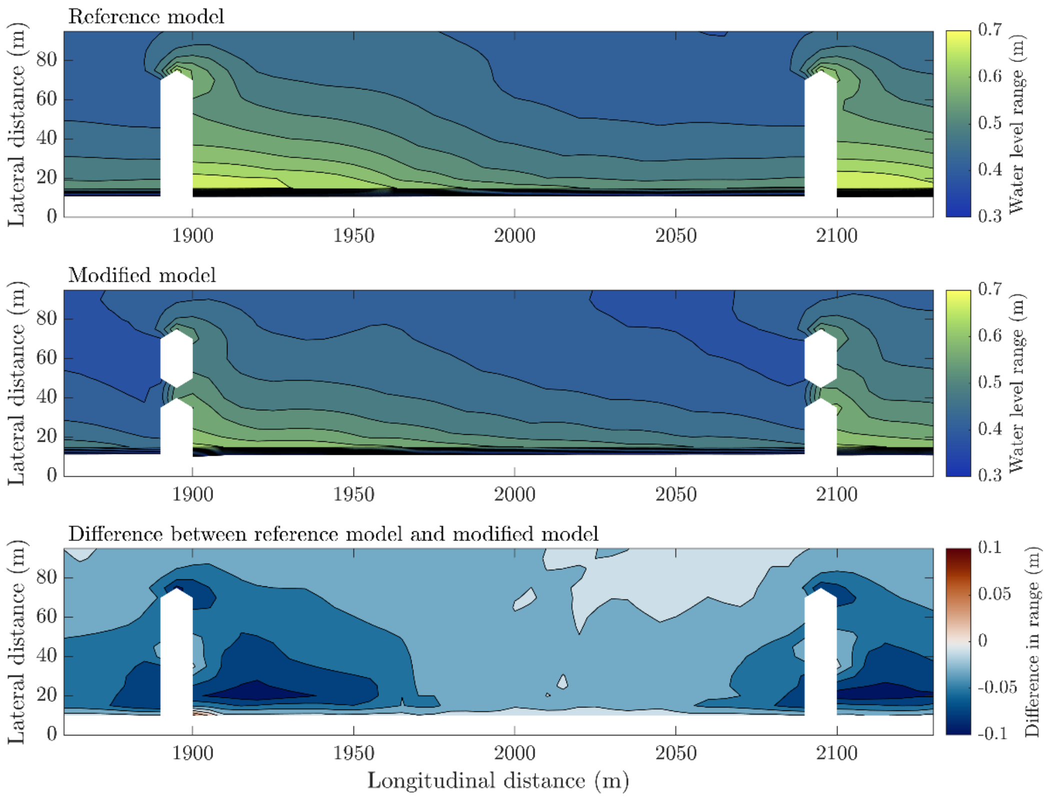


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
2.118	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
2.218	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

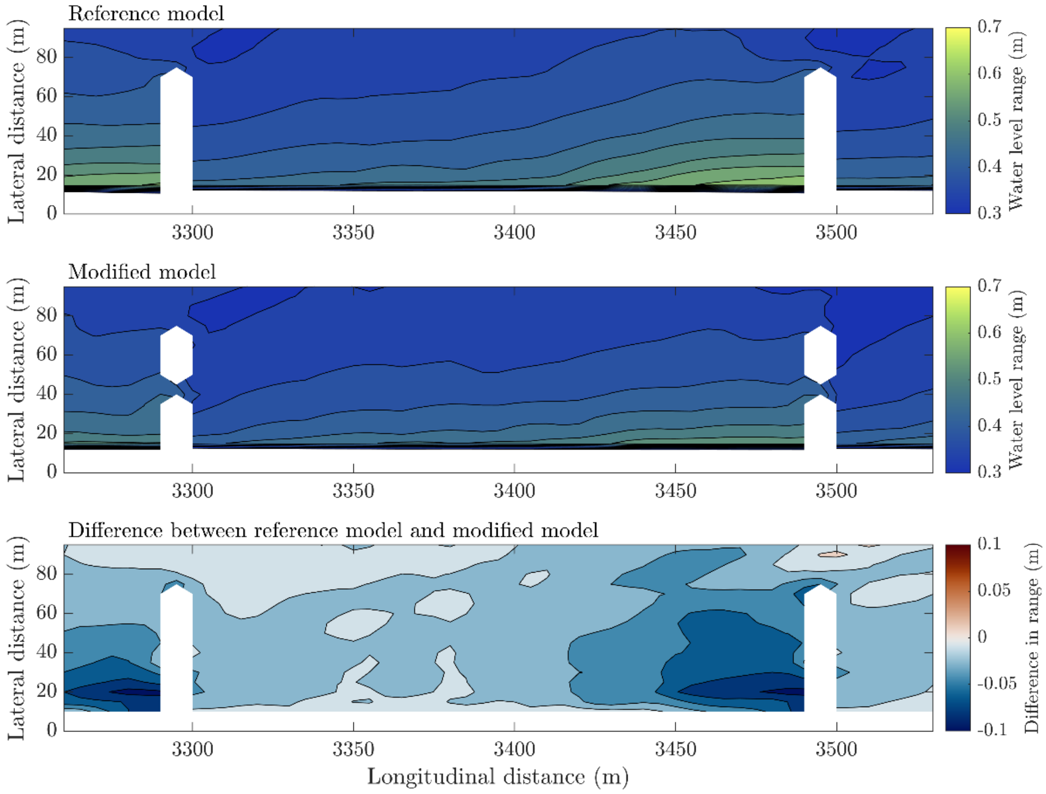
Number of notches	Location of notch	Width notch	Depth notch
1	30 m	10 m	3.0 m



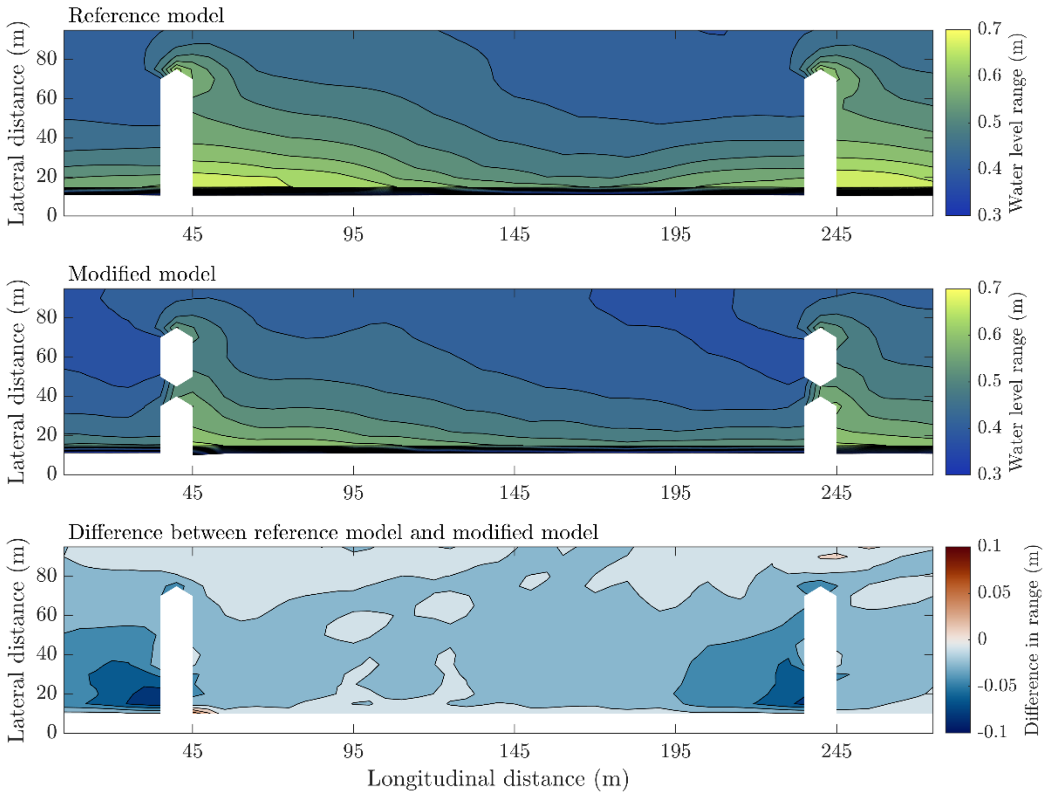
Water level range upstream sailing



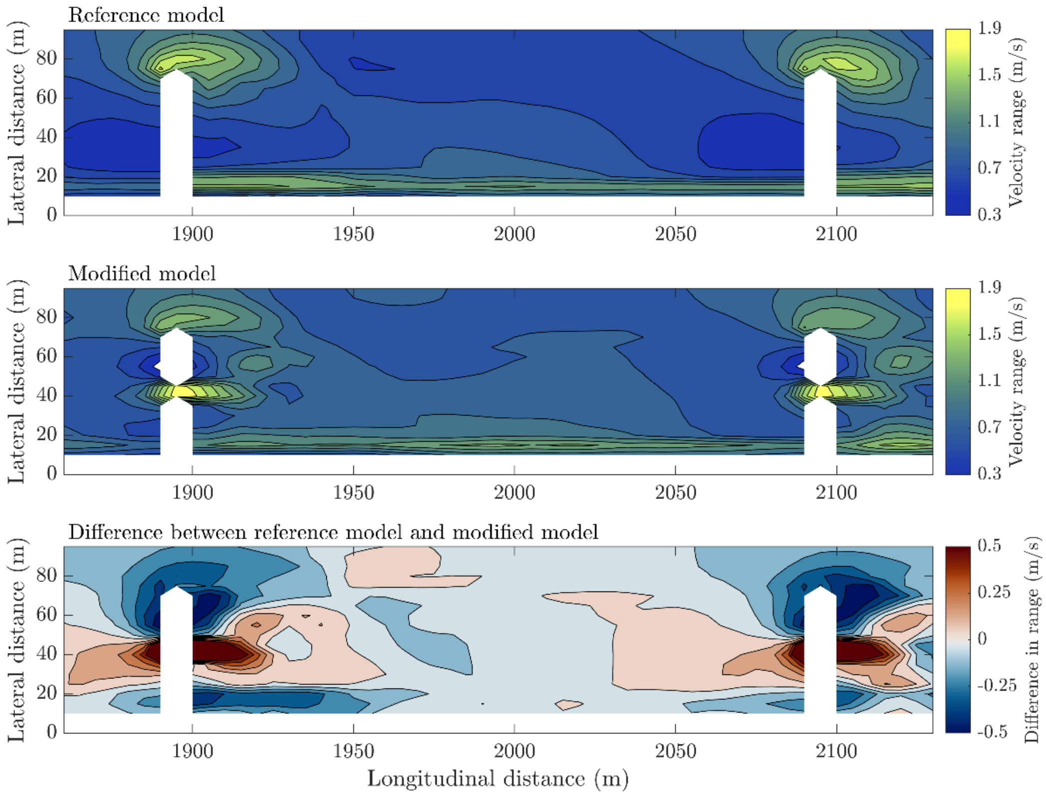
Water level range downstream sailing



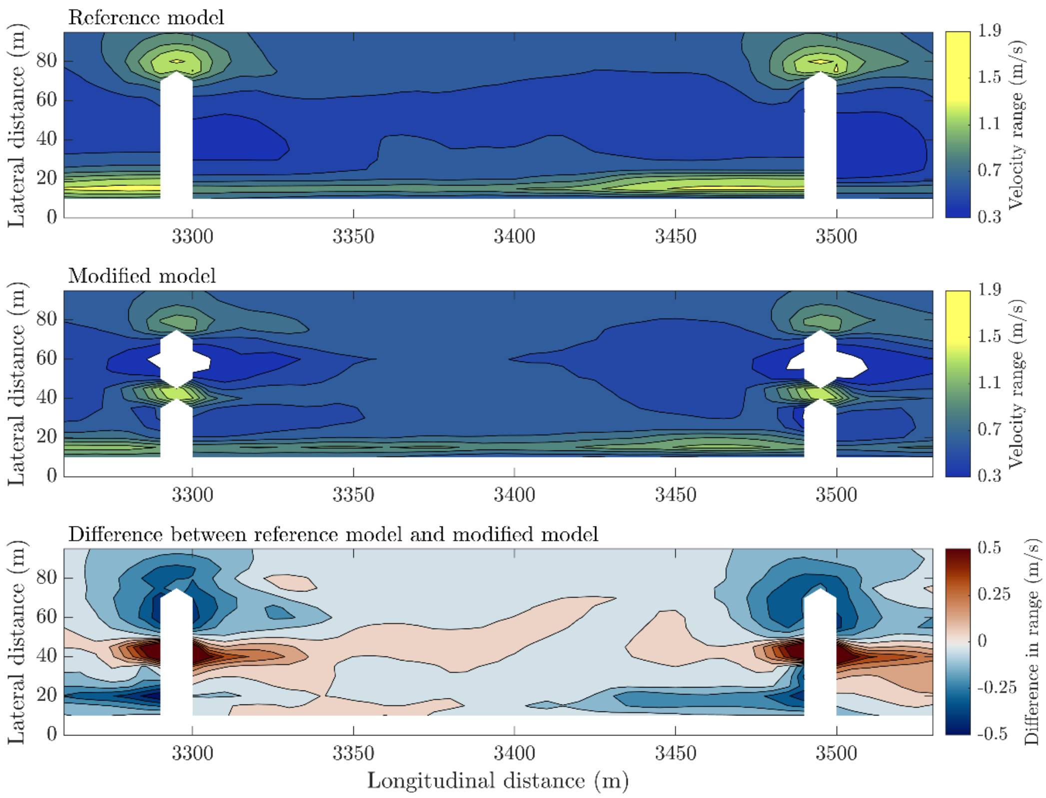
Combined water level range



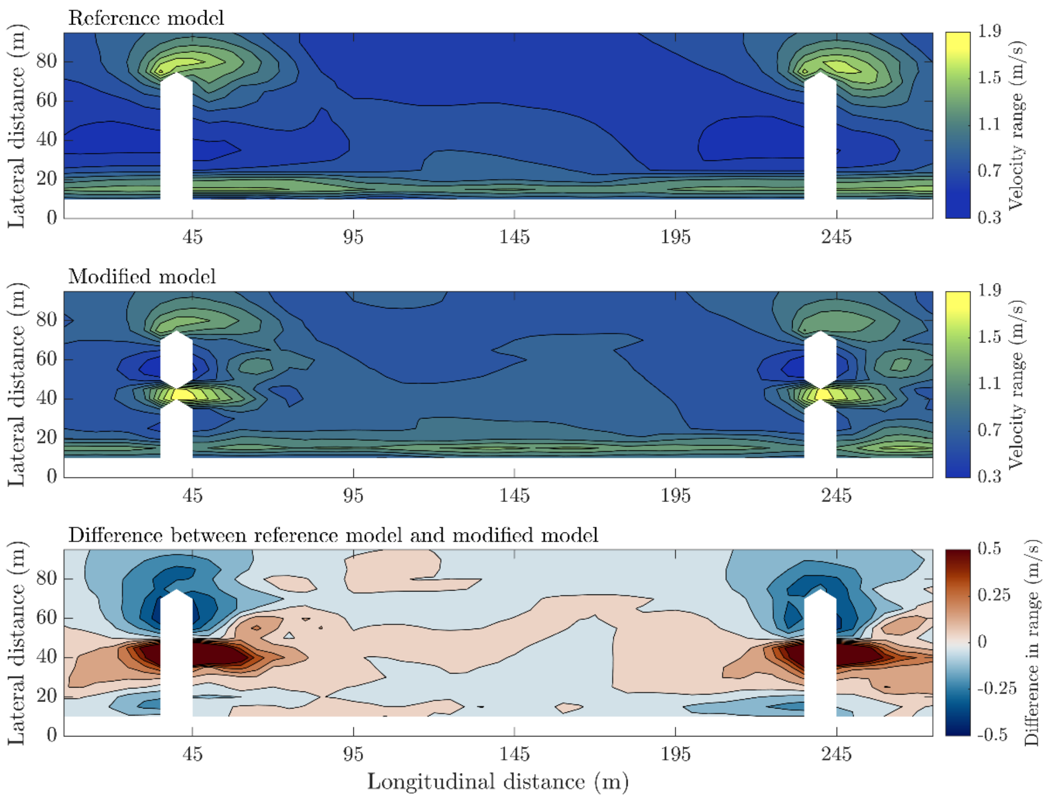
Velocity range upstream sailing



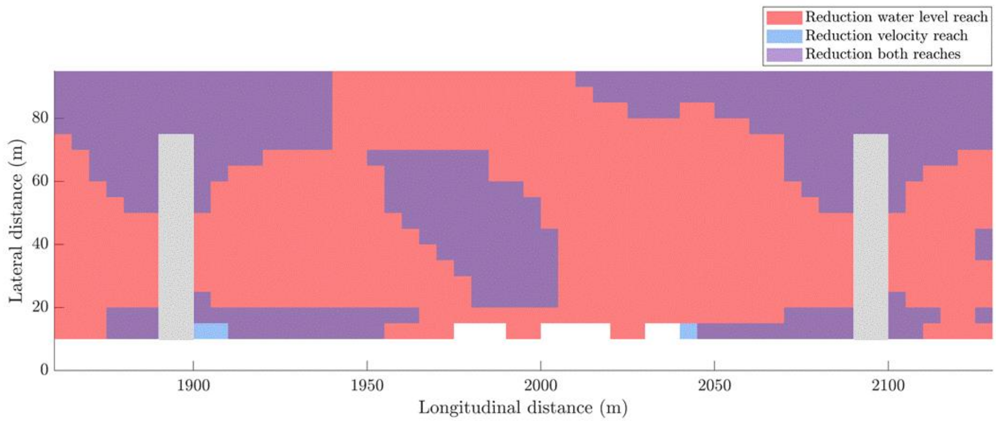
Velocity range downstream sailing



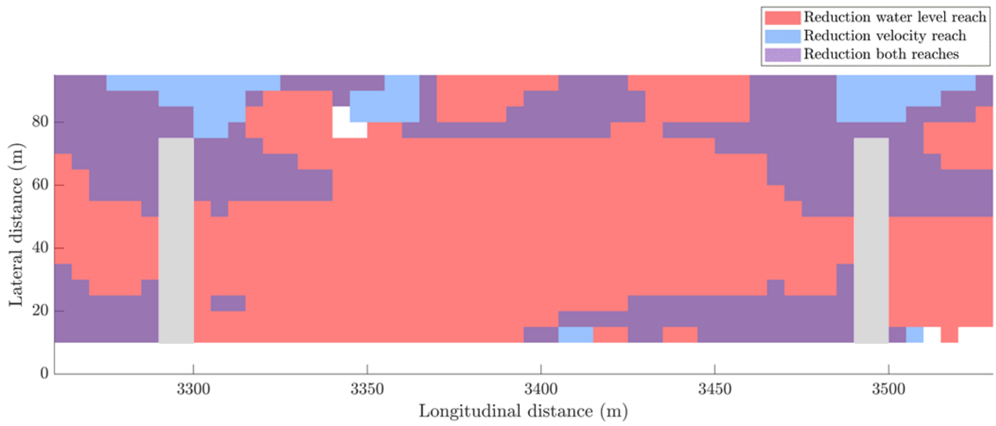
Combined velocity range



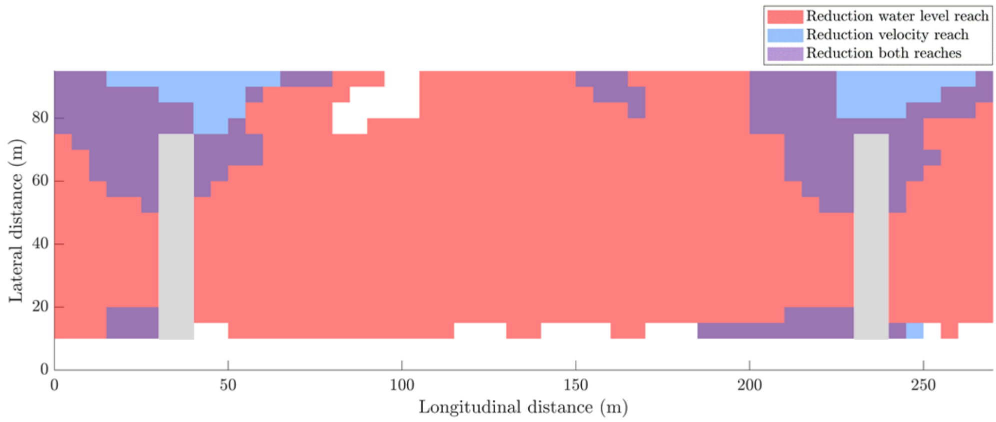
Overview plot upstream sailing



Overview plot dowstream sailing



Combined overview plot



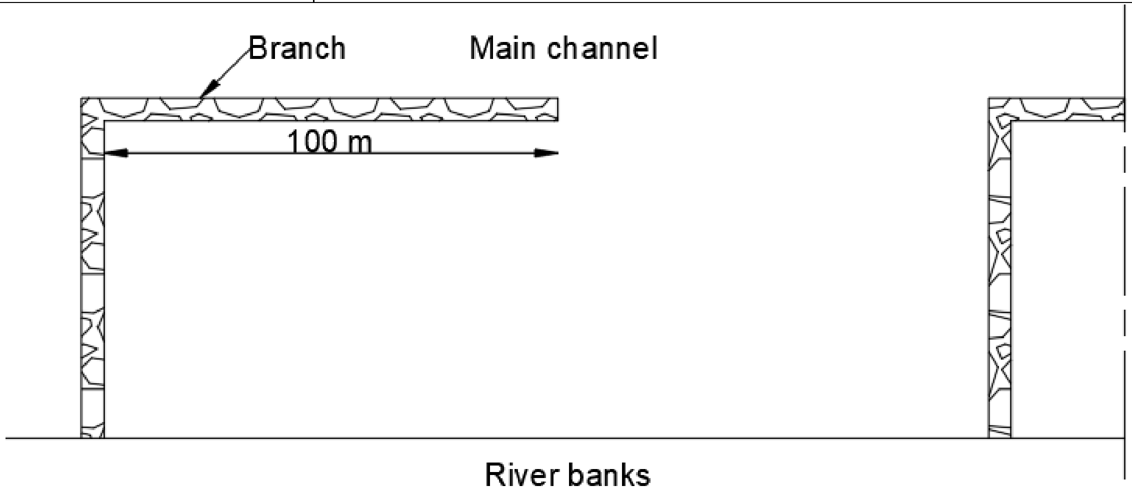
C.2 Results of the L-shaped groynes

In the graph below an overview of the pages of the runs is given. The fourth cell called "used for dependency on" refers to the study, one run can be used for multiple dependency studies. In Section 5.4 the study is split up in 3 different L-groyne characteristics to determine the dependency of the flow pattern in the groyne field on these characteristics. In this cell is displayed which run is used to determine the dependency on various characteristics.

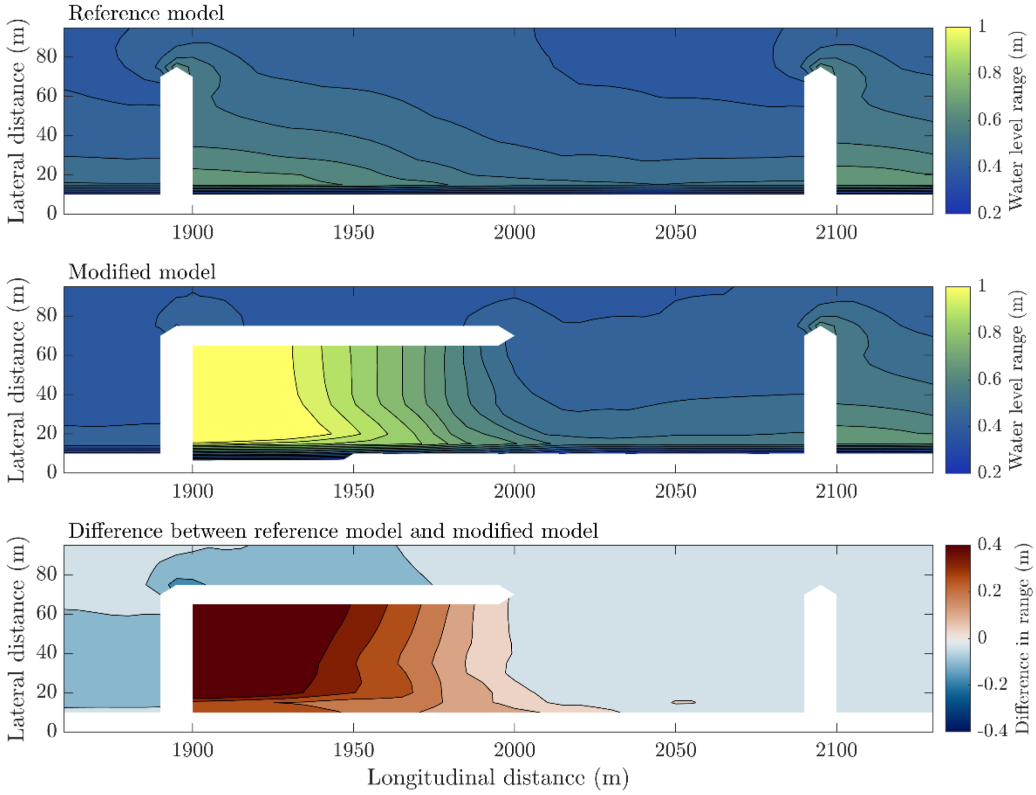
Run number upstream / downstream	**Length of branch [m]**	**Notch direction**	**Dependency on**	**Page number**
3.101 / 3.201	100	Downstream	Number of modified groynes	178
3.102 / 3.202	100	Downstream	Number of modified groynes / Branch length / Notch direction	183
3.103 / 3.203	100	Upstream	Notch direction	188
3.104 / 3.204	50	Downstream	Branch length	193
3.105 / 3.205	150	Downstream	Branch length	198
3.106 / 3.206	175	Downstream	Branch length	203
3.107 / 3.207	25	Downstream	Branch length	208

Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
3.101	1.1	Push Tow	Upstream	4.5 m/s	L-groyne
3.201	1.2	Push Tow	Downstream	4.5 m/s	L-groyne

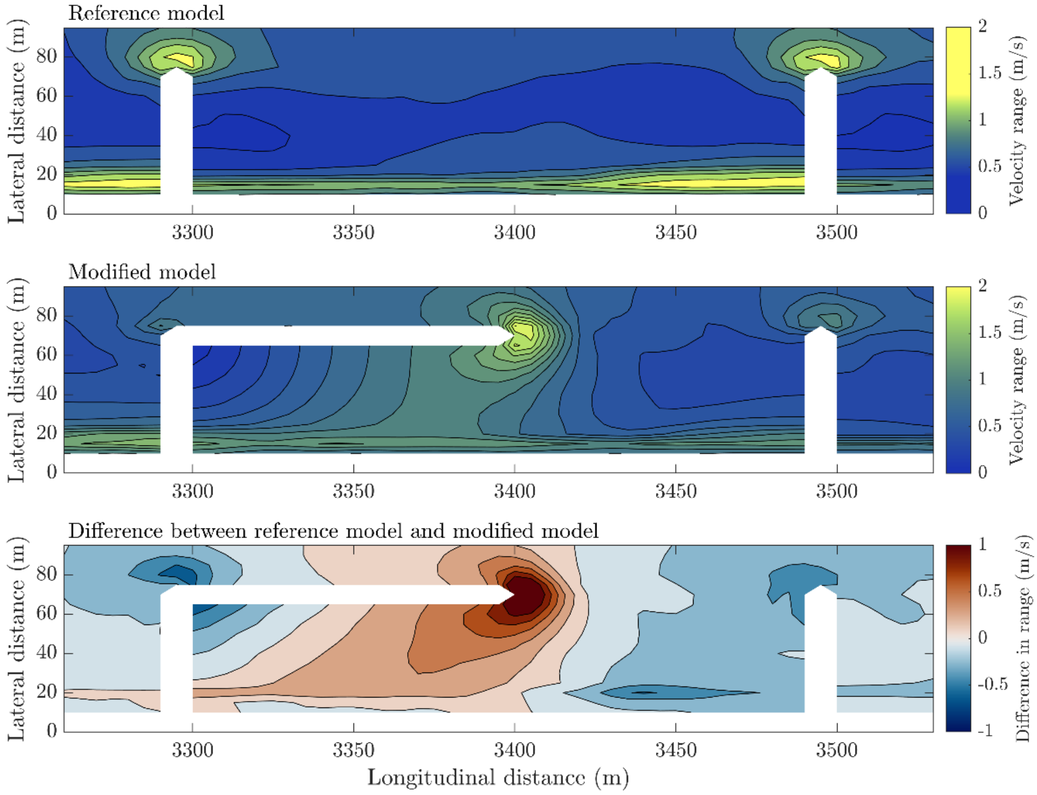
Length of branch	100 m



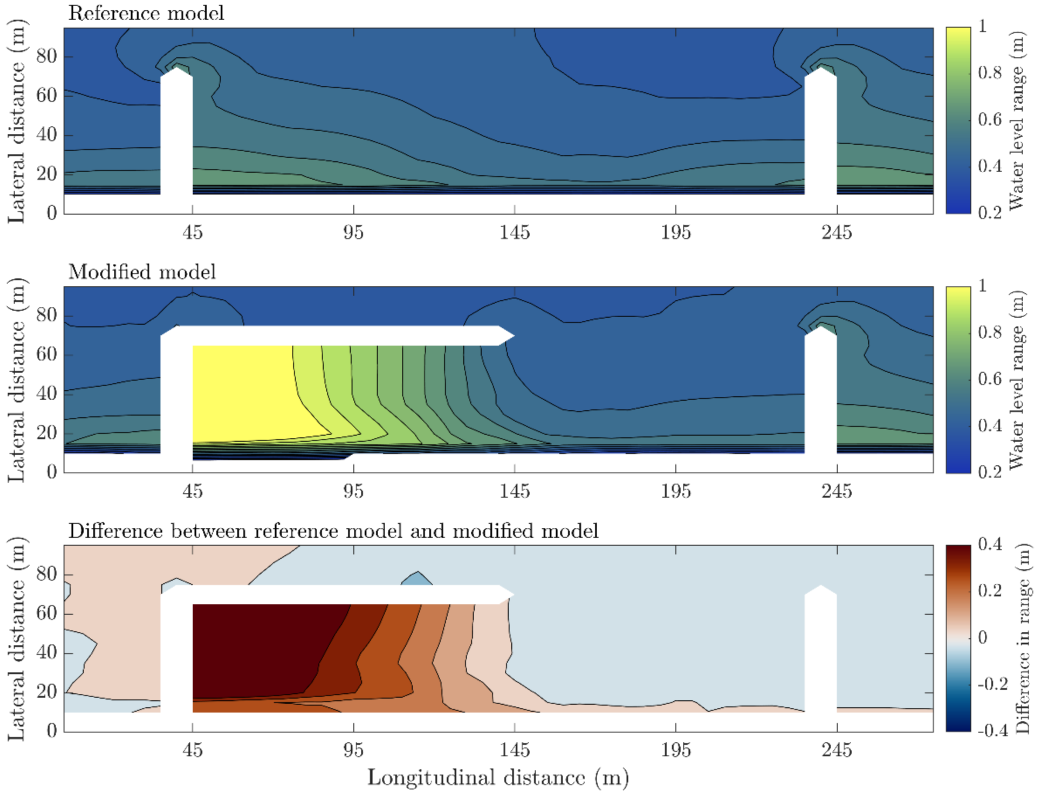
<u>Water level range upstream sailing</u>



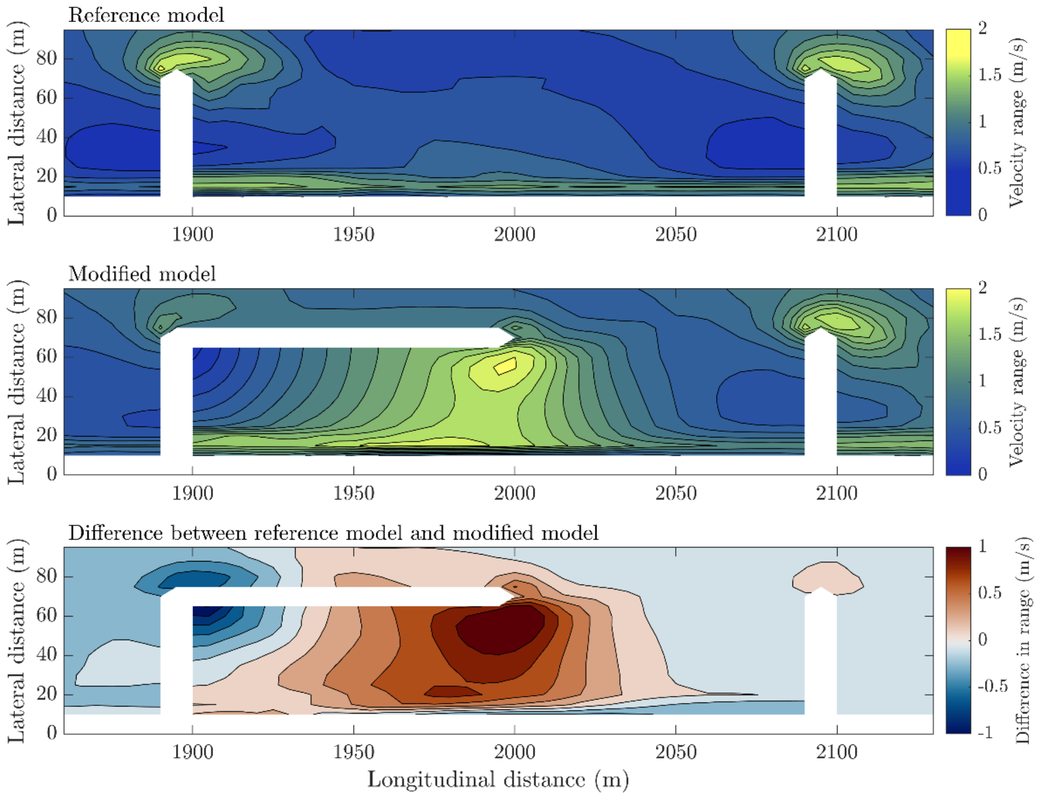
Water level range downstream sailing



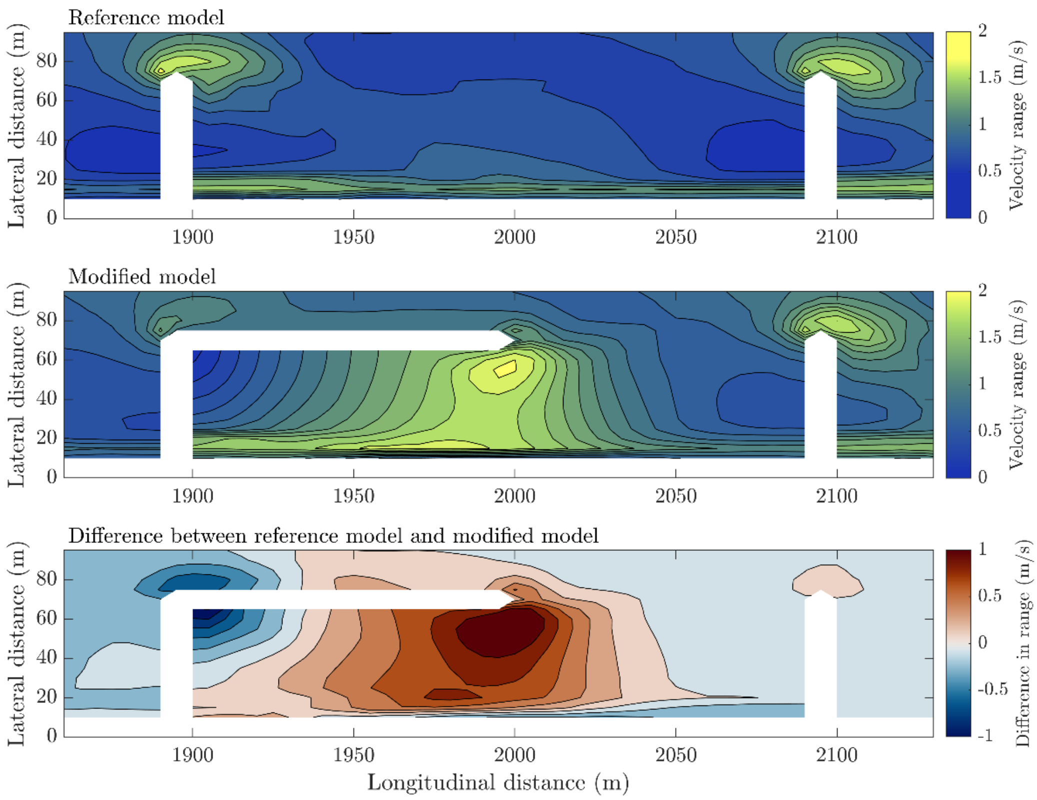
Combined water level range



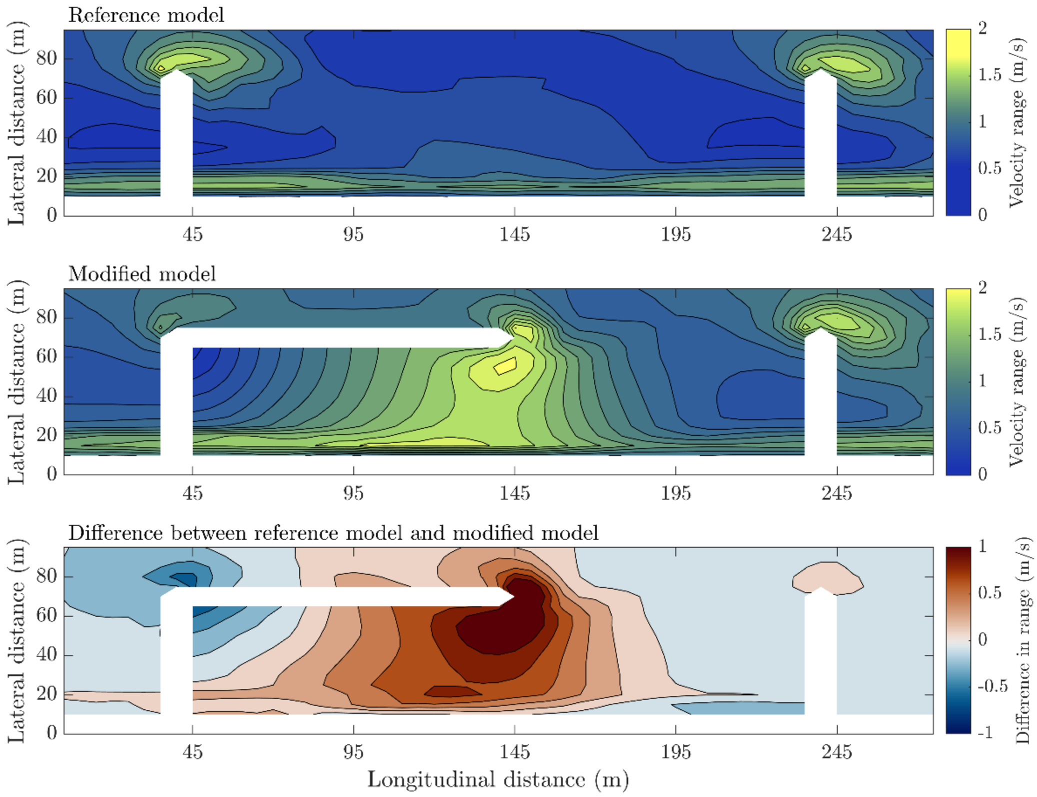
Velocity range upstream sailing



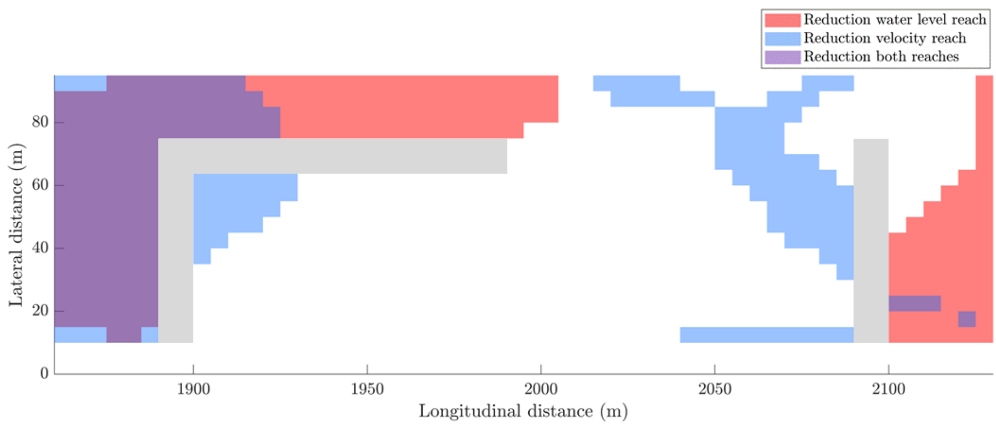
Velocity range downstream sailing



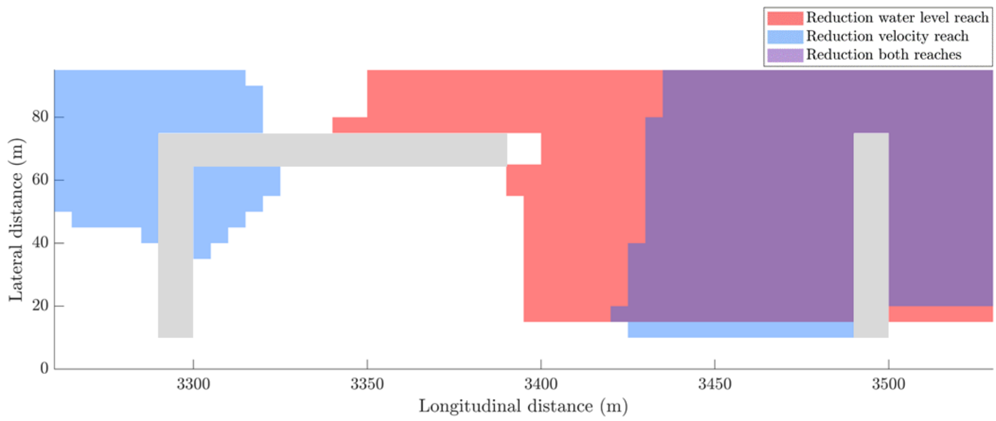
Combined velocity range



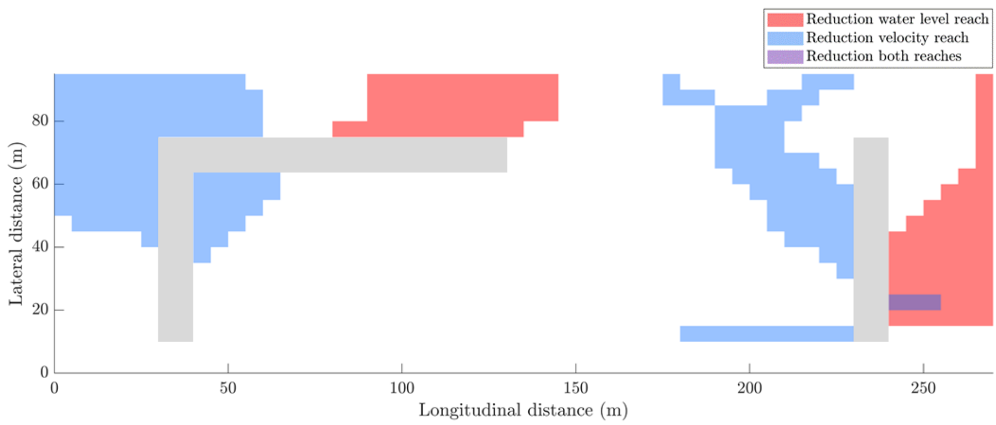
Overview plot upstream sailing



Overview plot dowstream sailing

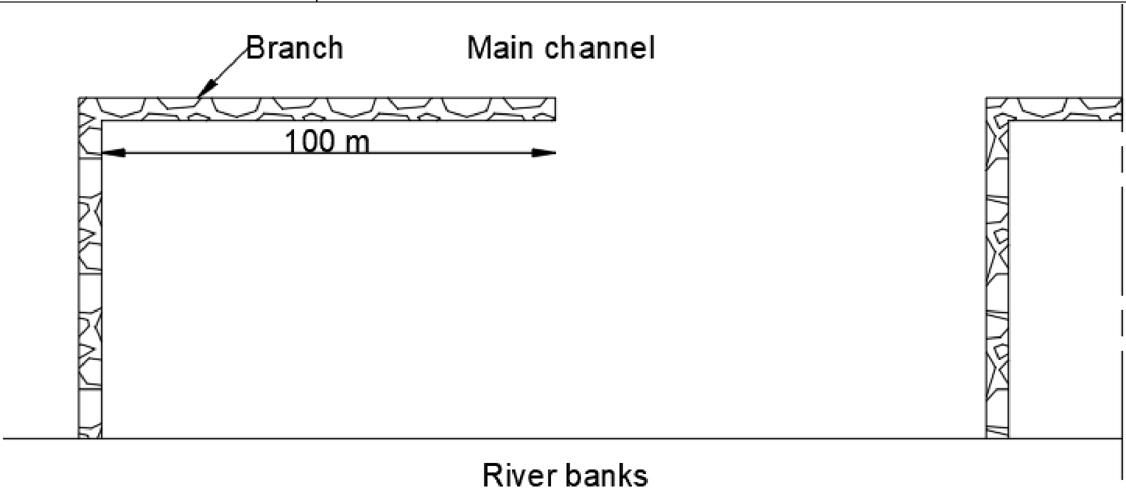


Combined overview plot

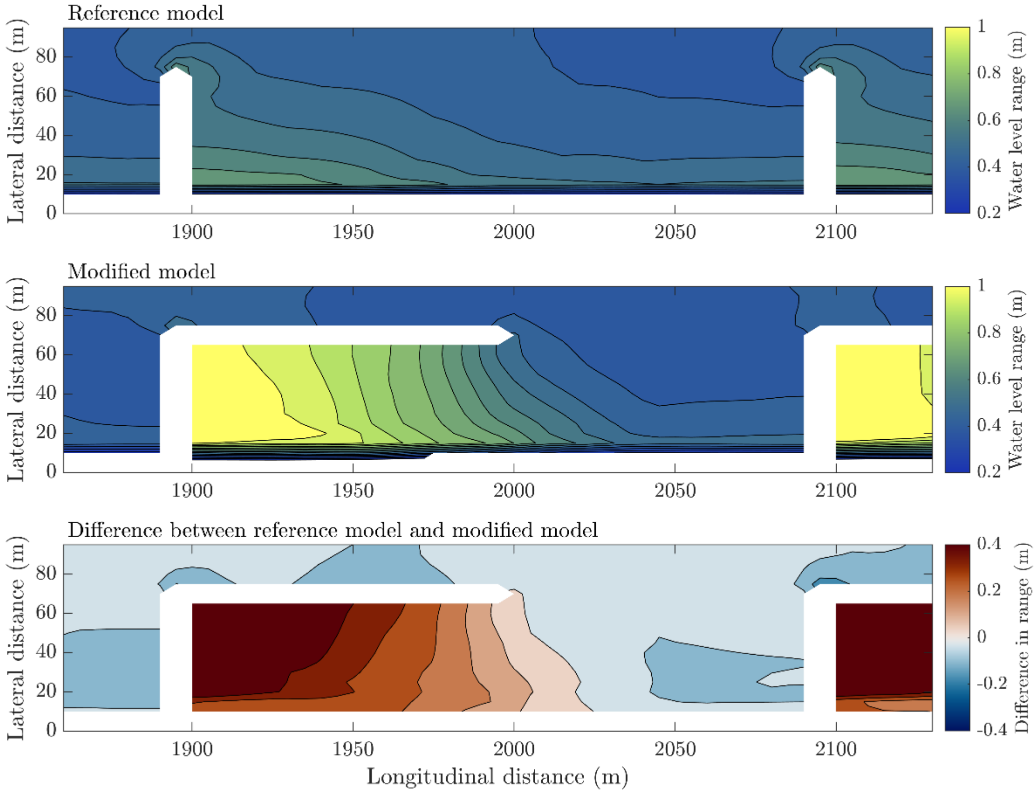


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
3.102	1.1	Push Tow	Upstream	4.5 m/s	L-groyne
3.202	1.2	Push Tow	Downstream	4.5 m/s	L-groyne

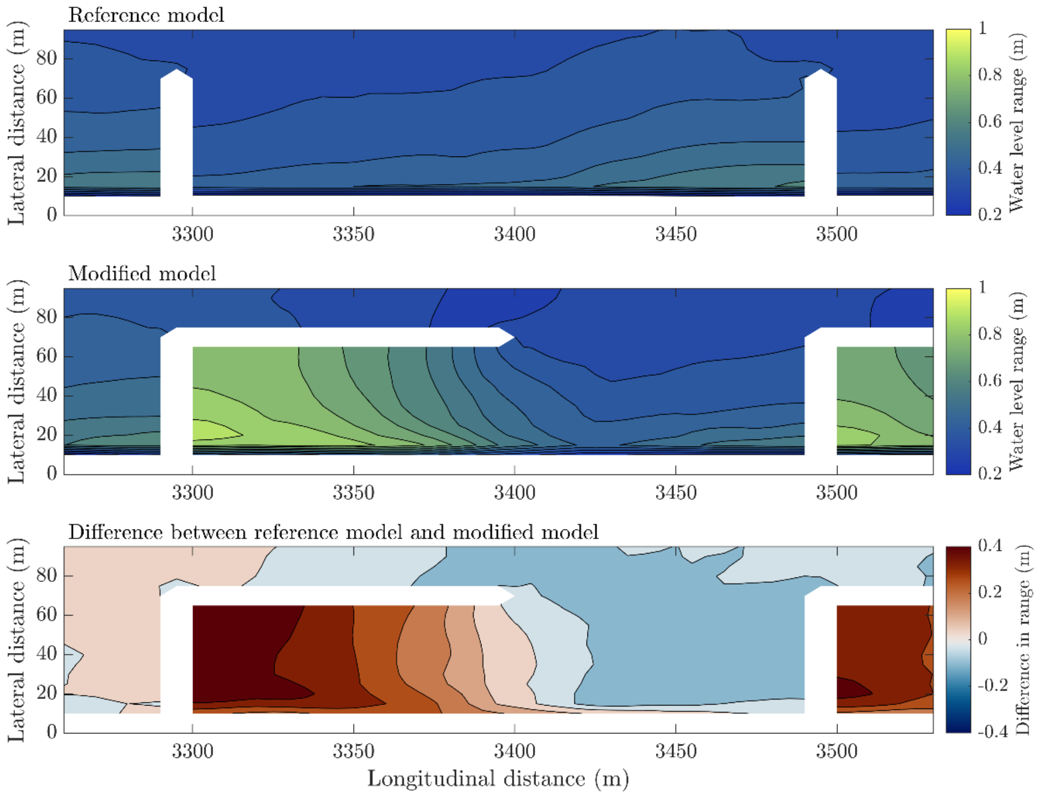
Length of branch	100 m



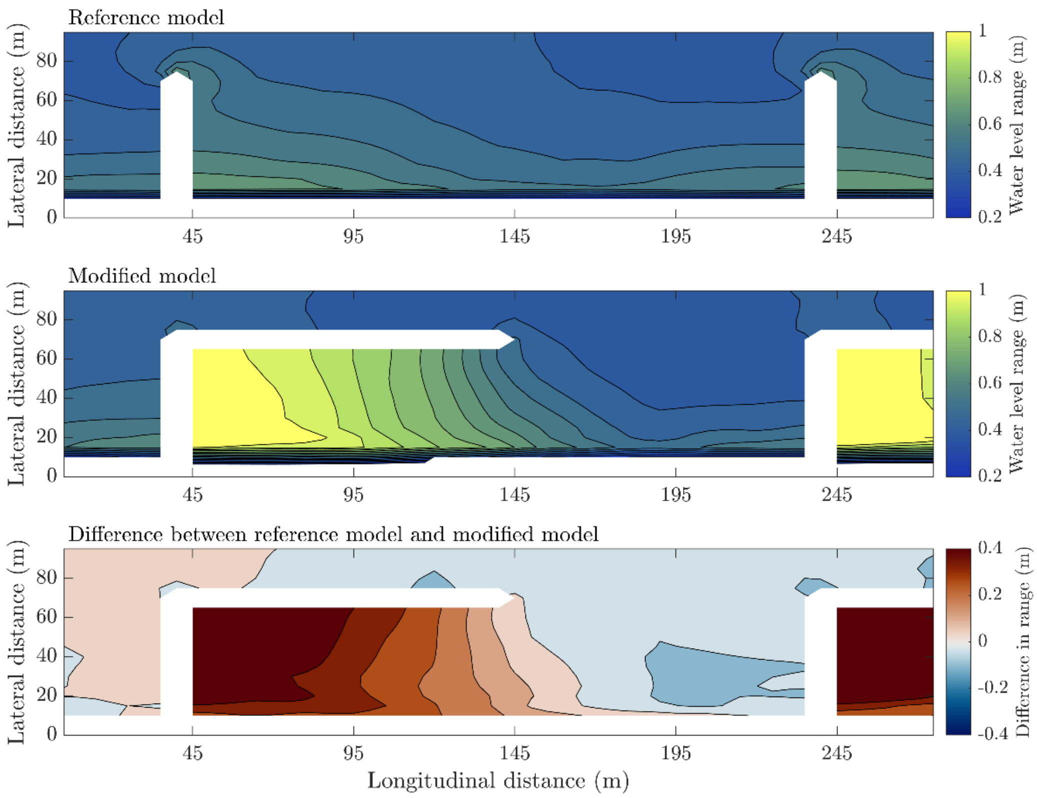
Water level range upstream sailing



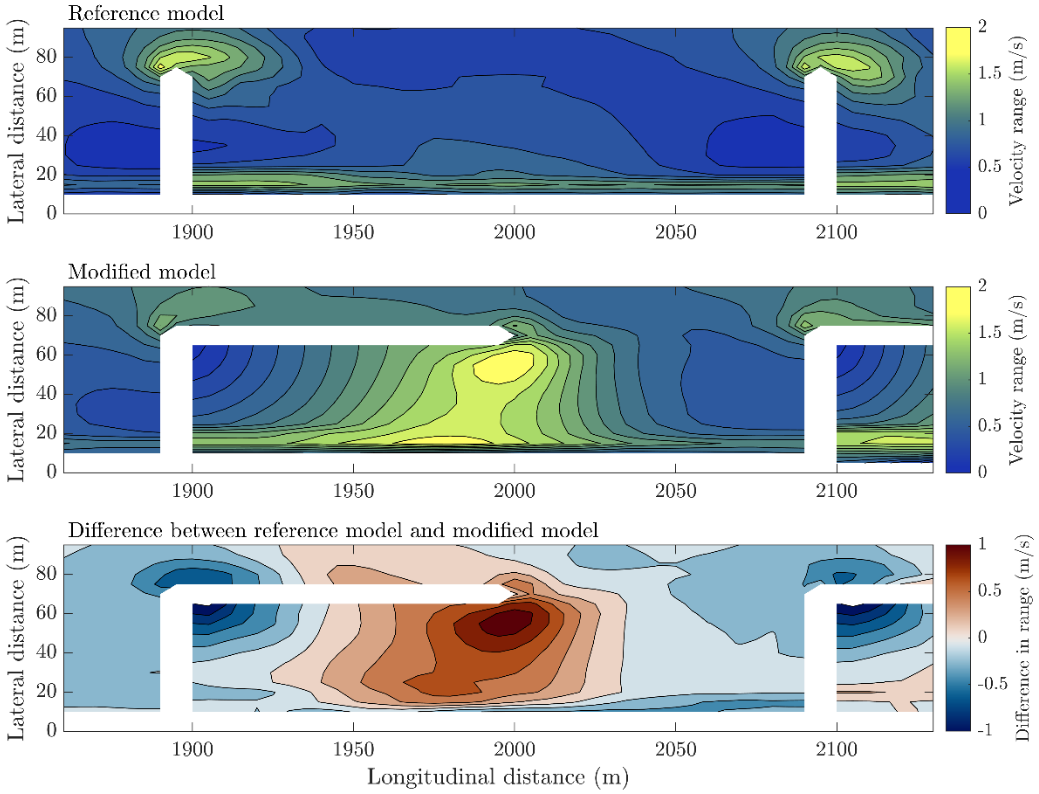
Water level range downstream sailing



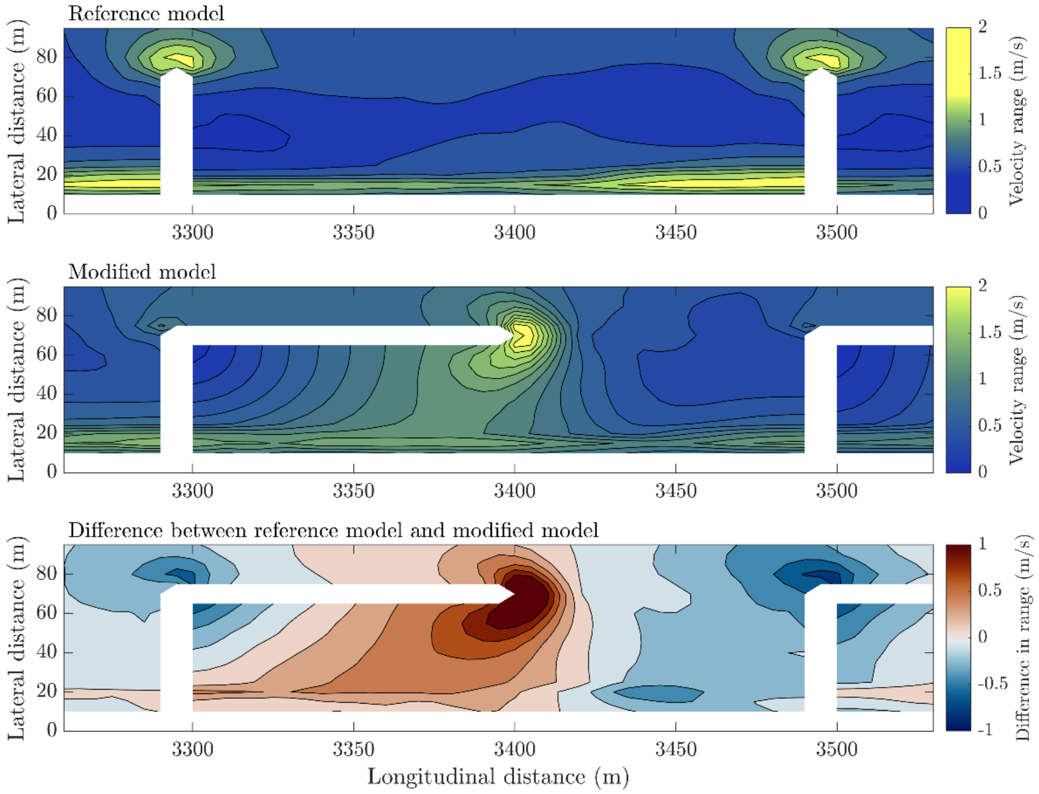
Combined water level range



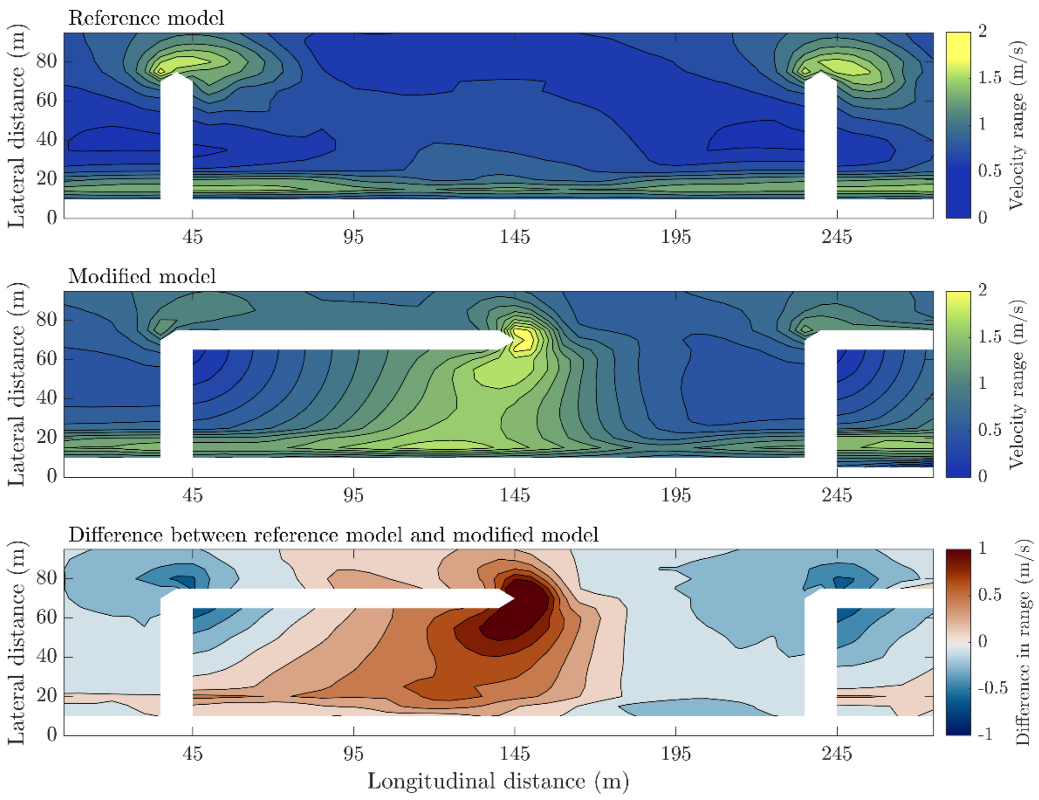
Velocity range upstream sailing



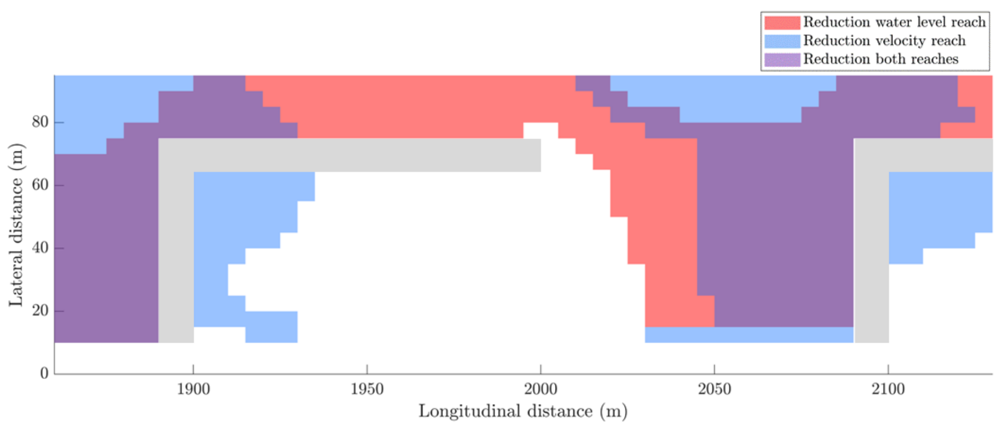
Velocity range downstream sailing



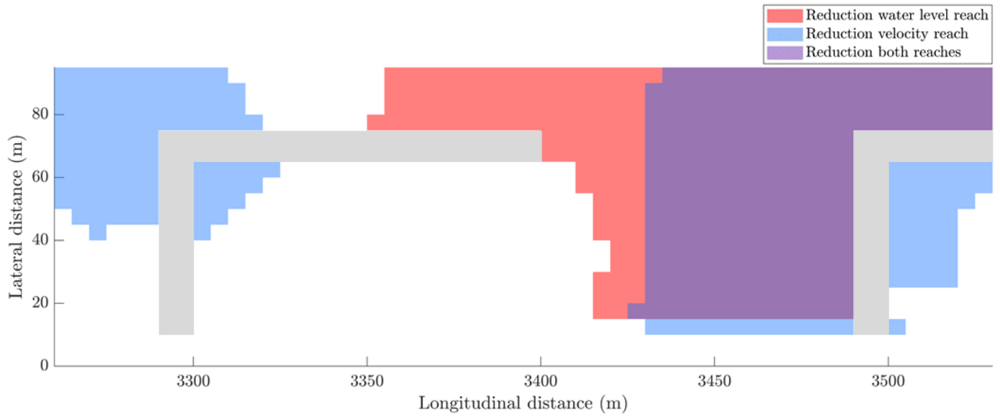
Combined velocity range



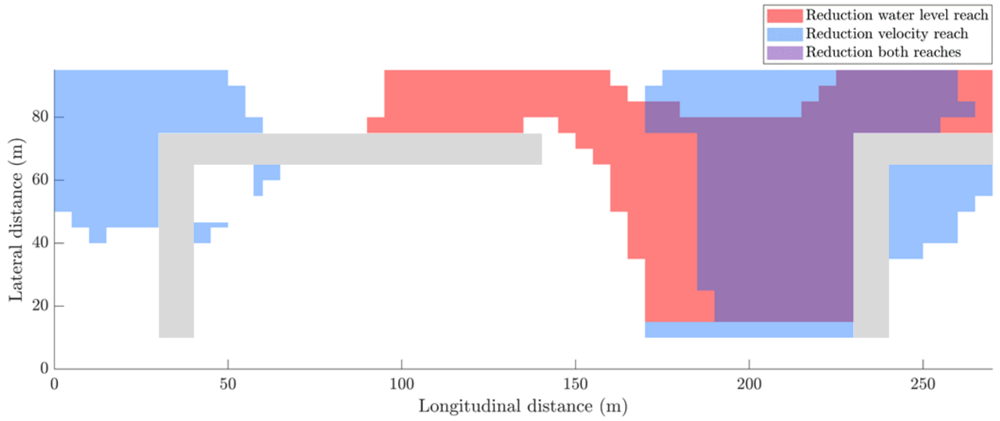
Overview plot upstream sailing



Overview plot dowstream sailing



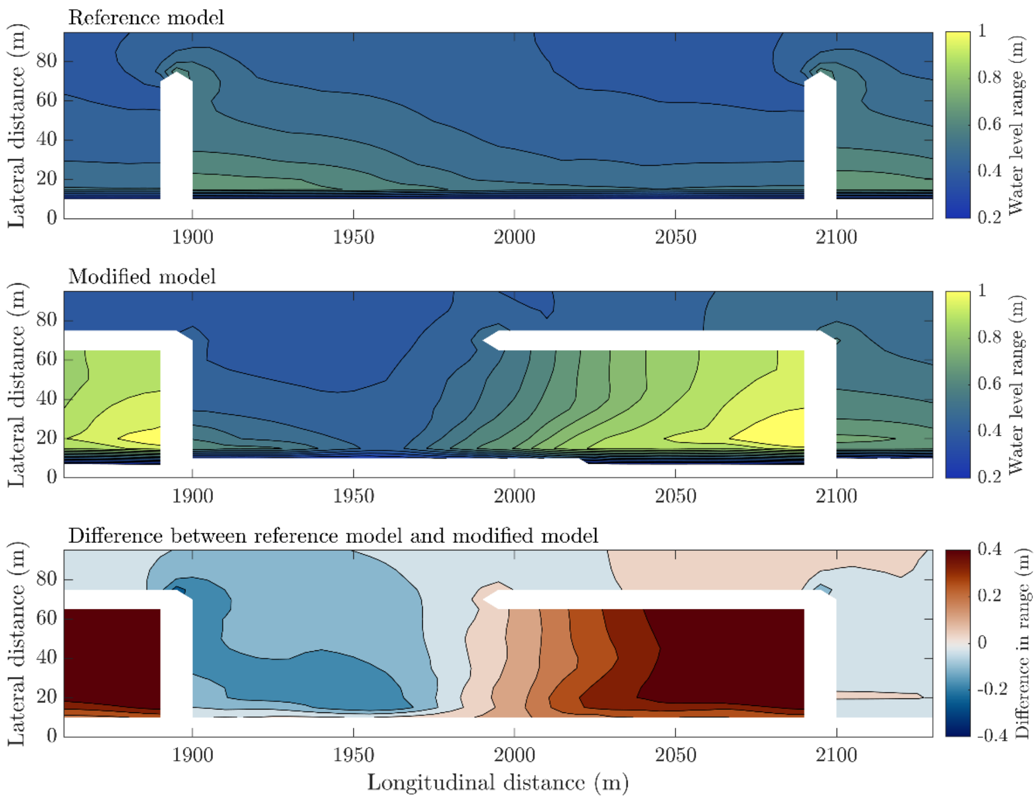
Combined overview plot



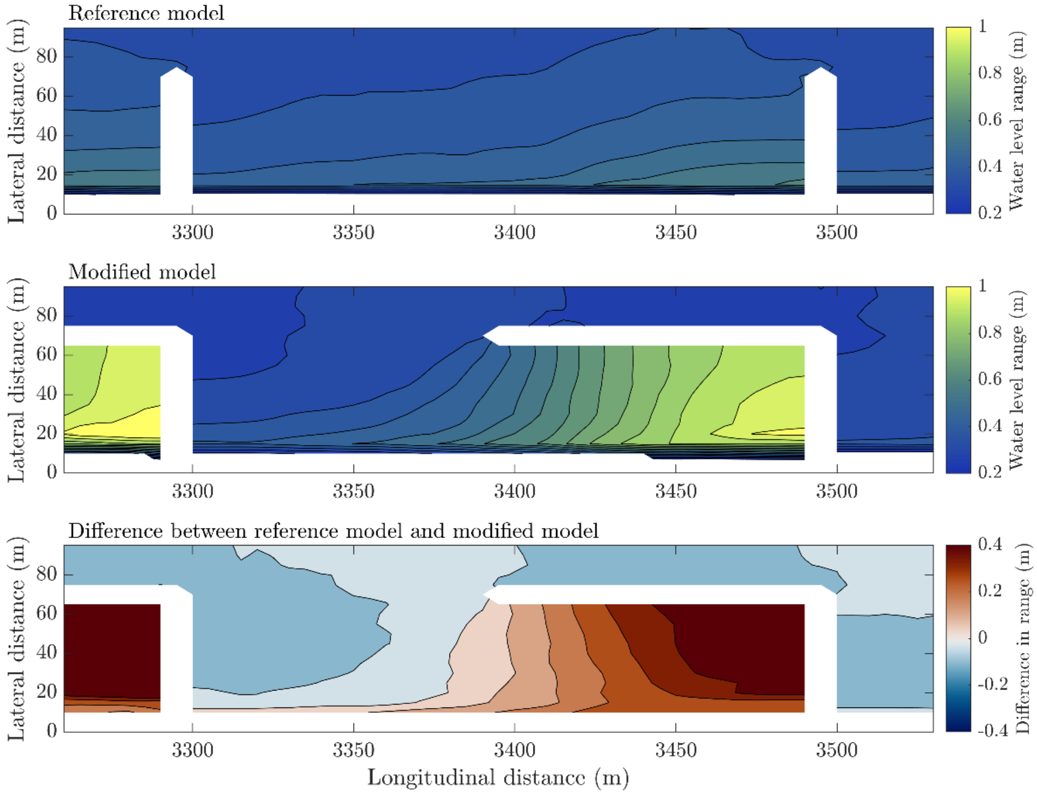
Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
3.103	1.1	Push Tow	Upstream	4.5 m/s	L-groyne
3.203	1.2	Push Tow	Downstream	4.5 m/s	L-groyne

Length of branch	100 m

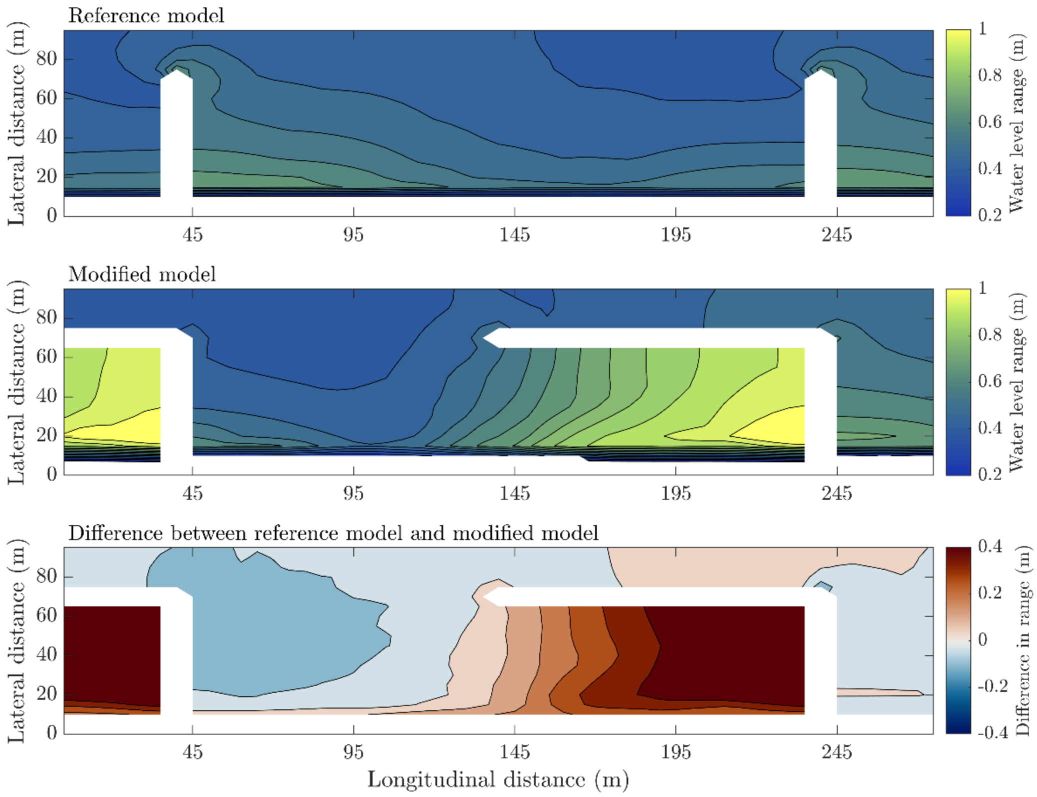
Water level range upstream sailing



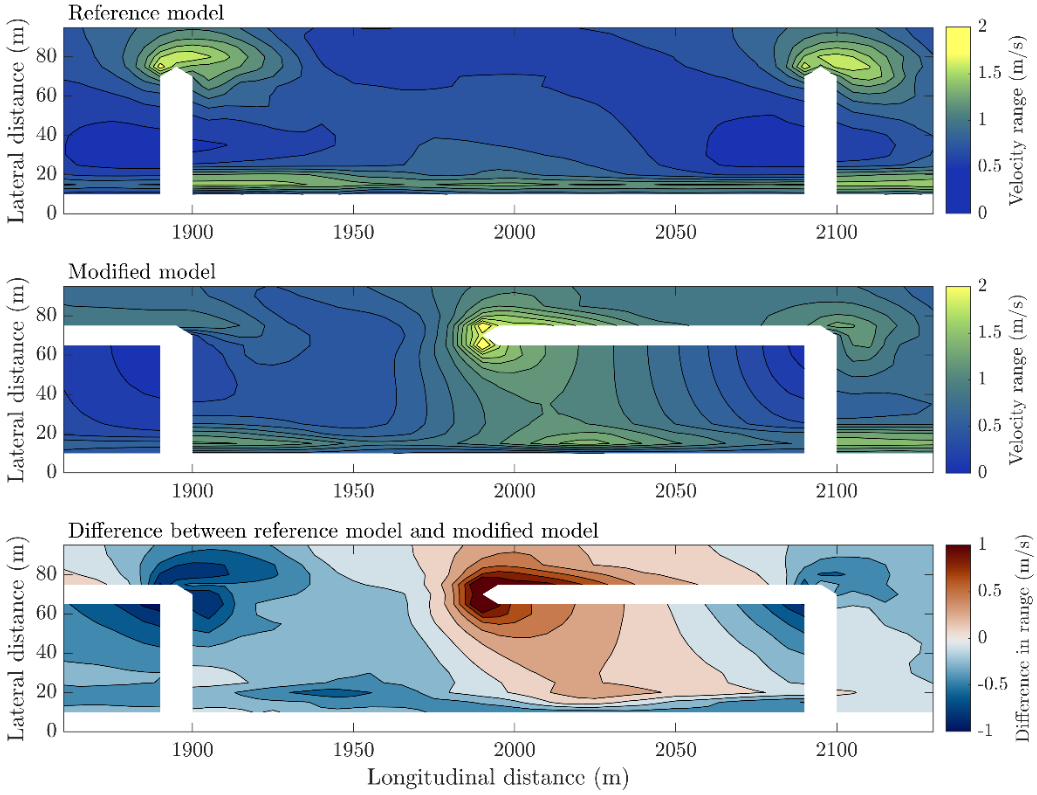
Water level range downstream sailing



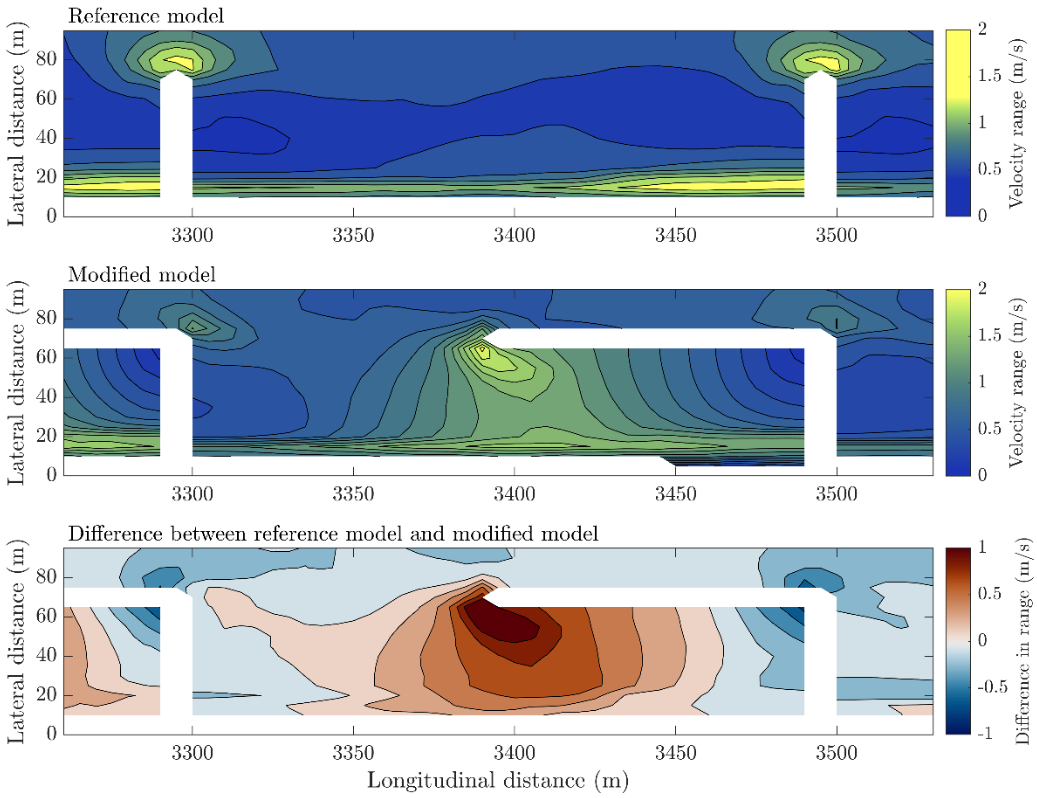
Combined water level range



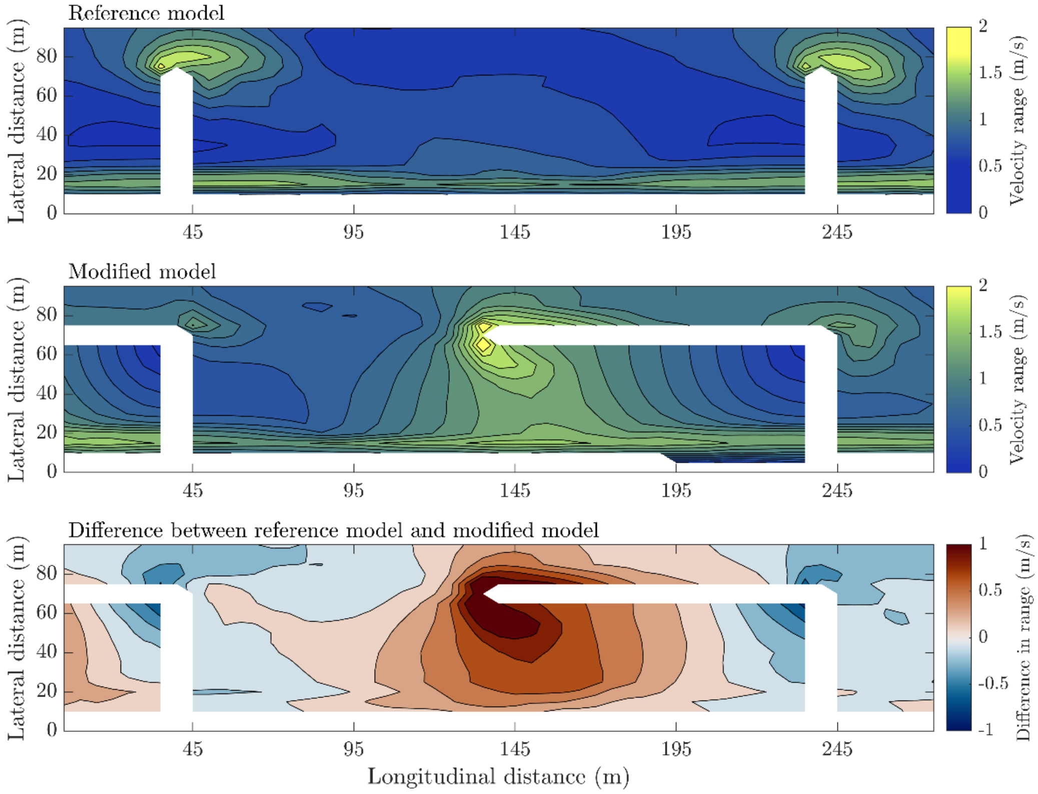
Velocity range upstream sailing



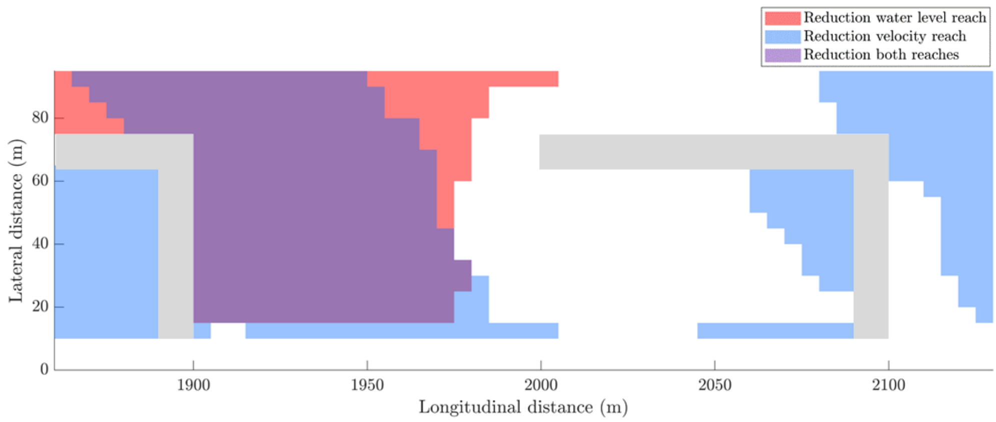
Velocity range downstream sailing



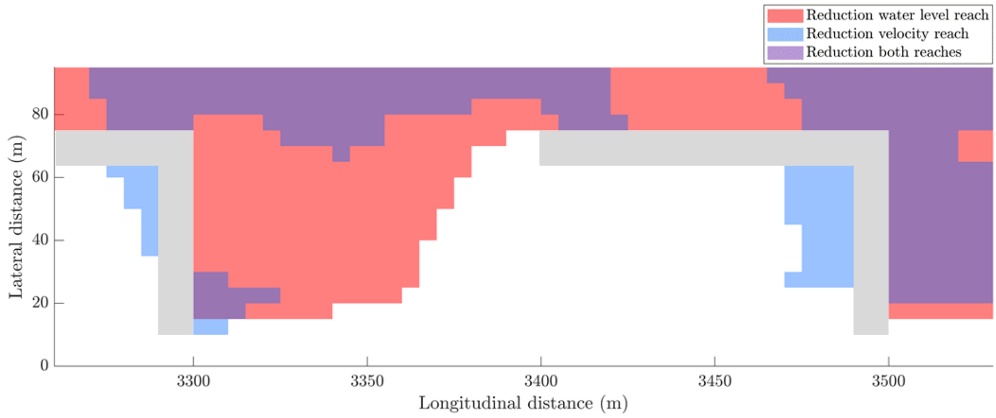
Combined velocity range



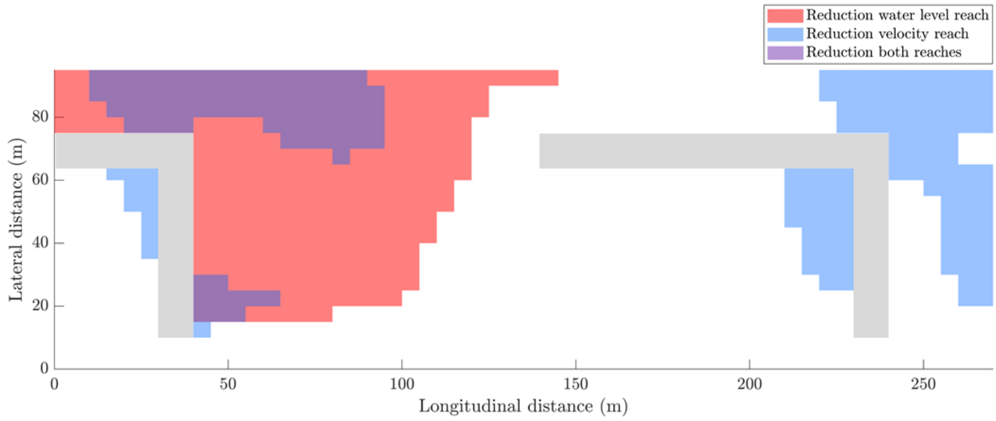
Overview plot upstream sailing



Overview plot dowstream sailing

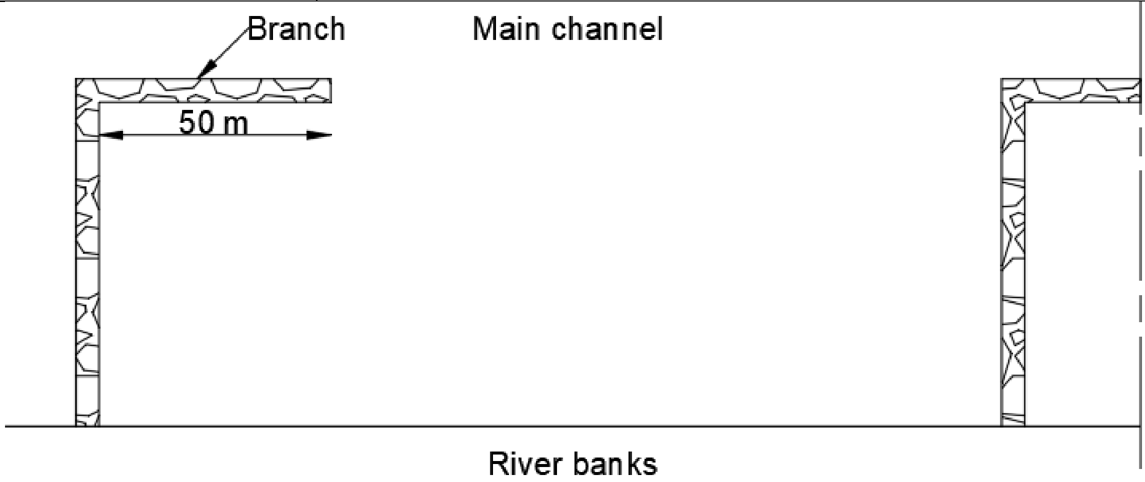


Combined overview plot

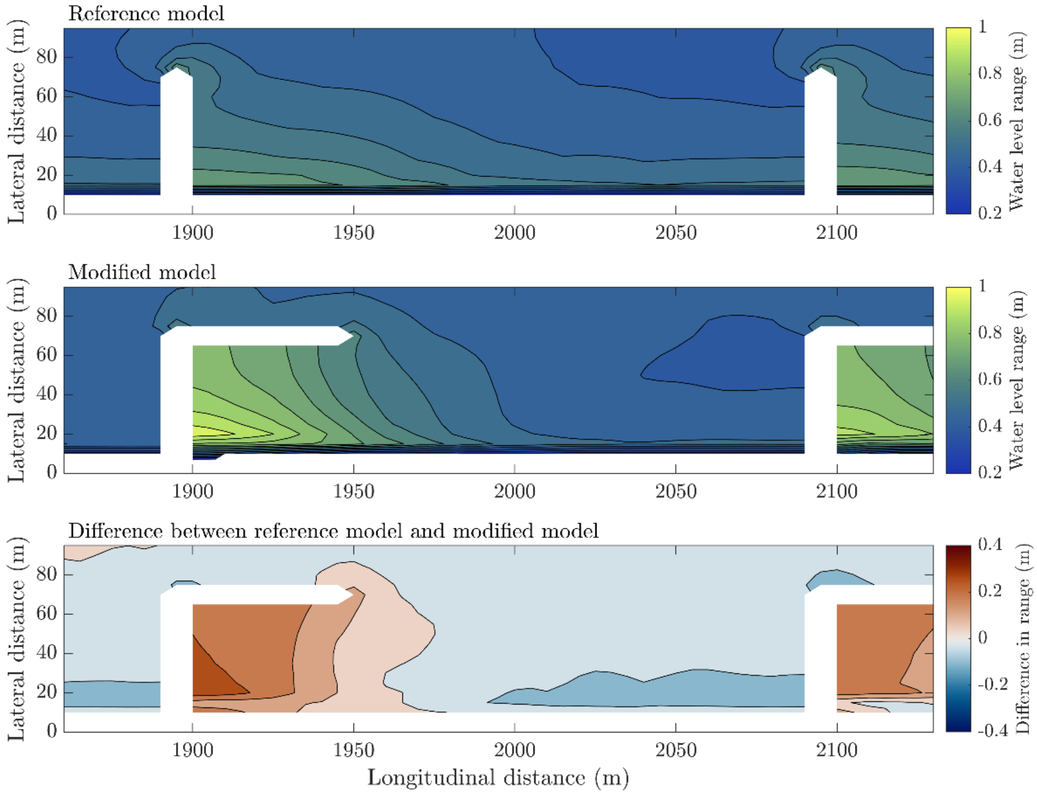


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
3.104	1.1	Push Tow	Upstream	4.5 m/s	L-groyne
3.204	1.2	Push Tow	Downstream	4.5 m/s	L-groyne

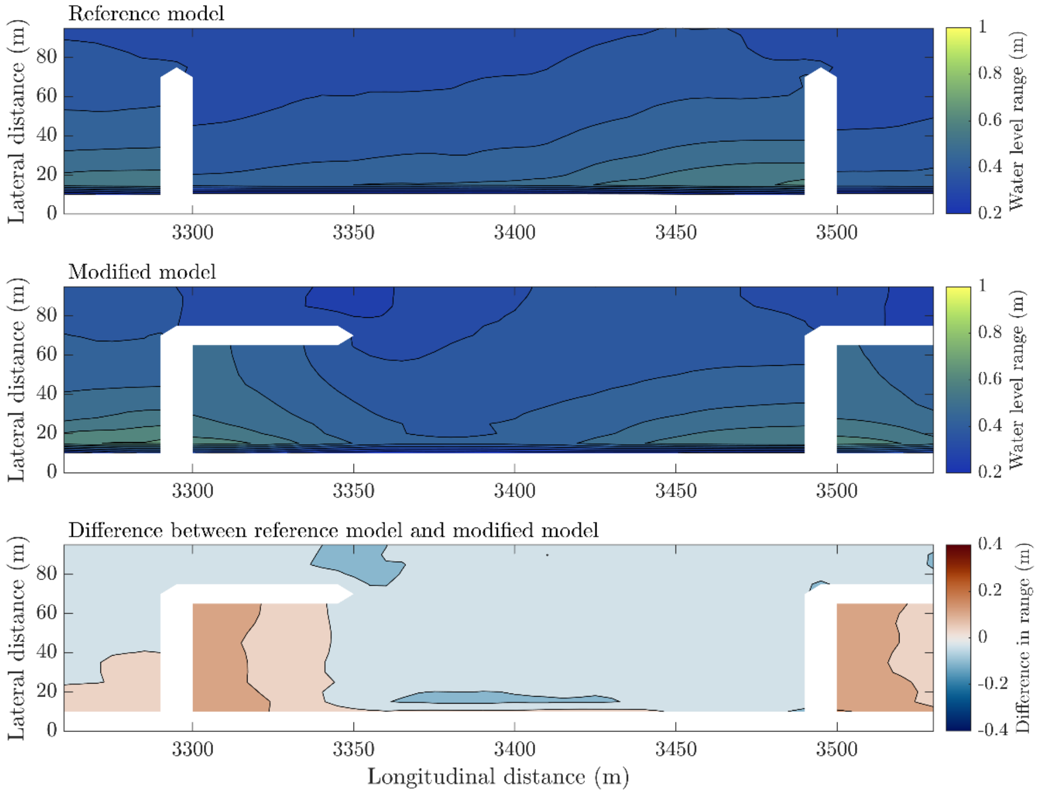
Length of branch	50 m



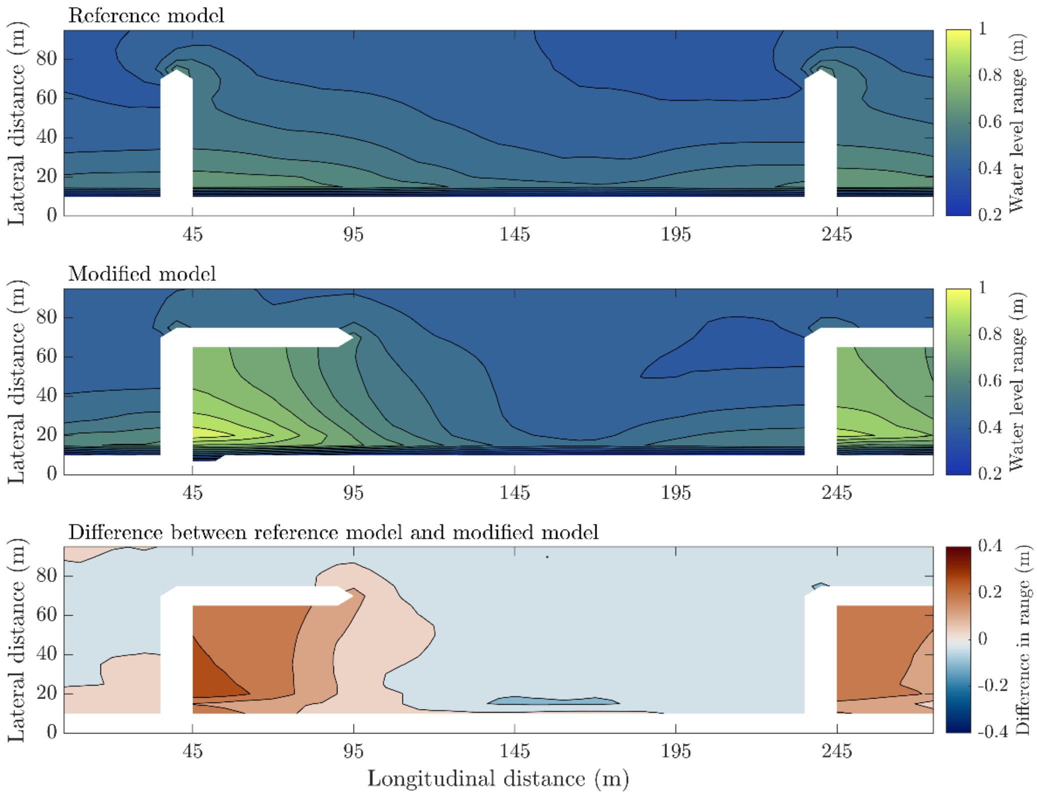
Water level range upstream sailing



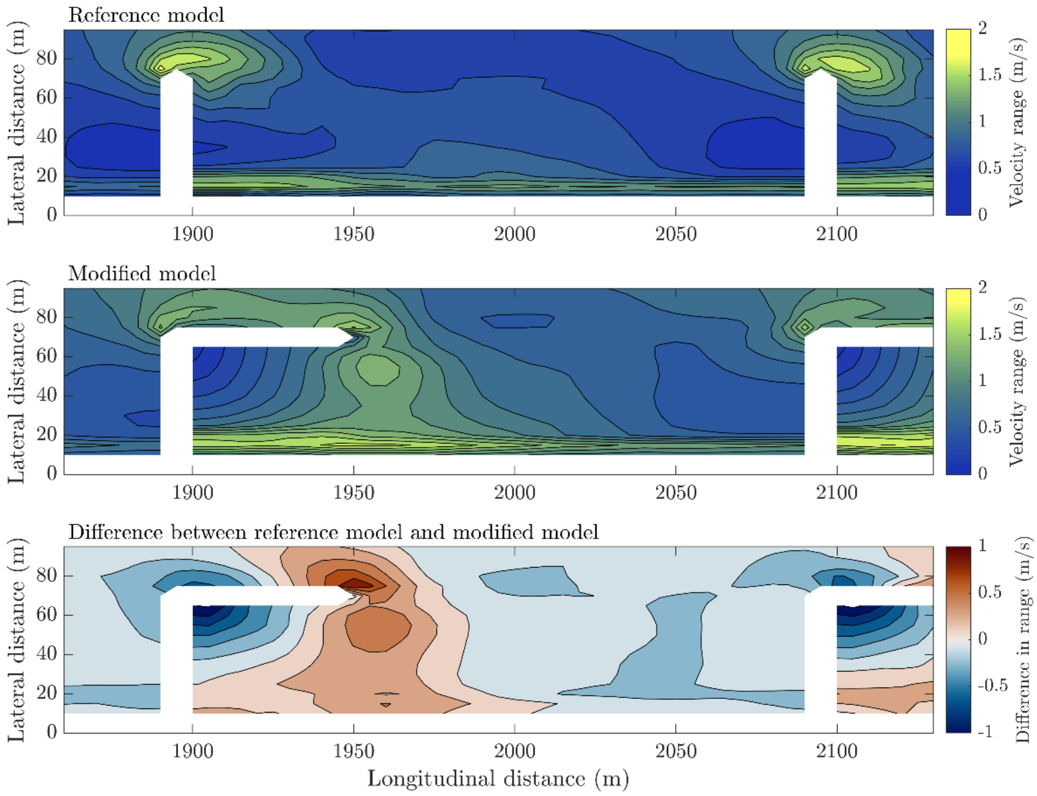
Water level range downstream sailing



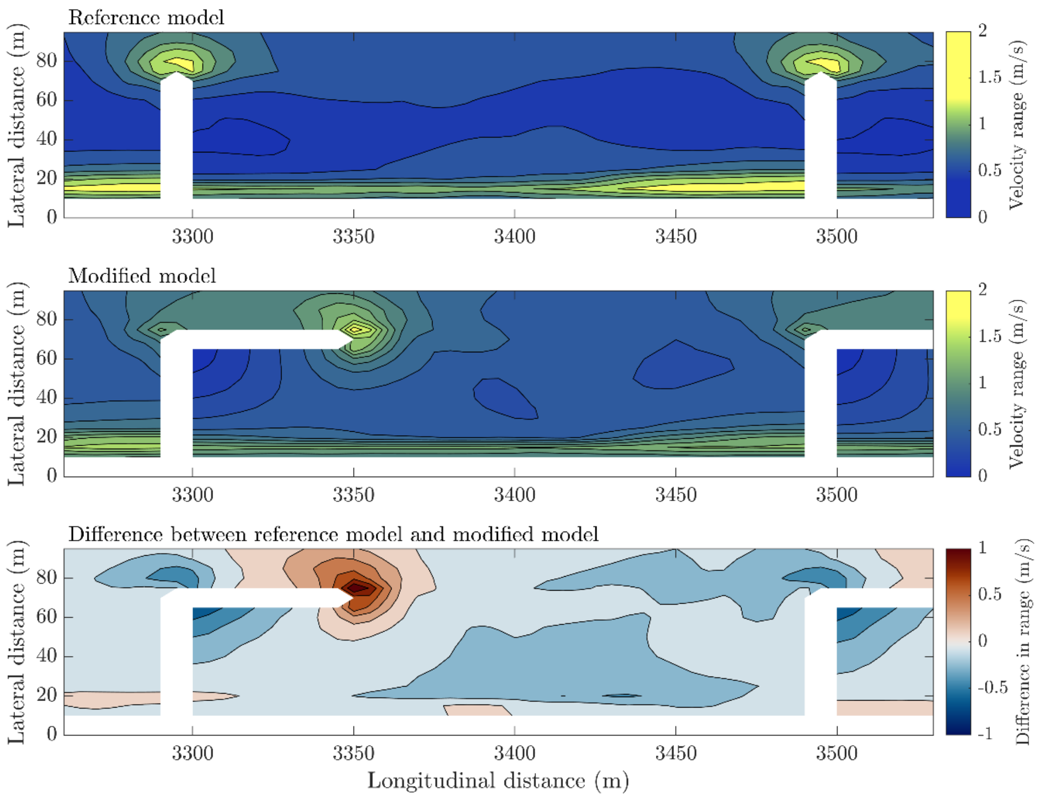
Combined water level range



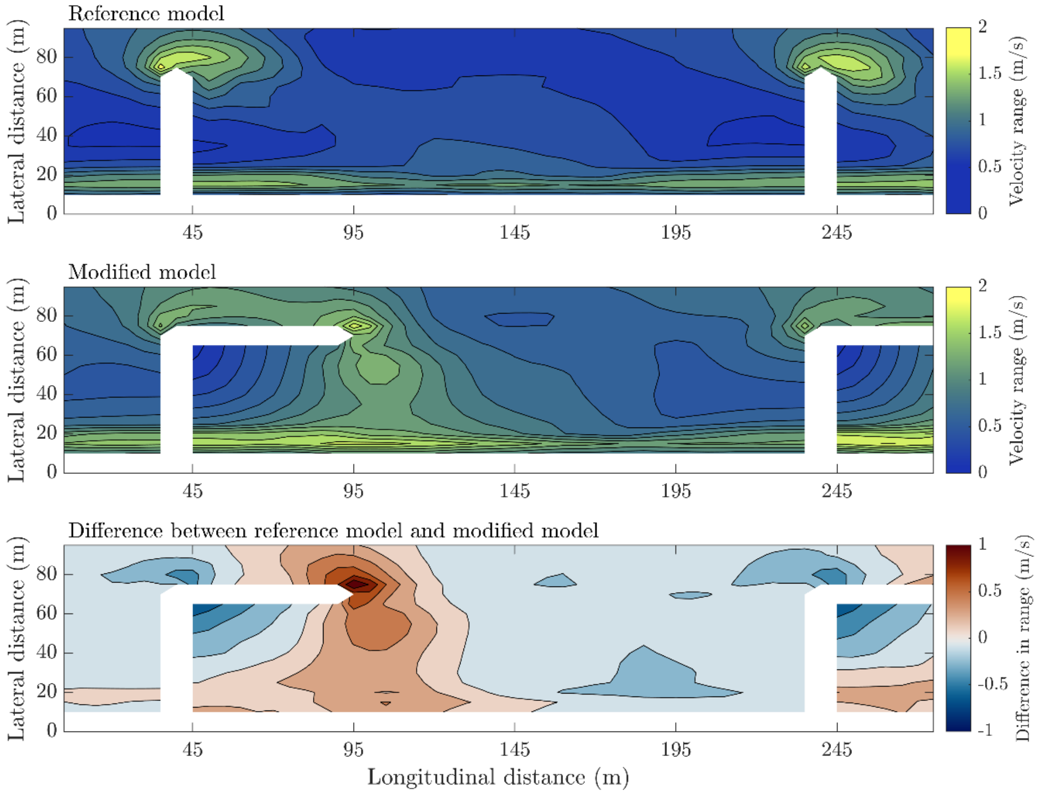
Velocity range upstream sailing



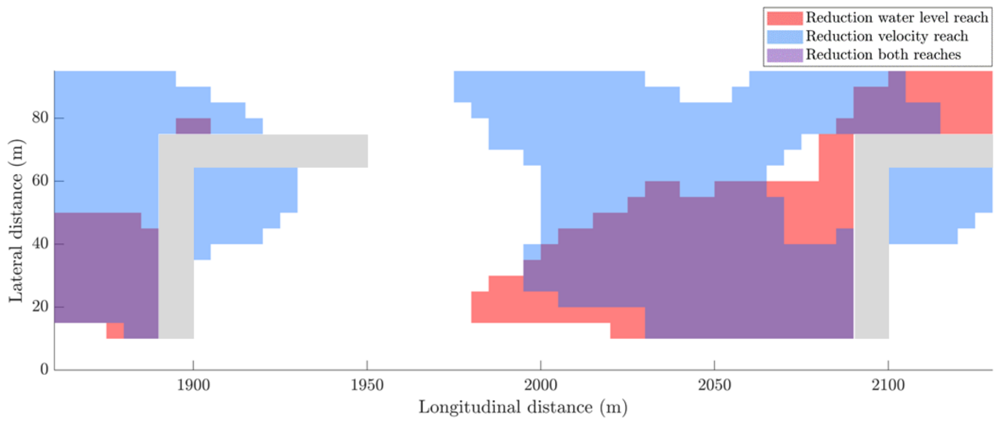
Velocity range downstream sailing



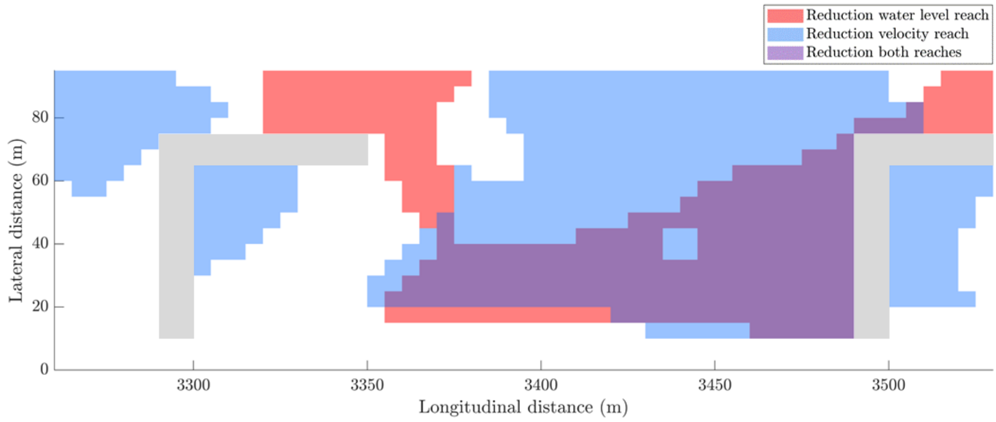
Combined velocity range



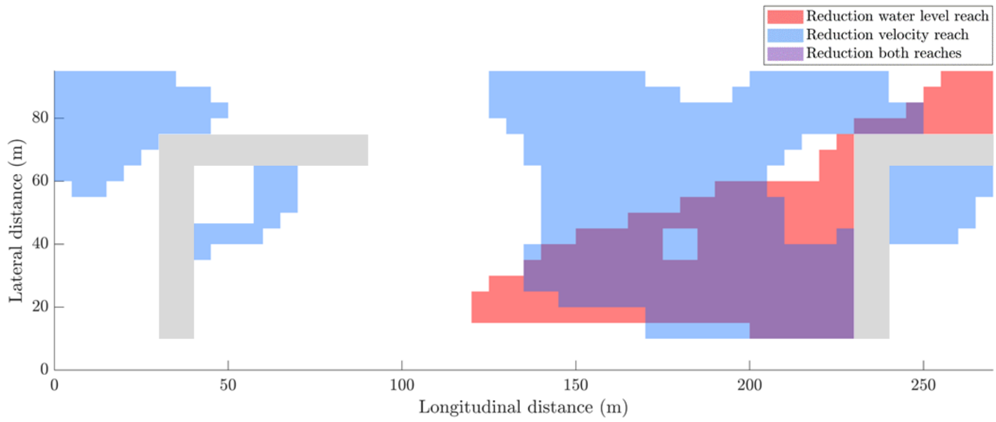
Overview plot upstream sailing



Overview plot dowstream sailing

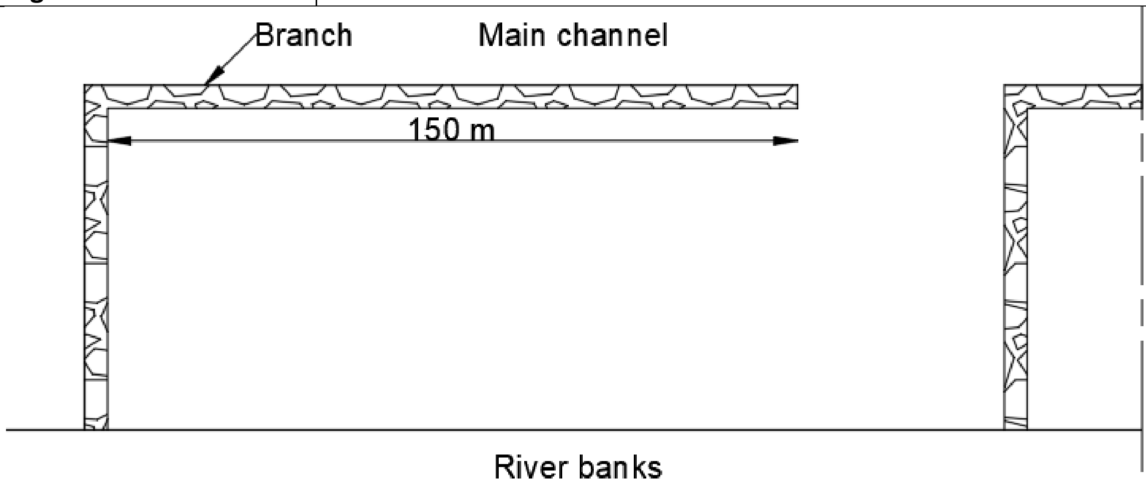


Combined overview plot

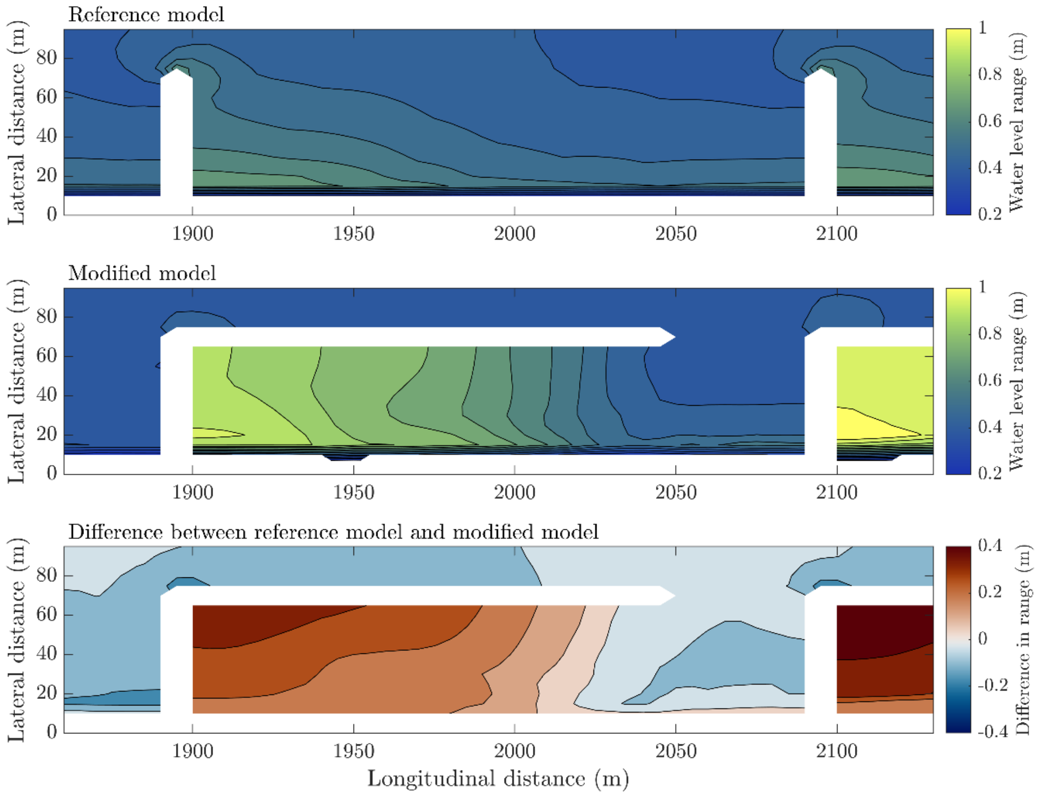


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
3.105	1.1	Push Tow	Upstream	4.5 m/s	L-groyne
3.205	1.2	Push Tow	Downstream	4.5 m/s	L-groyne

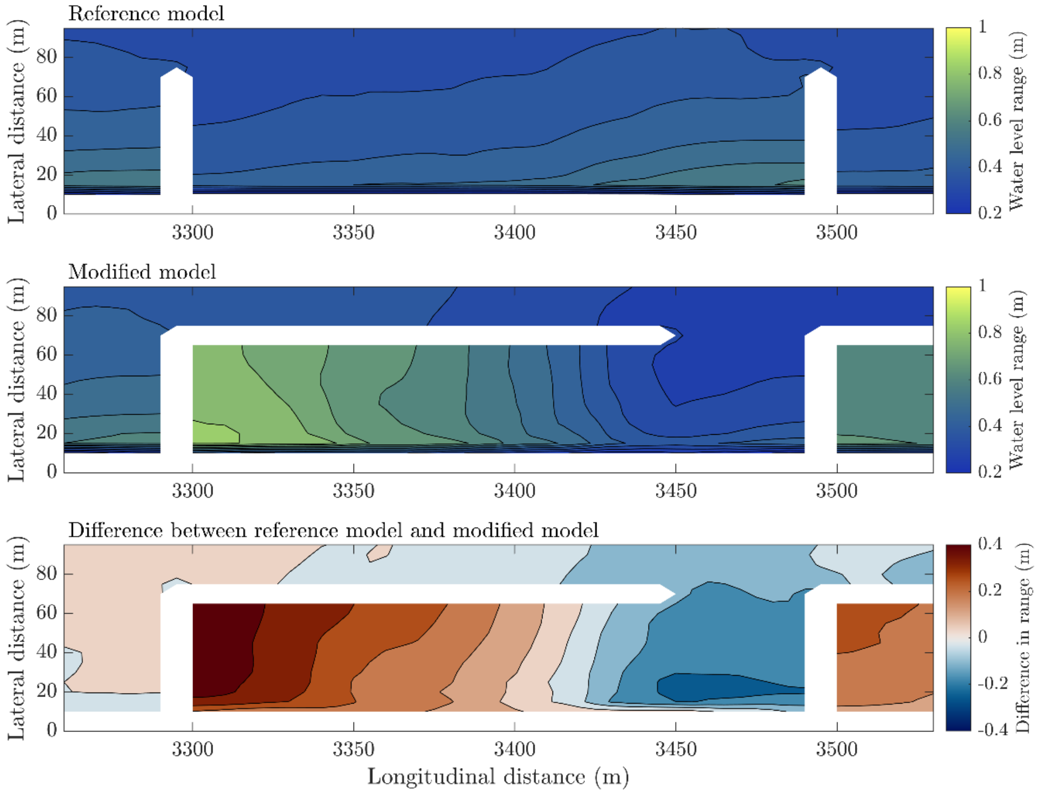
Length of branch	150 m



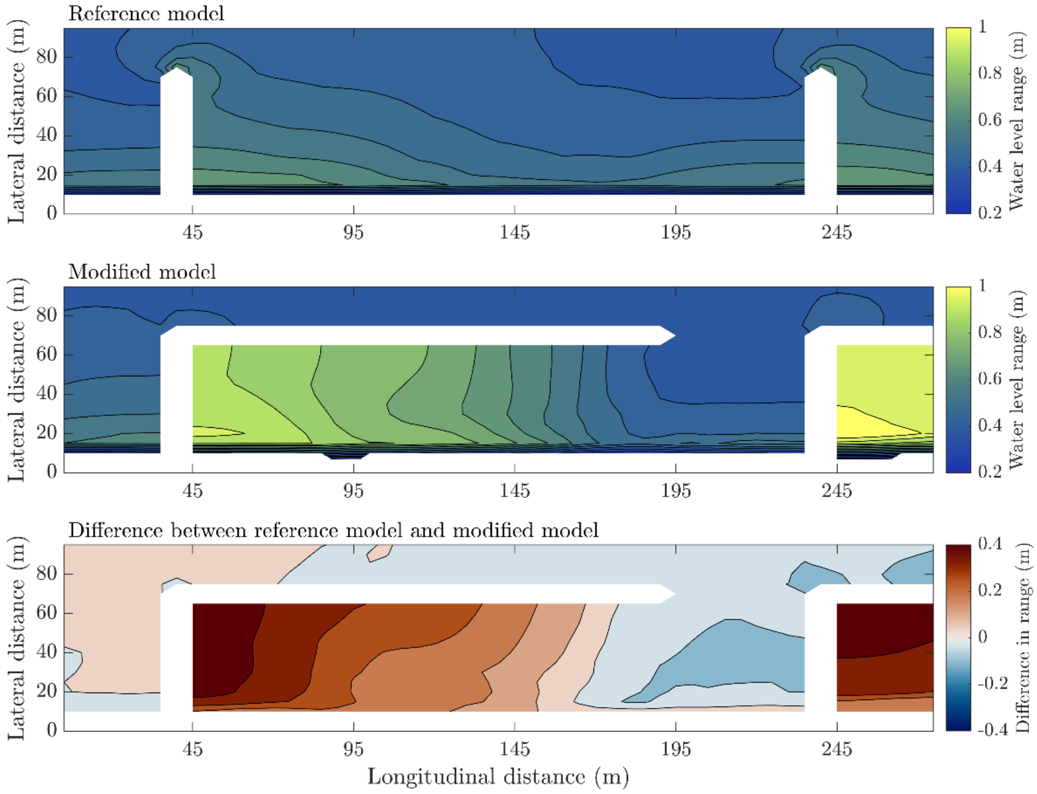
Water level range upstream sailing



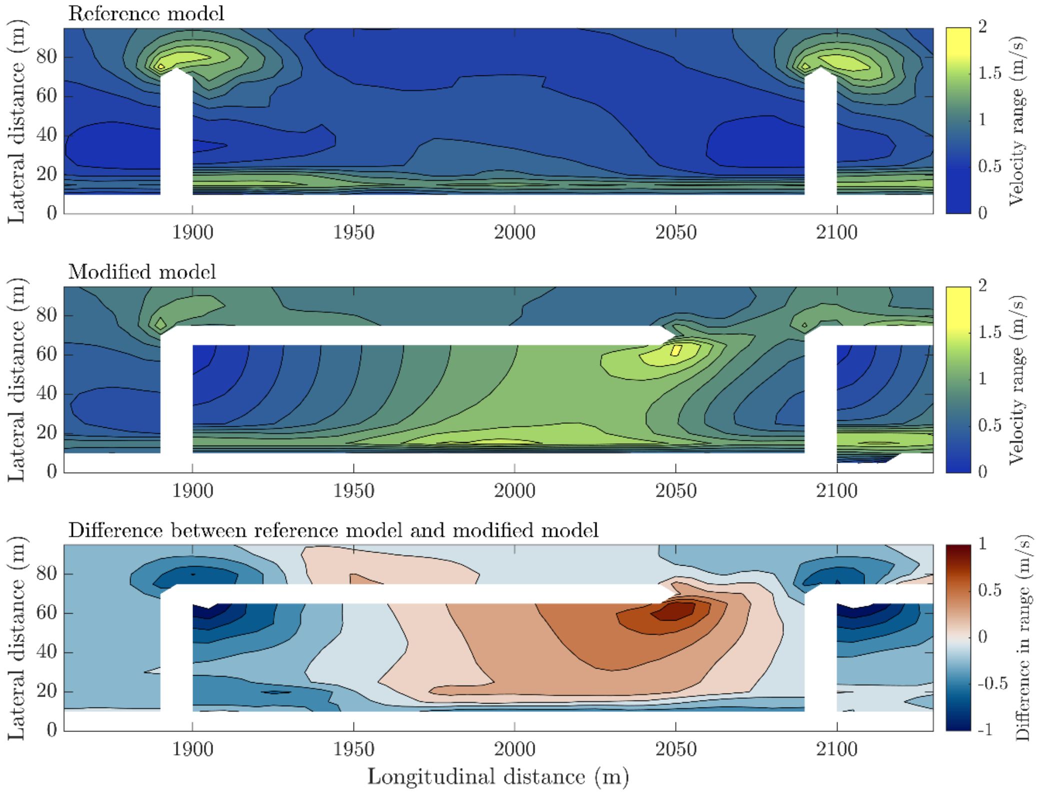
Water level range downstream sailing



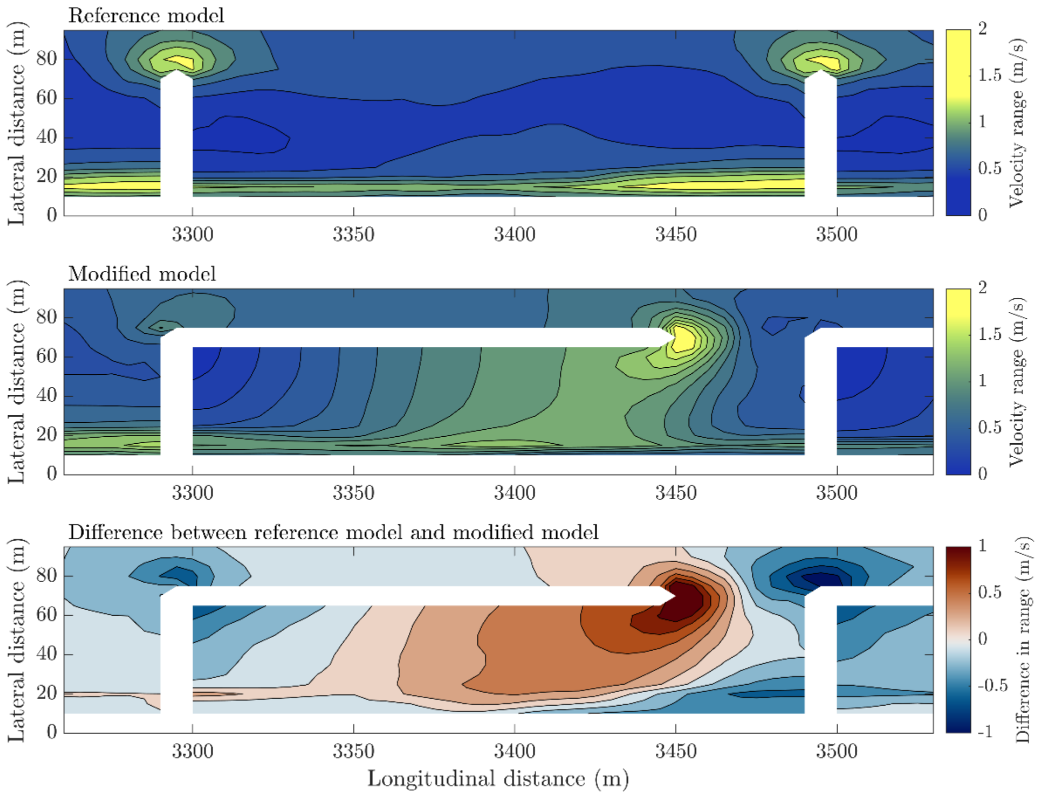
Combined water level range



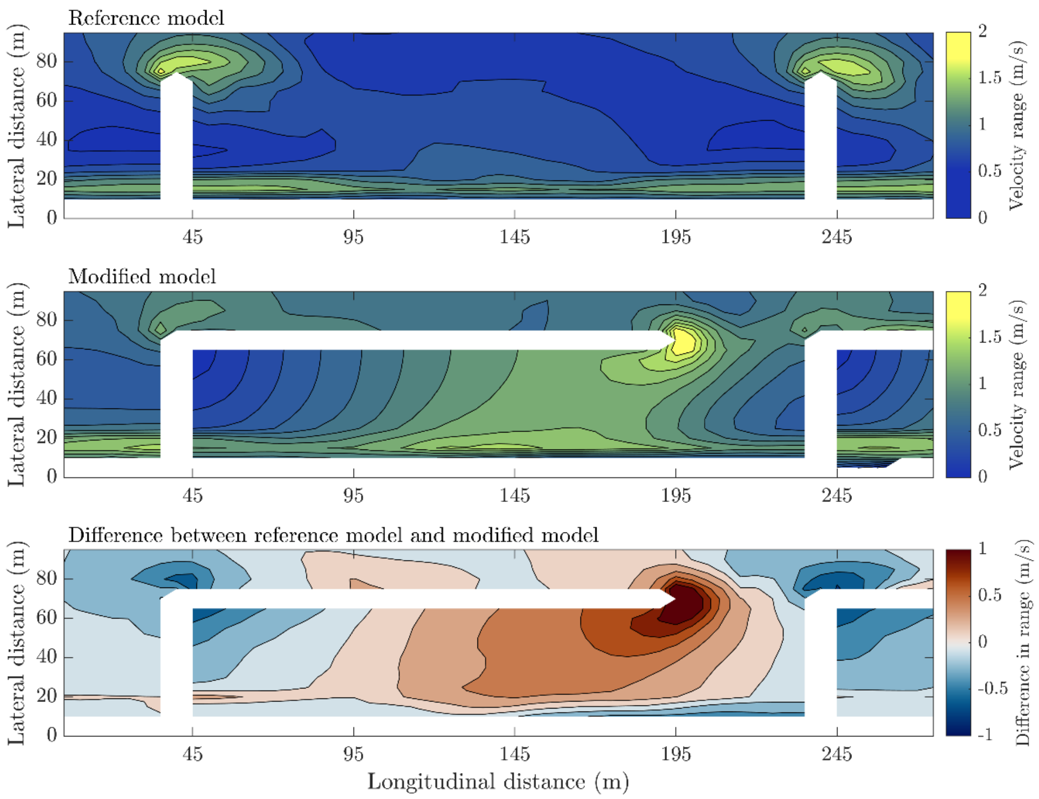
Velocity range upstream sailing



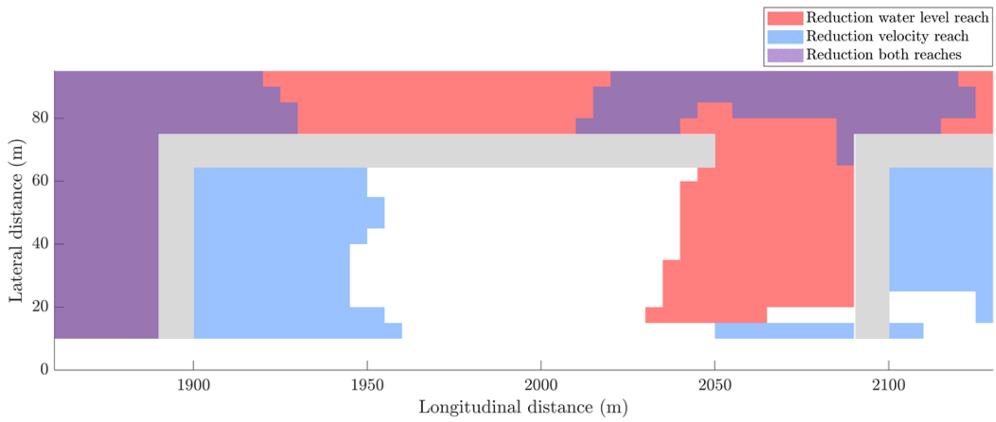
Velocity range downstream sailing



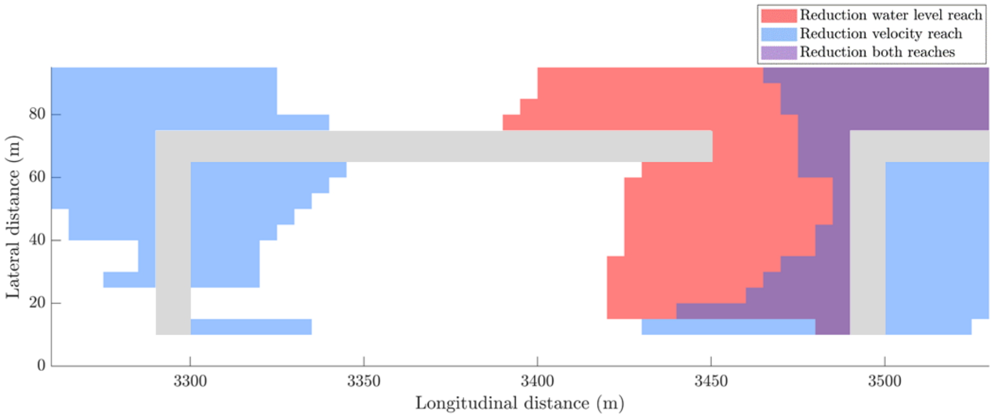
Combined velocity range



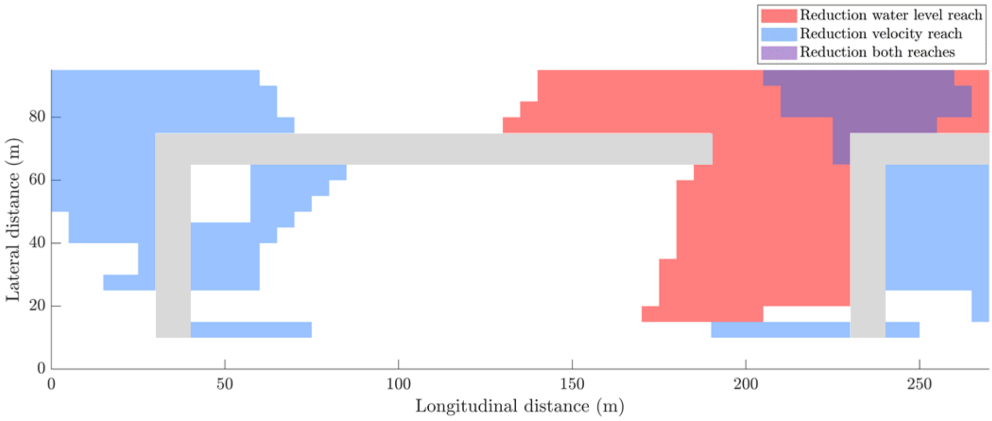
Overview plot upstream sailing



Overview plot dowstream sailing

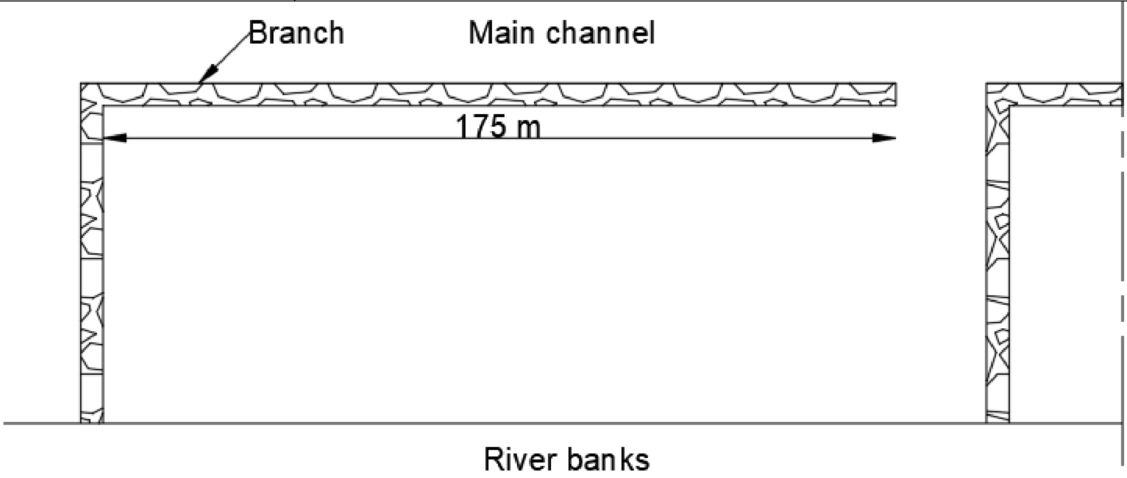


Combined overview plot

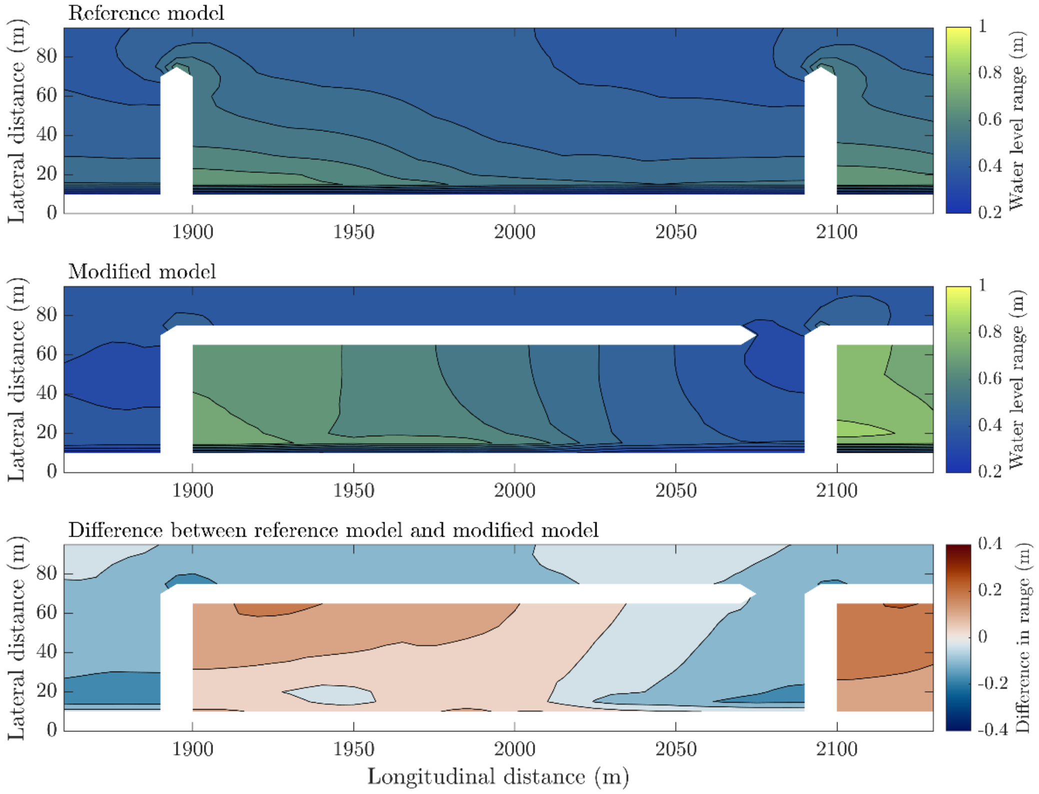


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
3.106	1.1	Push Tow	Upstream	4.5 m/s	L-groyne
3.206	1.2	Push Tow	Downstream	4.5 m/s	L-groyne

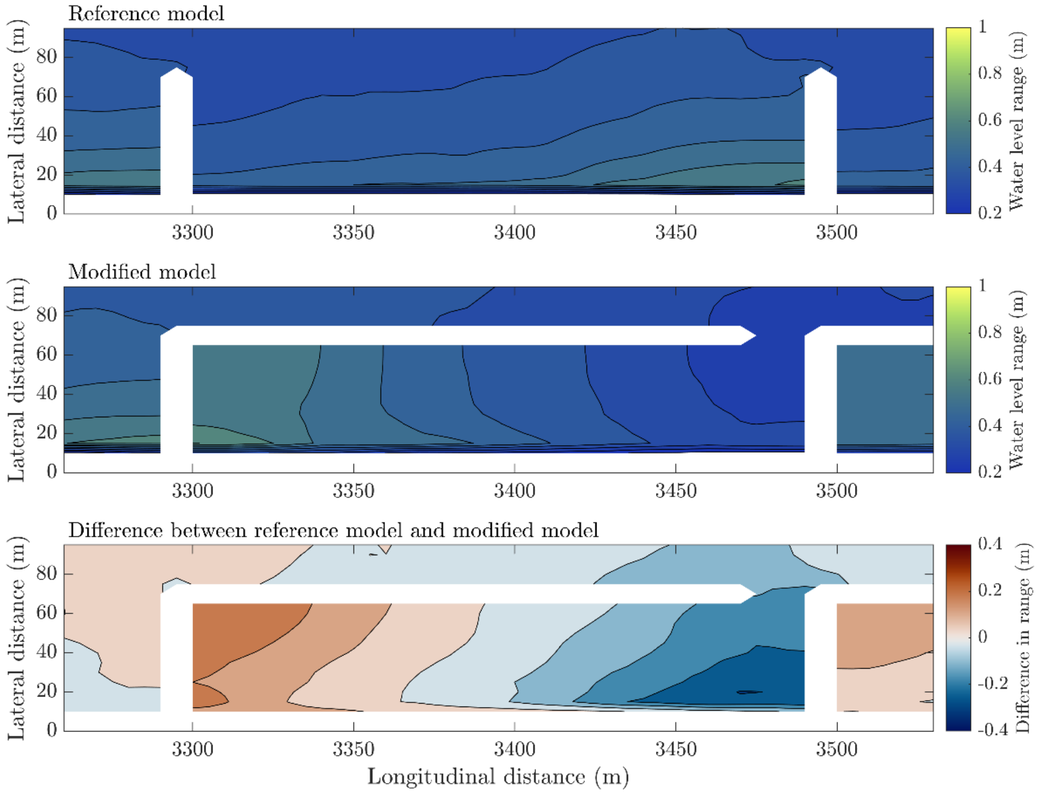
Length of branch	175 m



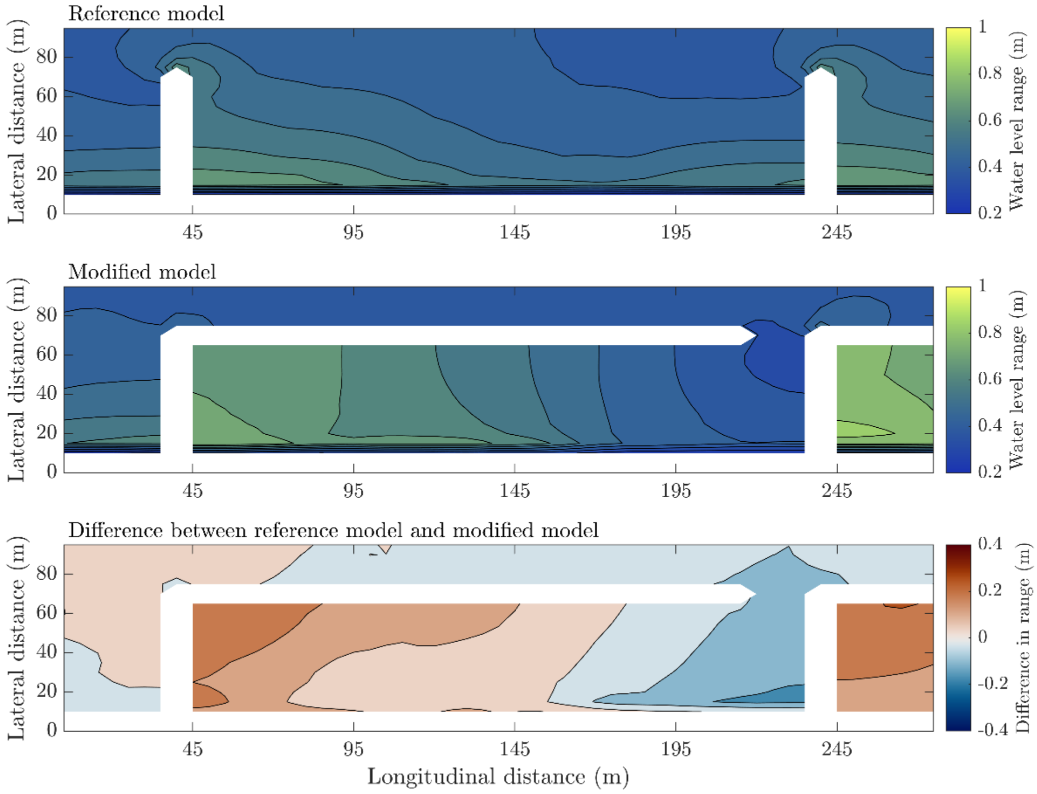
Water level range upstream sailing



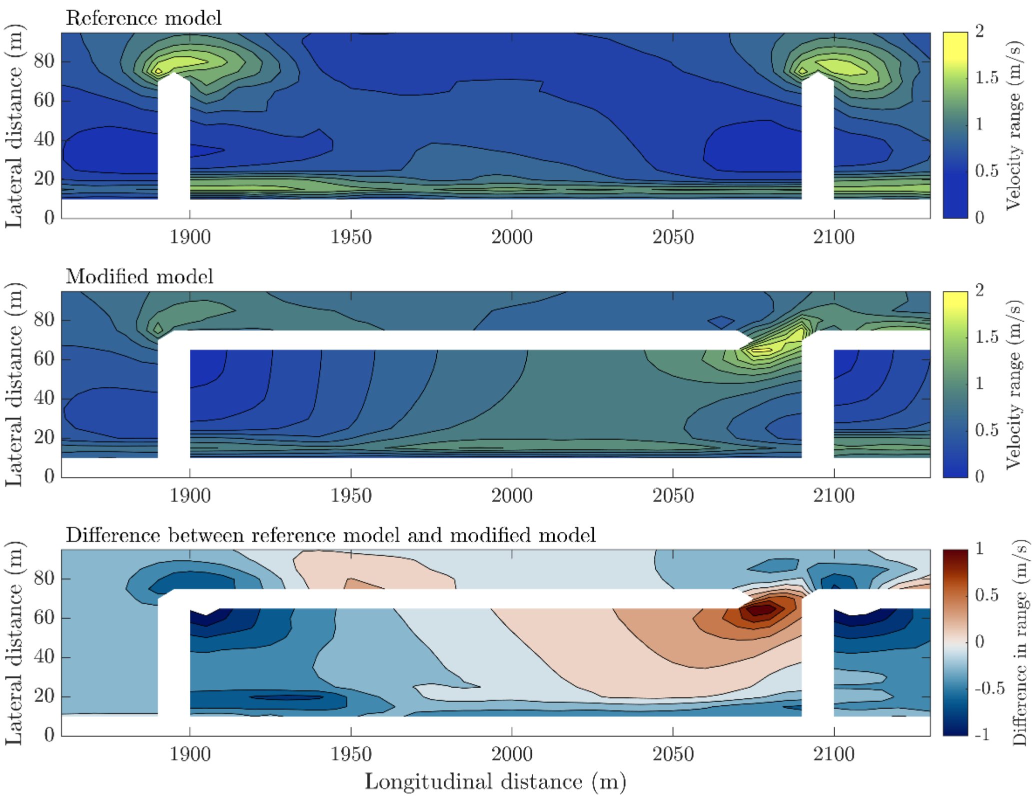
Water level range downstream sailing



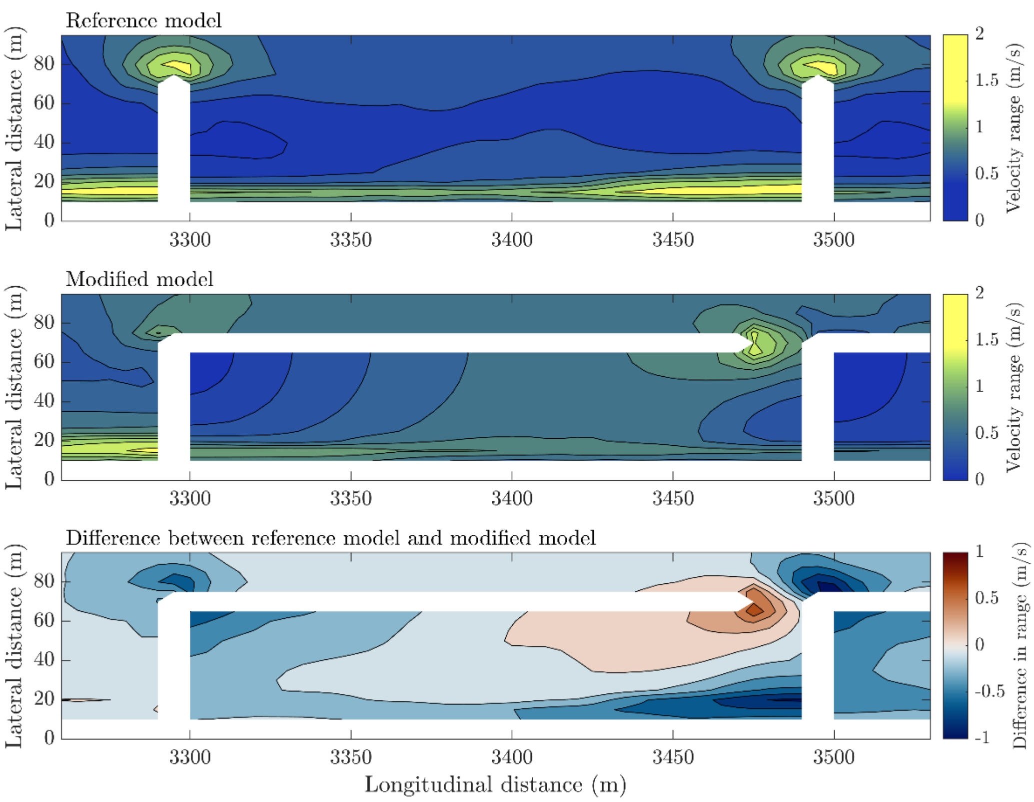
Combined water level range



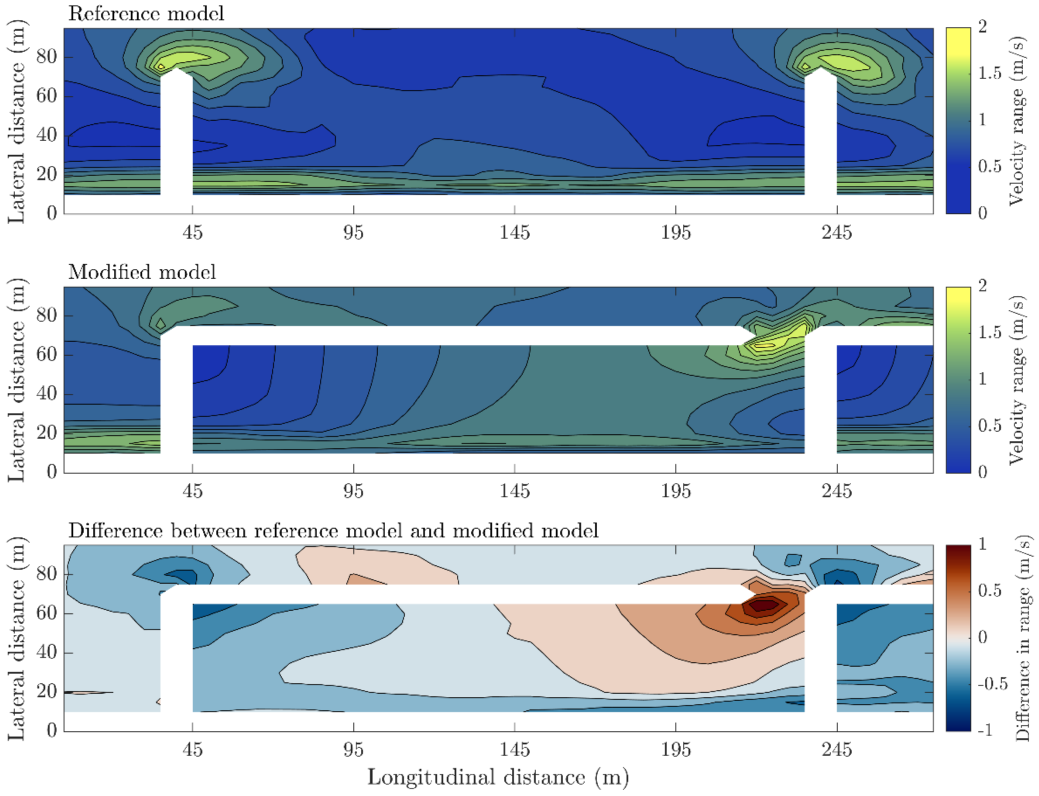
Velocity range upstream sailing



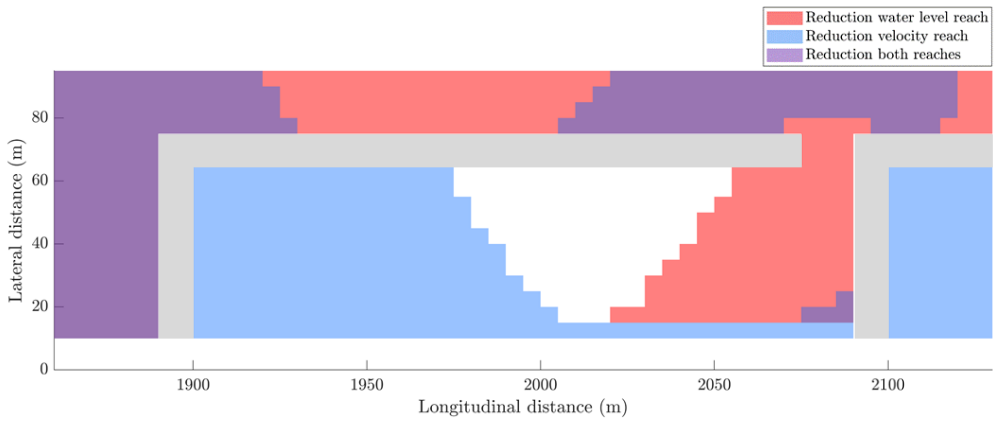
Velocity range downstream sailing



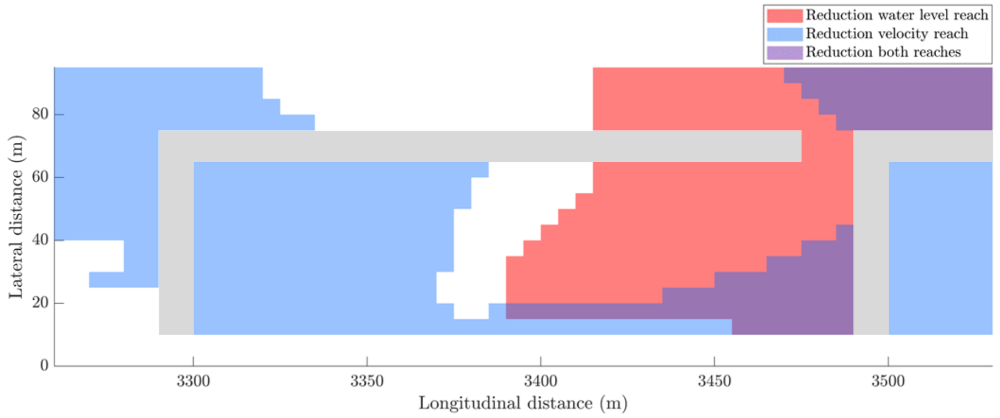
Combined velocity range



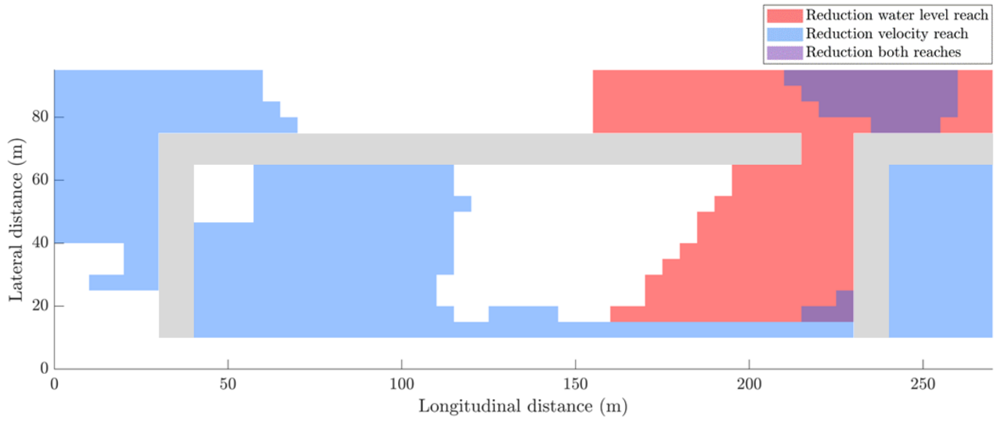
Overview plot upstream sailing



Overview plot dowstream sailing

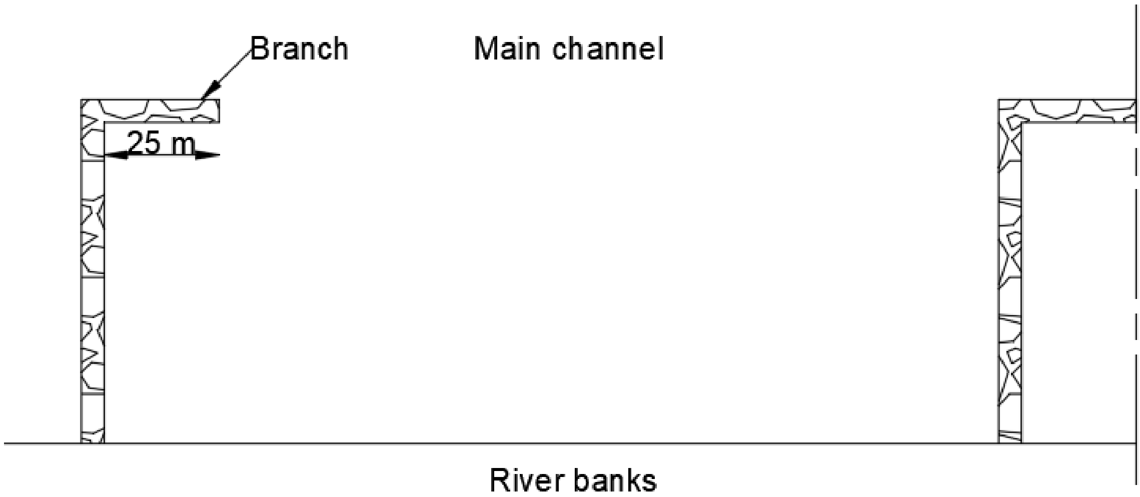


Combined overview plot

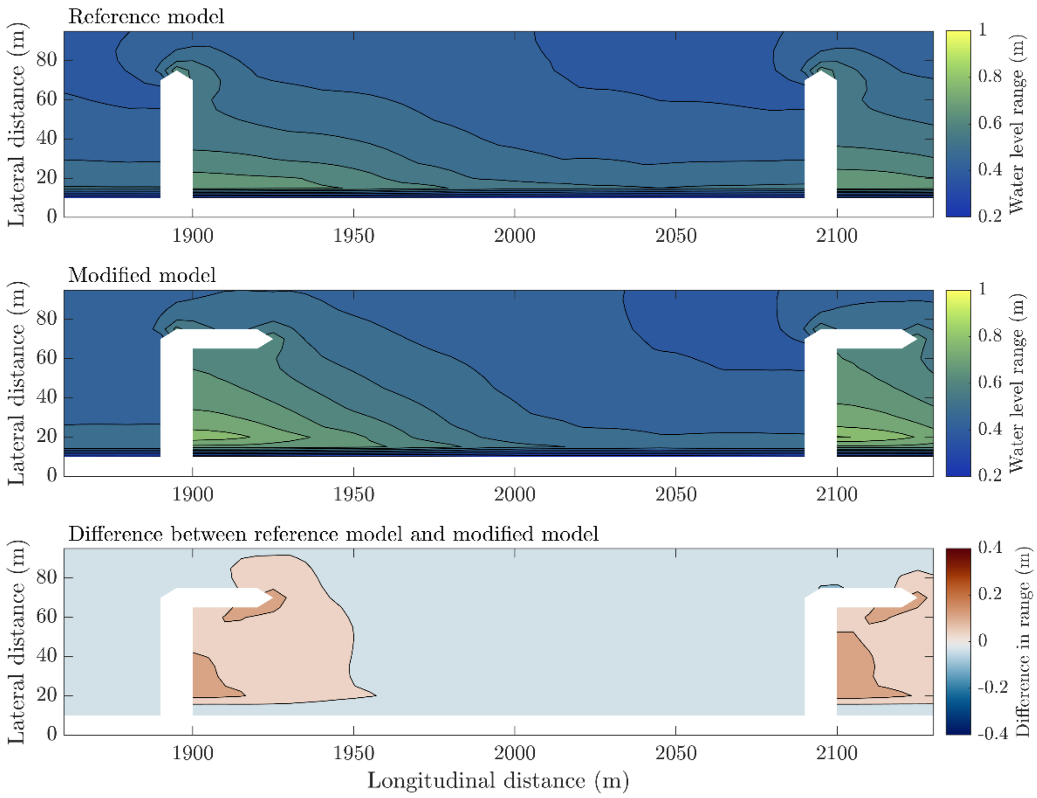


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
3.107	1.1	Push Tow	Upstream	4.5 m/s	L-groyne
3.207	1.2	Push Tow	Downstream	4.5 m/s	L-groyne

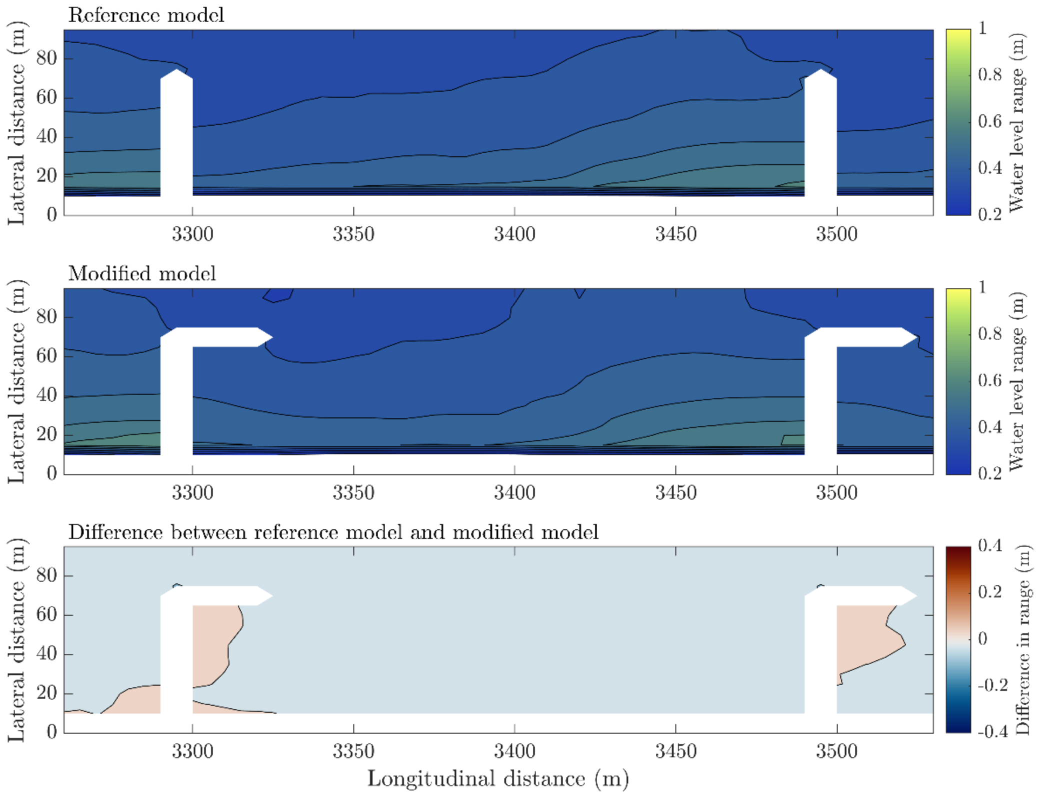
Length of branch	25 m



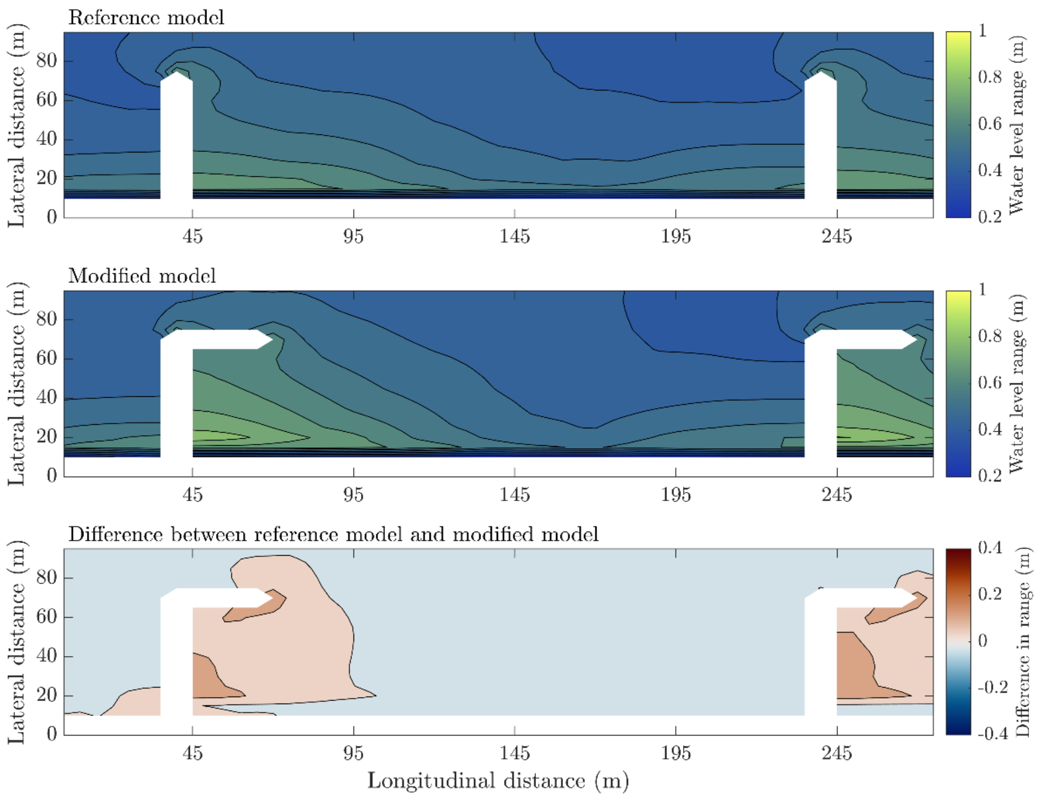
Water level range upstream sailing



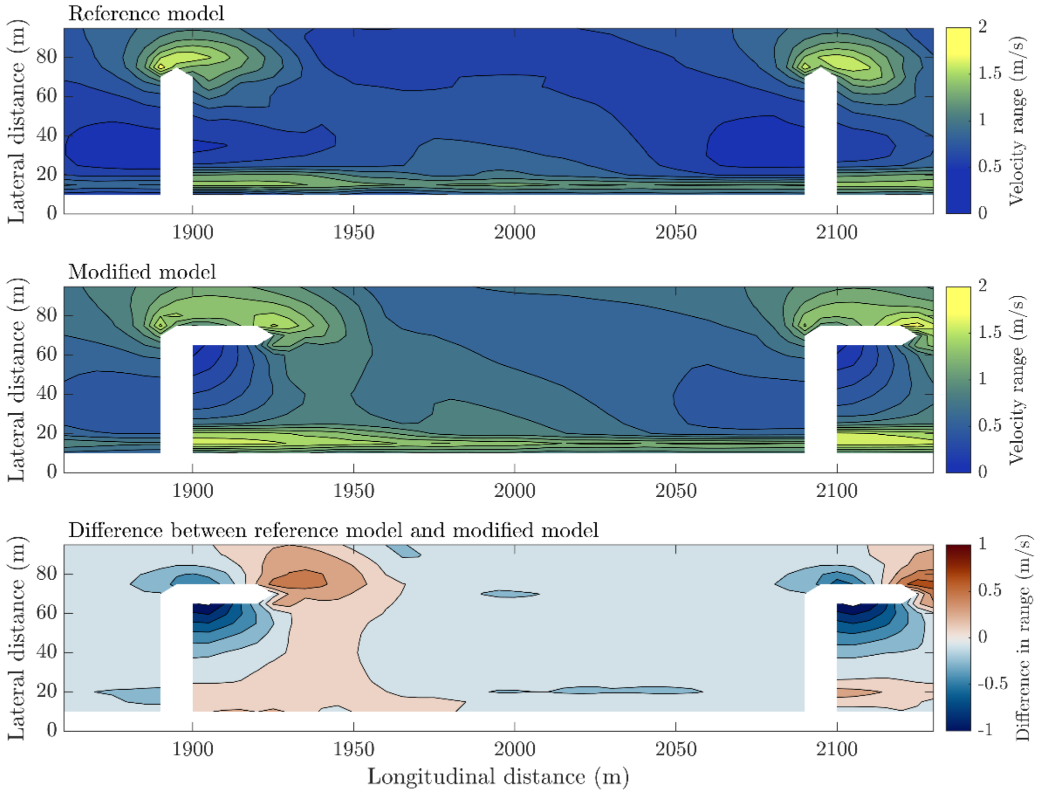
Water level range downstream sailing



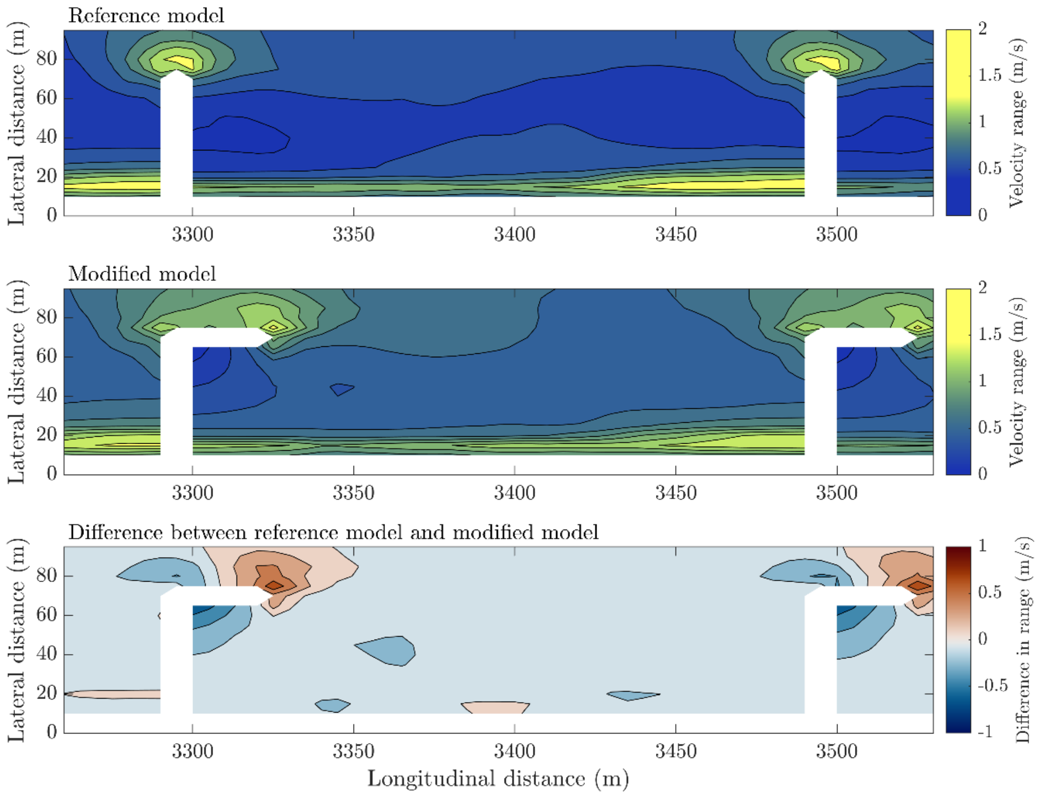
Combined water level range



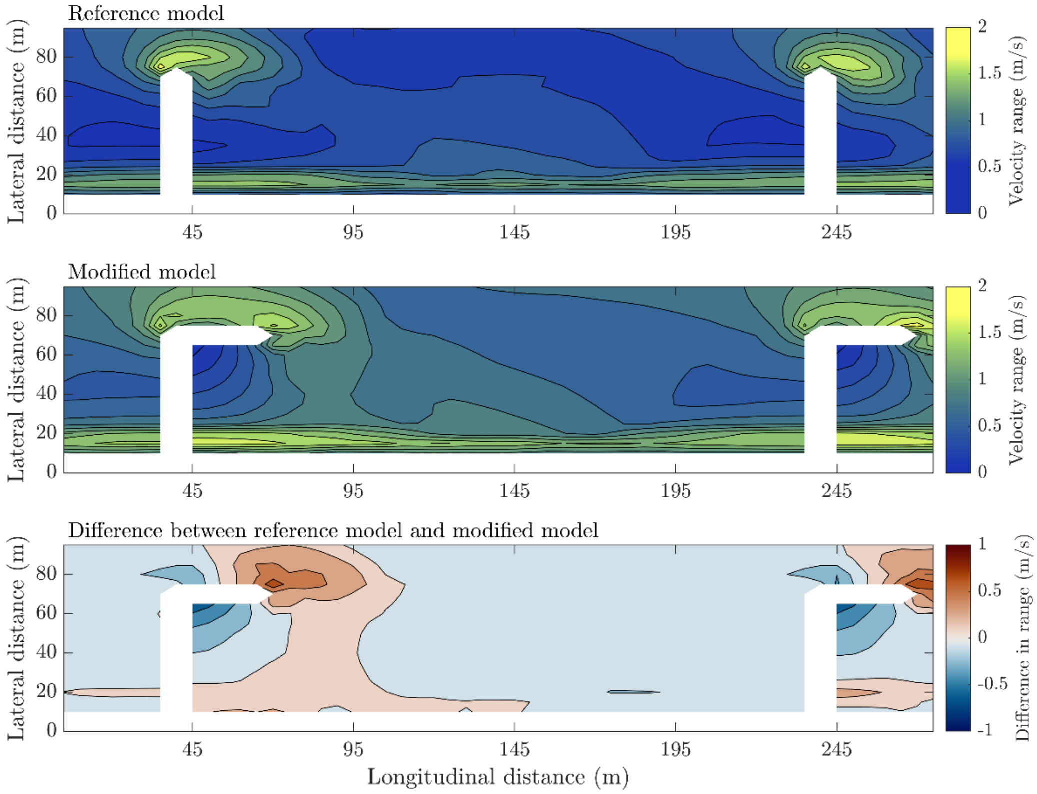
Velocity range upstream sailing



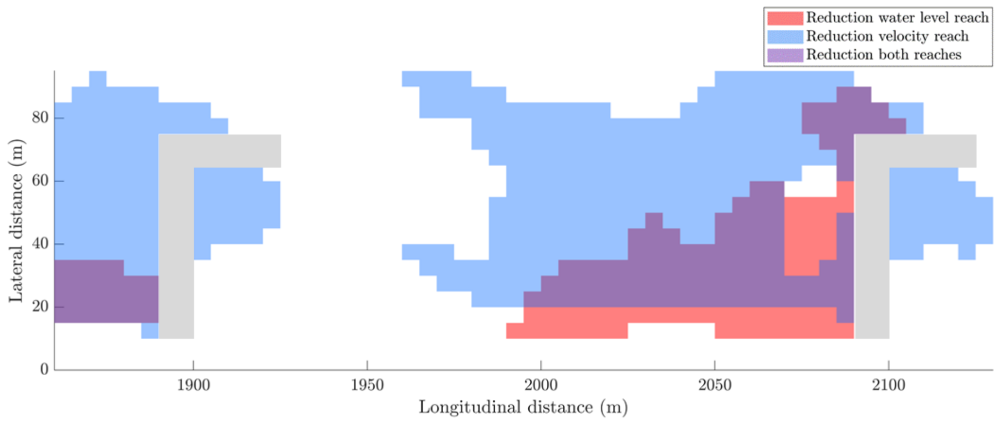
Velocity range downstream sailing



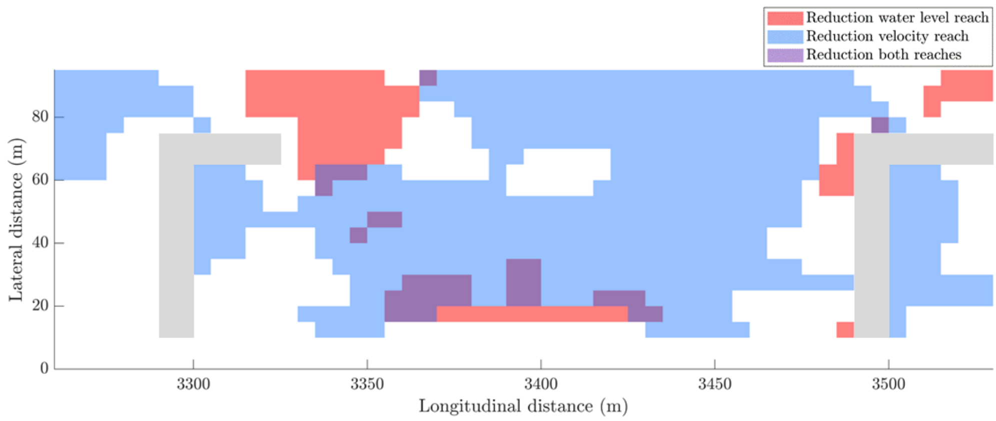
Combined velocity range



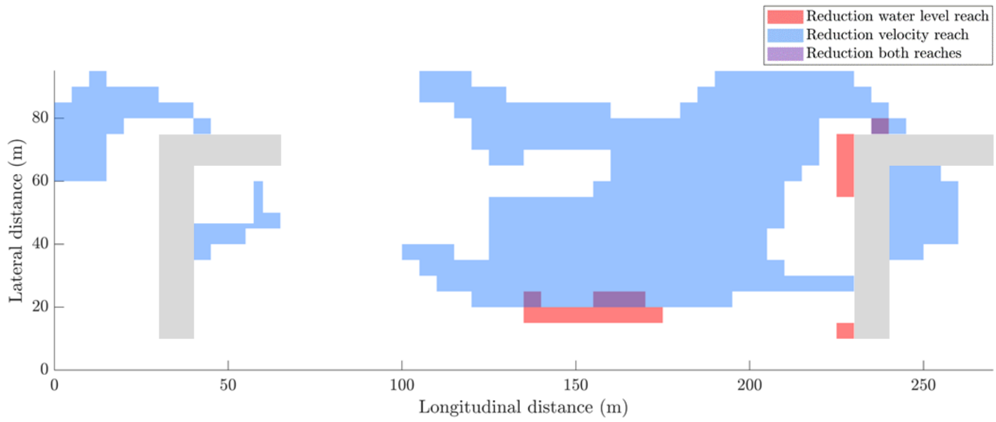
Overview plot upstream sailing



Overview plot dowstream sailing



Combined overview plot



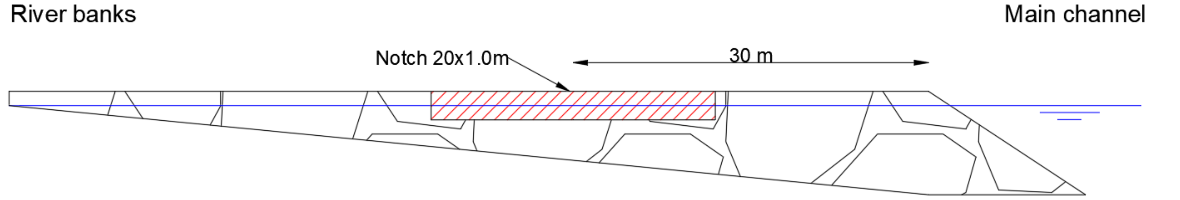
C.3 Results from the conceptual design

In the graph below an overview of the pages of the runs is given. The sixth cell called "used for" refers to the effect researched. All runs use the optimal design as determined in Section 5.5.1.

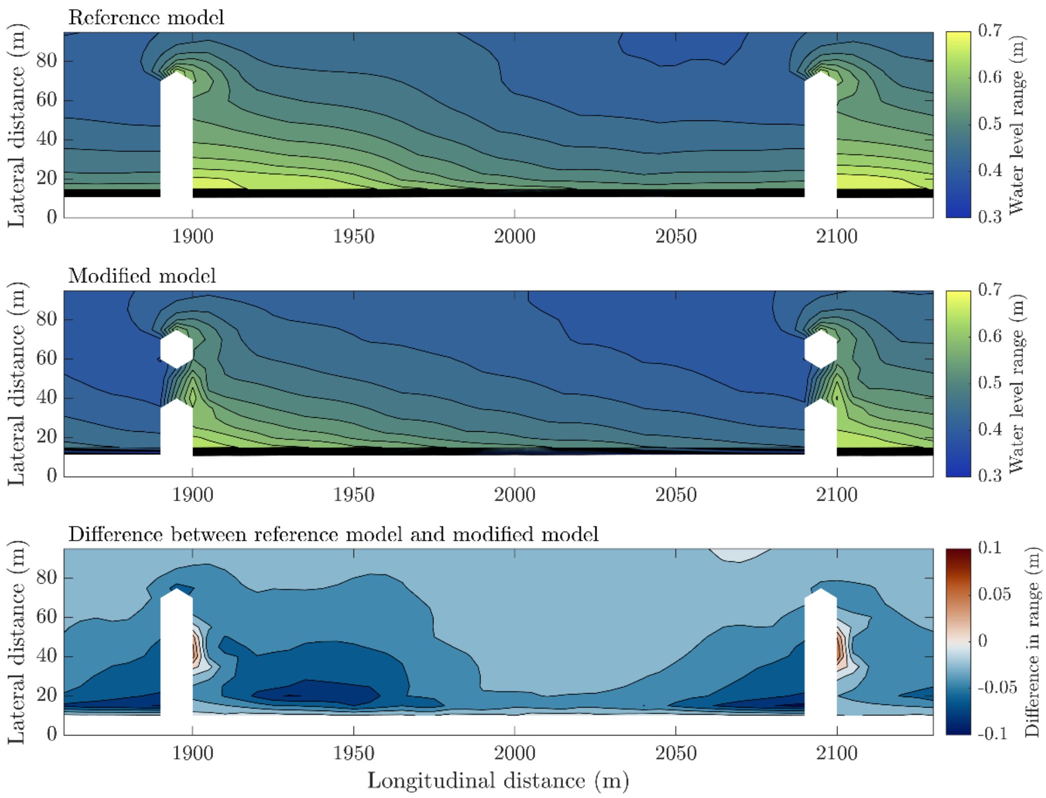
Run number upstream / downstream	Number of notches	Location of notch from tip groyne [m]	Width notch [m]	Depth notch below water level [m]	Used for	Page number
4.101 / 4.201	1	25	20	1.0	Optimal design	214
4.102 / 4.202	1	25	20	1.0	High water	219
4.104 / 4.204	1	25	20	1.0	Small vessel	224
4.106 / 4.206	1	25	20	1.0	Side channel	229

Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
4.101	1.1	Push Tow	Upstream	4.5 m/s	Notch(es)
4.201	1.2	Push Tow	Downstream	4.5 m/s	Notch(es)

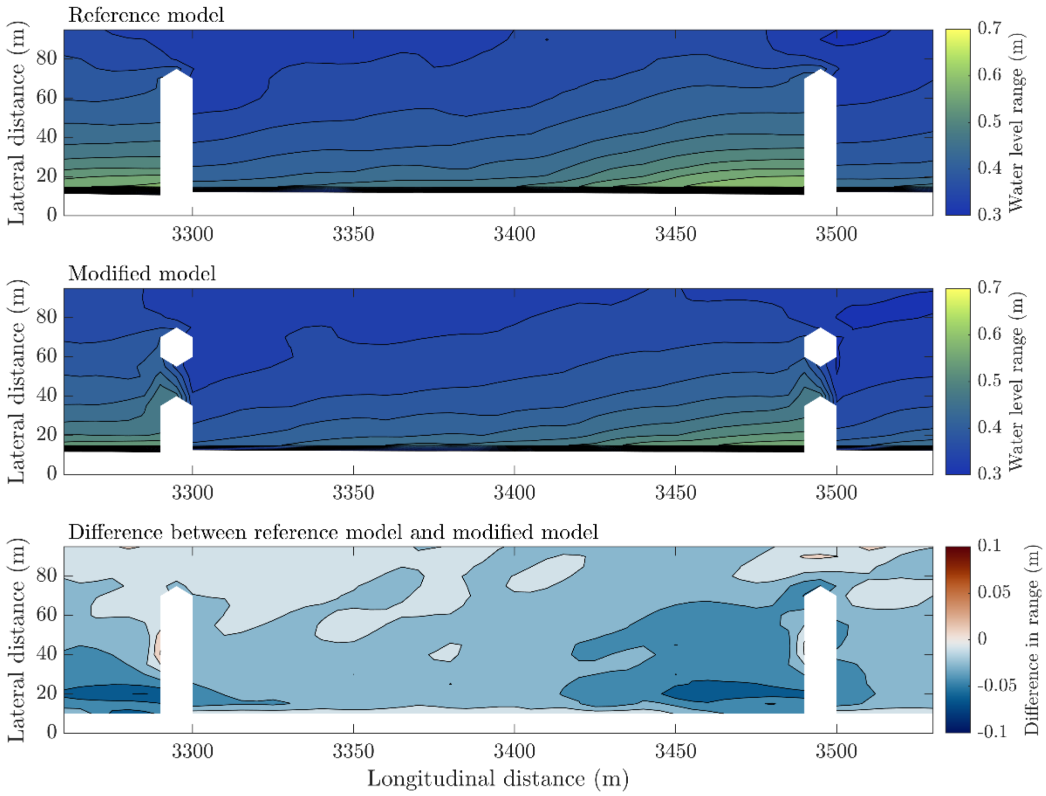
Number of notches	Location of notch	Width notch	Depth notch
1	30 m	20 m	1.0 m



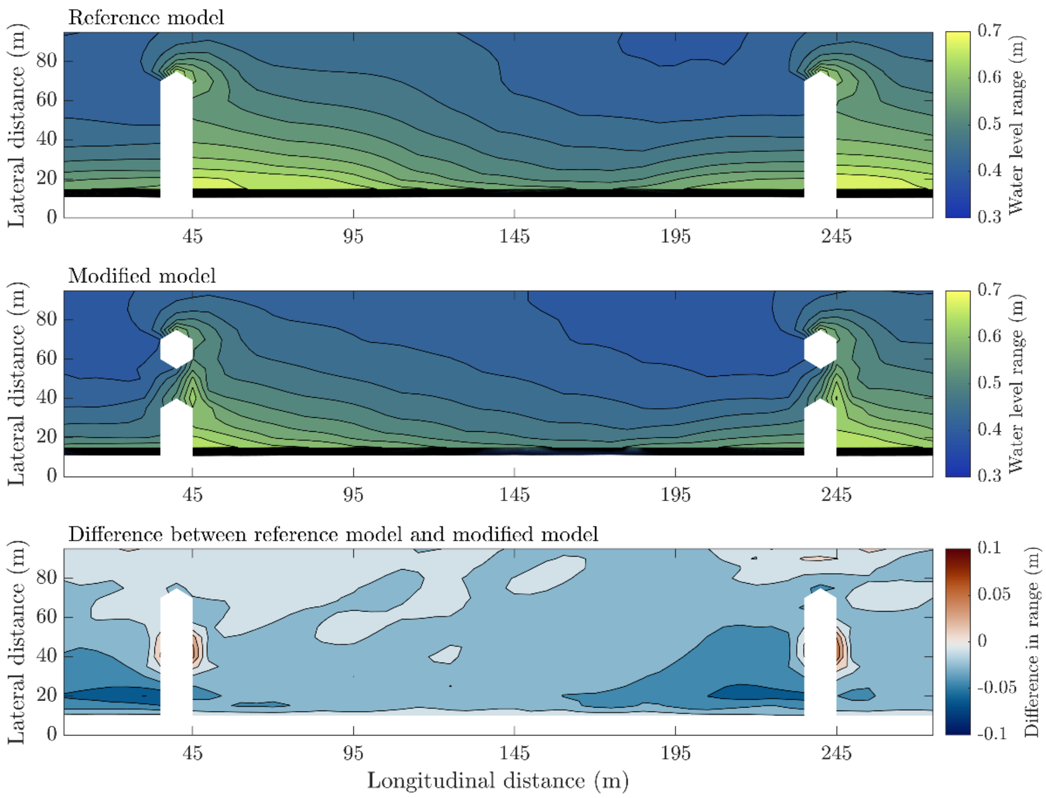
Water level range upstream sailing



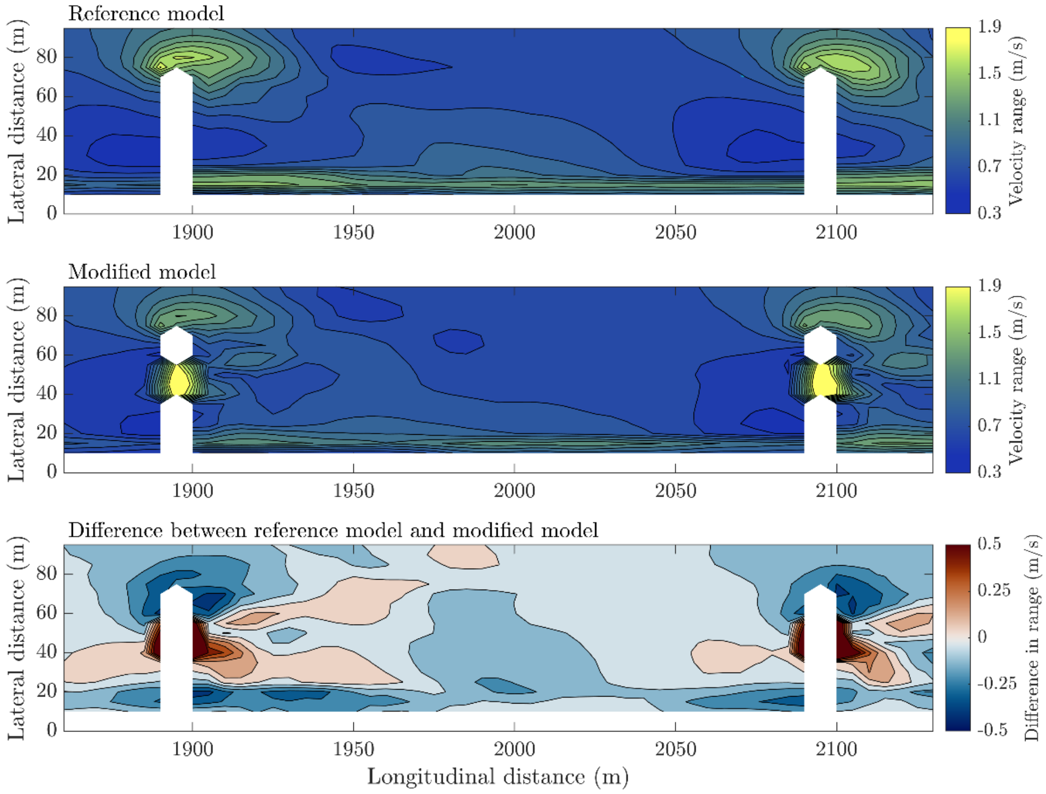
Water level range downstream sailing



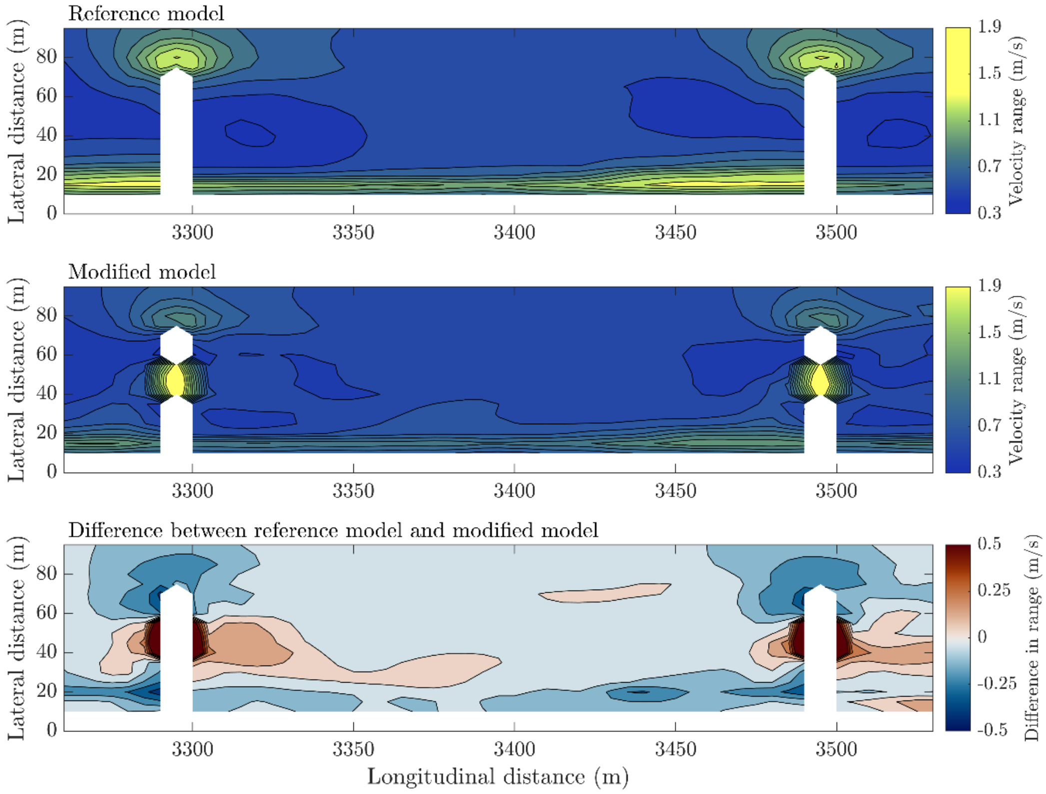
Combined water level range



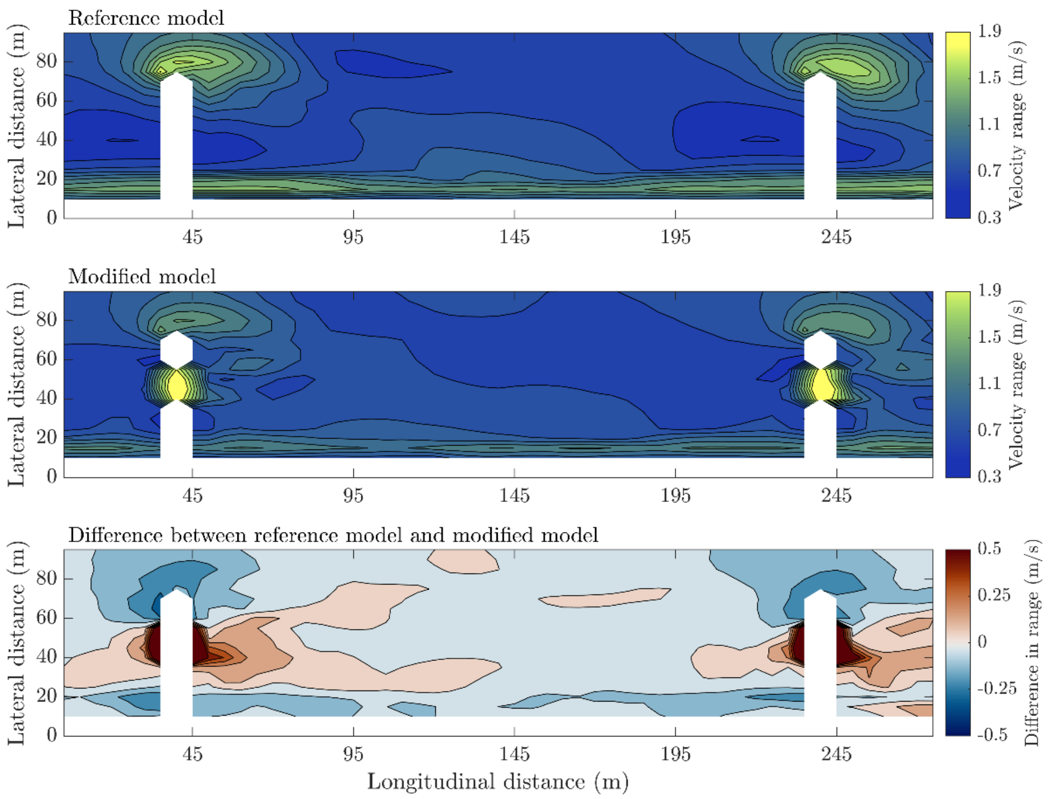
Velocity range upstream sailing



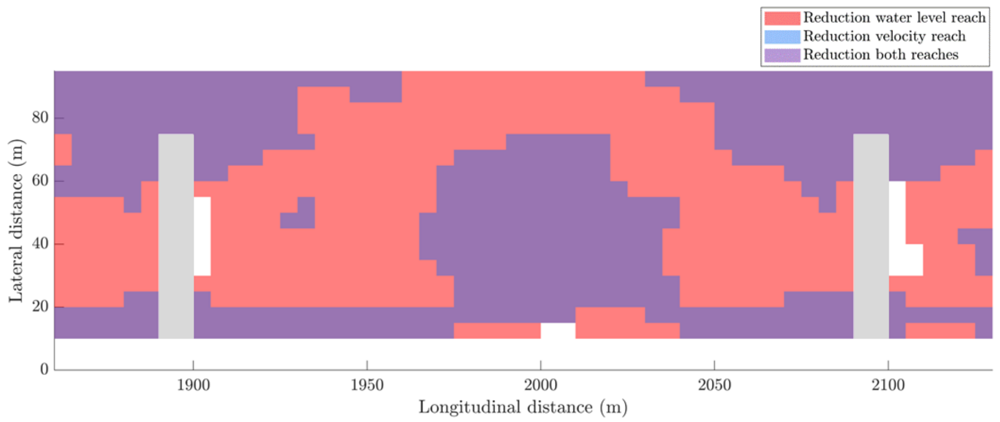
Velocity range downstream sailing



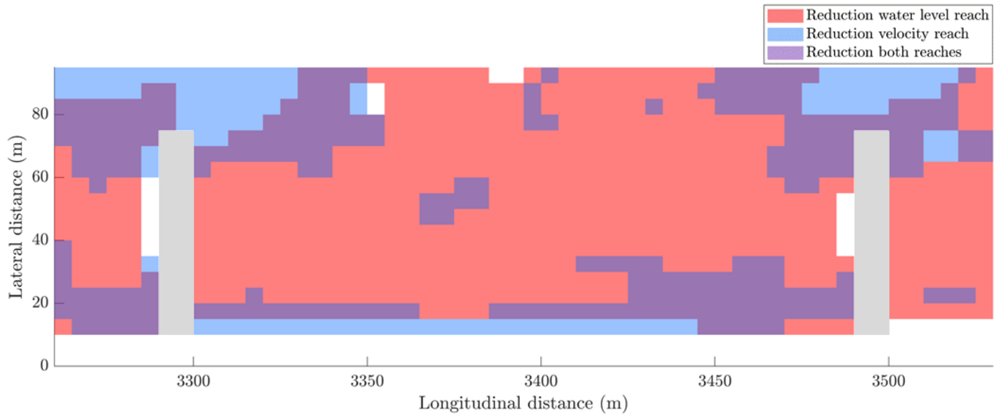
Combined velocity range



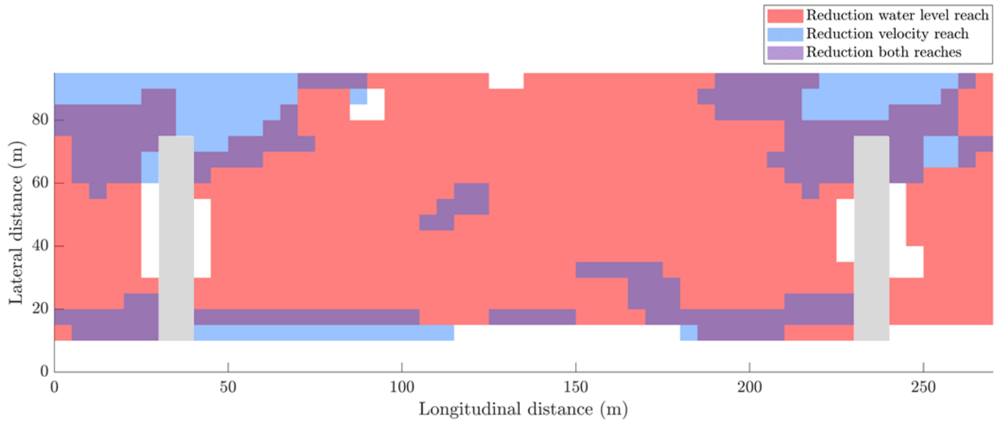
Overview plot upstream sailing



Overview plot dowstream sailing

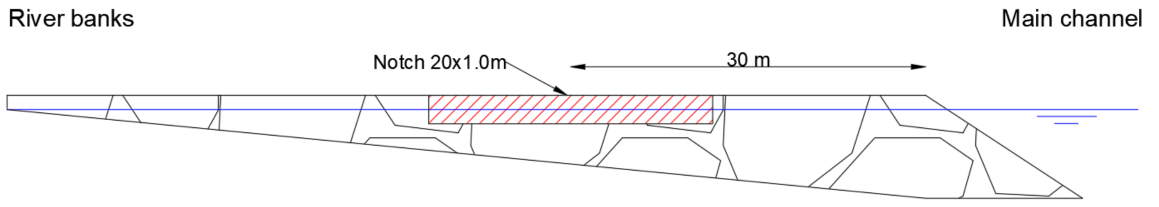


Combined overview plot

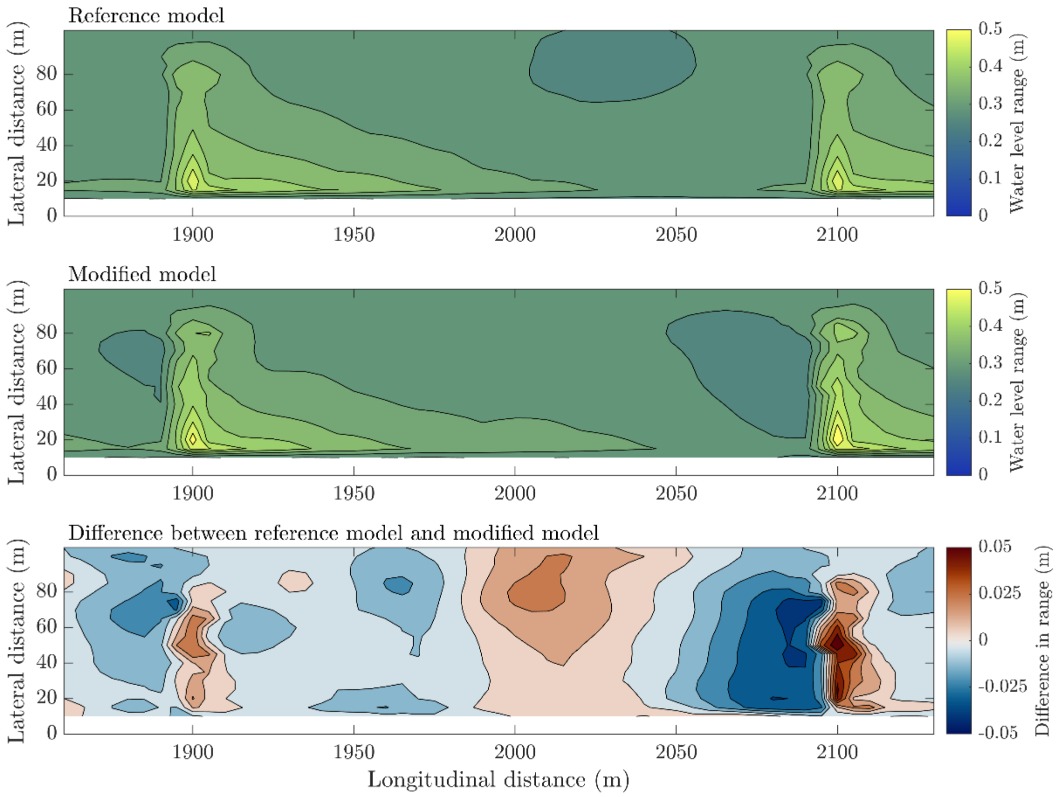


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
4.102	4.103	Push tow	Upstream	4.5 m/s	Notch(es) high water
4.202	4.203	Push tow	Downstream	4.5 m/s	Notch(es) high water

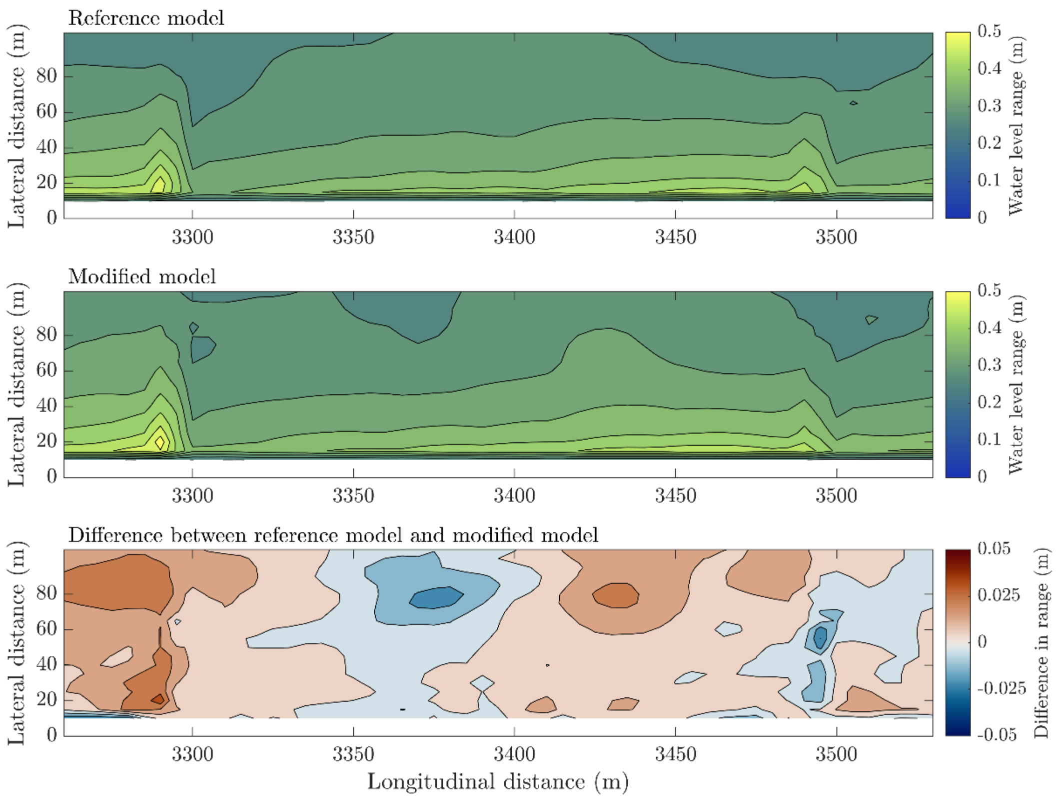
Number of notches	Location of notch	Width notch	Depth notch
1	30 m	20 m	1.0 m



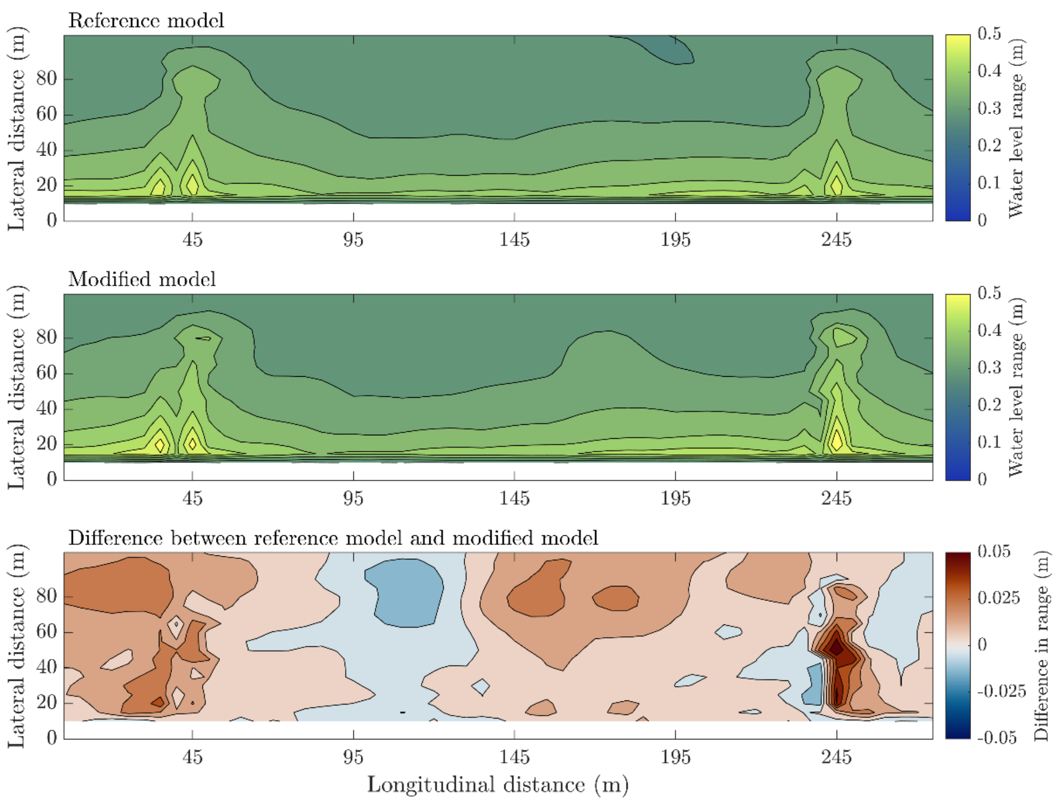
Water level range upstream sailing



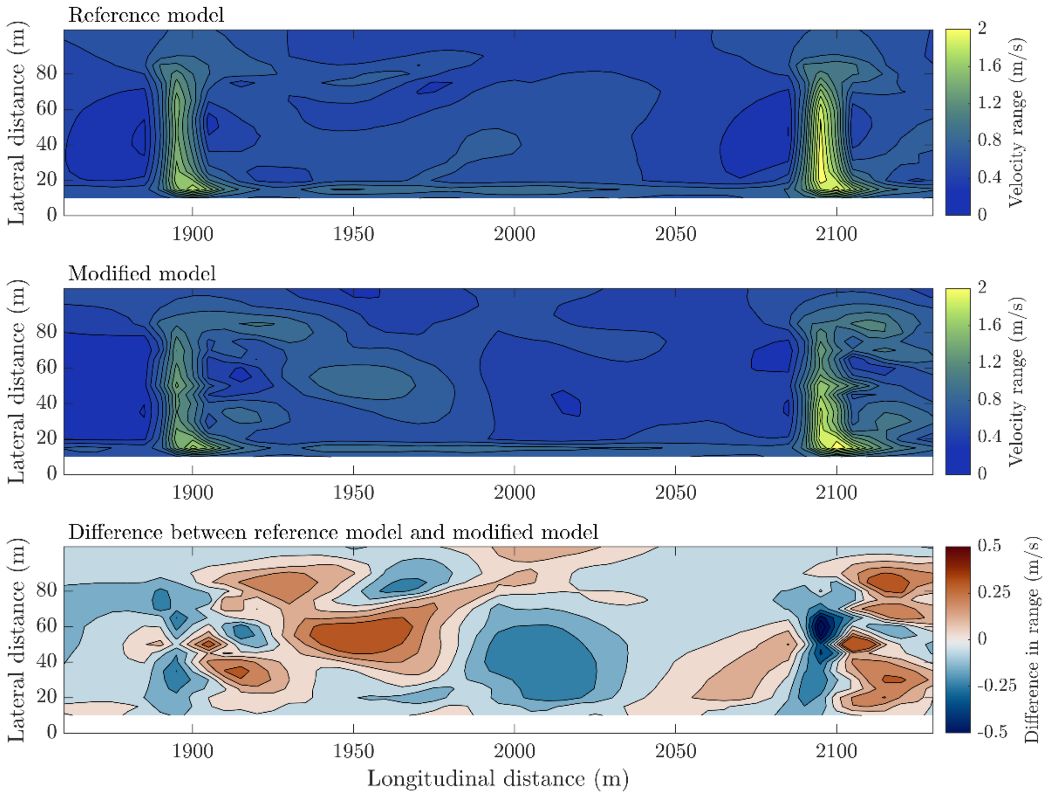
Water level range downstream sailing



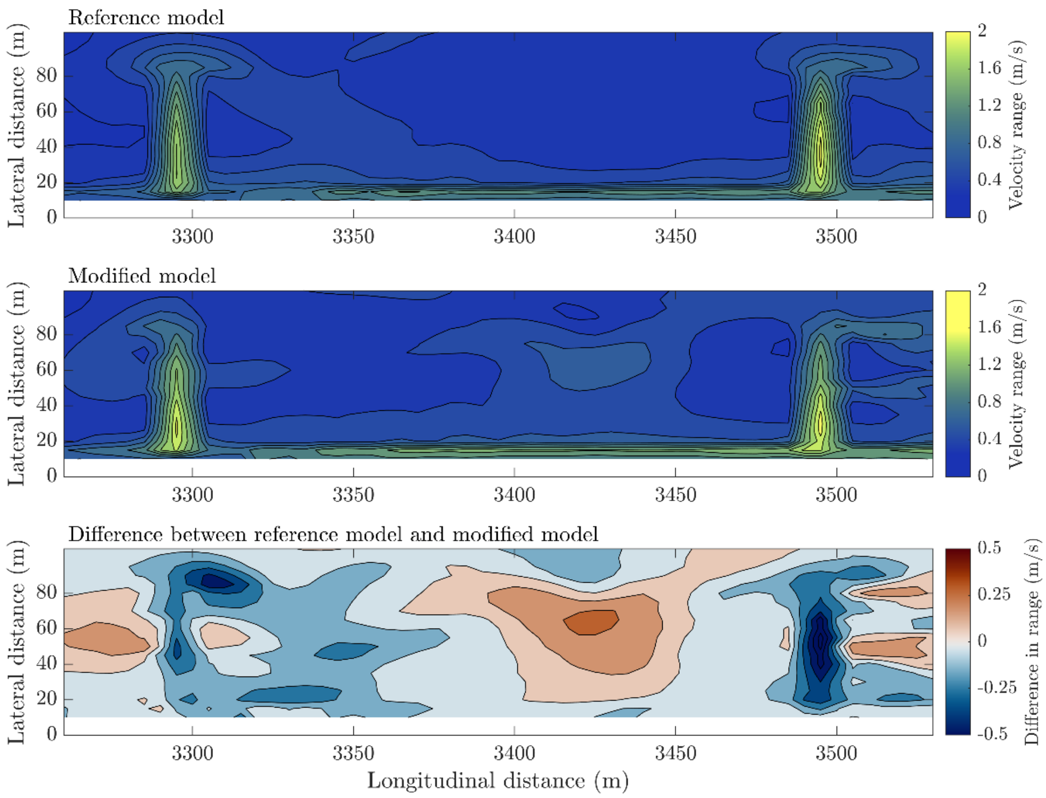
Combined water level range



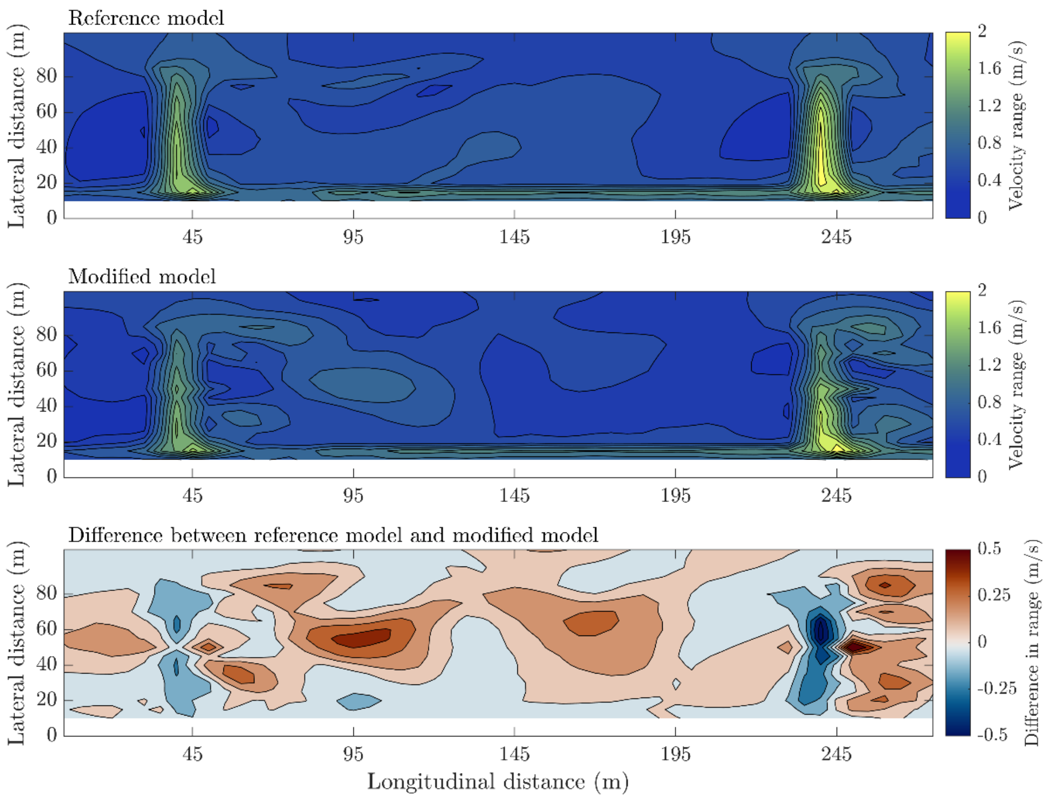
Velocity range upstream sailing



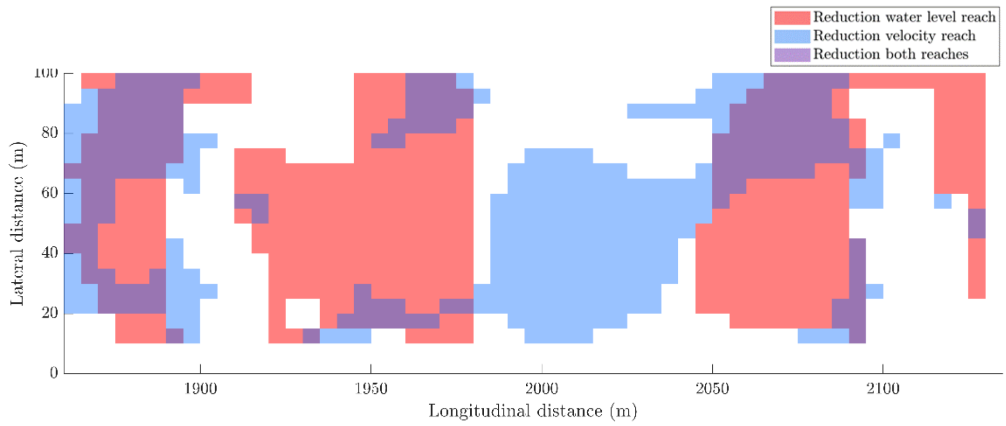
Velocity range downstream sailing



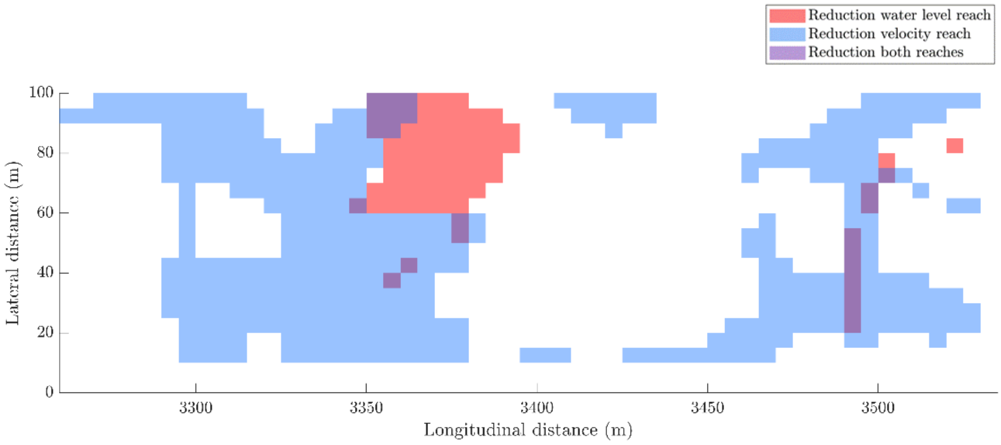
Combined velocity range



Overview plot upstream sailing

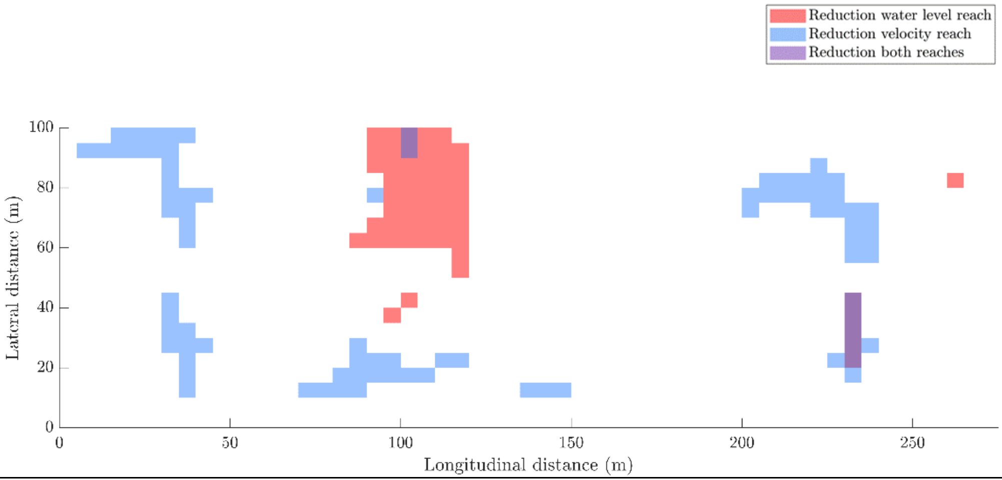


Overview plot dowstream sailing



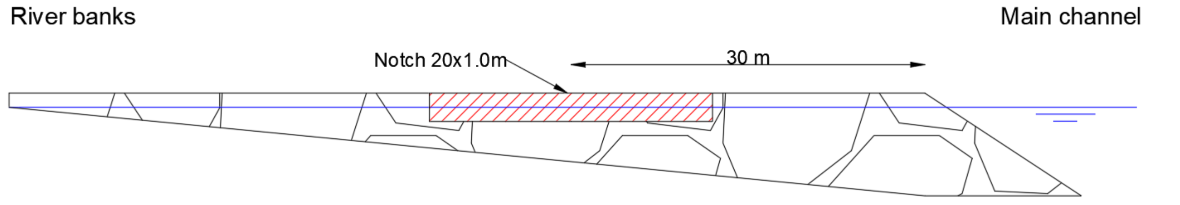
Combined overview plot

0

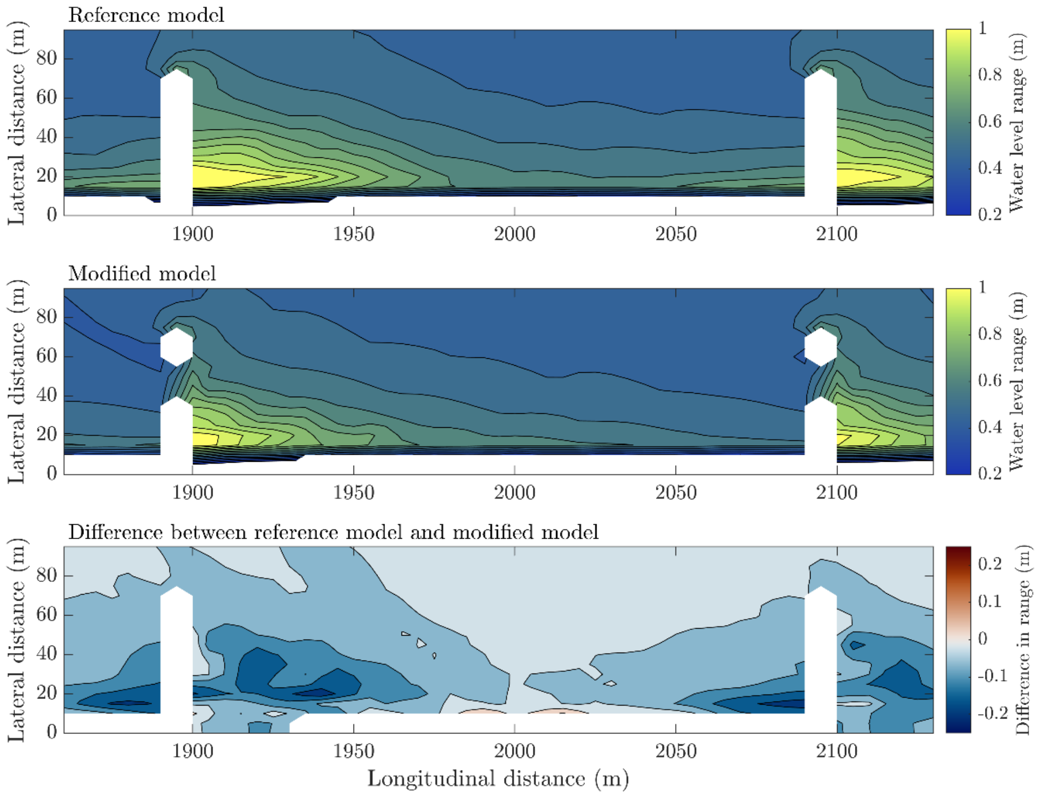


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
4.104	4.105	Rijnmax	Upstream	4.8 m/s	Notch(es)
4.204	4.205	Rijnmax	Downstream	4.8 m/s	Notch(es)

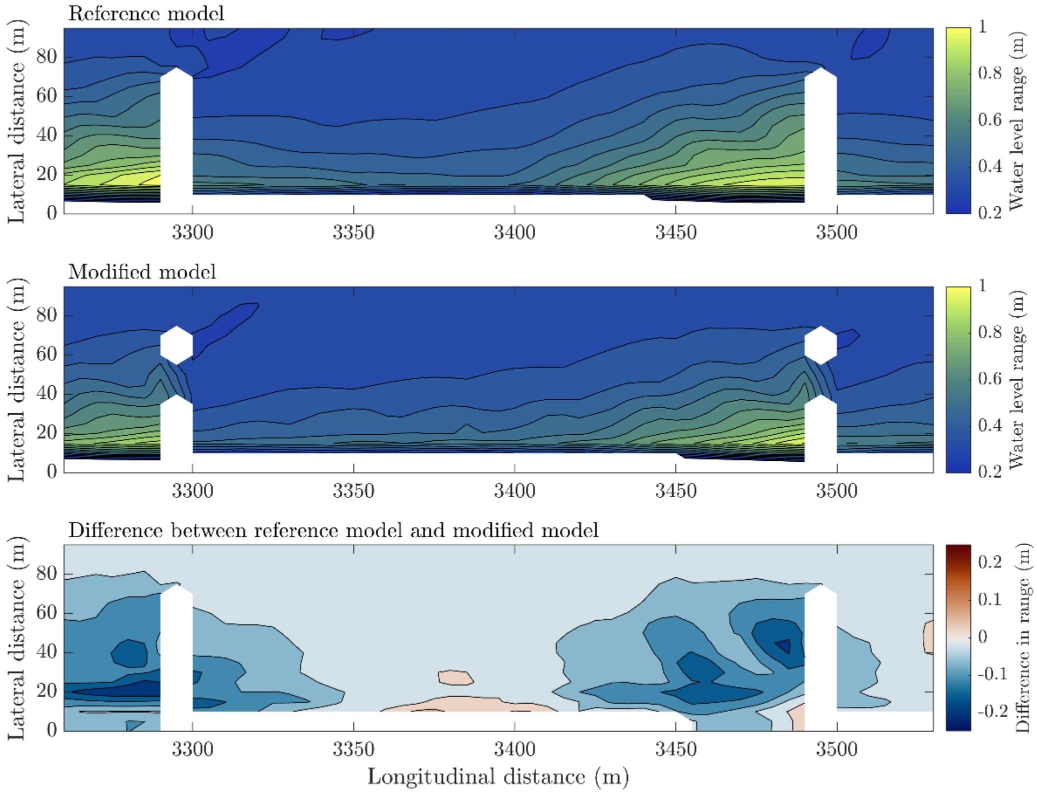
Number of notches	Location of notch	Width notch	Depth notch
1	30 m	20 m	1.0 m



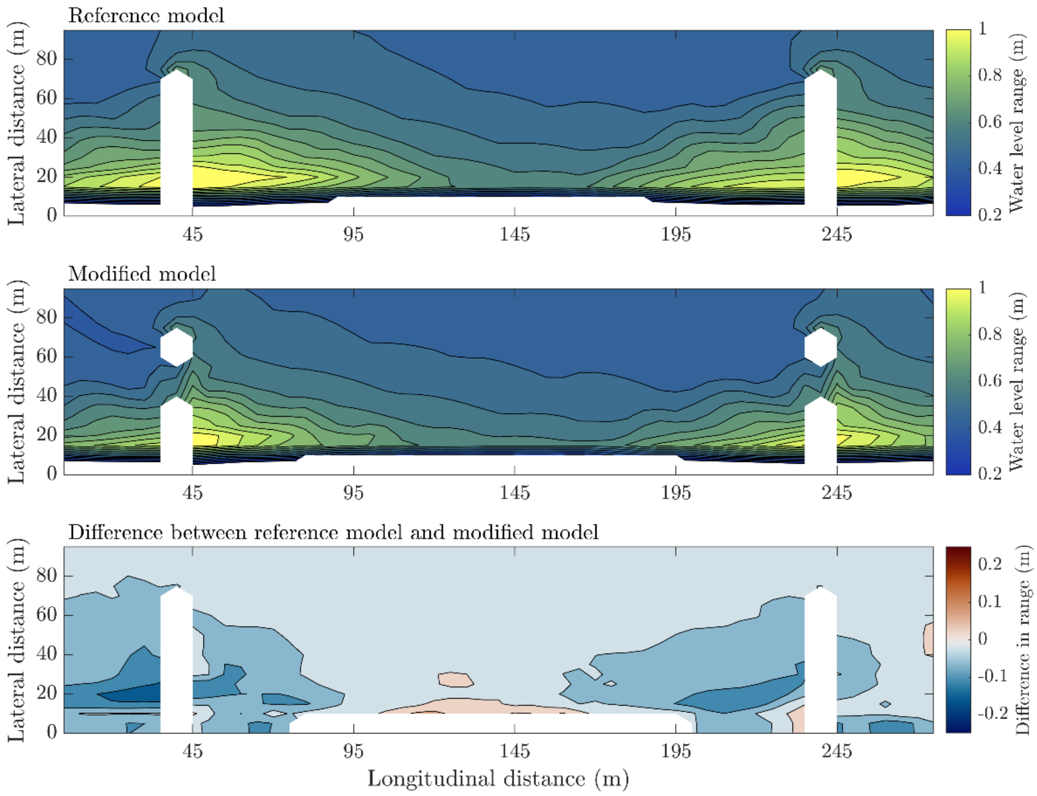
Water level range upstream sailing



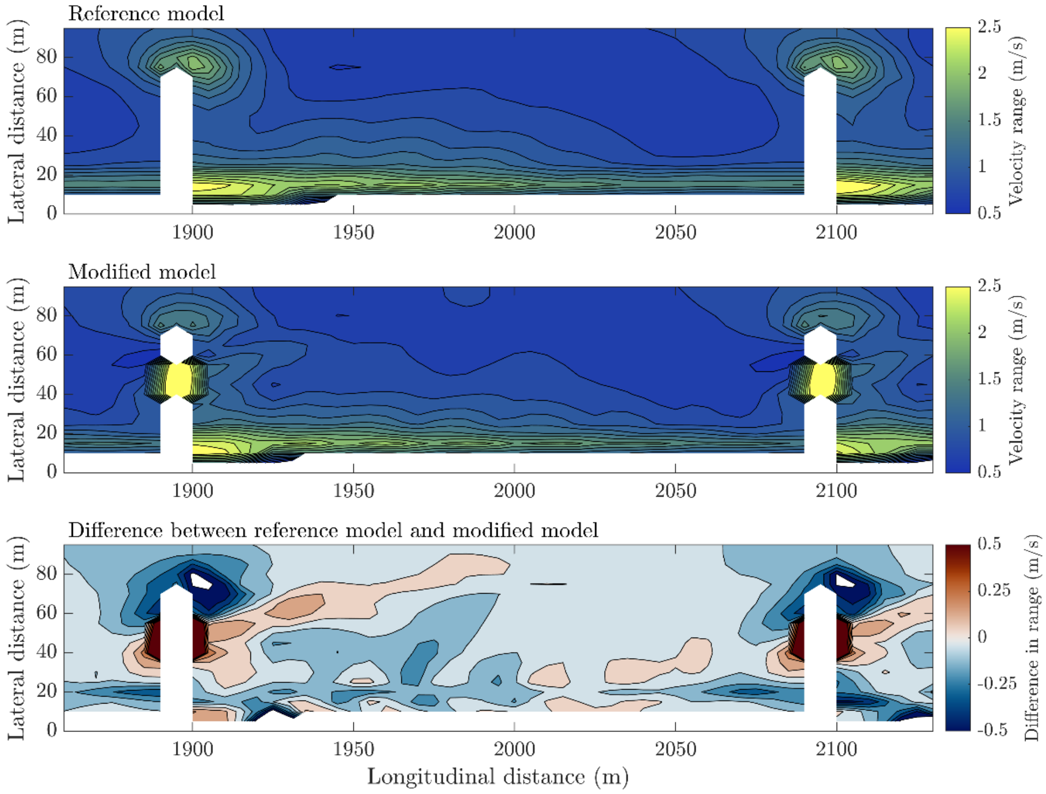
Water level range downstream sailing



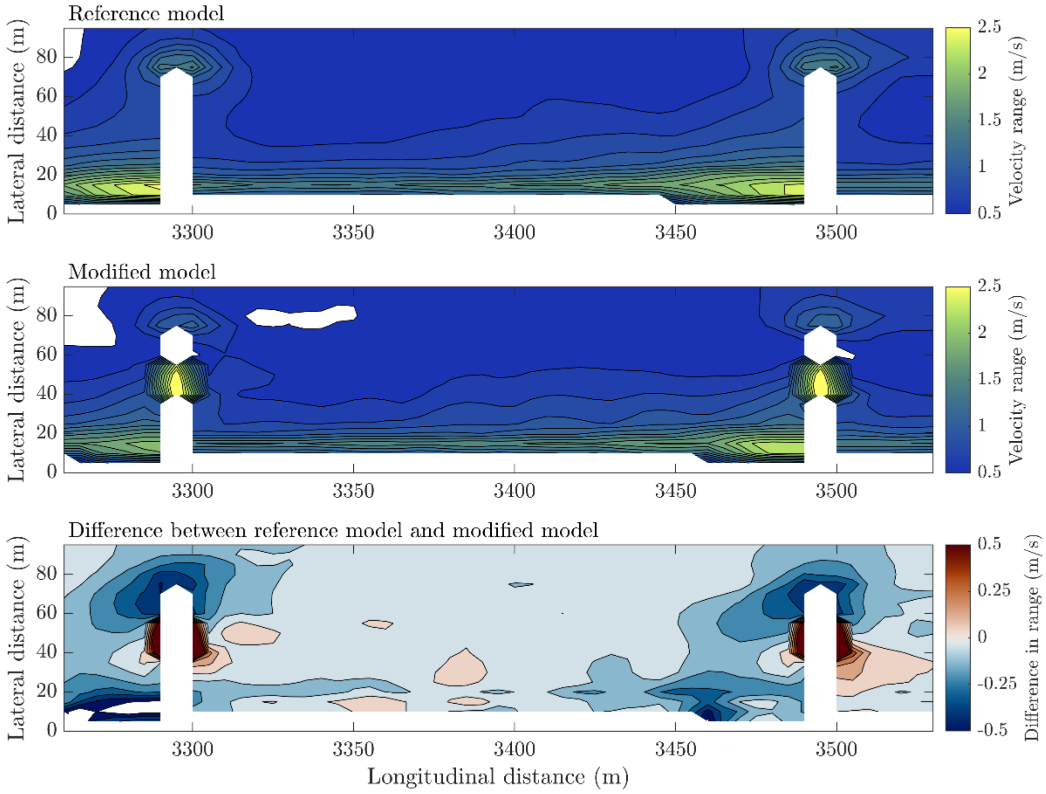
Combined water level range



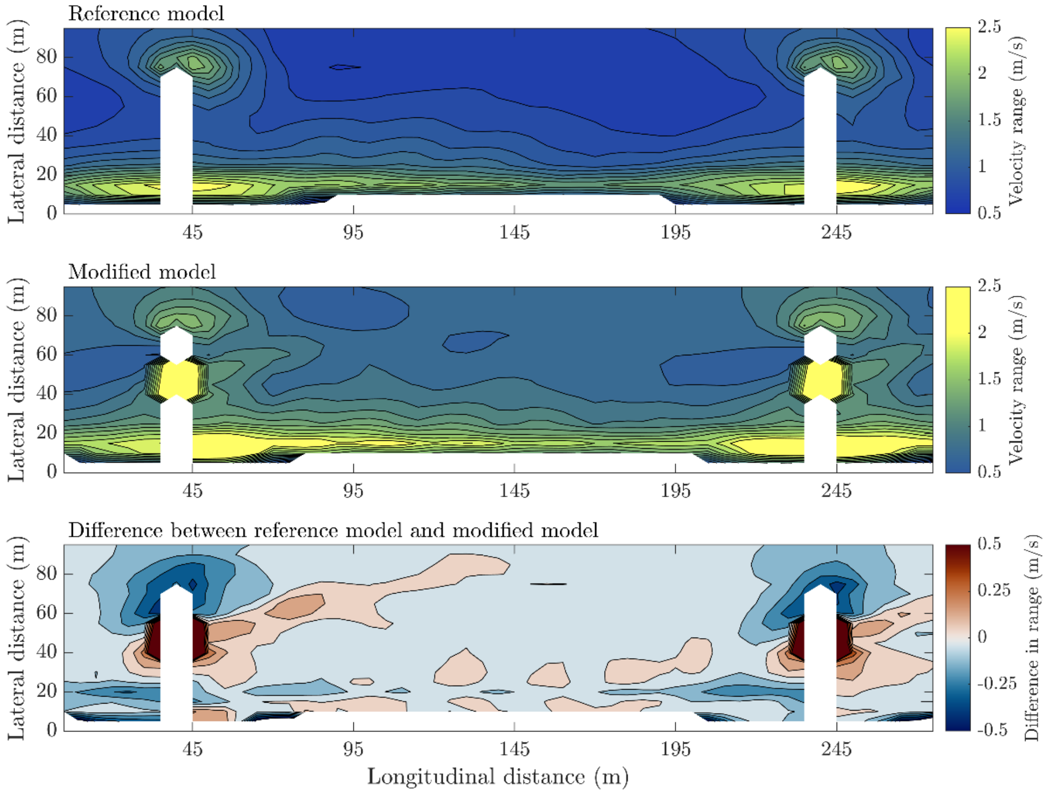
Velocity range upstream sailing



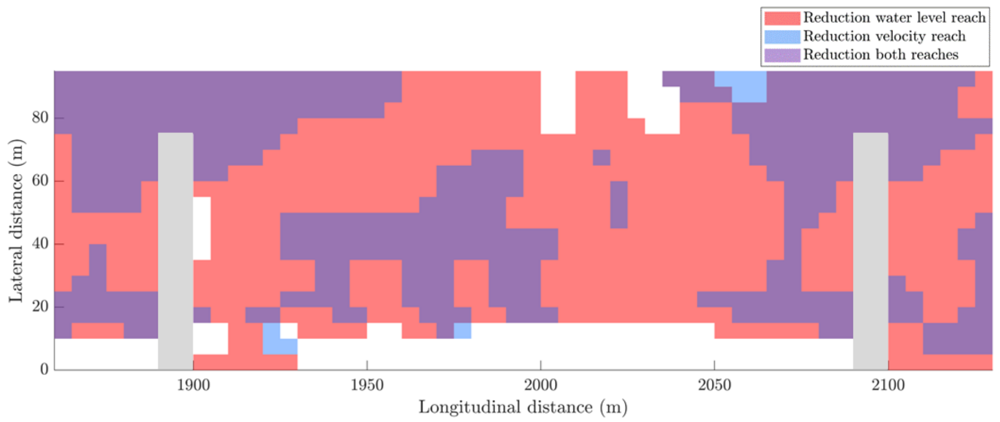
Velocity range downstream sailing



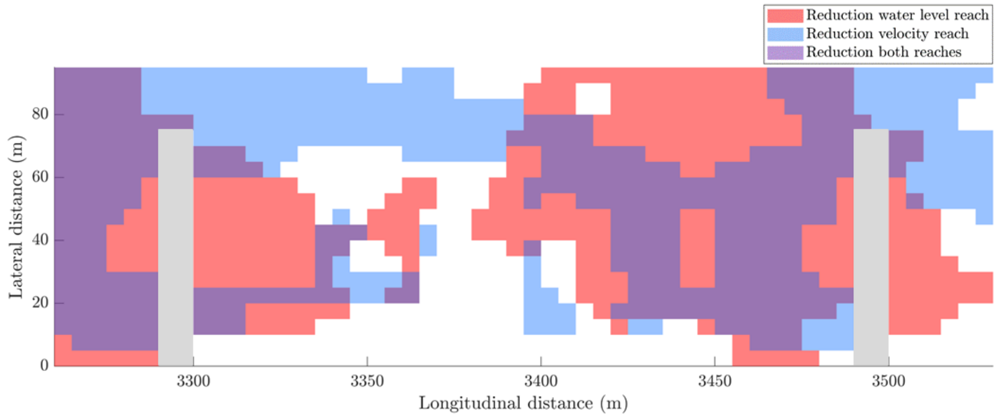
Combined velocity range



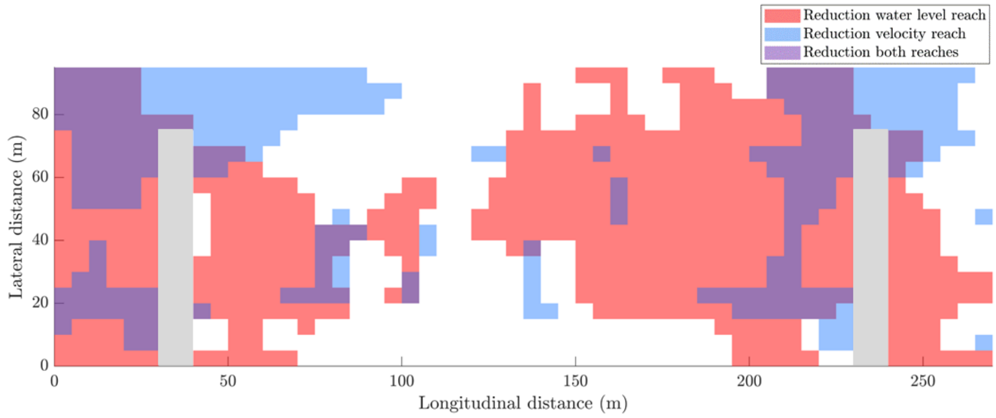
Overview plot upstream sailing



Overview plot dowstream sailing

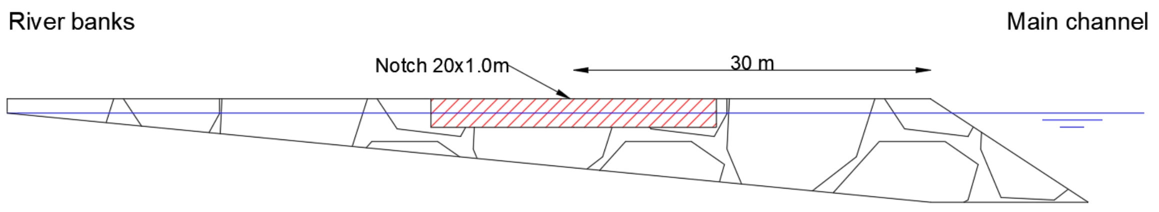


Combined overview plot

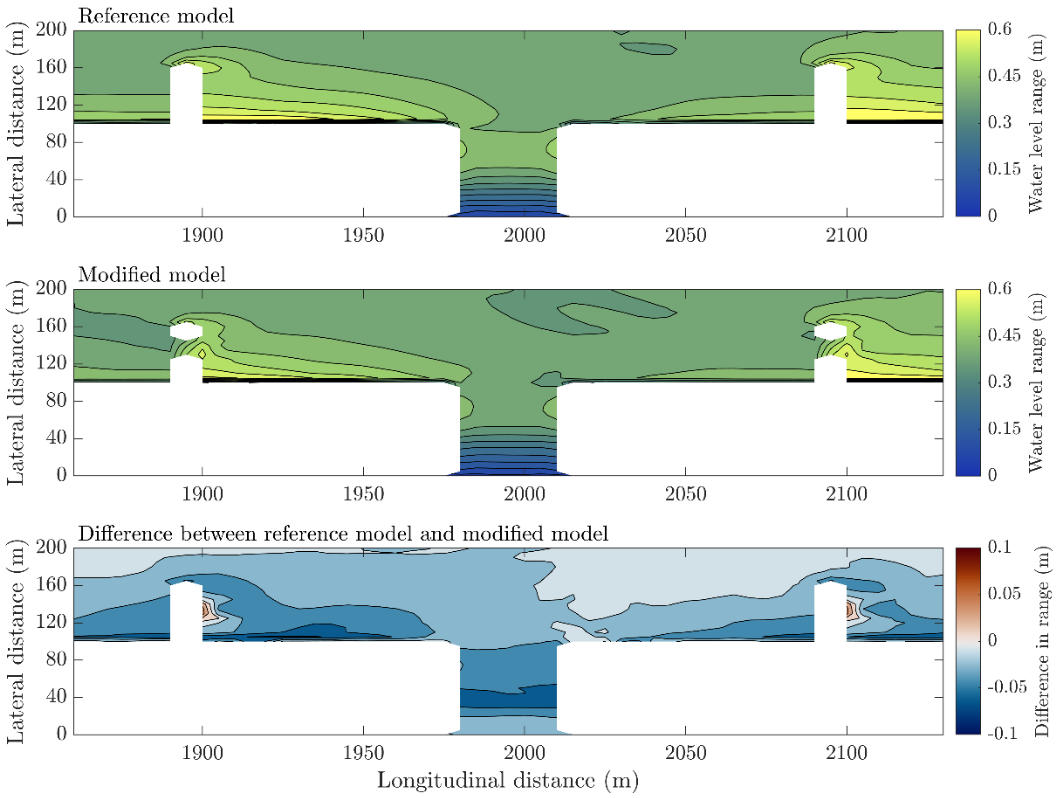


Run Number	Compare to run number	Ship type	Sail direction	Sail velocity	Groyne modification
4.106	4.107	Push tow	Upstream	4.5 m/s	Notch(es)
4.206	4.207	Push tow	Downstream	4.5 m/s	Notch(es)

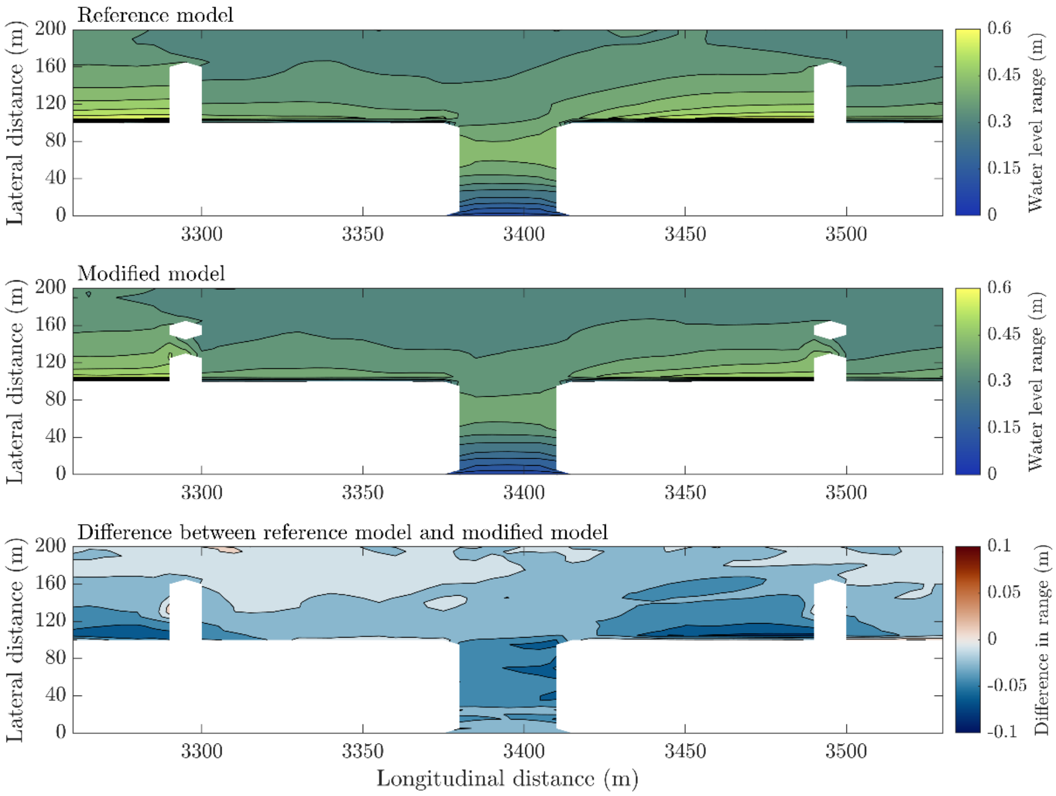
Number of notches	Location of notch	Width notch	Depth notch
1	30 m	20 m	1.0 m



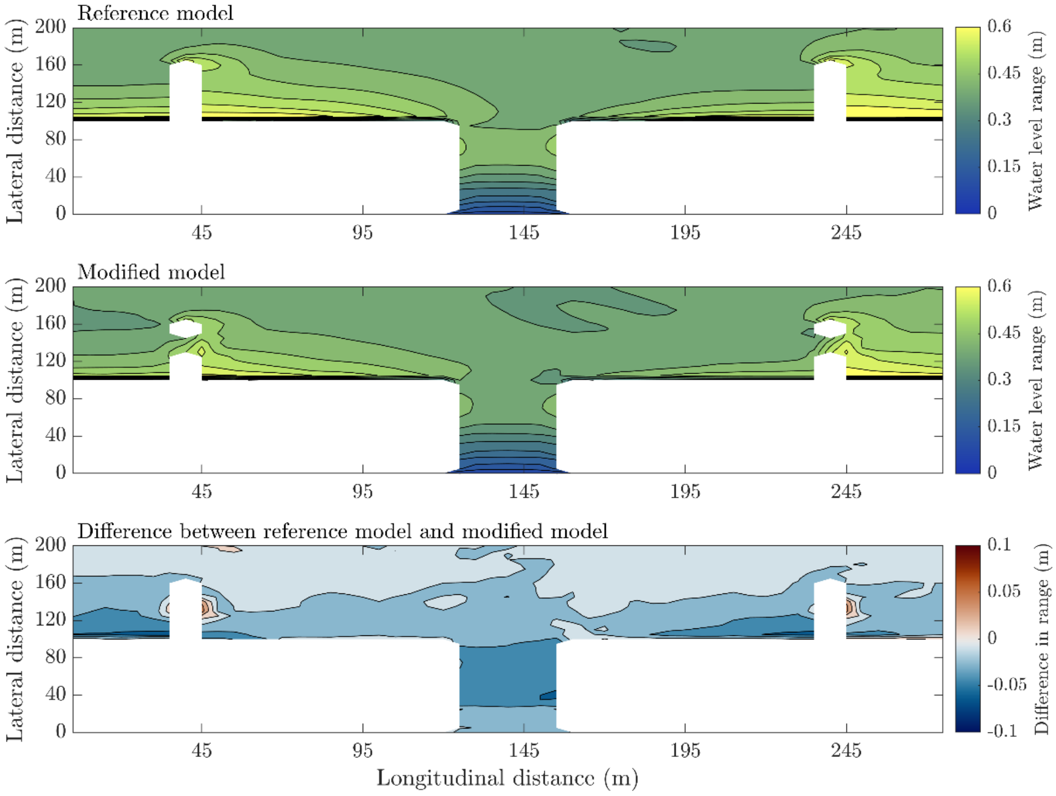
Water level range upstream sailing



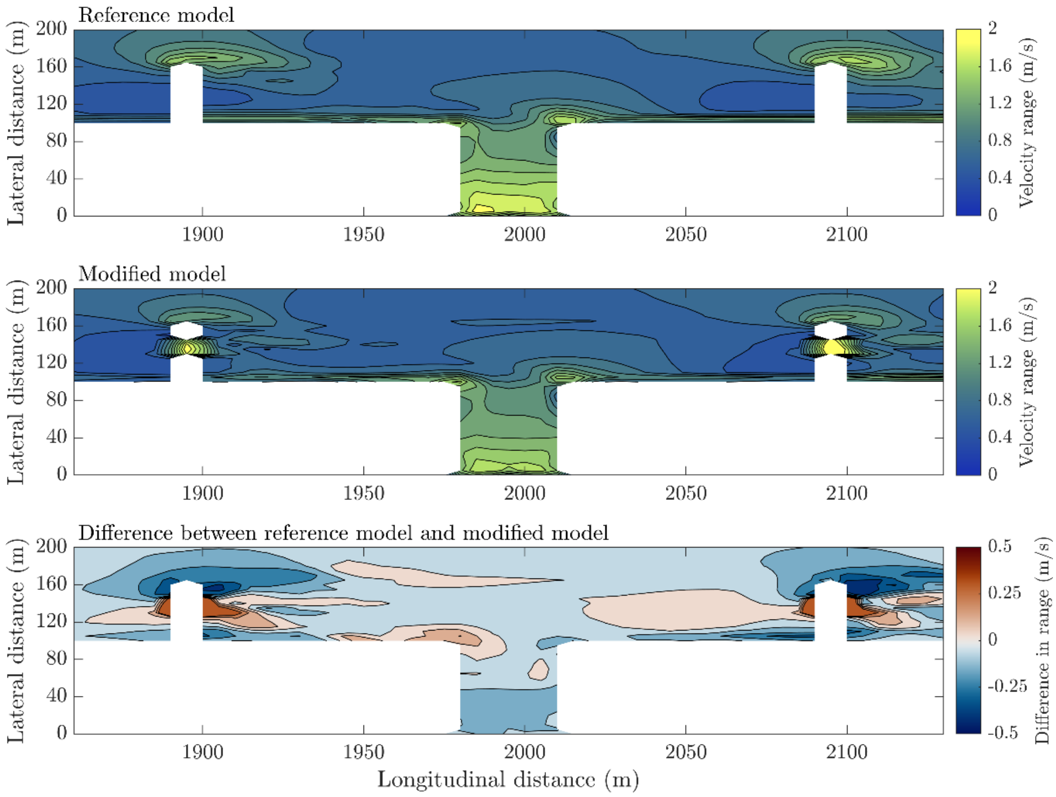
Water level range downstream sailing



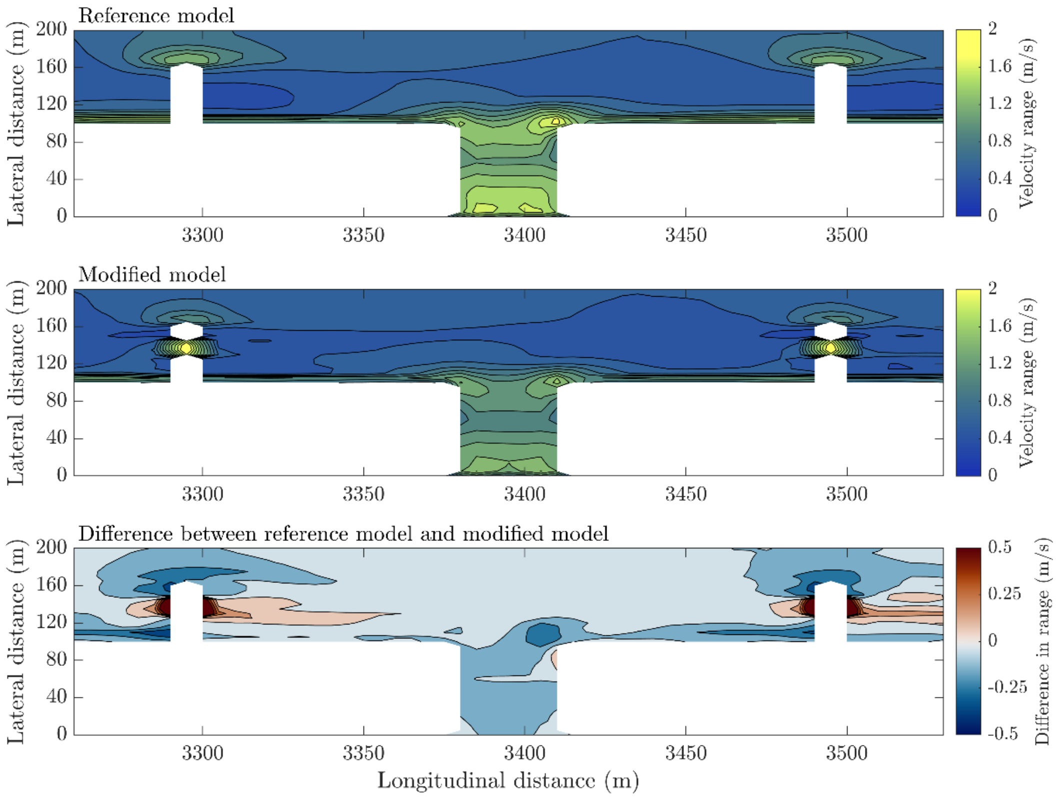
Combined water level range



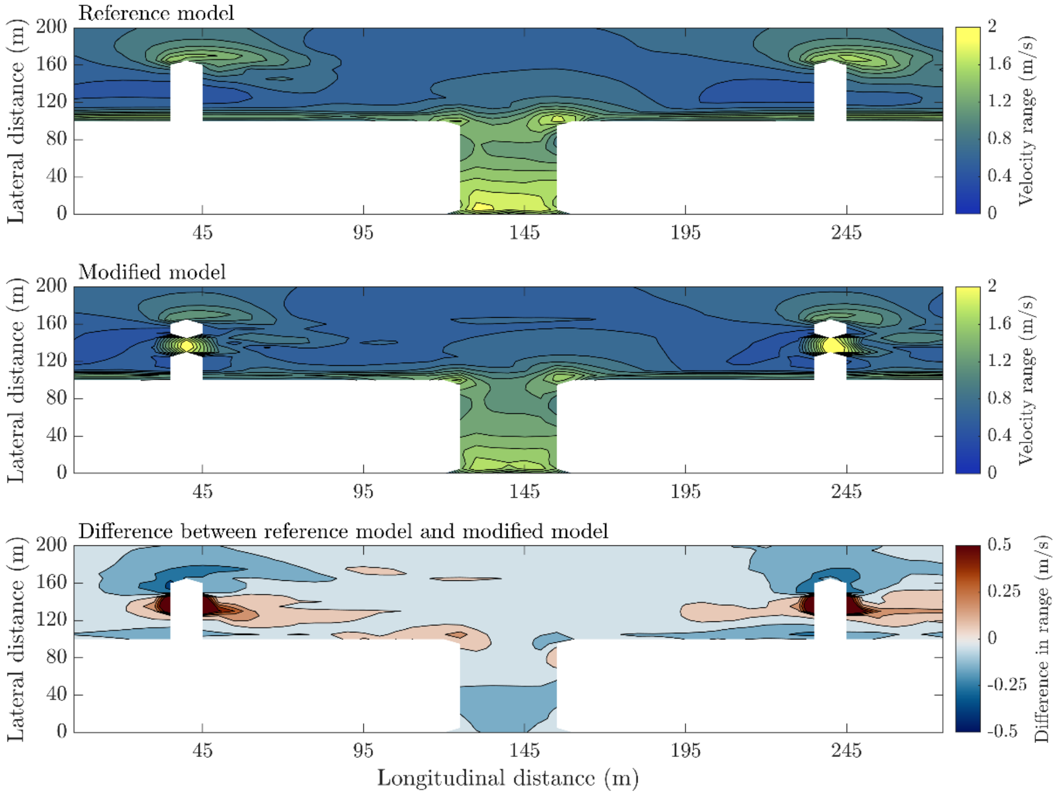
Velocity range upstream sailing



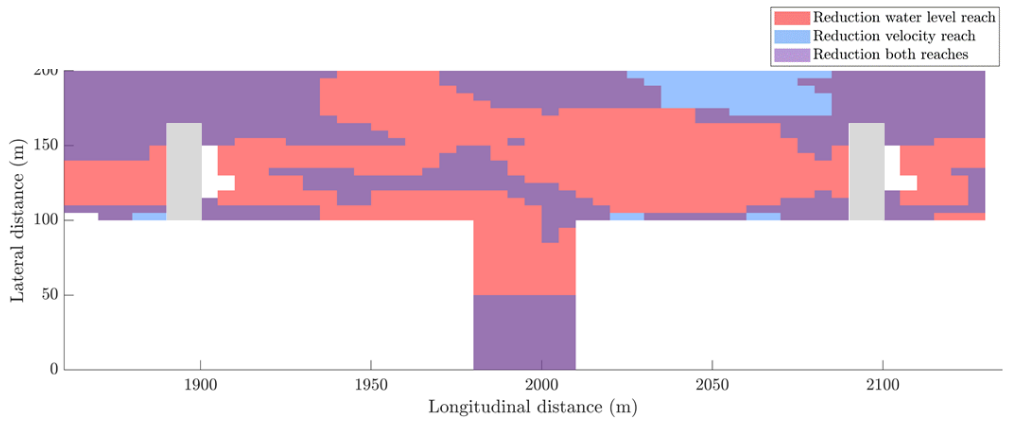
Velocity range downstream sailing



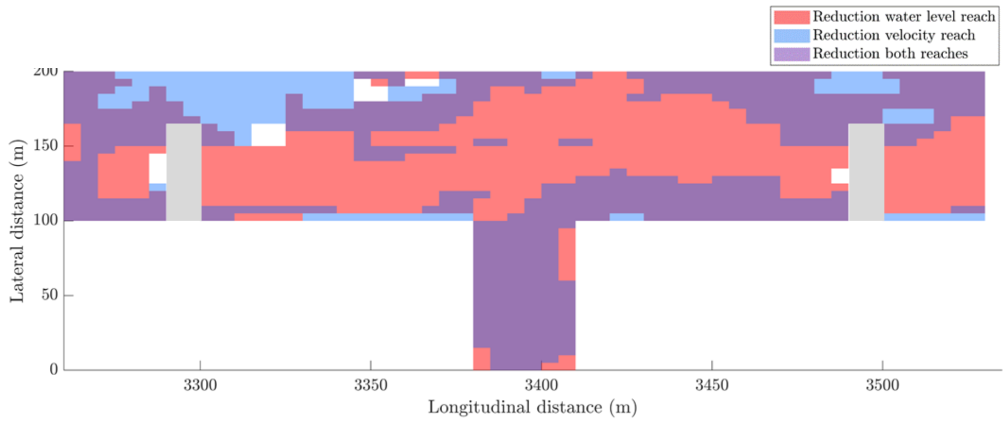
Combined velocity range



Overview plot upstream sailing



Overview plot dowstream sailing



Combined overview plot