Paper 137 - Simulating Lock Operations in the Generic Salt Intrusion Model WANDA-Locks

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ABSTRACT: Salt intrusion resulting from lockages is an important aspect to be studied in the design process of shipping locks situated on the interface of salt and fresh water. To this end, Deltares has developed the generic salt intrusion model WANDA-Locks. This paper presents the development of an additional method within WANDA-Locks, allowing more accurate calculations of salt intrusion by simulating the actions of the lock operator more explicitly and allowing the inclusion of the stochastic nature of traffic demand. This method has been applied in a study considering the application of salt intrusion mitigating measures at the Krammer locks in the Netherlands.

1 INTRODUCTION

Locking ships at the interface of salt and fresh water bodies causes a two-way transport of water. The inward transport of salt water affects the salinity and quality of inland water systems. The relevance of this phenomenon is given by the need for fresh water for agriculture and drinking water as well as by the inland ecology.

As seaborne transport developments demand bigger as well as higher capacity shipping locks, it has become increasingly important to quantify salt intrusion through locks. The effect of mitigating measures should equally be quantifiable.

Deltares has developed the generic salt intrusion model WANDA-Locks to assist in these kind of predictions. WANDA-Locks models the various processes of salt transport through a lock and accounts for the impact of mitigating measures.

2 SALT INTRUSION THROUGH LOCKS AND MITIGATING MEASURES

Two types of processes contribute to salt intrusion through locks. The water transported through the lock heads carries salt. This is apparent during the levelling process, in which the lock chamber's water level is changed, for example by the flow of water through gate openings or culverts. This process is called advective or barotropic transport.

Note that for shipping locks bordering on the sea, the water level at the seaward side changes by tide. The water level difference is positive and negative alternately and the method of levelling changes accordingly. This naturally should be considered in the hydraulic description of the levelling process.

The other process of salt intrusion is a result of the density difference between both sides of the lock and starts when the door opens. During levelling, the water level difference has reached an equilibrium value, i.e. the integral pressure is equal on either side of the lock head. No net transport of water occurs. However, the vertical pressure profile is steeper at the salt side of the lock head, see Figure 1. The pressure difference in the vertical induces an exchange of saline and fresh water. This baroclinic transport is aptly known as lock exchange.

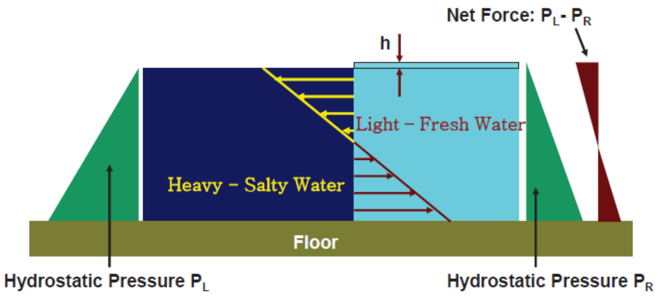

Figure 1: Vertical pressure profile inducing baroclinic transport.

To reduce salt intrusion through locks, various mitigating measures exist. We differentiate operational and technical measures. Examples of technical measures are a bubble screen, a water screen and a flushing discharge or a combination of these measures, see Figure 2. These measures are discussed in Keetels et al. (2011) and Uittenbogaard et al. (2015).

The operational measures vary for example from no locking at high tides to closing doors quickly after the shipping passage.

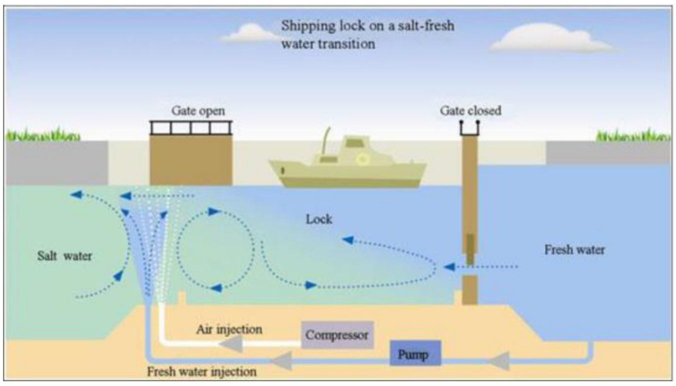

Figure 2: Salt intrusion mitigating measures in a shipping lock on a salt-fresh water transition. From Keetels et al. (2011).

3 CALCULATING SALT INTRUSION WITH WANDA-LOCKS

WANDA (see reference) is a one-dimensional computational program developed by Deltares. The origin of the program is found in calculations on flow through pipeline systems. Various hydraulic components, such as pumps and valves, are included in its library. In the graphical user interface, the components are visually depicted by icons that can be connected, see Figure 3.

The WANDA-Locks library (see reference) allows the determination of the salt mass in the reservoirs. The formulae used are based on Uittenbogaard (2010).

The lock chamber is a component included in the WANDA-Locks component library, see Figure 4. Approach harbours can be modelled using the boundary condition for water level and salinity. The lock chamber and approach harbour are connected via valves that can comprise both the levelling system and the doors. Details of these components are given in Van Os (2015).

In case of advective flow the computation can be thought of as bookkeeping: the incoming discharge has a known salinity and can thus be taken as a load of salt being added to the reservoir.

In case of baroclinic flow the hydrodynamic formulae simulate the density current using a fourth component in the WANDA-Locks library. These formulae are extended to include the impact of mitigating measures such as water and/or bubble screens by defining a so-called salt transmission factor, see Weiler et al. (2015).

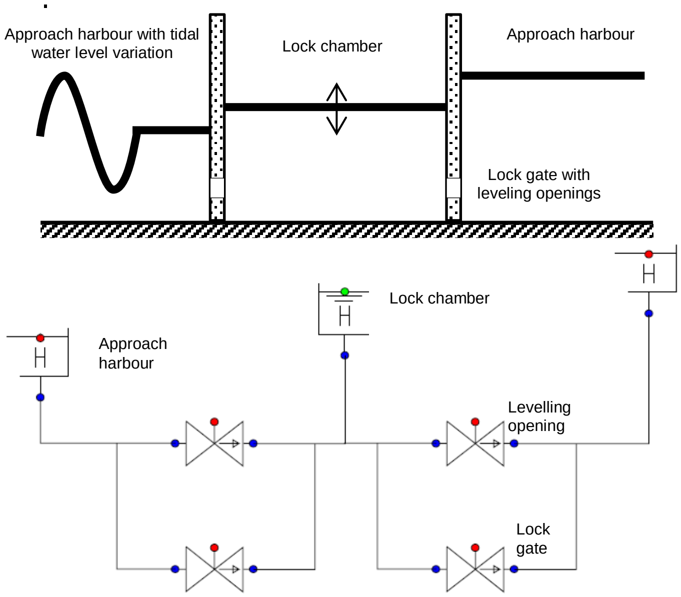

Figure 3: An illustration of a simple shipping lock with lock gate openings (top) and its representation using WANDA components (bottom).

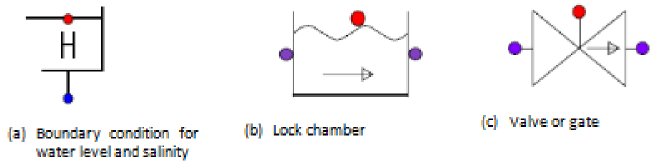

Figure 4: Three components defined in WANDA-Locks.

By using the modular schematization from WANDA, the method of determining the salt intrusion using WANDA-Locks has been made explicit and generic. This allows the simulation of different lock geometries.

WANDA-Locks has been validated using measurements at the Stevin Locks (De Groot (2015)) and the Krammer Locks (Weiler et al. (2015)).

4 INCLUDING A PREDESCRIBED LOCKAGE SEQUENCE BY USING CONTROL COMPONENTS

The salt intrusion through a lock during a day of lockages is determined by the number of lockages and the salt intrusion for each of these lockages.

The number of lockages depends on the traffic passing the lock, which has a highly stochastic nature, and on how the lockkeeper handles this traffic. The lock operator decides, for example, how many ships are dealt with in one lockage.

The amount of salt intrusion per lockage depends on the salinity difference between the lock chamber and the approach harbour, as well as the water level and the duration of the doors being open.

A locking sequence can be defined beforehand. This sequence may be an averaged pattern, in which lockages are spread evenly per day and mean values of door open times are used. More realistic sequences consider the distribution of lockages over time (e.g. heavier traffic during in the daytime, lower traffic on Sundays).

Essentially, the locking cycle follows from a sequential control of the hydraulic components: levelling is simulated simply by opening the valves. Basic control operators available in WANDA can be used to manipulate hydraulic components according to a predefined schedule. The result of such a computation is shown in Figure 5.

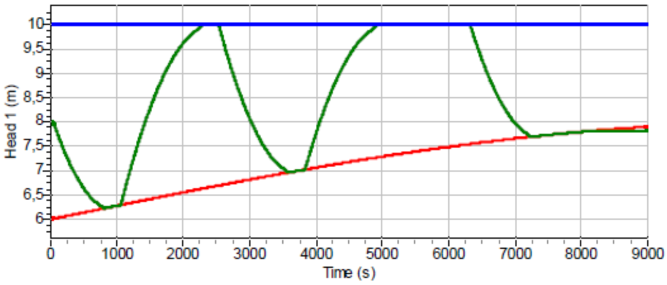

Figure 5: The timeseries of water levels in the approach harbours (blue, red) and lock chamber (green), resulting from a simulation with a predefined schedule of valve openings. The locking sequence can be recognized in the raising and lowering of the lock chamber's water level.

A drawback of this method is that all actions of the hydraulic components must be predefined. Hydraulic computations must be made beforehand or iteratively to establish the moment at which components must be manipulated. For example, the moment the door may open depends on the levelling process that is simulated in WANDA.

5 DEVELOPED METHOD FOR INCLUDING LOCKAGES MORE ACCURATELY

A more realistic prediction of salt intrusion is not based on predefined time series of opening and closing times of valves and doors. Instead, the hydraulic components are set according to locking procedures and therefore are triggered in response to the water level in the lock. The locking procedure is commenced by requests, which are set at times generated randomly or according to a 3rd party simulation. The procedure explicitly incorporates the considerations of the lockkeeper.

5.1 *Subsequent steps in method*

In order to simulate the actions of the lock operator correctly we developed a generic method. The method is contained in a single new WANDA component called LOS (abbreviation for lock operation simulator), which executes three subsequent steps.

1. The requests (arriving ships) are queued or treated.
2. For the handling of the request, which is ultimately the lockage of a ship, a series of phases has to be run through.
3. Each phase is related to certain components of the lock (e.g. the door or leveling system). To complete the phase, the hydraulic components of the components are controlled.

5.2 *Request definition*

A request is defined by five parameters:

1. A moment in time at which sailing into the lock commences, assuming the lock is set accordingly.
2. The duration of the vessel(s) sailing into the lock.
3. The duration of the vessel(s) sailing out of the lock.
4. The total displacement of the vessel(s).
5. The vessel's direction.

An example of an input sequence is shown in Table 1.

Table 1: Example of an input sequence.

Request time	Direction	Displacement	Duration sailing inward	Duration sailing outward
20 s	1 (L → R)	4800 m^3	120 s	120 s
620 s	-1 (R → L)	6000 m^3	300 s	325 s

Note that a request may include multiple vessels. In fact, the routine does not distinguish vessels.

5.3 *Request handling*

Each request handling consists of the following phases.

- Sailing into the lock
- Closing the door
- Levelling of the lock chamber
- Opening the door
- Sailing out of the lock

Depending of the direction of the lockage (seaward or inland) and the status of the lock (water level and door opening), some phases have to be gone through twice.

For example, a request may need two successive levelling actions. If the lock's water level is not at the water level of the approach harbour at which the levelling request has been made, picking up the vessel(s) requires an additional levelling action first. The levelling action with the vessels in the lock, to get those to the opposite side, is the obvious second levelling action.

5.4 *Lockkeeper variables*

The characteristics of the phases are determined by the lock operator.

In reality, a lockkeeper does not commence the locking cycle only after a vessel has reported ready for lockage at the lock entry. Rather, the lockage is anticipated either by a call made by the vessel prior to arrival or after the vessel has been noticed visually by the lockkeeper. If required the lock is levelled empty towards the side at which the vessel is approaching.

Likewise, the door is opened when the vessel approaches the approach harbour to facilitate sailing into the lock without delay.

Two variables are defined to account for these considerations.

- T_PREVLEVEL
  The anticipation by the lockkeeper with respect to the locking process. This means that the lockkeeper will commence the locking process this length of time prior to the request.
- T_PREVDOOR
  The lockkeeper will open the door this length of time before the ship will be able to sail into the lock.

The doors can be opened when levelling has completed. Usually, the doors may already be opened before the water level has been decreased to zero. The remaining water level difference at which the door may be opened is given by the following parameter.

- DH_OPEN
  Remaining water level difference at which the door may be opened.

When a locking cycle has been completed and the vessel(s) have sailed out of the lock, the lockkeeper checks for approaching traffic and keeps the lock gates open if approaching vessels are nearby.

- T_IDLE
  The duration of time before the lockkeeper considers the next action to take.
- T_OPENMAX
  Maximum duration of waiting for the next ship with opened doors. If a new request is within this time, the door will remain open.
  Otherwise, the lockkeeper will shut the door.

To illustrate the meaning of these variables, consider the following example; see Figure 6a.

After completion of a lockage, vessels have sailed out (orange vessel). The door remains open (indicated by green patch). The next request for lockage (yellow line) will only be made some time later – the request is not yet known by the lockkeeper, i.e. he cannot act on it yet.

The variable T_IDLE (purple arrow) determines the moment at which the lockkeeper considers the next step. When he allows a long duration of waiting for the next ship with open doors (blue arrow), given by T_OPENMAX, the door will remain open until the next request.

During the next locking cycle vessels will sail into the lock (yellow vessel), the lock door will close (indicated by red area), and the lock chamber will level to the other approach harbour's water level.

If T_OPENMAX is chosen smaller, see Figure 6b, the lockkeeper will close the door before the next request. The door will then be opened just before the vessels are ready to sail into the lock, for which the period T_PREVDOOR is given.

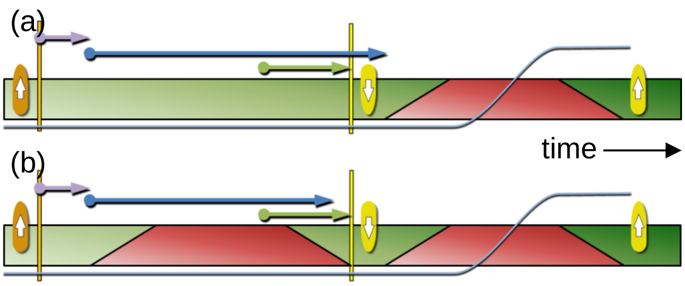

Figure 6: Closing the door after the sailing out following a lockage, before the sailing into the lock for the subsequent lockage.

Note that during that time of the doors being open, the lock exchange continues – contributing to the intrusion of salt through the lock. In case of shipping locks on the interface between salt and fresh water the duration with which the door remain opened awaiting approaching traffic does thus not only affect the traffic capacity of the lock but the amount of salt intrusion as well. This will be shown by an example in Section 6.

5.5 *Determination of successive phases*

The transition of successive phases is determined by the state of the hydraulic components. The levelling phase, for example, is finished when a defined remaining water level difference has been reached; only then can the phase in which the doors are opened be started. Waiting times are user-defined parameters which are chosen in accordance with the lockkeeper's practice.

Within each phase the state of different hydraulic WANDA components are controlled. After the phase of opening the doors has started, for example, the valve component in the WANDA scheme schematizing this door is set to an opened state. The motion lasting a number of time steps is imposed using a tabular description.

The setting of the components can be dependent on the phase of the tide, as follows from the levelling process of the lock.

5.6 *Generic functional diagram*

In order to make the method generically applicable for all possible situations we designed a generic functional diagram, shown in Figure 7.

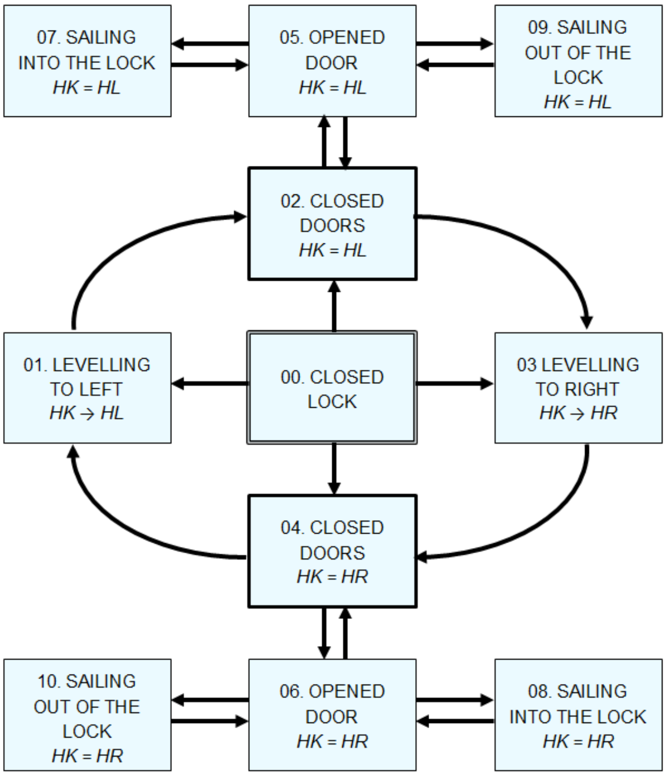

Figure 7: The generic functional diagram on which the locking procedure is based. The arrows between phases denote the conditions to be met before a transition to the next phase.

To illustrate the use of this diagram, consider one request for a lockage going from left to right, see Figure 8. The simulation starts in phase "00", with no vessel being present in the lock chamber. When the lock chamber has a water level not equal to the left hand side approach harbour, levelling to this level is the first step. To this end, phase 01 is realized and according to the tide the hydraulic components are set, e.g. valves are opened.

When the water level difference has reached a required value, phase 02 is entered. The lock is idle, both doors remain closed. If applicable a flushing discharge is realized by setting the hydraulic components appropriately.

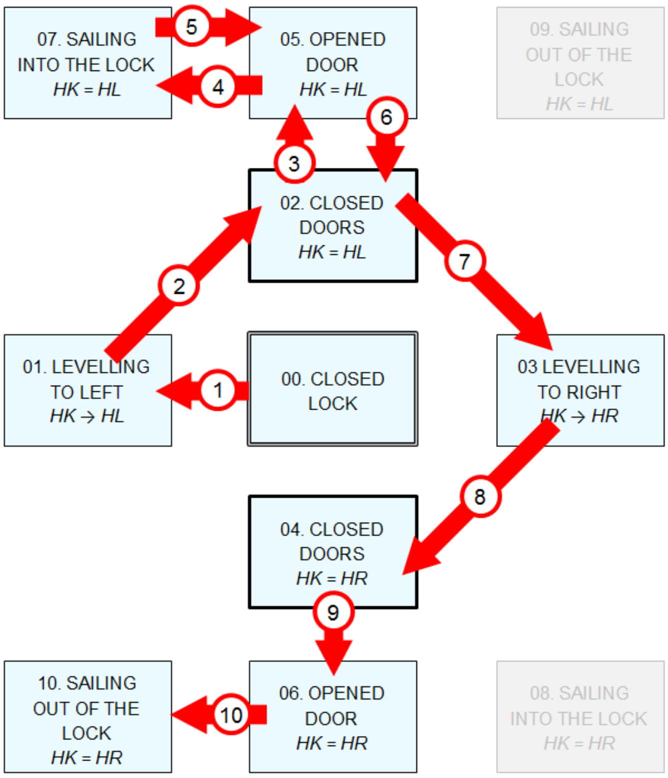

Figure 8: The sequence of actions in order to realize a lockage from left to right, as described in Section 5.6.

Phase 05 is entered to open the doors. Subsequently, the operation goes to phase 07 and remains there for the duration of vessels sailing into the lock, a parameter given as property of the lockage request.

Via phase 05 the operation returns to phase 02 in which the doors are set to close. Again this takes several time steps, for which the motion of the door is set in a tabular component.

After levelling to the right hand side water level (phase 03), the operation jumps through phase 04 to phase 06, as the conditions to open the doors on the right hand side lock head are met. Finally the vessels sail out of the lock with a duration set as lockage parameter.

The lock operation then remains in phase 10, ready to receive vessels travelling in opposite direction or to close when the next request is again to transfer vessels from the left hand to the right hand side. If no request follows, the lockkeeper determines when the door is shut as discussed earlier.

As can be seen, this single request requires ten steps to be completed. With the developed method, however, these follow automatically based on very basic input.

6 METHOD APPLICATION AND APPLICATION RESULTS

WANDA-Locks, including the LOS component, has been applied in a recent study concerning the Krammer locks complex, in the South of Holland. This study included a pilot on two recreational locks that has been described in Weiler et al. (2015), to which reference is made for the project's background.

The study considers the application of salt intrusion mitigating measures at the Krammer locks. These needed to reduce the salt intrusion to an allowable 20 kg/s (1700 tonnes per day) for the entire lock complex.

Both the present situation (i.e. 2012) and various future scenarios (2025, 2045 and 2115) were considered. Furthermore, the situation with the two existing commercial locks was considered as well as the hypothetical situation with three commercial locks.

A realistic forecast of the yearlong sequences of requests was provided with the simulation program SIVAK (De Gans (2010)). This program schedules the traffic taking into account the occupancy level of the lock, but lacks a detailed hydraulic computation or calculation of salt intrusion.

To address the impact of the lock operator's considerations, the following variations have been simulated.

1. No limitation on the duration of the doors being opened.
2. Closing the doors after the vessels have sailed out. The lockkeeper closes the door in case the time between the end of sailing out and the start of sailing in of the successive lockage is over 15 minutes. This seems a realistic value as this means that the doors should be closed after a lockage if the next ship has not (by far) reached the approach harbour.

The simulations are based on an identical traffic sequence, which is the scenario used for the 2012 simulations. This simulation comprises approximately 12,800 locking cycles for two lock chambers combined (i.e. approximately 18 lockages per day per lock).

When closing between lockages is performed (red bar in Figure 9) the number of door openings has increased by approximately 6,000. The doors are most likely to be closed during the originally longer moments of opened doors. These are now replaced by two periods of opened doors, which in total are shorter than the original single moment.

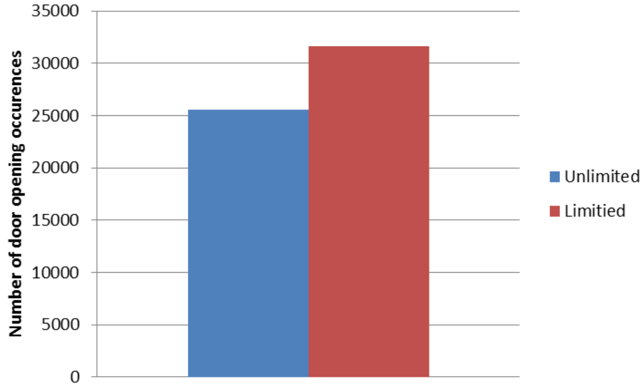

Figure 9: Number of occurrences of opened doors.

The distribution of the duration with which the door remains opened is shown in Figure 10. A significant effect of closing the door between lockages can be seen: only 4% of door openings now exceed 30 minutes, whereas in the unlimited case this duration was exceeded by 29% of occurrences. The average duration of door open time is reduced from 28.4 minutes to 11.8 minutes.

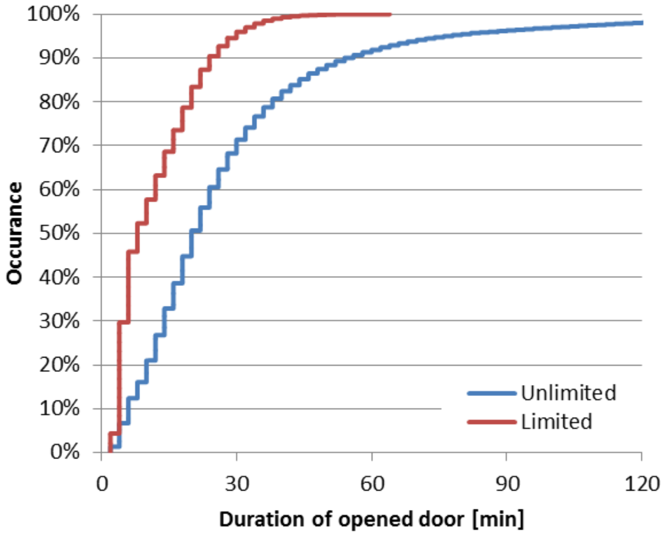

Figure 10: Distribution of the duration of opened doors.

Although the number of door openings has increased, the effect on the total duration of opened doors is favourable. In the unlimited case, doors were opened for 12,115 hours in total. This means, for both locks, that doors are opened 69% of the time. The limited maximum duration of door opening decreased the total duration of opened doors to 6,228 hours (36%).

The resulting salt intrusion was reduced with about 20 – 30 kg/s (1700 – 2600 tonnes per day) which is equal to or greater than the allowable salt intrusion of 20 kg/s.

7. CONCLUSIONS

The computational model WANDA-Locks, developed for the prediction of salt intrusion through shipping locks, includes a method to simulate the operations of a lock in a very generic way.

This method allows for the stochastic nature of traffic demands: lockages are distributed unevenly over the day and week. Taking this distribution into account increases the accuracy of salt intrusion predictions.

The manner in which traffic is handled is determined by the considerations made by the lockkeeper. These considerations are schematized in the developed method and adjustable using several variables.

The method has been applied during a study regarding salt intrusion mitigating measures on the Krammer locks, The Netherlands. In this application two different locking approaches are used: (1) allowing an unlimited duration of opened doors, (2) closing the door if the start of the successive lockage is only after 15 minutes or more.

The effect of closing the door between lockages is significant: the total duration of door opening has been decreased by 49%.

The rate of salt intrusion thus depends heavily on lock operation. The inclusion of these operations is therefore an added value of the WANDA-Locks library.

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WANDA
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