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Bakker, Floor P.; van Koningsveld, Mark

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Optimizing navigation lock operation when climate change strikes

Floor P. Bakker[1*], Mark van Koningsveld[1,2]

[1]Department of Hydraulic Engineering, Delft University of Technology, The Netherlands

[2]Van Oord BV, Rotterdam, The Netherlands

(*f.p.bakker@tudelft.nl)

Abstract

Navigation locks are complex structures crucial for water management. While locks facilitate vessel passages over essential hydraulic structures, they also form bottlenecks in water transport systems by inducing vessel delays. Furthermore, lock operation can impact freshwater availability, as freshwater is lost and saltwater intrudes. Consequently, during droughts, authorities often impose ad-hoc operational countermeasures to reduce these impacts. However, these impacts are often not quantified, potentially leading to ineffective measures or excessive vessel delays. To enhance decision-making regarding these countermeasures, we present a simulation-based method that jointly quantifies lock vessel delays, freshwater loss, and saltwater intrusion. Using geospatial, vessel, and hydrodynamic data, we apply the method to the sea lock complex on the route to the Port of Amsterdam, demonstrating its validity and effectiveness in a real-world setting. By testing various countermeasures, we conclude that vessel clustering based on maximum waiting time is most effective in reducing saltwater intrusion while keeping vessel delays acceptable, outperforming the common practice of limiting lock operation hours. Although further improvements are possible, the current method enables objective decision-making regarding resilient lock operation strategies worldwide in light of climate change.

Keywords

discrete-event modelling, vessel delay, saltwater intrusion, freshwater shortage, closed system

1 Introduction

Navigation locks form critical links in water transport systems, enabling the passage of vessels over hard structures, such as dams and weirs (see Figure 1). These structures are often essential for regulating water levels for navigation, storing freshwater, and separating water bodies with different salinities. Efficient lock operation is paramount, as excessive vessel delays around locks threaten the entire transport system's viability. This necessitates fast vessel handling, which can limit the full utilisation of the lock chamber's capacity, leading to an increase in lockages. Each lockage typically involves water exchange that leads to net freshwater loss and saltwater intrusion, interfering with the system's freshwater supply.

Figure 1

Aerial photograph of the lock complex of IJmuiden, the gateway to the Port of Amsterdam

Source: Rijkswaterstaat

During droughts, the competing interests between water transport and freshwater supply can lead to major conflicts. In response to emerging water shortages, authorities often take operational countermeasures to reduce the number of lockages, such as vessel clustering and limiting operating hours. These measures often result in significant vessel delays, posing a threat to the resilience of the water transport system. On the contrary, continuing normal lock operation can exacerbate freshwater shortages. Examples of the Panama Canal (Calvo Gobbetti & Ríos Córdoba, 2024) and the Port of Amsterdam (Hendriks et al., 2024) strongly underpin the above challenge.

Implementing effective water-saving operational countermeasures that minimize disruption to water transport is crucial. In practice, however, countermeasures are often taken ad-hoc, lacking a comprehensive understanding of the measures' impacts on water transport and freshwater supply. As a result, an evaluation report of the most recent draught in The Netherlands recommended dedicated research to the effectiveness of these countermeasures, in particular, their impact on water transport (Hendriks et al., 2024).

To the researchers' knowledge, the above knowledge gap can largely be attributed to a lack of robust methodologies that simultaneously quantify vessel delays, freshwater losses and saltwater intrusion mass fluxes around locks. While various models exist in the literature, they either focus on water transport or hydrodynamics separately. Examples of logistical lock passage models are SIVAK by Rijkswaterstaat (2000) (ten Hove & Bilinska, 2015), Macharis et al. (2011), Bačkalić & Bukurov (2011), Chen et al. (2013), Verstichel (2014), Liao (2018), Van Adrichem (2019), OpenTNSim by Delft University of Technology (Baart et al., 2022; van Koningsveld & Den Uijl, 2019), and Zhang (2023). Regarding the lock hydrodynamics, refined CFD methods are presented by Nielsen (2011) and Oldeman (2020), and a 1D model, called WANDA-locks, was developed by Deltares (van der Ven et al., 2015). System-scale approaches were established by Parchure (2000), Augustijn (2011) and Rinehimer (2019). Hydrodynamic lock models that specifically include vessel traffic demand are SWINLOCKS by Wijsman (2013) and the Zeesluisformulering (Weiler et al., 2019; Weiler & Bijlsma, 2023). However, these methods are not suitable for quantifying vessel delays.

To fill this gap, we propose a method in this paper that simultaneously resolves vessel lock passage delays and lock water exchange fluxes. Such a method enables impact quantification of various operational countermeasures on water transport and freshwater availability, required to evaluate and trade-off countermeasures based on their effectiveness. We apply the method to a real-world case study of the navigation locks at IJmuiden to the Port of Amsterdam, the fourth largest European port, demonstrating its applicability for optimising lock operations worldwide.

2 Background

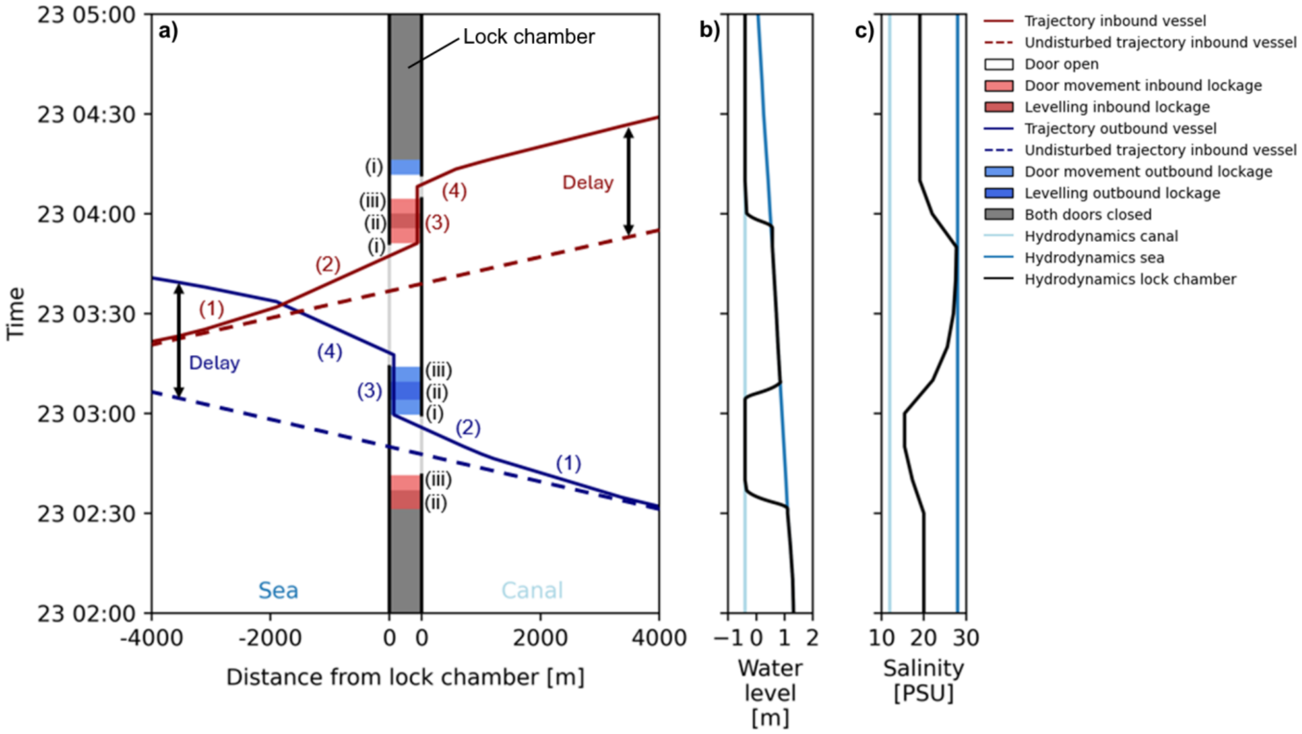
2.1 The lock operation

Lock operation consists of repeating cycles, comprising three phases, called a lockage (see Figure 2): (i) door closing, (ii) levelling, and (iii) door opening (van Koningsveld et al., 2023). During the levelling phase, the lock chamber's water level is adjusted by gravity to match the ambient water level, enabling vessel passage. During each door open phase, a gravity-induced exchange current occurs between the lighter fresh and heavier saline waters between the lock chamber and the ambient waters. Doors can be closed between lock operations to prevent the lock's water from becoming saline and fully intruding into the canal.

A vessel's lock passage involves the following stages (see Figure 2): (1) approaching the lock, potentially involving waiting time for an available lockage, (2) entering the lock chamber through the open door and berthing, potentially waiting for other vessels, (3) levelling, and (4) de-berthing and exiting the lock. Throughout these stages, the vessel interacts with the lock complex and other entering and leaving vessels. For example, to avoid collisions, the lock doors must be opened well in advance of entering vessels and vessels must maintain safety distances. Vessel delays, i.e. the additional time of passing the stretch of waterway due to the lock's presence, are caused when vessels wait for lock chamber availability, are being levelled, and decelerate and accelerate when sailing in and out of the lock, respectively. Vessels also contribute to freshwater losses and saltwater intrusion by exchanging water between the lock chamber and the ambient water.

Figure 2

A schematic overview of typical lock operation: (a) a time-distance diagram showing the trajectories of an outbound (blue solid trajectory from canal to sea) and inbound vessel (red solid trajectory from sea to canal) consecutively passing the lock chamber. The diagram visualises the different phases of the lock cycle (i-iii) and the vessels' lock passages (1-4), as mentioned in the text. Vessel delays are defined by the difference in vessel departure times for a situation with (solid trajectories) and without a lock (dashed trajectories). The water exchange fluxes are shown in (b) water levels and (c) salinity.



2.2 Countermeasures

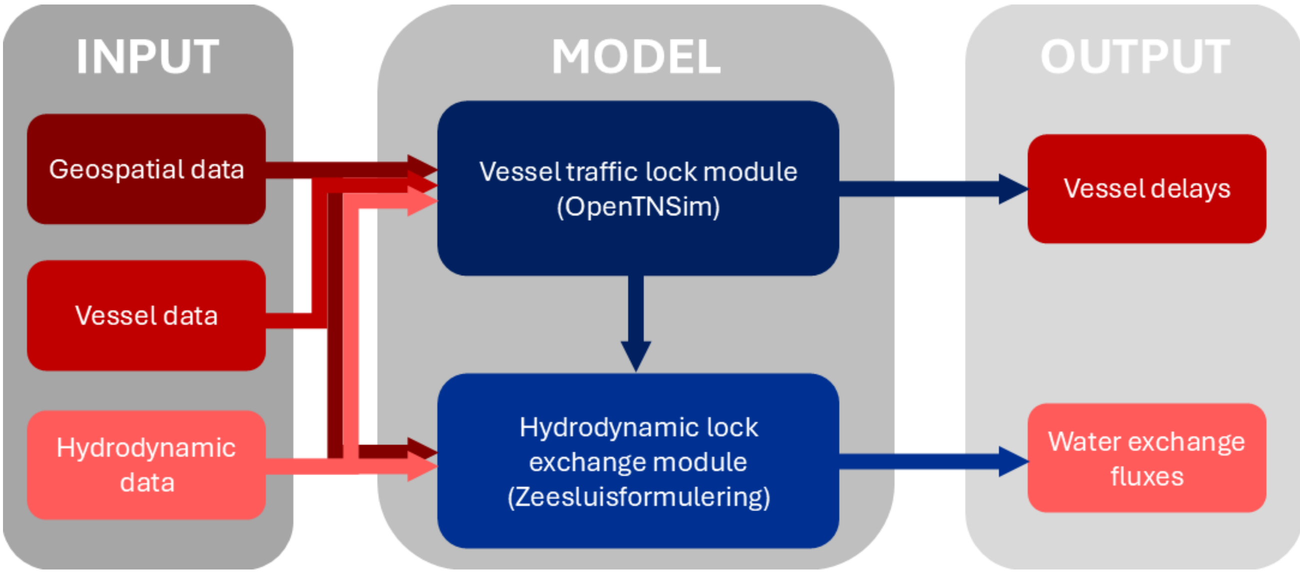
To reduce freshwater loss and saltwater intrusion through locks various countermeasures can be taken. While infrastructural measures, such as water-saving basins, bubble and water screens, sills, flushing discharge, and selective withdrawal by pumps can be effective (PIANC, 2021; de Fockert et al., 2021; O'Mahoney et al., 2023), we focus on operational measures in this paper. These measures focus on restricting the number of lockages, reducing door open times, and limiting levelling prisms by modifying the lock operation (PIANC, 2021). Examples are: vessel clustering (e.g., through limiting lock operation hours, or dynamically based on a minimum lock chamber occupancy or a maximum waiting time), tight planning of vessels and door movements, closing both lock doors in between operations, and levelling during moments of similar ambient water levels (in case of tides).

3 Methodology

The method presented in this paper consists of a vessel traffic lock module and hydrodynamic lock exchange module that uses various data sources to determine vessel delays, freshwater losses and saltwater intrusion masses (see Figure 3).

Figure 3

Schematic overview of the method



3.1 The vessel traffic model

The vessel lock passage model is built within the OpenTNSim library, which was initiated and further developed by the Delft University of Technology (van Koningsveld & Den Uijl, 2019; Baart et al., 2022). This Python-based library enables discrete-event simulation modelling of vessels (agents) navigating over a water transport network (graph) while interacting with port and waterway infrastructure objects and the physical environment (e.g., water levels and current velocities). A separate lock module exists within the package, which was expanded for this study.

The lock module allows the inclusion of lock complex objects in the waterway graph through which vessels interact and experience delays. The object consists of a lock chamber and two waiting area objects, at user-defined distances from the lock, and a lock master who schedules vessels into lockages through 2D bin-packing and controls vessel traffic and lock cycles. Vessels register themselves to the lock master at a user-defined distance from the waiting areas. When the lock is congested, the lock master can force vessels to wait in the waiting area or through dynamic speed control.

The method requires the following input (see Figure 3): (1) geospatial data, to obtain the dimensions and layout of the lock complex, and derive a network of the main waterways, (2) hydrodynamic data, namely water levels for determining levelling times, and (3) vessel data, to derive vessels of call, their dimensions, and sailing speeds over the network. The method's output contains the behaviour of vessels and the lock complex, from which vessel delays are derived.

Specific parameters are available to adjust vessel behaviour around locks. First, the infrastructural components can be changed. These entail the capacity-determining dimensions of the lock chamber and waiting area, and door opening and closing times. Also, the levelling times can be adjusted through a sluice gate flow relation and gate opening times, or completely overruled by observed levelling time relations. Second, lock operational parameters can be modified. These include the anticipation time of door operations, and additional countermeasures, such as clustering based on lock occupancy or a maximum vessel delay. At last, vessel behaviour components can be modified by altering vessel speeds over the network and around the lock, and by changing maintained safety distances.

3.2 The coupled hydrodynamic model

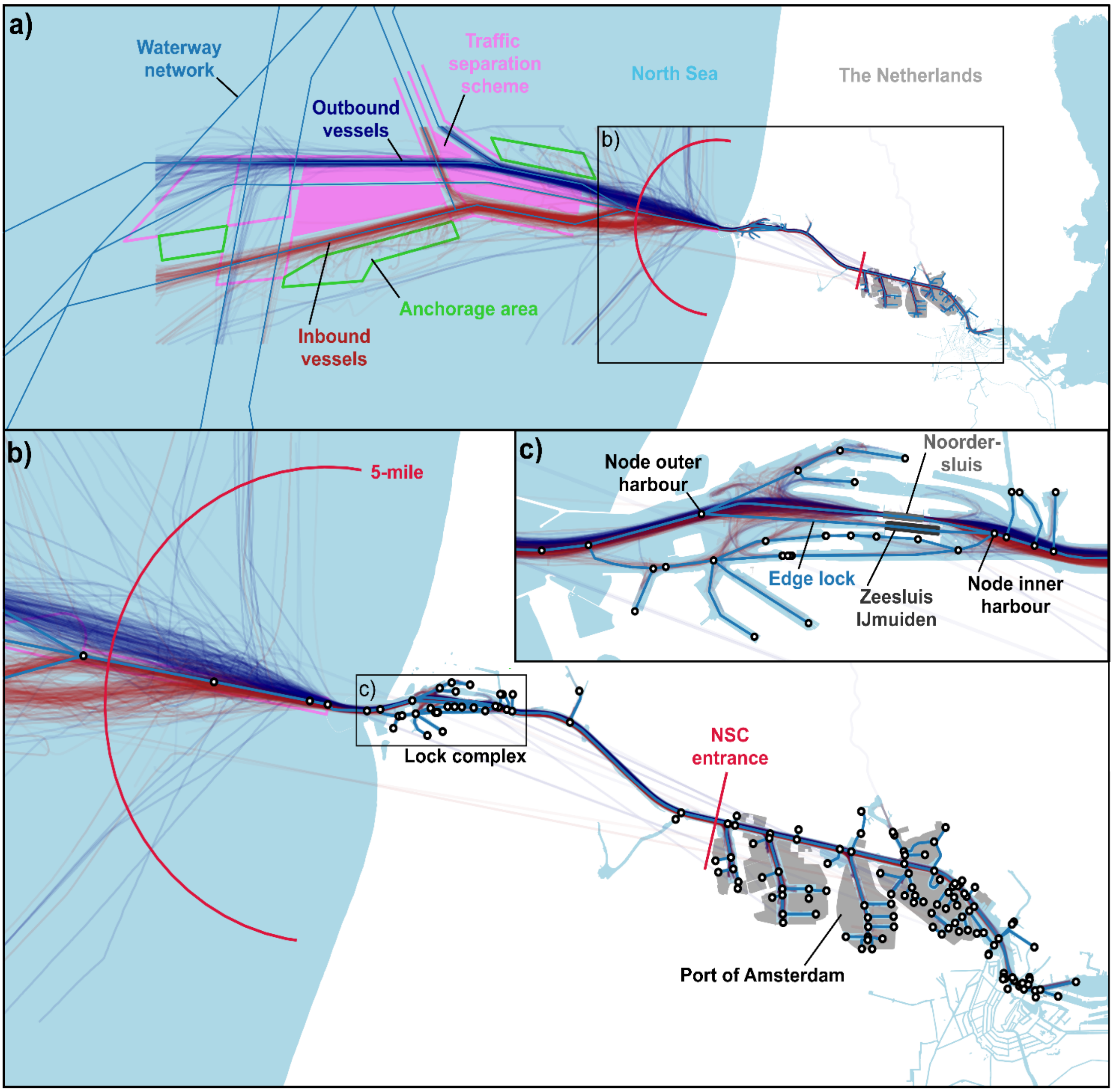
The vessel traffic model is coupled with an analytical, semi-empirical hydrodynamic lock exchange model to rapidly estimate the effectiveness of operational countermeasures for limiting freshwater loss and saltwater intrusion mass fluxes. This model, called Zeesluisformulering (Weiler et al., 2019), is developed by Deltares and distinguishes between door open and levelling phases during which the described water exchange fluxes are assumed to occur sequentially. For the setup of the model, the following data should be collected (see Figure 3): the lock chamber dimensions (derived from geospatial data), the water level and salinity differences between the lock chamber and the ambient water (derived from hydrodynamic data), and the replaced water volumes of the vessels and the door open times (as output from the vessel traffic model). More details of the model can be found in Weiler et al. (2019)

3.3 The Port of Amsterdam case

The Port of Amsterdam is accessible to sea-going vessels through the North Sea Canal (NSC), which is depicted in Figures 1 and 4. For navigability, this canal is closed off from the sea by a sluice complex at IJmuiden, comprising a discharge sluice and a navigational lock complex. Thereby, it separates saltwater from freshwater, which is required for agriculture, industry, and ecology.

Figure 4

Overview of the lock complex of IJmuiden: geospatial data, AIS data, and the waterway network



Based on interviews with the lock masters, normal lock operation is driven by actual vessel demand. For this, agents register their vessels with the lock master days in advance, enabling the master to plan vessels into lockages. When approaching the lock (i.e., when passing the 5-mile distance from the breakwaters, or entering the NSC), the vessels' pilots announce their estimated arrival time at the lock to the lock master, allowing the master to anticipate vessel arrivals. As there are no specific waiting areas for the lock complex, vessels wait by reducing their sailing speed. Long waiting times are accommodated in anchorage areas and at the terminal.

In 2022, a new navigation lock, called Zeesluis IJmuiden, was opened at IJmuiden to replace the expired Noordersluis. With dimensions of 545 m in length, 70m in width, and 18 m deep, Zeesluis IJmuiden accommodates a further growth in vessel traffic and size, enabling the operation of the deepest-draughted (13.72 m) design vessels during low tide. However, these lock dimensions contribute significantly to freshwater losses and saltwater intrusion fluxes when operating, causing salinity limits in the NSC to be exceeded during the 2022 drought. These effects were mitigated by the authorities by implementing 12-hour operating windows, through which vessels were clustered, reducing the number of lockages. Although successful in decreasing the NSC's salt concentrations, this countermeasure caused significant vessel delays and subsequent economic loss for water transport (Hendriks et al., 2024).;

3.4 Testing the effectiveness of countermeasures

The presented method is applied to test the impact of the above and alternative countermeasures on vessel delays and saltwater intrusion mass flux into the NSC. The following data sources are used for the model's input: (1) the fairway information system network of Rijkswaterstaat (see Figure 4), (2) geospatial data from OpenStreetMap (see Figure 4), (3) Automatic Identification System (AIS) data, analysed based on Bakker et al. (2024) (see Figure 4), and (4) water level and salinity data from Rijkswaterstaat and Deltares from a measurement campaign conducted between the 20th of February and the 20th of March of 2023 by Van der Hout (2023) (see Figure 5). The model's output comprises the vessels' behaviour, and the lock chamber's water level and salinity, from which vessel lock passage delays and saltwater intrusion follow.

The coupled model is validated for the period of the measurement campaign. For this, vessels that were detected to navigate the Zeesluis are initiated in the model at the first nodes in front of the 5-mile line and NSC entrance at their observed departure time at these notes. They are given properties, such as their documented dimensions. Moreover, they navigate over the network at observed averaged vessel speeds. The behaviour of the lock master (i.e., typical anticipation times for door movements, levelling and clustering times) and the estimated saltwater intrusion mass fluxes are calibrated.

The validated model is used to test the effectiveness of the following drought countermeasures over a two-week period, from February 23rd to March 9th, 2023, selected due to data availability and time constraints: (1) limited operation hours in blocks of 12 hours, (2) reducing door open times by halving sailing in and out gaps between vessels and anticipation times of door movements, and dynamic clustering based on (3) a minimum number of locked vessels and (4) a target maximum waiting time. For this testing, only vessels are considered that must use Zeesluis IJmuiden given their dimensions.

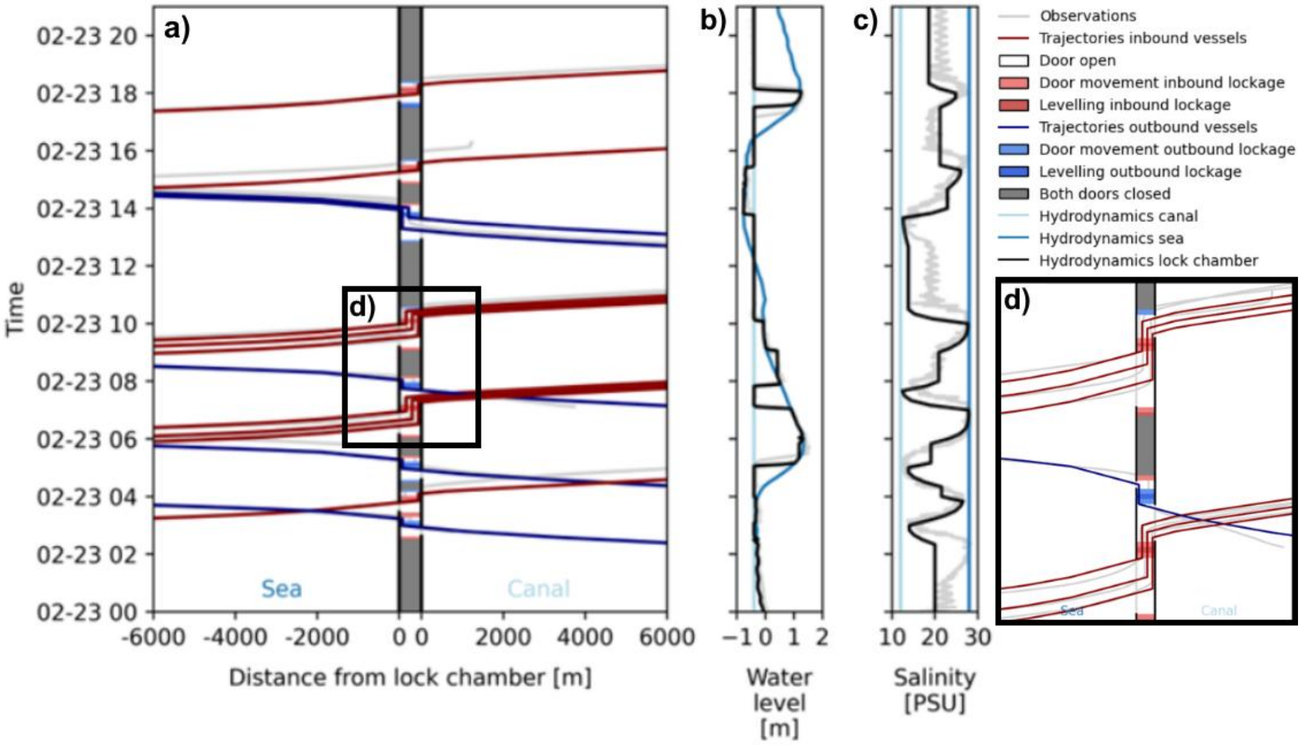
4 Results

4.1 Validation of the waiting times and saltwater fluxes

Observations and model outcomes are visualised in Figure 5 for a certain timeframe within the validation period. In- and outbound vessels interact with each other and the lock chamber. Moreover, the chamber's water level and salinity are constantly affected by levelling and door open phases.

Figure 5

Comparison between the observed and modelled vessel behaviour and lock hydrodynamics: (a) a time-distance diagram of observed and modelled in- and outbound vessels passing Zeesluis IJmuiden, including (d) a close-up, and the corresponding lock chamber's (b) water level and (c) salinity.



As observed in Figure 5b, the lock masters implement clustering of vessels. This may be primarily to limit vessel delays during high demand and secondly to reduce saltwater intrusion. During clustering, the vessels remain a significant distance from each other in the order of 10 minutes. In Figure 5a (salinity) the locks are often fully exchanged, as door open times are long: the lock masters open the doors 20 minutes in advance of a vessel's arrival. Due to the massive lock chamber volume compared to the relatively small water level differences between the sea and canal (see Figure 5a, water level) and vessel volumes, most saltwater intrusion occurs during door open phases by gravity-driven exchange currents. When possible, given the anticipation times of door movements, the lock masters close doors in between operations to reduce saltwater intrusion.

The coupled model matches with the observations. Regarding the vessel traffic model, the discrepancy between the modelled and observed vessel delays is 21.03 minutes, meaning a model underestimation. The mismatch is mainly caused by the levelling times (see Figure 5b). Here, the door movement and levelling events follow too closely in the model, while in reality, time gaps occur. This is likely caused by the model's missing berthing process. Regarding the hydrodynamic model, an underestimation of 18.9% is found between the measured and modelled total chloride masses. Most of this error is caused by underestimated gravity-driven exchange current speeds. Hence, increasing the speed by a calibration factor of 1.65 (i.e., 1.65 times faster exchange speeds) resulted in an underestimated total intruded chloride mass by only 0.4%, with errors in individual lock operations remaining below 20%. However, due to mismatching levelling and door open times, the moments of saltwater intrusion in the model generally lead in time (see Figure 5a, salinity).

4.2 The effectiveness of countermeasures

Table 1 summarises the impact of (alternative) operational countermeasures as predicted by the model for Zeesluis IJmuiden in the two-week study period. During normal lock operation, the door at the canal side is predicted to be opened 146 times, contributing to a chloride mass intrusion equivalent to that of 90.05 full lock exchanges. Most salt (87.1%) is estimated to be intruding during the door open phases which on average last 26.4 minutes at the canal side. Hence, the lock chamber is not always fully exchanged. Vessel delays are limited, most frequently at 15.6 minutes per vessel.

Limiting operating hours, as was the implemented countermeasure during the 2022 drought, is predicted by the model to reduce the intruding saltwater mass by 39.2% compared to the above situation without any countermeasures. However, this is at the expense of an excessive increase in median vessel delay by 3.65 hours. Alternatively, reducing the door open times can achieve an estimated reduction of 16.1% in intruded chloride mass without deteriorating vessel waiting times (the median vessel delay decreases by 4.2 minutes). This reduction results from faster completion of lock operations.

Moreover, the model predicts that dynamic demand-based vessel clustering outperforms the above countermeasures. Clustering using a minimum lock chamber occupancy of two vessels results in an estimated 40.3% reduction in intruding saltwater compared to the situation of normal lock operation, at the expense of a 1-hour increase in median vessel delay. Further increasing the minimum occupancy reduces the total intruded chloride mass, but leads to excessive maximum individual vessel delays during periods of low vessel demand. However, this delay remains below that of the situation with the limited operation hours.

Table 1

The implications of operational countermeasures on vessel delays and saltwater intrusion mass fluxes

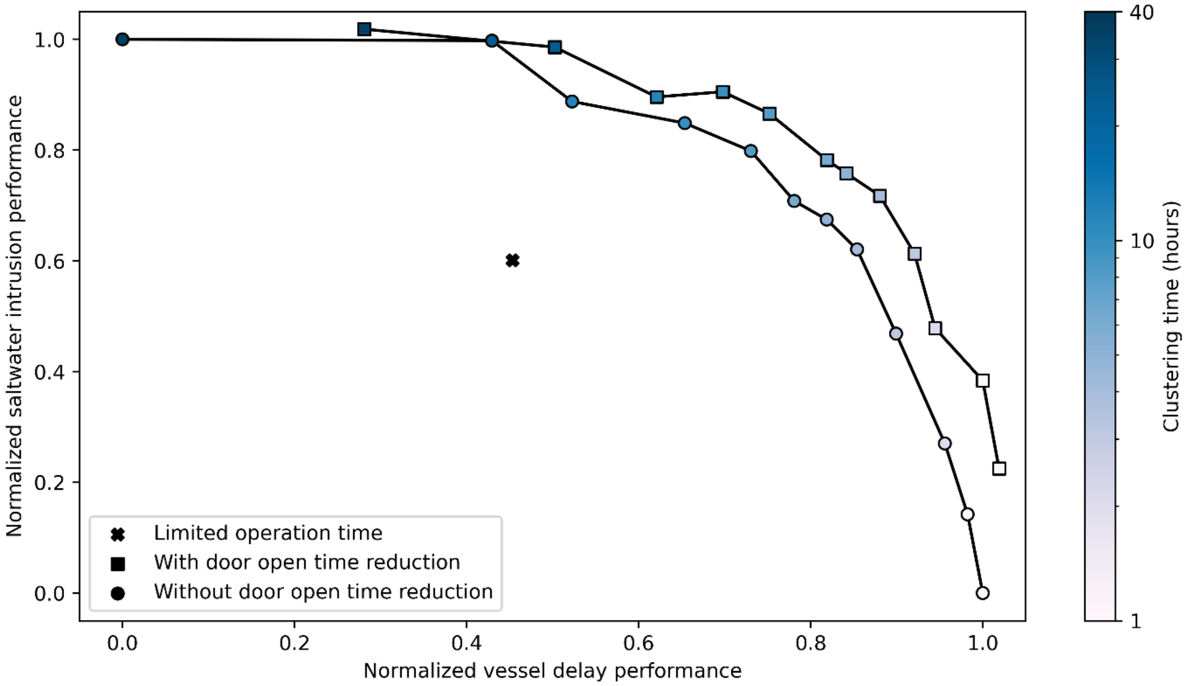
Countermeasure	**None**	**Limited operating hours**	**Reducing door open times**	**Clustering on minimum vessel occupancy (vessels)**		**Clustering on target maximum waiting time (hours)**		
				2	3	2	4	8
Number of door openings at the canal	146	83	165	88	63	121	87	68
Mean door open time at the canal (hours)	0.44	0.59	0.25	0.54	0.60	0.42	0.54	0.59
Median vessel delay (hours)	0.26	3.91	0.19	1.27	2.37	0.66	1.40	2.43
Maximum vessel delay (hours)	1.62	14.01	1.56	13.63	23.11	2.66	4.78	9.53
Total intruded chloride due to door opening (10^6 kg)	472.00	278.12	382.56	270.27	203.73	397.14	275.8	209.89
Total intruded chloride mass (10^6 kg)	542.08	329.55	455.03	323.79	249.56	454.08	325.90	255.33
Total intruded chloride mass (equivalent fully brackish lockages)	90.05	54.75	75.60	53.79	41.46	75.44	54.14	42.42

The model furthermore predicts clustering based on a target maximum waiting time to be the most effective countermeasure. This measure can achieve an estimated 16.2% reduction in intruded chloride mass compared to the situation without countermeasures, at the cost of only increasing the median vessel delay by 24 minutes, and a maximum waiting time of two hours. A clustering time of eight hours could achieve intruded chloride masses in the same order of magnitude with clustering by having a minimum of three vessels in the lock chamber, however at the expense of significantly lower maximum vessel delays.

Figure 6 further explores the impact of maximum waiting time-based clustering with and without additional measures to reduce door open times. It presents two trade-off curves between the normalized relative average vessel delay and predicted chloride mass performances. The curves show that the longer the maximum clustering time, the more the reduction in saltwater intrusion mass and the more vessel delays increase, and vice versa. Due to the curve's parabolic shape, clustering is most effective in reducing saltwater intrusion at short-to-medium clustering times, while long clustering times excessively increase vessel delays at little extra saltwater intrusion reduction.

Figure 6

Trade-off curves for clustering based on a target maximum waiting time, without and with reducing the door open times.



Combining clustering with additional measures to reduce the door open time can both reduce saltwater intrusion mass and vessel delay. The effectiveness of this additional measure deteriorates with longer clustering times, as more vessels have to sail in and out of the lock in between lock operations, leading to almost full lock exchanges.

The trade-off curves can be read as such that an optimum clustering time magnitude is found by maximizing the area below the graphs. Hence, if vessel delays and saltwater intrusion mass would have equal stakeholder value, an optimum clustering time of roughly 7 hours can be derived, decreasing to roughly 6 hours for clustering without door open time reduction. In addition, Figure 6 shows that the performance of the measure of limiting lock operation hours is predicted to be sub-optimal, underperforming clustering.

5 Discussion

5.1 Significance of the results

Given Table 1 and Figure 6, the presented method provides valuable insights into the impact of operational countermeasures at locks. It can be used at both operational and tactical levels to optimise short-to-medium-term drought intervention plans and successfully execute them, allowing for flexible and adaptive management. Moreover, the method can be used strategically to integrally optimize lock designs, given long-term expected vessel traffic. These method's functionalities offer substantial advantages over other state-of-the-art methods, as listed in the introduction.

5.2 Enhancing the Port of Amsterdam case study

Despite the success of this study, further enhancements can be considered that improve the interpretability of the results and the model's predictive reliability and applicability. First, a more thorough hindcast study and validation of the vessel traffic behaviour and lock hydrodynamics during the 2022 drought should be performed to enhance confidence in the model's predictions regarding the actual effectiveness of countermeasures to reduce saltwater intrusion mass and their impact on vessel delays. Such a study requires hydrodynamic and vessel data of this period to serve as boundary conditions for the model. Second, further research should include the feasibility of clustering and door-open reduction in practice. Third, the water transport dependency between the lock complex of IJmuiden and the Port of Amsterdam should be further investigated, as vessel delays at the locks may lead to cascading waiting times at the port (Bakker et al., 2024). At last, the estimated water exchange fluxes should be implemented in a numerical model to predict the far-field impacts on freshwater users rather than only the near-field source terms. The latter two recommendations allow for a more intuitive trade-off curve between water transport and freshwater availability performance, as in Bakker et al. (in review), which can be better valued by the actual stakeholders, leading to a more accurate optimum.

5.3 Further method improvements

The presented method has to be further improved to facilitate the above study improvements. First, the underlying code of the vessel traffic model should be further tested to exclude modelling errors. Second, other applications are required to test the model's general applicability and to discover further needed improvements to the model. For example, a Panama case study would require the addition of water-saving basins in the levelling time calculation and hydrodynamic lock exchange model. For the case of the Port of Amsterdam, the deployability of the method as a real-time operational tool may become desirable. The open-source OpenTNSim library allows for further development.

6 Conclusions

This paper presented a novel method that simultaneously quantifies vessel lock passage delays and fresh and saline water exchange fluxes through locks. The method successfully assessed the effectiveness of operational countermeasures (i.e., limiting lock operation times, door open times, and demand-based vessel clustering based on lock chamber occupancy and a target maximum waiting time) in limiting saltwater intrusion, while assessing the subsequent additional vessel delays. For the Port of Amsterdam case, clustering based on a target maximum waiting time proved to be significantly more effective. By varying this clustering time, the method established a preliminary trade-off curve between the performance of water transport and freshwater availability based on which an optimum could be derived. Although further research is required to test other countermeasures and study other cases, the presented method already proved highly capable of comparing and selecting the most resilient lock operation strategies.

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