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Tool to evaluate countermeasures at locks to limit freshwater losses and saltwater intrusion while minimizing waiting times for shipping

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Climate change puts stress on the efficient operation of lock complexes. During more frequent and more severe periods of drought, freshwater losses and saltwater intrusion fluxes through lock operations have to be kept to a minimum to guarantee sufficient freshwater availability. Reduction of the number of lock operations is a measure that is frequently applied. Such measures, while effective to limit saltwater intrusion, generally lead to delays and economic losses for the transport sector. Tools that simultaneously simulate lock operations and saltwater intrusion, appear not to be available in open literature. To contribute, this paper presents a method that is able to perform such analyses, combining a meso-scale logistical model with a semi-empirical hydrodynamic model of a lock. We demonstrate the applicability of the model through a theoretical experiment on the effectiveness of vessel clustering to reduce the number of lockages. Clustering indeed helps to limit saltwater intrusion, at the expense of a significant increase in vessel delay times. Although the model can still be refined, it already enables us to quantify the relationship between vessels' delay times and local saltwater intrusion fluxes. As such the presented method is an important step forward in the optimization of lock operation in periods of drought.

Keywords: saltwater intrusion, lock operations, simulation modelling, logistics, hydrodynamics

Introduction

In 2023, we experienced, once more, the vulnerability of our vital global, seaborne transport network to climate change. Panama suffered one of the most extreme droughts in its history, which led to extremely low water levels in Lake Gatún and Miraflores. To prevent the water levels from dropping further, which would lead to an even greater disruption of the global supply chains that rely on the Panama Canal shortcut, the number of daily lock operations had to be limited. This resulted in average waiting times for vessels of three weeks with queues reaching more than 150 vessels, leading to damages in the millions of dollars. Traffic disruptions around locks due to droughts were not limited to Panama; similar problems were experienced at the locks at IJmuiden, which forms the gateway to the Port of Amsterdam. Due to severe droughts in the Netherlands, saltwater intruded far inland, threatening the operability of various freshwater intake points along the Noordzeekanaal that are critical for agriculture. To limit this salt intrusion, a locking regime was installed which limited its operating hours from 6.00 AM to 6.00 PM and aimed to maximize clustering of vessels, using the smallest lock as possible. This measure, however, led to long waiting times for the seaborne traffic.

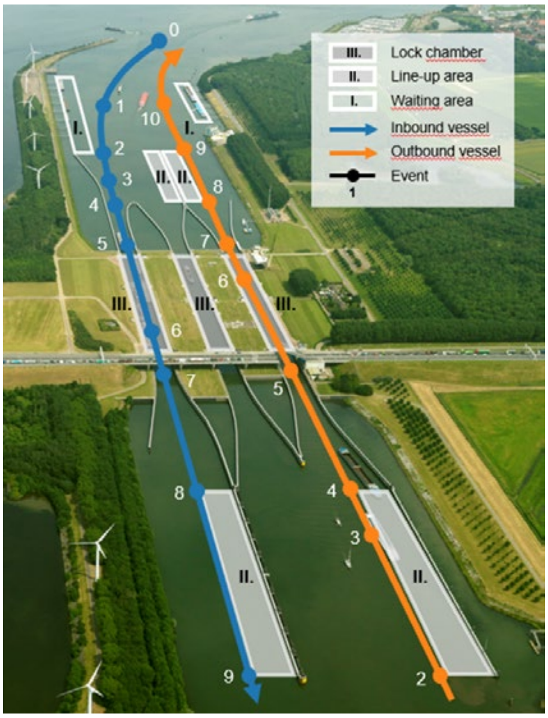

Figure 1 The Volkerak lock complex with highlighted infrastructural elements that are critical for modelling the vessel behaviour (logistics) during lock passages. Critical elements and events are numbered (image by F.P. Bakker & M. van Koningsveld, is licenced under CC BY-SA 4.0, the background image was retrieved from https://beeldbank.rws.nl, Rijkswaterstaat).

With increasing traffic and growing vessel sizes, deeper waterways, larger navigational locks and more lock operations are required. These developments are expected to worsen the problems, as most often locks are the largest source of saltwater intrusion, which is sometimes overlooked. This tendency is strengthened by ongoing climate change that leads to higher sea levels and longer and more frequent periods of drought.

Currently, like in the above examples, drastic emergency measures at locks seem to severely impact the performance of the vessels in the seaborne transport network, while other stakeholder functions seem to be affected less. For the example of the case of IJmuiden, the Dutch national drought plan states that preservation of agriculture and industry are prioritized over shipping. However, a long disruption of the seaborne traffic may eventually lead to equally severe adverse consequences for the society.

Various countermeasures can be taken at the lock to limit freshwater losses and saltwater intrusion fluxes. Infrastructural countermeasures are bubble and water screens, selective withdrawal of saltwater, and water saving basins. They do not or only minorly impact shipping. Additional operational measures that affect shipping are draft limitations, reduced number of lock operations, unfavourable lock operation strategies (e.g. vessel clustering), and flushing.

The question arises which (packages of) local countermeasures can be implemented to cost-effectively enhance freshwater availability without having detrimental effects on the performance of the seaborne traffic (i.e. delay times of vessels). Such trade-offs of different, system-scale stakeholder objectives are, however, not commonly included in lock designs and operational strategies, which tend to focus more on local aspects in and around the locks at shorter time scales. This complex decision-making namely requires a tool in which a local lock-scale model is coupled with a system-scale model, which simultaneously evaluate performance indicators of various users in sufficient detail.

To the authors' knowledge, such tools are not yet available in literature. Logistical models that estimate the efficiency of the seaborne transport network, as well as hydrodynamic models that estimate the hydrodynamics (i.e. water levels, currents, and fresh- and saltwater transport) exist in literature, both on lock- and system-scale. However, these models fail to couple lock logistics and hydrodynamics directly, which can lead to significant errors in the estimated fresh- and saltwater fluxes through the lock. For example, a different lock operation strategy as a measure against saltwater intrusion will lead to a different vessel behaviour around the lock and, consequently, to changes in the number of lock cycles and door open times, which on their turn lead to different water fluxes. This coupling between logistics and hydrodynamics is, therefore, highly needed.

This paper therefore presents a new tool that couples the vessel behaviour (logistics) and hydrodynamics in and around locks. Thus, the tool will be able to predict the water fluxes through the lock as a direct consequence of the interaction between the vessel traffic with the lock. It can furthermore explicitly estimate the waiting times of vessels, which are a good measure for the efficiency of the transport network. An application of the model on the joint effect of clustering on saltwater intrusion and vessel delays will be presented.

Materials and methods

The tool consists of a combination of a mesoscopic logistical and a semi-empircal hydrodynamic model of the lock. Based on the system-scale approach of OpenTNSim [1], the simulation efficiency of the Zeesluisformulering [4], and the similarity between the discretization of the two models, it was decided to combine these models into one tool. The two models are briefly discussed in this chapter. An example application of the tool is discussed in the next chapter.

Lock logistics

OpenTNSim is an open-source, discrete-event model, developed by Delft University of Technology that is able to simulate traffic in port and waterways systems. The Python-based model uses a graph of nodes and edges over which vessels sail and interact with schematized infrastructure and detailed hydrodynamics. In this way, mesoscopic interactions can be modelled. Comprehensive priority and accessibility policies can be included. Thus, vessel behaviour can be resolved based on the limitations of the network. This results in performance indicators of vessels and infrastructure on efficiency, capacity, sustainability and safety [3].

A lock module has been included in the model, which is able to simulate vessel behaviour around locks. It spatially discretises locks in five components (see Figure 1): an outer and inner waiting area (I) in each harbour which are used by vessels to wait if the lock is unavailable, a line-up area (II) after the waiting area to prepare vessels to enter the lock chamber, and the lock chamber (III) in which the vessels are locked. The model discretises a lock passage in time in eleven phases (see Figure 1): arrival of vessel within a certain time range from the lock (0), sailing towards the waiting area (0→1), waiting in the waiting area (if required, 1), sailing towards the start of the line-up area (1→2), positioning in the line-up area (2→3), waiting in the line-up area (if required, 3), sailing to the end of the line-up area (3→4), sailing to the first encountered lock doors (4→5), positioning in the lock chamber (5→6), waiting for other vessels (if required, 6), levelling of the lock chamber (6), sailing to the second encountered lock doors (6→7), sailing to the opposite line-up area end (7→8), sailing to the opposite line-up area start (8→9), and sailing to the opposite waiting area (9→10).

The lock module uses the concepts of resources (finite integer number of available spots, such as a jetty) and containers (finite, continuous amount, such as a quay length) to schematize the availability of lock doors (one vessel at a time leaving/entering a sluice) and available length of the lock chamber (finite number of vessels that can enter a lock, depending on their total length). By carefully keeping track of the vessels' requests for the lock doors (to enter/leave the lock), and the lock length (if the lock is full or available for the next vessel), lock operations can be modelled and the corresponding vessel behaviour can be resolved. Hence, the waiting times of vessels can be estimated, amongst many other performance indicators of vessels and the lock. Prioritization rules, operational hours, and clustering regulations can be included in the model.

Lock hydrodynamics

The 'Zeesluisformulering', developed by Deltares, is a semi-empirical model that algorithmically describes how saltwater is exchanged by lock operations, and helps to quantify the impact of mitigating measures. Although the formulation is set-up in a very simplified manner with many assumptions which, in reality, are frequently violated, it is able to rapidly estimate the order of magnitude of saltwater intrusion. Since traffic is not directly included in the Zeesluisformulering, but rather aggregated by averaging of operational parameters and by using calibration factors based on observations, it was added to OpenTNSim. The Zeesluisformulering discretises the lock operation in four phases: two door-open phases to both harbours, separated by (two) levelling phases. For each phase, it calculates the water discharges in and out of the lock, including their salinities, which are assumed to be homogeneous in the lock and both harbours. There is a clear separation between events during a door-open phase. First, the preceding vessel(s), if any, will sail out of the lock. Then, the exchange flow between the fresh- and saltwater will start (starting when the doors are half opened). Last, the exchange flow will stop (when the doors are half closed) and the next vessel(s), if any, will sail into the lock. Each event results into fresh- and/or saltwater fluxes between the lock and the harbour. The speed of the exchange current is assumed to be constant and dependent on the water depth and salinity difference between the lock and the harbour. Additional flushing of freshwater can be applied during the door-open phase, which results in a reduction factor for the exchange volume of saltwater, as well as a freshwater flux to the lock. Moreover, additional reduction factors to the exchange are used if bubble screens are used. In principle, the lock chamber will be fully exchanged if the current has advected to the closed lock door and fully reflected to the opened lock door (a distance of two times the lock length). The fraction of exchanged water follows a relation according to the hyperbolic tangent, roughly equally the natural behaviour of the exchange. During the levelling phase, either fresh- or saltwater is used, depending on the water levels of the opposing harbours. More details on the formulation can be found in the reports of Deltares [4].

Combining the models

The two models are fully complementary as they explicitly model the same locking phases. OpenTNSim, in which the ambient hydro-dynamics (i.e. water levels and salt concentrations) are included, is able to provide the necessary information to the Zeesluis-formulering for each lock operation separately. This includes the exact door open times, the total volume of vessels sailing in/out of the lock, the water depths, the salt concentrations, and the levelling volumes. The levelling volumes and times can be based on discharge curves of various filling and emptying systems and the governing water levels.

Experiment

In this paper, we will run a simple case study to show the applicability of the model. We consider

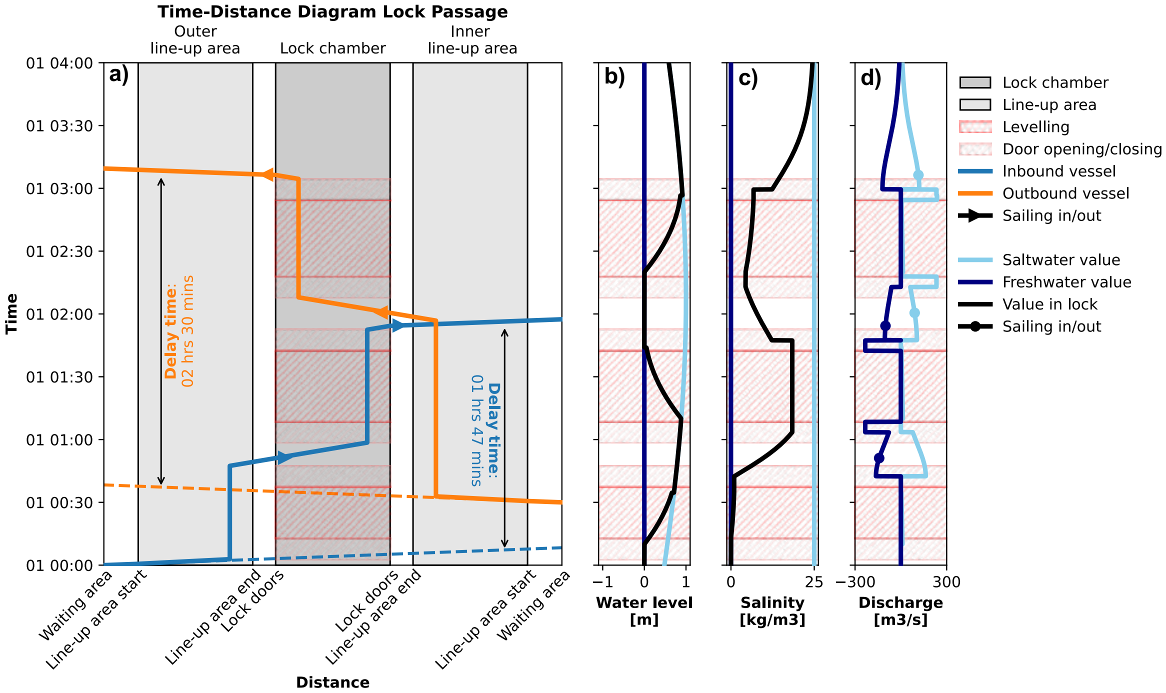

Figure 2 Simulation result of a two way lock passage: a time-distance diagram of the in- and outbound vessel (a), the water levels (b) and salinity concentrations (c) of both harbours and the lock chambers, and the fresh- and saltwater (brackish) fluxes through the lock doors (image by F.P. Bakker & M. van Koningsveld, is licenced under CC BY-SA 4.0).

a lock complex for sea-going vessels with a single lock. The lock has a length of 500 m, a width of 40 m, and a depth of 10.5 m. The outer harbour (seaside) has a sinusoidal tidal wave with an amplitude of 1 m and a salt concentration of 25 kg/m^3. The inner harbour has a constant water level of 0 m without any salinity. We generate vessels with lengths of 200 m, beams of 35 m, and draughts of 10 m, according to a uniform arrival distribution with an average of two vessels per hour (intensity/capacity = 0.25), on both sides of the lock. To show the effect of clustering of vessels on saltwater intrusion and delay times of vessels, we will run various clustering rules that prescribe maximum additional waiting times for vessels to be locked. A maximum of two vessels can be locked simultaneously. If a second vessel is not expected within the prescribed waiting time, the lock will be levelled with only one vessel. We run the model for two weeks to resemble a drought.

Results

A typical lock passage, as predicted by the tool, is presented in Figure 2. In Figure 2a, we see an inbound vessel arriving and slowing down in order to enter the lock chamber. While the vessel is being berthed, the door closes. When both processes have been finished, the lock is being levelled. In the meantime, an outbound vessel arrives at the lock, and waits in the line-up area to enter the lock, after the current lock operation has been finished. After the lock door has been opened, the inbound vessel has de-berthed and passed the outbound vessel, the latter vessel can enter the lock chamber and the process can be repeated. The door opening, levelling, door closing, and door open times are clearly marked.

In Figure 2b, we observe the water levels at both harbours and in the lock chamber. The lock chamber clearly follows the water level of the harbour of the opened door. Furthermore, we see that the levelling time is clearly dependent on the water level difference. The salinity of the lock in Figure 2c varies in between the salt concentrations of the harbours. During the time that the door is opened at the seaside the salinity of the lock chamber gradually increases. We can moreover observe the effect of the vessels that sail out of the lock. The vessel's volume will be replaced with salt- or freshwater, increasing or decreasing the salinity of the lock chamber. Also the levelling with saltwater (when the water level at sea is greater than the inner harbour), increases this salinity. The corresponding

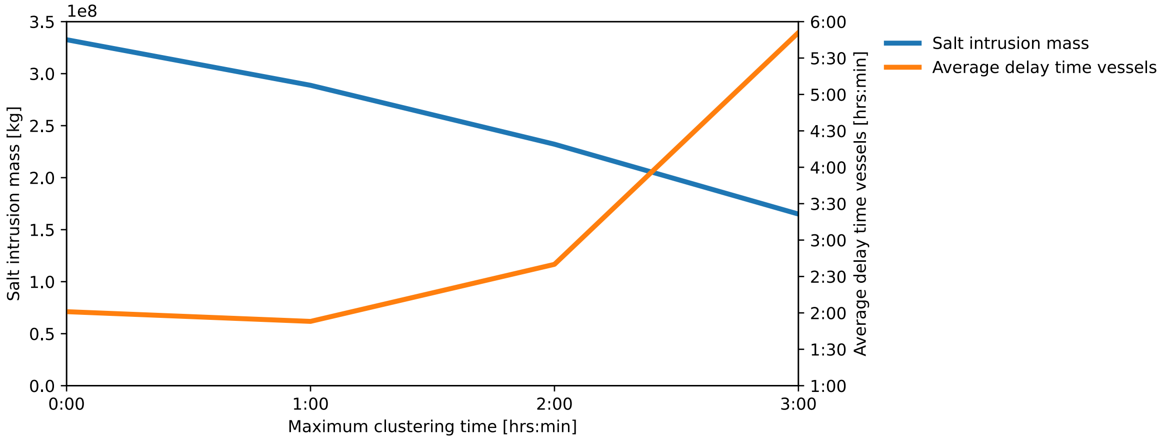

Figure 3 Trade-off curve between the salt intrusion mass and the average delay times of vessels in hours, as a function of the maximum clustering time in hours (image by F.P. Bakker & M. van Koningsveld, is licenced under CC BY-SA 4.0).

exchange discharges are presented in Figure 2d. We can clearly see the assumption of the separate, individual events of the Zeesluis-formulering: first the volume of the vessels sailing out of the lock chamber is replaced, then the exchange current will occur, gradually slowing down due to the decreasing difference in salinity between the lock chamber and the harbour, and the volume of water that is replaced by the vessel(s) sailing in. The latter two discharges cause the saltwater intrusion flux at the inner harbour. Note in Figure 2, that the moments of sailing in/out in the Zeesluisformulering are not aligned with the logistical model.

Clustering: delays vs freshwater availability

In Figure 3, the trade-off curve between the salt intrusion mass and the average delay time of vessels as a function of the maximum clustering time is presented. The maximum clustering time is the time that a vessel will wait for another vessel that fits in the lockage, if this vessel is expected to arrive to the lock within this time. We clearly see the saltwater intrusion with increasing maximum clustering time. This is because the clustering results in less lock operations: 316 lockages (without clustering) to 235, 208, and 196 operations (one, two, and three hours of maximum clustering time, respectively). In the graph, about every 0.5*10^8 kg of intruded salt mass equals 10 lock chambers filled with sea water with a salinity of 25 kg/m^3, fully exchanged to the inner harbour. We furthermore observe that, as a consequence of the decrease in lock operations, the delay times of vessel will increase exponentially with increasing clustering times. This behaviour is caused by cascading effects; during the additional waiting time of vessels in the lock chamber, vessels on the other side of the lock chamber will also wait, increasing their lock passage time as well. Initially, we see a small drop in average delay time of vessels if the maximum clustering is limited by an hour.

The model furthermore predicted that increasing the maximum clustering time would not lead to different results compared to the clustering time of 3:00 hours. Most saltwater, around 90%, is intruded during the exchange flow, when the lock door is open. Most of the rest of the saltwater mass flux is caused by the vessels sailing in from the inner harbour side. Emptying of the lock to the inner harbour side had only a marginal effect on the saltwater intrusion. Moreover, the relative increase in salinity in the lock chamber during filling with saltwater (when the sea level is higher than the inner water level), which promotes saltwater intrusion, was negligible. The most efficient way to reduce saltwater intrusion in this example is to limit the door open times. This was not applied to the model, but could have resulted in a significant reduction to the values presented in Figure 3.

Discussion

Based on a simple theoretical experiment, we saw how clustering can be an effective measure to limit saltwater intrusion. The question arises whether the same results will be found for a real case study. The logistical part of the model makes various simplifications and assumptions. In this application presented in this work, we assumed an uniform interarrival distribution of a homogeneous fleet with constant vessel parameters (e.g., the sailing-in and sailing-out speeds of vessels, priority), and a lock complex with a single lock chamber. In reality, the lock complexes can exist of multiple locks with different interarrival distributions and vessel properties. OpenTNSim is capable to include this. Successful calibration of the delay times for vessels that have to pass locks with multiple lock chambers has been performed using AIS data [2]. Operational data, such as the Object Data Services (ODS) data of Rijkswaterstaat, can help to calibrate the door open and levelling times. More features to the model are yet to be added, such as explicit priority rules and vessel-dependent sailing speeds. The open-source nature of the model helps to speed up this development.

The hydrodynamic part of the model also has its major simplifications. Although more details and information on the assumptions on the Zeesluis-formulering can be found in the reports of Deltares [4], we want to stress two crucial simplifications. First, the salt concentrations are assumed to be uniform over the depth, while the salinity is also uniformly distributed over the lock chamber. In reality, there is a more layered salt concentration structure with complex mixing processes that affects the total exchanged salt mass. Second, the different exchange flux mechanisms are decomposed and are modelled in sequential. For example, the sailing-in and sailing-out of vessels, in reality, occur simultaneously with the exchange current between the fresh- and saltwater. The total effect of these assumptions should be investigated more in-depth using measurements of salt concentrations around locks. Research is currently on-going on this topic (as part of the SALTISolutions project).

This research was limited to the application of the tool to model the near-field salt intrusion fluxes only and delay times of vessels. The next step is to translate these fluxes into the system-scale stakeholder objectives (i.e. freshwater availability windows based on the salt concentrations further inland). The obtained time-series of discharge and salinity, including the specific door open and levelling times, are however well-suitable to be included as a boundary conditions in a numerical model. Such hydrodynamic models are able to produce these results and can be coupled online to the tool, meaning that the actual predicted salt concentrations at the outer and inner harbour can be used in the prediction of the discharges and salt fluxes in the Zeelsluisformulering. This is critical as more lock operations will result in a more brackish inner harbour. The application of the tool did not yet include this. In addition to the saltwater intrusion, the effects for the vessels should be modelled in system-scale logistical models as more cascading waiting times due to interaction with port and waterway capacity can be expected.

Conclusion

This paper successfully developed a lock simulation tool that is able to jointly predict traffic related vessel delay times, and saltwater intrusion fluxes and freshwater losses. The tool is based on the logistical model of OpenTNSim and the hydrodynamic formulation of the Zeesluisformulering. It was applied to a theoretical experiment to show the effectiveness of clustering of vessels in the same lockage to limit the saltwater intrusion flux. This mass flux was indeed reduced with increasing maximum clustering time, as accordingly the number of lock operations were reduced. As a consequence, however, the average delay times of vessels passing a lock increased exponentially with increasing maximum clustering time. More open-source development to OpenTNSim and the Zeesluisformulering, including calibration and application to real-world data and case studies, will result in an even stronger tool.

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Bibliography

[1] Baart F., Jiang M., Bakker F.P., Van Gijn M., Frijlink T., and Van Koningsveld M. (2022). OpenTNSim, https://doi.org/10.5281/zenodo.7053274

[2] Kuiper F. (2019). Understanding the locking process using vessel tracking data. Master’s thesis. Delft University of Technology, Delft, The Netherlands.

[3] Van Koningsveld M., Verheij H., Taneja P., and De Vriend H.J. (2021). Ports and Waterways -Navigating the Changing World. Delft University of Technology, Hydraulic engineering, Ports and Waterways, Delft, The Netherlands: TU Delft Open. https://doi.org/10.5074/T.2021.004.

[4] Weiler O., O’Mahoney T. and Burgers R. (2019). Zoutindringing schut- en spuisluizen, Opzet en verkenning Zeesluisformulering. Kennisprogramma Natte Kunstwerken Kennisplan 2018.