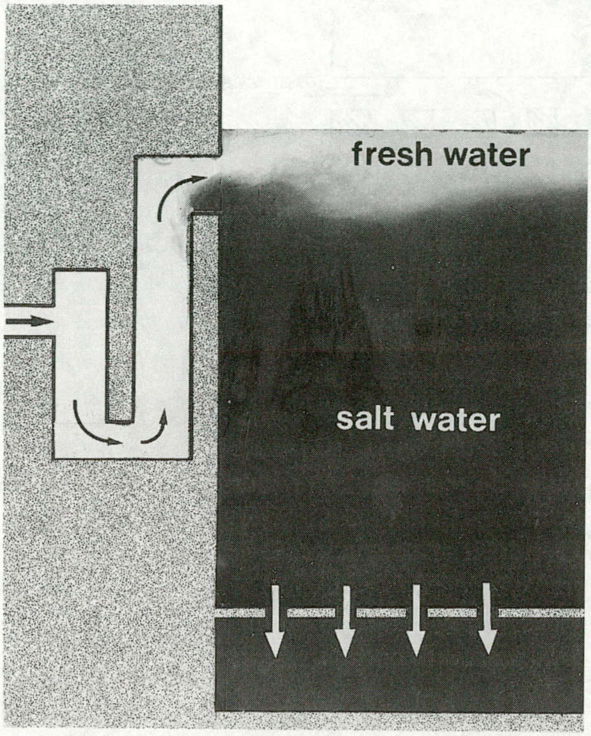


Figure 21. Lab test in which fresh water is admitted to the salt water chamber.

be mentioned that in the Dutch locks it is found that the salt-water level can rise up to the bottom of the ship). Then fresh-water draining operations will be terminated.

g) The chamber is filled further with salt water. After opening the gates ships will leave the chamber.

It is crucial that no heavy blending should occur. Therefore the fresh water admission slots will have to be positioned as high as possible (just below the water level). Further, avoiding blending is a question of applying the correct dosage in an appropriate form at the right moments in the process. Nevertheless, the influx discharge of fresh water cannot be too small, otherwise a small under current of salt water could penetrate the slots in the walls (refer to Appendix D). Figure 21, part of lab testings, illustrates how the salt water can penetrate and how some blending occurs during the admission process.

The advantage of the Dunkerque system is that salt penetration is prevented with a minimum loss of fresh water. The disadvantages are; operation demands extra time, the presence of forces that thwart ships, and a large quantity of water has to be pumped. Part of the loss in time is caught up because of a perfect lock-filling system operative through the floor. With a floor filling system levelling can be done fast, without causing great forces to be exerted on the mooring cables of ships in the lock. With lock doors open, no exchange currents occur, so

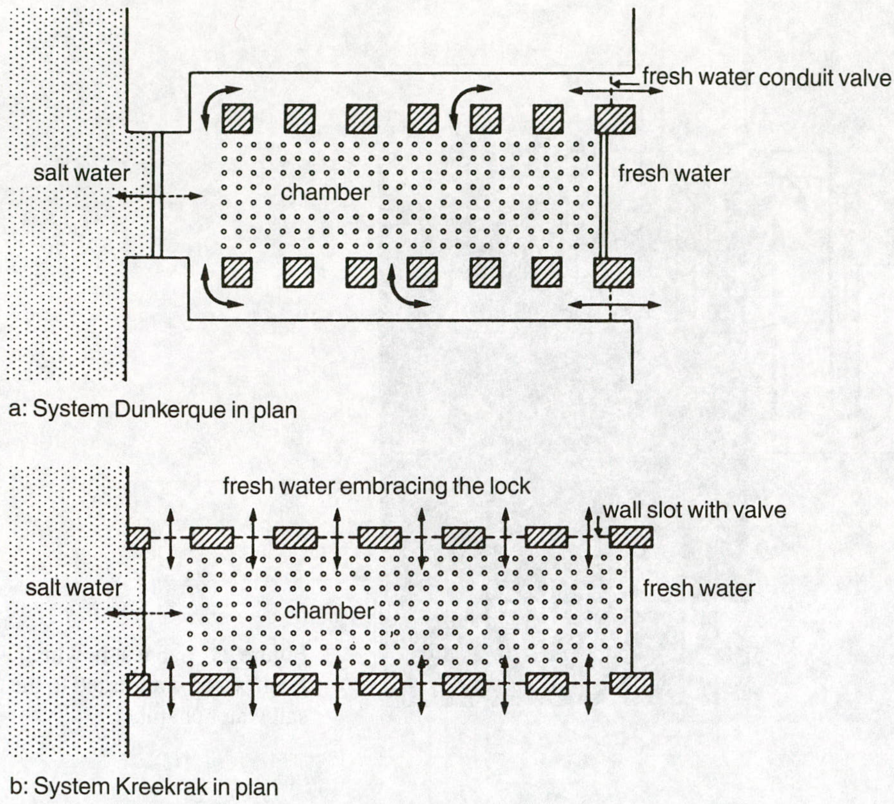


Figure 22. Preventing salt up by means of chamber interchange with closed gates (view from top).

the mooring of ships is easy which also produces a gain in operation time over operations without measures against salt penetration.

Characteristic of the system is that salt-water admittance and drainage will have to be actively controlled (pumping it in or out of the chamber). The fresh water discharge will follow passively. Because of hydraulic losses the necessary fresh water discharge creates a head difference over the admittance conduit up to the slots. When the salt-water level which is being drained out, has dropped suffiently it allows the fresh water to now enter the chamber. The process works vice versa when salt water is being pumped into the chamber. Ships moored in the chamber will have to lay their propellers still to avoid extra blending.

With the Sogréah solution (Figure 22a) two fresh-water conduits run parallel to the chamber. In Dunkerque the salt water is constantly at a higher water level than the fresh water; the salt water conduit system is equipped with pumps. When the chamber is drained until the level is equal to that of the canal, then the sliding valves of the fresh water conduits are opened and they are connected to the fresh water canal. With Dutch varieties of this system (Figure 22b) sliding valves are

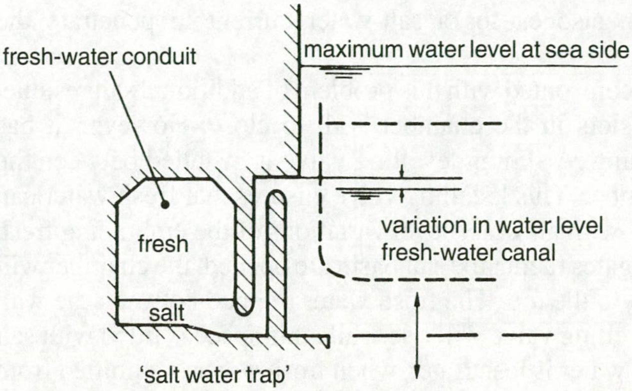


Figure 23. Cross-section of the lock at system Dunkerque.

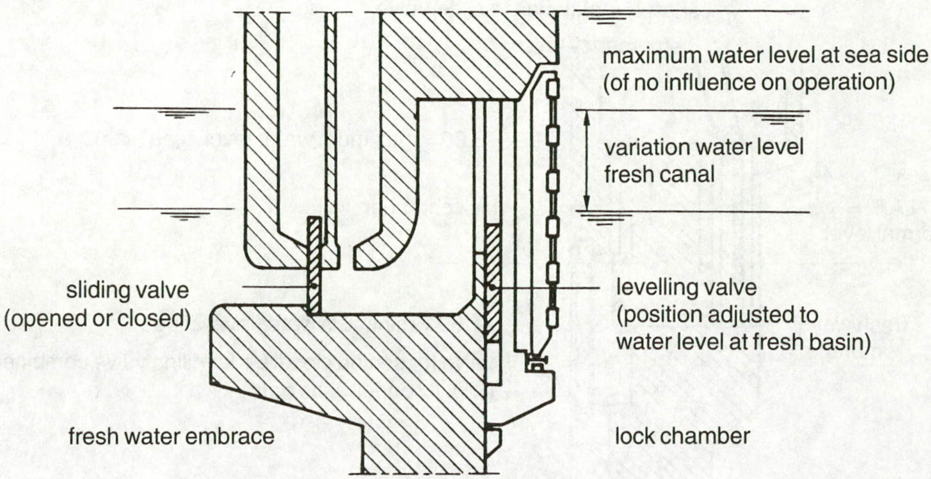


Figure 24. Cross-section of the chamber wall at the Kreekrak locks.

positioned over the entire length of the wall, while the canal stretches beside the entire lock ('fresh water embrace'). This concept was first applied at the Kreekrak locks at the Schelde/Rijn connection and is further examined in Kolkman and Slagter, 1976.

In order to facilitate a situation in which the fresh-water conduits remain fresh when the chamber fills with salt water, the Sogréah solution used a 'salt-water trap'. The device is based on the idea that fresh/salt-water separation only is stable when horizontal layering with the salt water on the bottom, occurs. Before this happens some salt water will penetrate the conduit from the chamber. The salt water will be pushed out when fresh water passes through the conduit on its way to the chamber. Of course some mixing will occur. Another form of mixing will occur when ships enter the chamber. An increased pressure front will form in front of the vessel, which also causes a salt-water current to penetrate the conduit.

The Dutch system is not confronted with this problem of additional salt residue, because it allows for the slots in the chamber wall to close. However, it has another potential shortcoming. A sliding levelling valve is installed between the wall slotgates and the chamber. This levelling valve ensures that fresh water can be admitted in the chamber with all water-level variations of the embracing fresh water. When the main lock gates facing the salt basin are opened, the chamber will be filled with salt water up to the top. The fresh water trapped between the wall slotgates and the closed levelling valve will rise while this space is filled with salt water. The volume of fresh water is lost. Later, when fresh water is admitted from

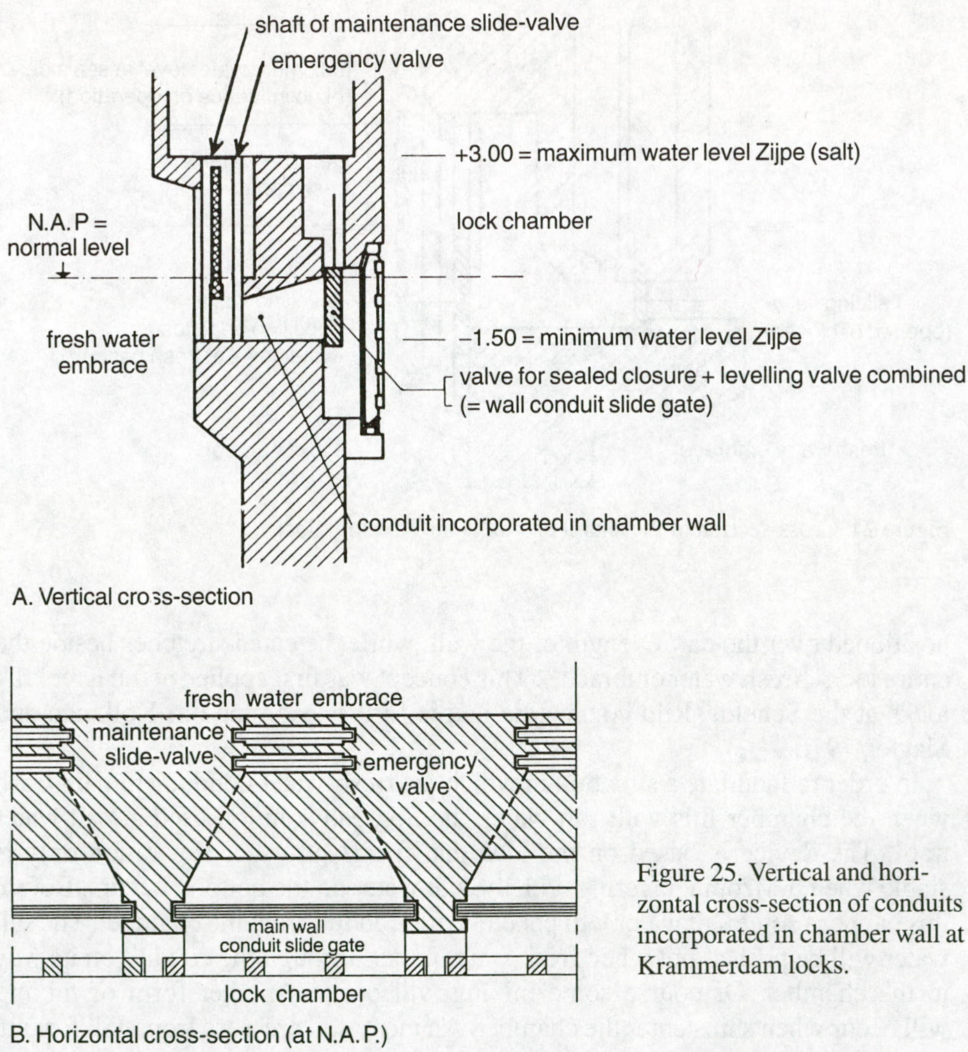


Figure 25. Vertical and horizontal cross-section of conduits incorporated in chamber wall at Krammerdam locks.

the embracing fresh-water pond, the salt-water volume between the closed valve and the wall slots will have to be driven out. This volume, 2 to 3% of the chamber volume, will cause extra salt penetration of the fresh water.

Figure 25 shows an improvement installed at the Krammer locks. The levelling valve is also used to close off the slots, so no volume of water is lost. All examples presented here have slots in both walls of the lock chamber. At smaller ship locks, however, slots in one wall are sufficient; this was the case at the lock for recreational crafts near the Krammer locks.

Sources of mixing: The lock systems that interchange with closed gates are based on interchange of the volume from salt to fresh or vice versa, while maintaining the layering. Mixing should be avoided as much as possible.

Downward interchange requires the fresh-water influx discharge through the conduit system to be low, otherwise the jet current will suck in a large quantity of salt water, or a sort of internal hydrolic jump could develop (Figure 26a). On the other hand the water velocities should not be so low that salt water penetrates the slots (refer to Figure 21). Theoretical analyses (Appendix D) and testings have

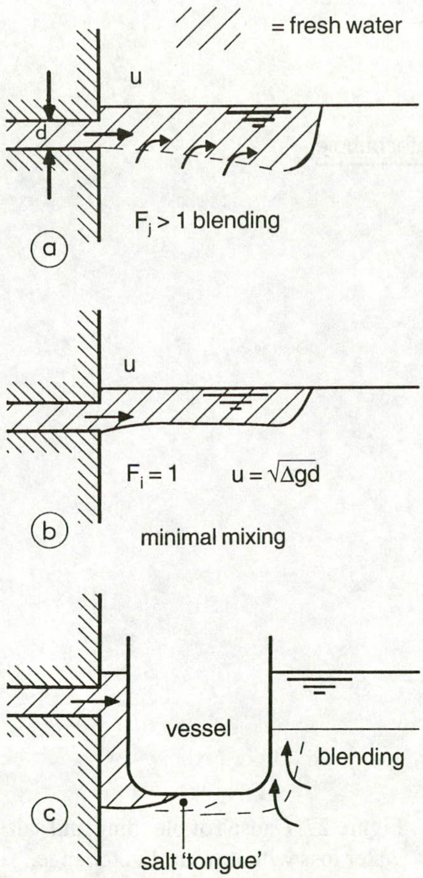


Figure 26. Causes of blending with downward interchange.

found that a velocity should be based on $F_i = 1$ (Figure 26b). The internal Froude number F_i was introduced earlier in Equation (15b).

Less blending will occur when a ship is moored along the chamber wall. The space in between the wall and the vessel swiftly fills with fresh water and this prevents that velocity differentation between the upper and lower layer occurs. The asymmetrical positioning of the vessel in the chamber does cause filling of the space between wall and vessel to take place quicker than on the opposite side. If the fresh water stream flows under the ship, it will ascend through the salt water layer on the other side. It will then be strongly mixed with salt water (Figure 26c).

With upward interchange salt water can enter the slots given the temporary presence of a fresh-water bubble at the ships bottom: It will have to stream upwards the sides of the ship. The limitation of discharge around the bottom edge

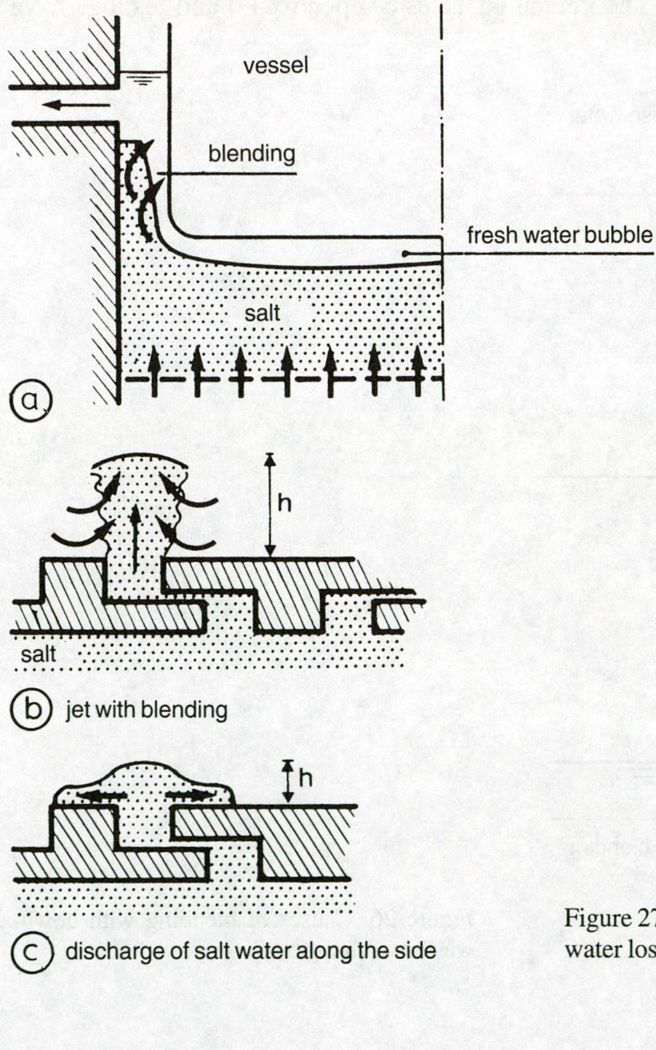


Figure 27. Causes of blending and salt water loss with upward interchange.

of the ship compares to the full discharge of a broad-crested weir. Since the fresh-water bubble stays behind, the salt-water level beside the vessel will rise faster than would theoretically be expected with an horizontal interface. Thus caution is required in retracting the fresh water, which cannot be done in too-large a quantity or too fast, since salt water will accompany it (Figure 27a).

At the perforated floor blending will also happen. To prevent a jet (Figure 27b), the discharge cannot exceed the value which can discharge over the side (Figure 27b). This value can again be expressed in a condition of the internal Froude number. It would be useful to reduce the discharge temporarily when the salt-fresh interface passes critical locations. This is not done in practice, however.

The asymmetry of the interface along an asymmetrically positioned vessel poses a problem with both upward and downward interchanges. Upward interchange causes salt to enter the wall slots on that side where the interface lies higher (between the wall along which the vessel is moored and the ship itself). To prevent this from happening the interchange procedure will have to be stopped prematurely. With downward interchange difference in level of the interface causes a force thwart ships (i.e. perpendicular) to come from the wall. The force produces a hindering effect. The vertical velocity at which rise and fall of the interface is selected is about 1 cm/s. We now consider the situation of a rising interface. Hydraulic resistance actually is determined by the slots in the wall where velocities are much higher (Figure 28). This initially causes a symmetrical outflow:

$$\Delta h = \alpha q^2 \tag{22}$$

In which: α = a measure for the resistance of the wall slot;
q = discharge per unit of length.

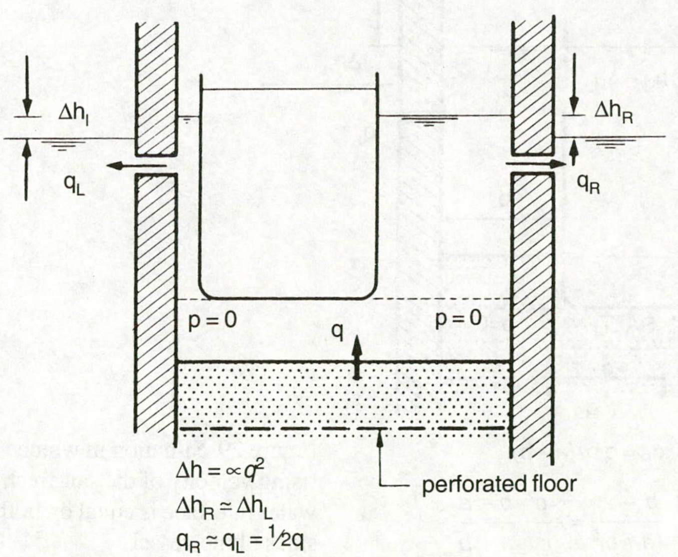


Figure 28. Influence of resistance of wall slots when the chamber is still fresh.

The head difference on the left and right walls is equal:

$$\Delta h_R = \Delta h_L \tag{23}$$

and so

$$q_R = q_L \tag{24}$$

When the salt-fresh interface comes alongside the vessel, the rise will become asymmetrical. There is a possibility for an equilibrium of the rise velocity on both sides to occur, although this is not always the case. Through the asymmetry in the interface position with a difference of height *Z*, combined with the symmetrical pressure in the salt water under the ship, an unequal fresh-water level (Figure 29) comes about:

$$\Delta h_R - \Delta h_L = \varepsilon . Z \tag{25}$$

Since with equal rising velocities and a floor discharge q it holds true that

$$q_L = q.a/(a + b) \tag{26}$$

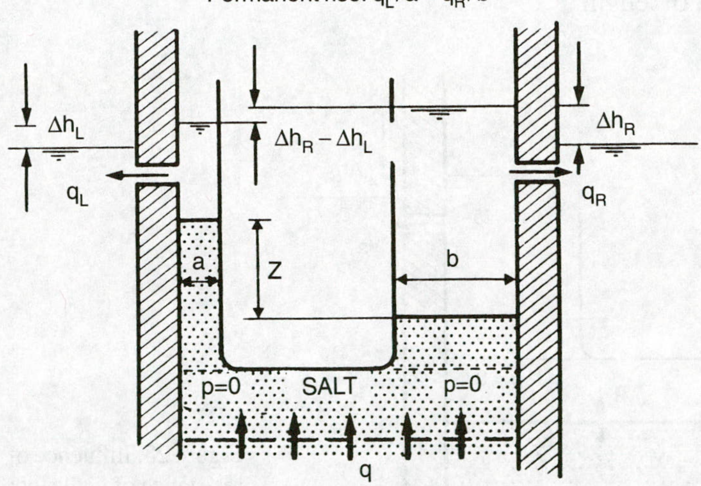
and also that

$$q_R = q.b/(a + b) \tag{27}$$

we can now calculate:

$$\Delta h_L = \alpha q^2 a^2/(a + b)^2 \text{ and } \Delta h_R = \alpha q^2 b^2/(a + b)^2 \tag{28}$$

Permanent rise: $q_L/a = q_R/b$



$q_L = q\,a/(a+b)$ $\quad q_R = q\,b/(a+b)$

$$Z = \frac{\Delta h_R - \Delta h_L}{\varepsilon} = \frac{\alpha q^2}{\varepsilon} \cdot \frac{b^2 - a^2}{(a+b)^2} = \frac{\alpha q^2}{\varepsilon} \cdot \frac{b-a}{a+b}$$

Figure 29. Situation in which rising velocity of the salt-fresh water interface is equal on both sides of the vessel.

so the athwards difference in interface position over the vessel becomes

$$Z = \frac{\alpha q^2}{\varepsilon} \frac{(b^2 - a^2)}{(a + b)^2} = \frac{\alpha q^2}{\varepsilon} \frac{(b - a)}{(b + a)} \tag{29}$$

The Equation shows that the effects of asymmetry can be diminished by reducing the discharge q and positioning the ship less asymmetrical. Also important would be a reduction of the resistance in the wall aperture and conduit system, although on the other hand, this resistance in turn fulfills a function in equalizing distribution of the discharge over the chamber length. The value $\Delta h_R - \Delta h_L$ should preferably be small. A small value will ensure that salt water is prevented from escaping to the fresh-water embrace (with upward interchange), and forces athwart ship are reduced (with downward interchange).

With the Dutch system variety it is very unfavourable if any salt water were to enter the wall slots since this volume would end up in the fresh-water basin. Since lowering the discharge would take up too much time, fresh water-intake is stopped when the salt-fresh water interface has reached the bottom of the deepest vessel. This translates into a fresh water loss of 0.3 to 0.4 of chamber volume. It is possible to slowly regain more fresh water. With the Sogréah solution more blended water can be accepted because the salt reaches the fresh water conduit but will be pushed out during the downward interchange operation, without causing too much blending (Figure 30).

The large locks for pusher tug vessels need large pumping discharges to reach acceptable operational timing (this period includes interchange). At times it is helpful to spread pumping over the whole period between lockages, which is possible with the aid of a support basin. Because at the Krammer locks the sea water level fluctuates beyond the level of the fresh-water basin in both directions, two support basins are even needed (Figure 31, upper diagram). It results in a

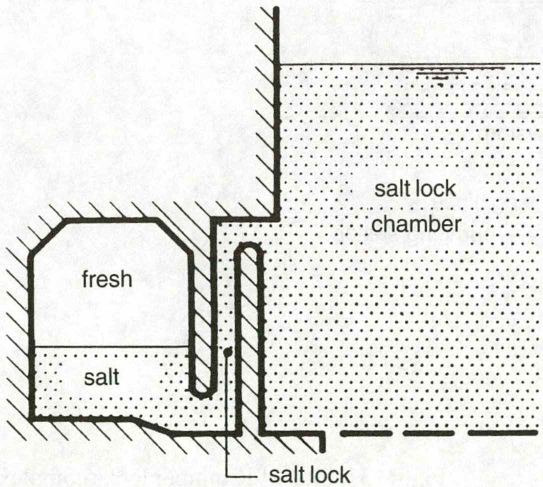


Figure 30. Salt penetration in the fresh water conduit with the Dunkerque solution.

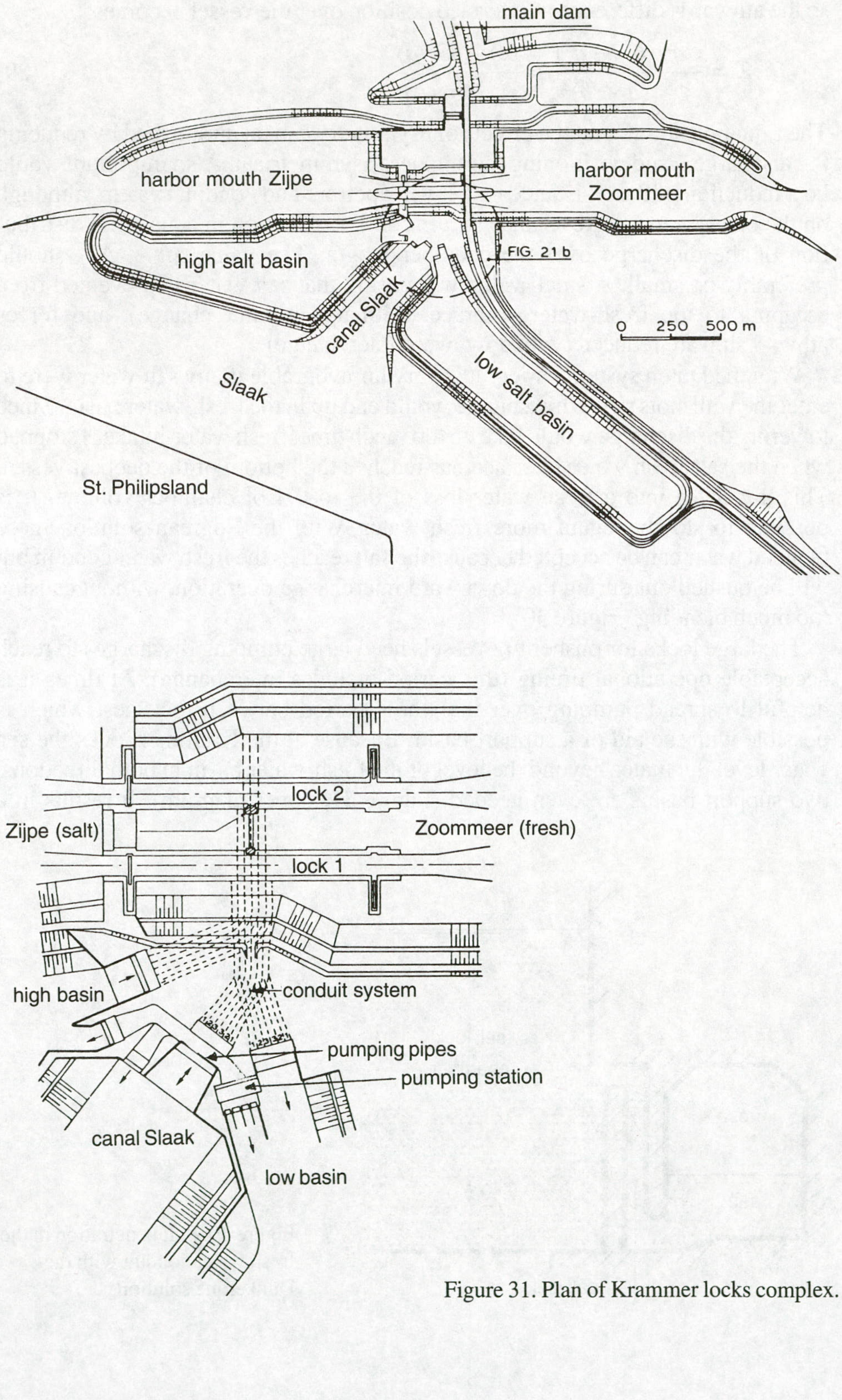


Figure 31. Plan of Krammer locks complex.

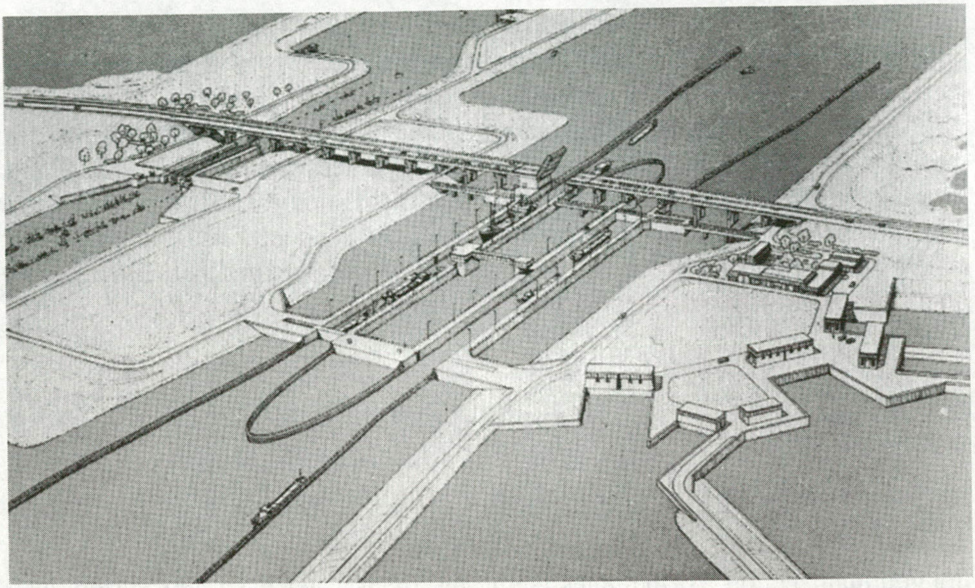


Figure 32. The Krammer pusher tug locks where the fresh water reaches alongside the locks' chambers (in the background we can see the lock for smaller recreational vessels).

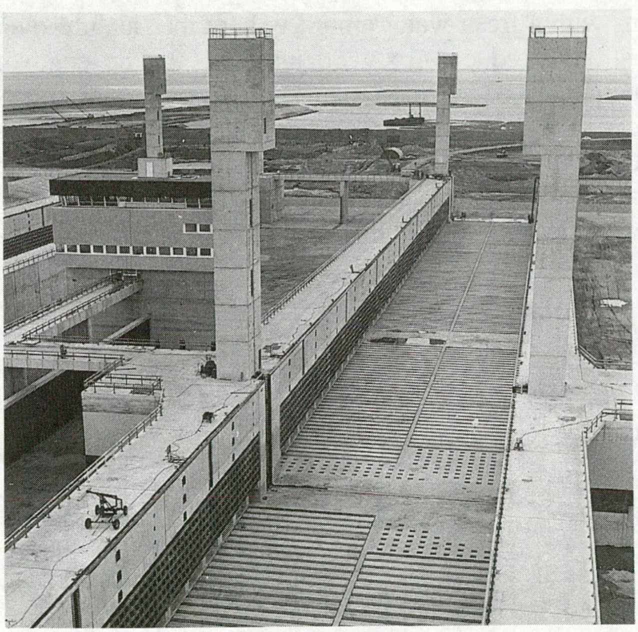


Figure 33. The Kreekrak locks during construction (Scheldt/Rhine connection). Notice the perforated floor to facilitate optimally distributed salt water supply and drainage.

complex conduit system (Figure 31, lower diagram). The pumping station is placed between the higher and lower basin. Figure 32 shows the complex in perspective. Figure 33 illustrates the floor construction of the Kreekrak lock type. The experiences with both the Krammer locks and the Kreekrak locks are positive. All qualitative expectations of the Zoommeer were met. Extensive and detailed prototype measurings and testings at the Krammer locks have indicated that well balanced lock management results in an excellent relationship between salt incursion and fresh-water consumption (Waterloopkundig Laboratorium/ Delft Hydraulics, 1989). The locks at Dunkerque also reported positive results, Quétin 1972.

5.2 SYSTEM HANSWEERT

The 'System Hansweert' draws largely from the applications at the Krammer locks. Figure 34 is similar to for example Figure 25, with the difference that it is a longitudinal section. At the gates facing the fresh-water basin this system also features a levelling valve, operated in accordance with the discharge. The valve ensures that during downward interchange the internal Froude number of the fresh upper stream flowing in is 1, just as with the transverse interchange system (with $F_i = V/\sqrt{\varepsilon g d}$, with V = average velocity above the levelling valve, $\varepsilon = (\rho_{salt} - \rho_{fresh}) / \rho_{fresh}$ and d = depth of layer above the valve).

Compared to the systems with a fresh-water embrace, here the 'length' over which fresh water enters is strongly reduced (1 × width instead of 2 × the length of the chamber) and construction costs are lower. In addition, minimal forces athwart ships are experienced. The density differences do cause additional forces to be exerted over the length, but this is a problem in all locks (situated in between a salt and fresh basin) that are filled through slots in the gates. The system Hansweert has never beeen applied, but tests with scaled models have provided a general introduction.

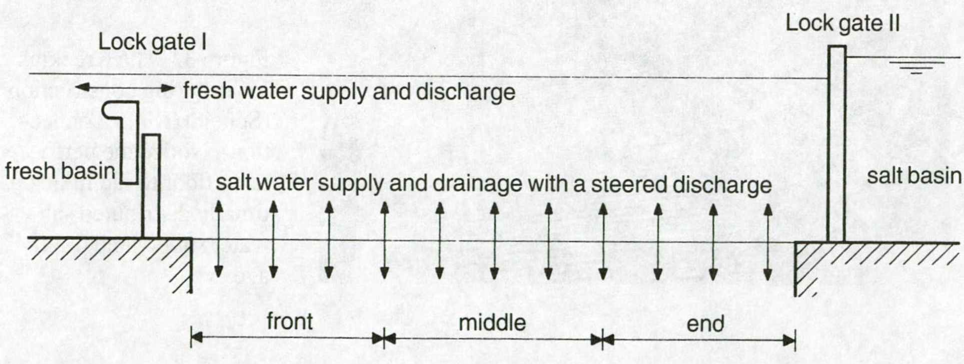


Figure 34. Longitudinal section of lock featuring 'system Hansweert'.

Figure 34 shows a longitudinal section of the system. Characteristic is the round shape of the weir crest of the levelling valve on the fresh-water side. This is necessary to prevent too much blending during the fresh-water incursion process. A sharp edge causes a current with a flow contraction on the bottom. In comparison with the average pressure over the entire current, the bottom flow then holds lower pressure. Now it should be prevented that the low pressure zone will allow salt water to penetrate the fresh water jet while it flows to the chamber. Given this situation, the internal Froude number related to the average velocity over the rim to be larger than 1 (around 1.4) and with maximum contraction of the current, even a higher number is required to avoid inflow as in Figure 21. But such a high Froude number produces extra blending. These results were obtained from research done with scale models. When the edge of the levelling valve is rounded, the situation becomes less problematic (good results were obtained with $0.7 < F_i < 1$).

When ships are moored in the very front of the chamber a rounded weir crest of the levelling valve will not be necessary, since the area between the gate and the vessel will quickly fill with fresh water and blending soon becomes obsolete. Figure 35 illustrates the situation where the floor has been perforated over its entire length, but testing has taken place in three subdivisions of the chamber length; front, middle and end. Figure 35A explains why the front location is very favourable in a situation without ships. The salt flow enters, flows through, reflects and is pumped out through the floor there where the maximum of salt water is located for a long period. With the presence of a vessel (i.e. with large block up) the situation is different, since the salt-water flow slowly progresses to the back and the area in front of the ship has been filled with fresh water before the

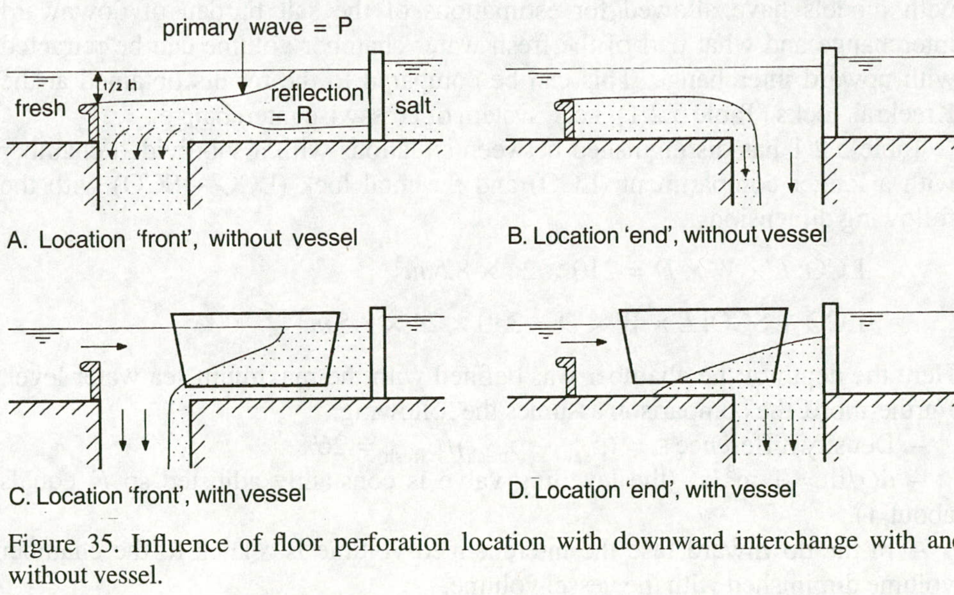


Figure 35. Influence of floor perforation location with downward interchange with and without vessel.

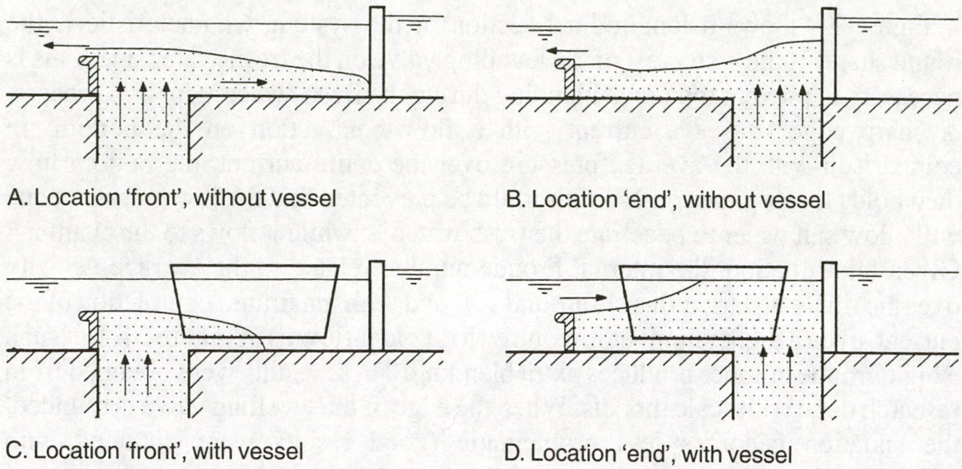


Figure 36. Influence of floor perforation with upward interchange.

salt flow has passed the vessel. This shows that the floor perforation in the front has now become inadequate (Figure 35C) and the perforation at the end does give satisfactory results (Figure 35D).

For fresh water retraction the perforations should be at the end in both situations with and without vessels (Figures 36B and D). Otherwise fresh water will still be present in the chamber, whereas salt water is already entering over the rim (Figures 36A and C).

All research data has concluded that a perforation at the end of the chamber, at around 70% of chamber length, gives optimal results. The results of experiments with models have allowed for estimations of the salt burden of downward interchange and what part of the fresh water chamber volume can be retracted with upward interchange. This can be compared to the results obtained at the Kreekrak locks (Table 5.2.1), i.e. a system of crosswise interchange.

Table 5.2.1 has distinguished between situations with a subdivided chamber with a longer compartment (LCO) and the total lock (LCO + SCO) with the following dimensions:

$$\text{LCO: } L \times W \times D = 210 \times 24 \times 8.5\, m^3$$

$$\text{LCO + SCO: } L \times W \times D = 330 \times 24 \times 8.5\, m^3$$

Here the depth of the chamber was defined with the maximum sea water level. Furthermore, the comparison assumes the following:

– Density difference $\varepsilon = (\rho_{salt} - \rho_{fresh})/\rho_{fresh} = 26‰$.

– $dQ/dt = 1\ m^3/s^2$ (the levelling valve is constantly adjusted so F_i equals about 1).

– In the downward fase the interchanged volume is related to the chamber volume diminished with the vessel volume.

Table 5.2.1. Comparison salt penetration with downward interchange and recouping fresh water with system Hansweert and with crosswise interchange according to scale-model studies at the Kreekrak locks.

Length of lock	Interchange system	discharge m^3/s	Vessel volume % *V*	Interchange vol. up/down % *V*	% *V*	Salt penetra-tion up/down % *V*	% *V*	Fresh water loss % *V*
LCO	longitudinal	100	25	85%	0%	4%	0%	85%
	wall slots	100	25	85%	0%	4%	0%	85%
	longitudinal	100	25	85%	0%	4%	2%	55%
	wall slots	100	25	85%	30%	4%	2%	35%
	longitudinal	150	25	85%	30%	6%	2%	55%
	wall slots	150	25	85%	50%	6%	2%	35%
LCO+SCO	longitudinal	100	25	85%	30%	4%	2%	55%
	longitudinal	100	25	95%	30%	3%	2%	65%
	wall slots	100	25	85%	50%	3%	2%	35%
	longitudinal	150	25	85%	30%	6%	2%	55%
	longitudinal	150	25	105%	30%	4%	2%	75%
	wall slots	150	25	85%	50%	4%	2%	35%

The conclusions of the comparisson are:

1. For the *long compartment* in the downward fase, results of the system which interchanges via slots in the gate (with optimal design of floor perforation) are comparable to those of the system which interchange via slots positioned over the entire length of the chamber (Kreekrak locks).

2. With optimal use of the system which interchanges over the chamber's length via a slot in the gate equipped with levelling valve, the results of the downward fase *for the total lock* are less advantageous as compared to the Kreekrak system. The difference amounts to a salt intrusion factor of 1.5 with equal interchange timing, or a factor 1.5 in interchange timing with equal salt intrusion.

3. In the upward fase the system which interchanges via slots in the gate gives worse results than the Kreekrak system. The latter can recoup about 1.25 to 2 times the volume of fresh water of the Hansweert system (at the cost of an equal salt intrusion rate).

5.3 THE SYSTEM 'SALT LIFT TROUGH'

When a smaller lock for inland navigation had to be built in an area near oyster farms (the Bergsediep lock at Bergen op Zoom, see Figure 1b), it appeared only to be possible if salt penetration in the fresh-water basin Zoommeer would be kept

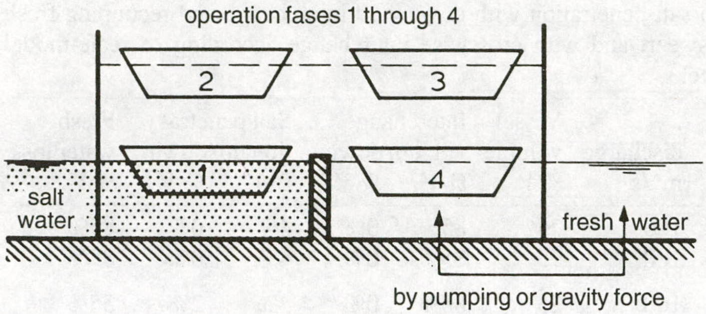


Figure 37. Lock with a high mid-chamber sill.

minimal, but also if fresh-water incursion in the salt water could be low. All existing systems were reviewed and some new ideas introduced. Again it was considered to pump out the entire salt chamber (and only then fill it with fresh water). Since laying the ships dry is unacceptable, the system could be further developed by installing a salt water trough under the level where the chamber floor would be, instead of laying the vessels dry. Pumping the water in and out would take place through slots in the wall, located low on the level of the gate's sill. Specialists in the areas of ship-building and recreation vessels were consulted to determine to what degree smaller ships can be laid dry. One of these discussions* brought forth the following idea (Figure 37): To design a chamber with twice the conventional height and a permanent wall positioned in the middle. By pumping in fresh water the ship will rise out of the salt water, with this salt water volume remaining on the floor, behind the wall. After navigating over the wall, the ship can be lowered again on the opposite side of the wall by sluicing out fresh water.

Figure 38 illustrates how this basic notion was improved. First, the reach of the fresh water in the chamber was elongated by having it flow beside the salt part (Figure 38a). One of the disadvantages was the vast fresh water volume that had to be pumped against a head difference that runs up to several metres.

The next variation was to lower the salt water trough with a hoist mechanism ('the salt lift trough'). Such a device saves energy and the vessel does not have to be repositioned (Figure 38b). At the salt-water side both the lock and the trough have a gate. It is possible to uprate the system with tidal variations of the water levels (Figure 38c), but it adds the condition that the salt water basin (i.e. the trough) and the hoist construction can resist relatively high differences in water pressure. Consequently, a system featuring a permanent outer chamber made of concrete was opted for in which fresh water (i.e. all the water outside of the steel lift trough) can be replenished up to the water level of the salt-water basin

* The text refers to a meeting with civil engineer R. E. P. Vallenduuk of the water recreation dept. of the ANWB (Dutch motorists and tourist association).

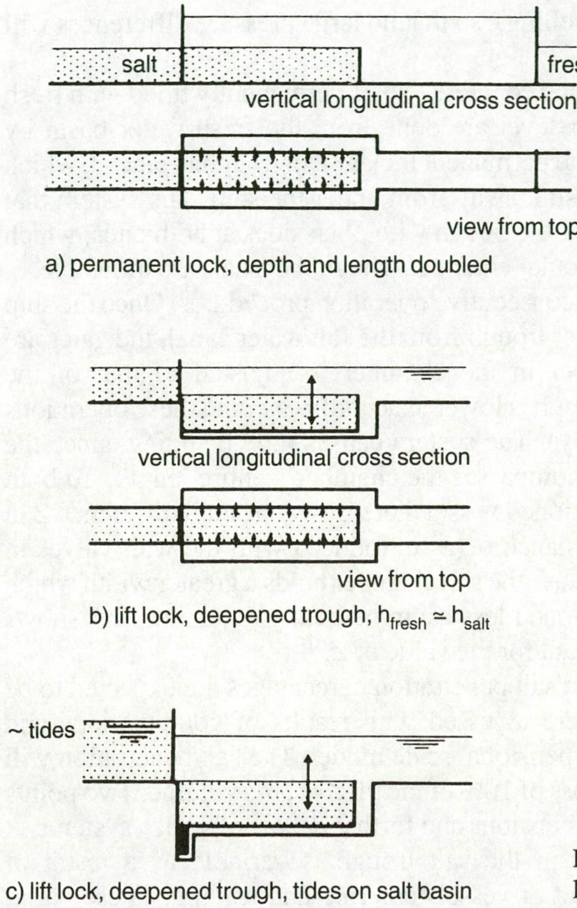


Figure 38. Developmental stages salt lift trough system.

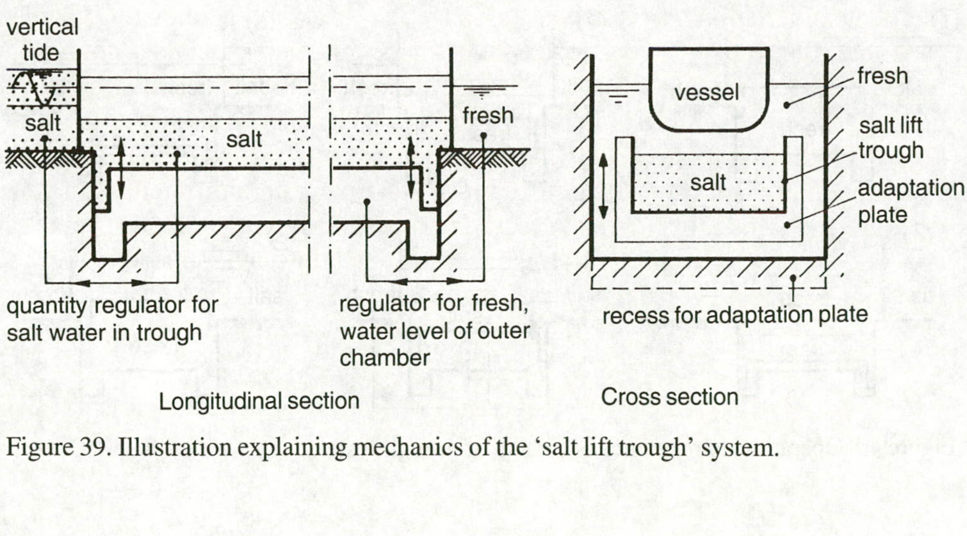


Figure 39. Illustration explaining mechanics of the 'salt lift trough' system.

(actually this is about normal levelling), so that no large pressure differences will occur over the lift trough.

Figure 39 shows how a deepened concrete lock is permanently filled with fresh water. Adjustments in the water level are done from the fresh-water basin by pumping or force of gravity. In the permanent lock a steel trough is placed, which is filled with salt water and can sink away from under the ship. The system that was finally opted for consists of a lift trough with open sides at both ends, which slides along the end walls of the outer chamber. The rubber seals are inflatable.

Figure 40 follows through the consecutive operation procedures. Once the ship has entered the elevated salt-water trough from the salt water canal, the gates are closed and the fresh-water level in the chamber is adjusted to that of the fresh-water basin and the salt trough is lowered accordingly (and these operations can be performed simultaneously). The system causes little blending, since the rim of the trough effectively encompasses the chamber's entire length. To both sides of the asymmetrically positioned vessel there is only a small difference Z in interface level, because the resistance α (as introduced with the wall valves in Figure 29), is now small and because the salt chamber holds a greater width which results in the vessel being positioned less asymmetrically. Equation (29) shows both these factors to be determinant for the value of Z.

With the salt lift trough system salt penetration percentages are expected to be very low. These estimations were assessed with results of computations and studies conducted with a two-dimensional scale model. The salt penetration will not exceed 5%, at a fresh water loss of 10% of the lift trough's volume. Two points should be made regarding the dimensions and further details of such a system:

– The volume of salt water in the salt trough is variable as a result of differences in water displacement of vessels entering and leaving. These variations will have to be adjusted with pumps connected to the salt-water basin (with the flexible hose commonly used in dredging technology).

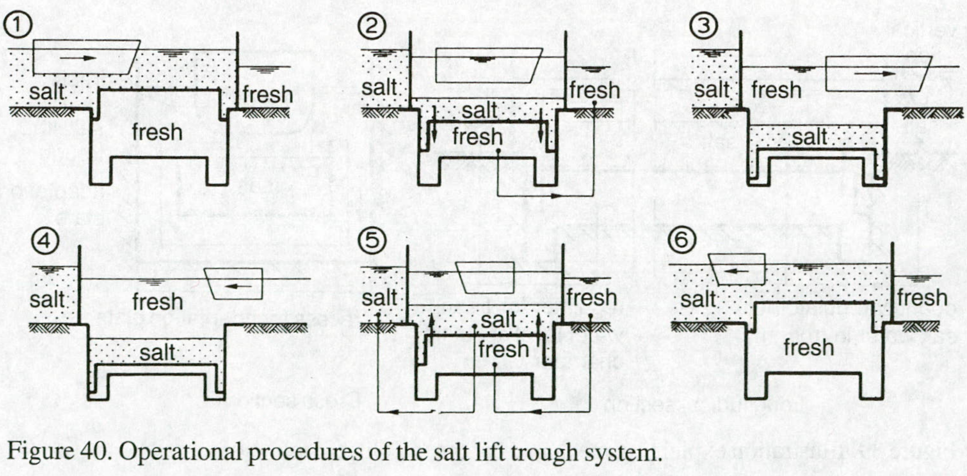


Figure 40. Operational procedures of the salt lift trough system.

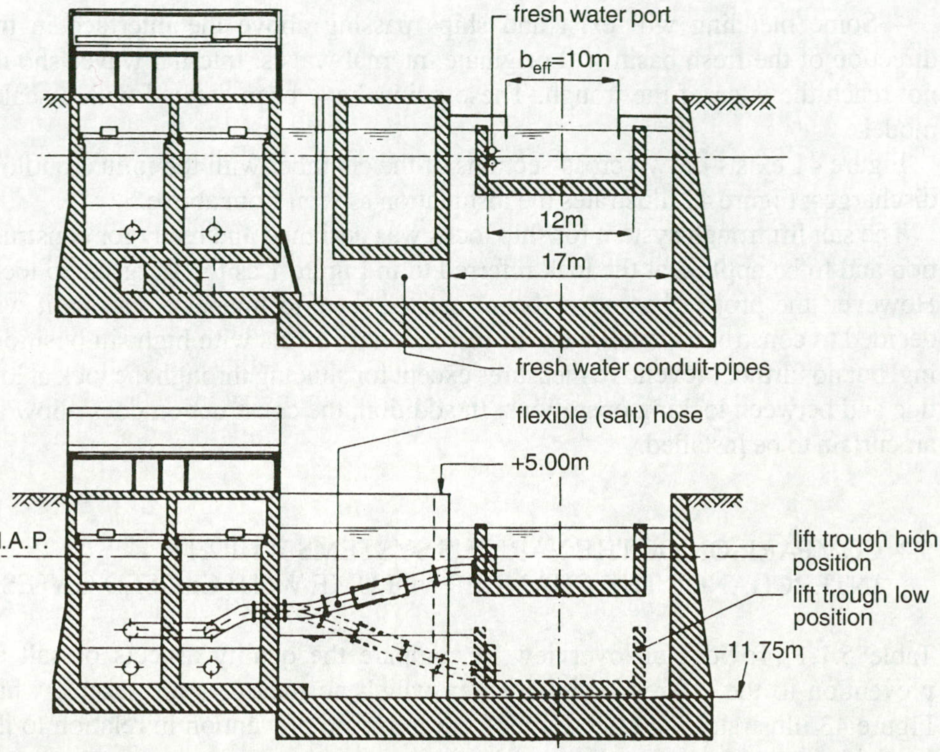


Figure 41. Cross-section of lock chamber and the pump system for salt-fresh water level adjustments.

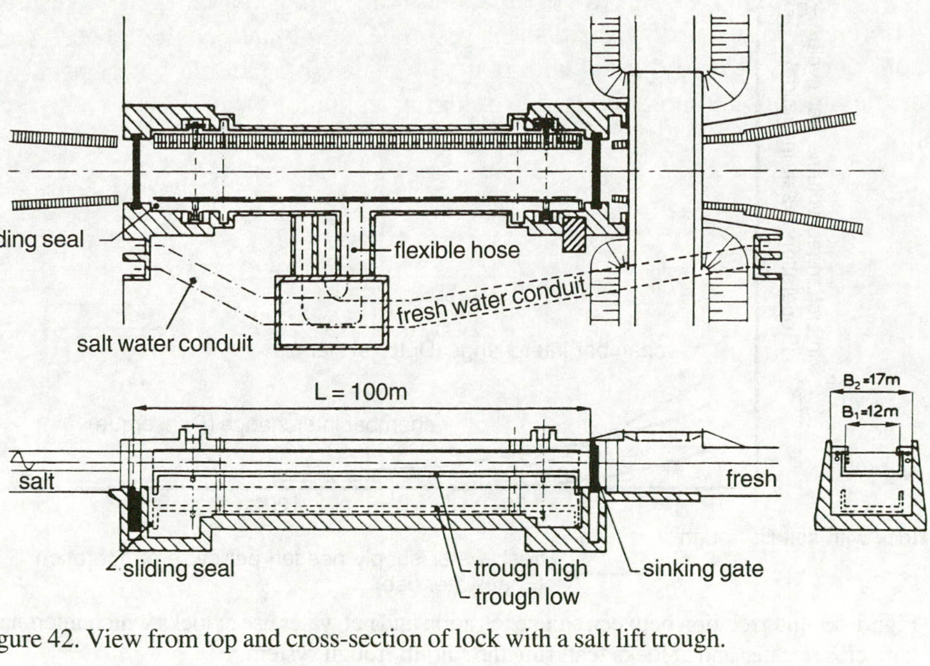


Figure 42. View from top and cross-section of lock with a salt lift trough.

– Some blending will exist and ships passing above the interface in the direction of the fresh basin will originate internal waves. Internal waves should not reach the edge of the trough. These points have been studied with a scale-model.

Figure 41 exists of two cross-sections of the chamber with the influx/outflow discharges; Figure 42 illustrates the installation as seen from above.

The salt lift trough system for ship locks was designed and ready for construction and to be applied at the lock referred to in Figure 1 as the Bergsediep lock. However, the project has never been realised. Due to financial reasons it was decided to construct a small lock for recreational vessels with high sill positioning, but no further preventive measures except for sluicing through the lock at low tide and between locking operations. In addition, the construction does allow an air curtain to be installed.

5.4 COMPARISON OF THE VARIOUS SYSTEMS WHICH INTERCHANGE THE CHAMBER VOLUME WITH CLOSED GATES

Table 5.1.1 provides an overview to compare the quality aspects of salt up prevention to the reference situation (in which no measures are taken), while Figure 43 illustrates the effectivity of salt intrusion prevention in relation to the available net volume of fresh water.

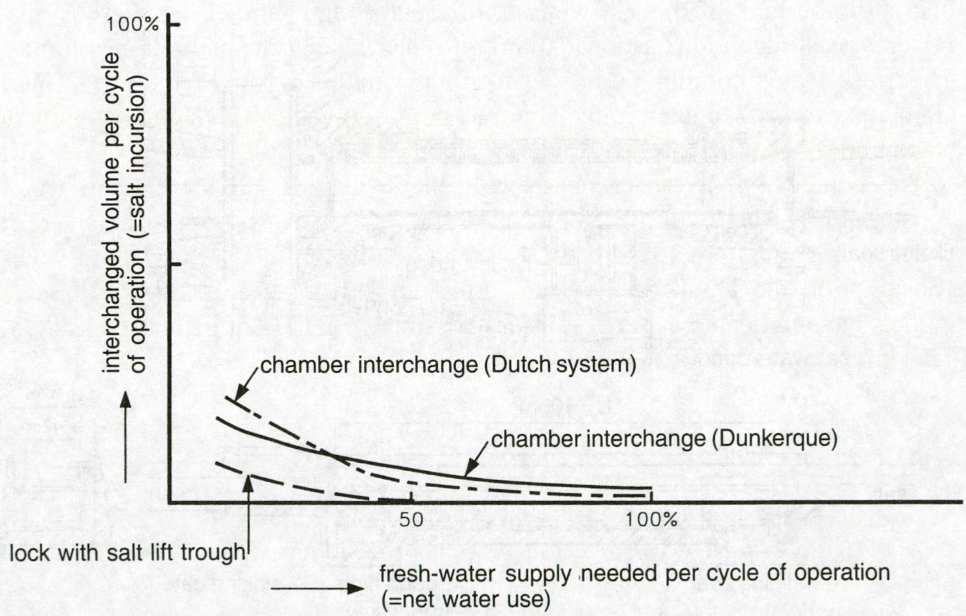


Figure 43. Interrelation between salt penetration and net water use at locks which interchange with closed gates and at locks featuring the salt lift trough system.

It has been attempted to order the various factors and to supply a conclusive graphic illustration, just as was done in Section 4.7. Here however, the situation is more complex since interchange velocity and the total duration of the operation (levelling and interchanging) has become an important parameter. In the comparison these parameters are kept as follows: the large pusher tug locks (L = 300 m, W = 24 m) need an average of 12 minutes with a 2 metre difference in water level of the adjacent basins. The subject has been intensively researched. Length and width of the lock built at Dunkerque are about half of those of the Dutch inland navigation locks. The depth is also lower, but the water-level difference can reach up to 4 metres. The timing of the entire interchange operation will theoretically amount to about 9 minutes for these smaller locks,* a figure which is similar to the experiences at Dunkerque. This means that results concerning salt penetration and fresh-water consumption can be compared. Nevertheless, the data in Figure 43 should be viewed qualitatively. The data used for the graphic are not completely homogenous.

From a qualitative point of view, we could state that with good management the lock at Dunkerque equals the Dutch locks. The application of valves in the wall slots enables the Dutch system to realize a better discharge distribution over the length. The valve's levelling abilities also allow the condition Froude = 1 to be true and closed valves allow ships to enter and leave quickly without this causing salt water to pentrate the fresh basin. At Dunkerque the salt-fresh water interface during upward interchange can rise past the bottom of the vessels, which is a plus in times of fresh-water shortage. The salt water will not directly enter the fresh basin but will first flow in the fresh-water conduit. During the following fase of operation the bulk of the salt water will re-enter the chamber. Dunkerque also features a salt-reception basin with pumps to catch small salt penetration volumes. The fresh-water conduit dumps its contents in this basin by gravity. These elements were added later. In the Dutch system, salt water which enters the fresh water embrace immediately becomes a salt burden.**

The conclusion of the comparison is that with a small increase in water consumption (when with the interchange from salt to fresh not too much fresh water is regained) the Dutch locks are more favourable; with lesser water consumption the Dunkerque system holds the advantage. Testing with scale models have indicated better results are possible with the salt lift trough system. This information can also be found in Figure 43.

* A model at Scale 2 indicates a time duration scale $\sqrt{2}$, in accordance with the Froude-scale (which also holds true for density currents when $\Delta\rho/\rho_{fresh}$ is reproduced in the model).

** The application of a salt receptor with pumps was considered at the Krammer locks but not actualized for financial reasons.

CHAPTER 6

Management of salt-fresh water separation systems

The issue in salt-fresh separation systems is to prevent interchange and blending of the water varieties at both sides of a ship lock. The controller of any lock will always have to deal with certain quantities of water. This also applies to conventional systems. The difference is that there the controller does not fulfil a direct managerial function for the quantitative and qualitative aspects of water. A convential lock levels by connecting the chamber to the basin towards which the lock is functioning. For lock operation *ad sic*, the chamber volume is of no importance. The velocities of gaps in apertures and conduits for filling and draining have already been determined during the design fase, and gates will always be opened to the maximum to ensure a fast levelling process. Besides filling and draining the controller does have the responsibility to sustain one of the basin's water levels.

When the issue of natural interchange of salt and fresh water comes up, operation becomes more complex. Levelling can be observed with the eye, as are variations in the water level. With interchange, only the surface current can be observed. It cannot be determined immediately if a fresh-water basin is becoming brackish. Assume a controller has, without access to any further information, a notion of about the water quantities or salt intrusion involved. Without more extensive knowledge, however, the controller will not be able to determine the volumes that should be retracted from the fresh basin in order to reduce salt intrusion. Playing it 'safe', would translate into unnecessary fresh water loss. If the fresh water is scarce to any degree, this, however, is not safe and will cause further loss.

To reduce salt-up in a cost-effective manner, the following are needed:

- Specifics on the quantity of salt water penetration;
- Specifics on the volume of salt water already penetrated in the fresh basin;
- A system which allows controlled draining of salt-water incursion;
- Information on the volume of fresh water available for the reduction of salt-up.

The information needed by the controller can only be obtained through

Table 6.1.1. Comparison of systems which interchange with closed gates and the lock featuring the salt elevation trough.

	No action	System Dunkerque	System Krammer/Kreekrak	Salt elevation trough
a	None	Double conduit system	Double conduit system	Double lock
b	72% (θ = 0.9)	2-6%	1.5-10%	1-5%
c	20%	0%	0%	0%
d	Yes	Minimal	Minimal	Minimal
e	None	20-80%	30-80%	20-40%
f	None	Yes	Yes	Yes
g	Longer than homogeneous condition	Extra interchange	Extra interchange	Partly simultaneous with lockage operation
h	Yes (gate filling)[1)]	Force thwart ships	Force thwart ships	Force thwart ships
i	Yes	Yes/no[2)]	Yes/no[2)]	Minimal
k	Not applicable	No	No	No

[1)]Force exerted longitudinally.

[2)]Yes when upward interchange is not performed.

Note: All changes are viewed with respect to the reference condition 'no action' at homogeneous condition'.

a Consequences for design and construction.
b Salt penetration in % of chamber volume, with zero drop and 20% vessel occupation.
c Influence lockage prism when sea level is higher (lockage prism and ship volume constitute 20% of chamber volume).
d Contamination fresh upper water.
e Net water use fresh basin.
f Energy consumption.
g Influence on operating time (no action will result in a longer duration compared to the homogeneous situation, because exchange causes hinderance to ships).
h Hindrance for vessels during operation.
i Hindrance for vessels that enter and leave.
k Possibility to install system later.

measurements and/or calculations. It should be noted that with the third point, another element is involved. The controller has to be able to regularly check the process of retracting salt water. With steering, once the process has been activated, no comparisons of the desired and measured quantities can take place, nor can the process be retained or fed back. With regular control and feed-back, however, this can be done.

In conventional water management the controller also steers and/or controls directly. Take for example a situation where at a canal with lock, one of the basins has a water level that is too low. The controller will now admit water into that basin. Once the basin has reached the desired water level, he will stop the process. He will directly control the process by feeding back from the water level of the basin, by opening the admission valves over a certain period. These are, in principle, simple operations and little can go wrong.

With a salt-fresh water condition, this would be different. Imagine the controller operates a lock that does not have a special salt-fresh separation system. Since the lock is positioned in a water route with little traffic, salt penetration is reduced by sluicing with the lock at low tide. The sluice flow should wash back the salt water that incurred during lock operation. However, it will be possible that a reverse effect will come about, i.e. more salt water penetrating the fresh basin. This would occur when the sluicing discharge is so small that the internal Froude number will be smaller than 1. Then the salt water will flow into the fresh basin (refer to Appendix D). The controller thus achieved a result opposite to the intended, at the cost of fresh water.

The above mentioned problem is easily resolved. The controller should only be careful not to begin sluicing too early, and not stop the process too late. But he should be able to read accurately and simultaneously the water levels at both sides of the lock. The critical limits in terms of a minimum head difference needed for sluicing, can be calculated. A hydrostatic analysis can check if pressure differences over the entire vertical plane are set in the same direction.

The more advanced the salt-fresh separation system, the more advanced the management method should be. At system Terneuzen with the salt-water pit, the controller can suffice with management similar to sluicing with the lock at low tide. This will, however, certainly not maximize economic efficieny. A study of the salt-fresh separation system's performance at the Terneuzen locks provides an overview of the variables and parameters involved in such a system Waterloopkundig Laboratorium/Delft Hydraulics, 1988.

The steering and/or direct control system with presence of a salt water pit can still be relatively simple. We can take the situation at the Koopvaarders ship lock at Den Helder as an example (refer to Section 4.3 and Figure 14). A pumping station flushes back the salt water from the pit in front of it. The data needed for operation of the steering system is the volume of salt water in the pit. This information can be obtained by measurements. Salt meters should be installed at various levels in the pit, or by application of a salt-vertical meter. Once the system has detected water with a stipulated density, the pumps will start operating. The station will stop draining once the salt content has decreased to a certain level. The system can be refined, depending on the limits the entire installation allows for. The draining instantaneous discharge, for example, can be related to the instantaneous density difference between the salt and fresh water, which would limit drainage volume of fresh water. It is also possible to have the system account for different tidal patterns. When pumping against a smaller head, less energy is consumed.

The salt-fresh separation system at the Krammer locks definitely influences the lock's operational process. When the chamber levels, for example, this happens through a buffer basin with a lower water level than the fresh basin (refer to

Section 5.1). The chamber is not directly connected to the fresh basin and simply connecting the chamber with the buffer basin will not result in equalization of water levels between chamber and fresh basin. Thus the levelling process will also have to be steered and/or controlled directly. The result could be optimalization of the levelling process (faster timing). Waterloopkundig Laboratorium/ Delft Hydraulics, 1991 describes in detail the steering/direct control system applied at the Krammer locks.

CHAPTER 7

Effectivity of all salt-fresh separation systems compared with standards for water quality

7.1 THEORETICAL APPROACH

Figure 44 summarizes the results of salt penetration as a function of the net fresh water loss (the lockage prism excluded) for the various lock systems. The figure is a compilation of Figures 20 and 43. Section 2.4 contains a graphic illustration (Figure 6), which states the maximum interchange between salt and fresh water allowed at the lock in relation to the sluicing discharge available. Although this graph expresses values in a qualitative sense, it will be interesting to study Figures 6 and 44 together.

What Figure 6 refers to as the interchange discharge, Figure 44 expresses as the interchange volume, i.e. salt-water incursion. The discharge flowing through becomes what Figure 44 calls the fresh-water supply necessary (if we ignore the situation where sluicing is performed via a lock designated for those purposes only). In Figure 44, as well as Figure 6, a line is plotted which indicates (at one determined qualitative standard) the relation between the maximum of the discharge flowing through the fresh water basin and the salt-fresh interchange at the lock. Again the line has a qualitative value.

When the ship lock is the only source of salt-up, the points of intersection of this line with the lines expressing the various salt-fresh separation systems give the minimum discharge of fresh water on the horizontal axis. When compared to the fresh-water discharge available, a theoretical choice of systems to reduce salt-fresh water exchange can be made.

7.2 PRACTICAL APPROACH

With just a glance at Figure 44, some practical conclusions can be drawn already:

– If no fresh water is available to repel salt-water penetration, air curtains combined with sound management are the first option. With each of these

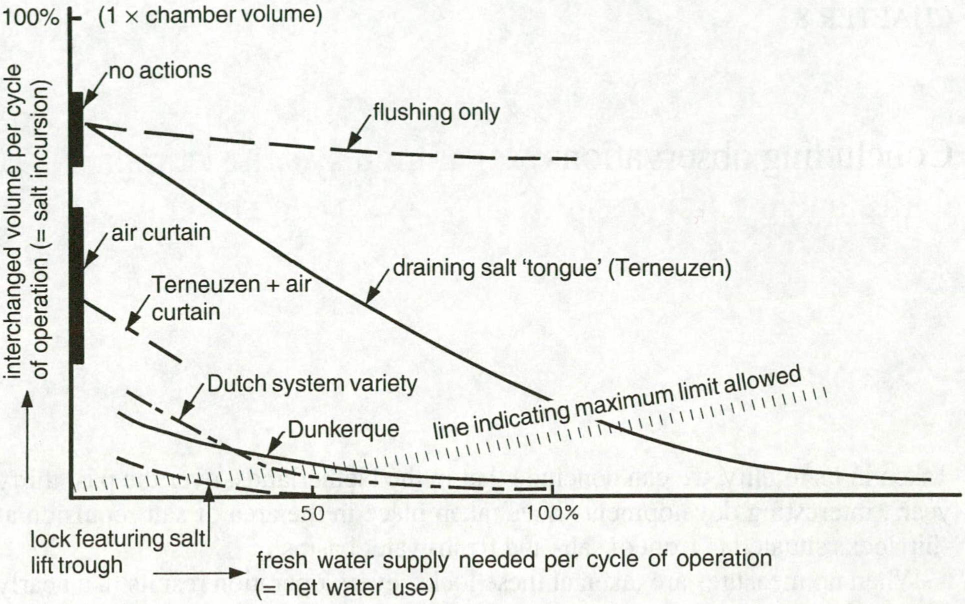


Figure 44. Quality comparison of the various systems, omitting influences of lockage prism and vessel volume.

elements a reduction of 50% can be reached (i.e. a total of 75% might be obtainable).

– If a high reduction of salt-fresh water exchange is needed, and little fresh water is available, then a system which interchanges with closed gates or a lock featuring the 'salt lift-trough' would be a much preferable option as compared to the air curtain, but also much more expensive.

– When adequate fresh water volumes are available during critical periods for agriculture, then good results can be obtained with system Terneuzen.

Sound management has not been included as a measure in Figure 44. It increases results in similar fashion as with the other systems.

In practice, more extensive studies on cost-effectiveness of these investments will be needed. Important factors are that demands concerning water quality and the availability of fresh water for salt repulsion strongly fluctuate with the seasons. Thus, prognoses become crucial, for agriculture as well as shipping.

In the Netherlands, the river Rhine is already contaminated with salt and other chemicals. This leaves little room for additional sources of salt intrusion. Since these other sources are present (for example percolating water), salt penetration at ship locks has to be absolutely minimized.

CHAPTER 8

Concluding observations

Taken in its totality, we can conclude that in the Netherlands, over the past thirty years, interesting developments have taken place in the area of salt repulsion at ship locks situated in front of salt- and fresh-water basins.

When no measures are taken at these locks, every operation results in a nearly 100% chamber interchange of salt and fresh water. With application of air curtains these losses are halved. In addition, a well-balanced management system which considers both water quality and vessel capacity, can improve the situation considerably.

Placing a salt-water pit in the fresh basin, which will contain the water until it is pumped back to the salt basin, is an important step in reducing salt-up. Because of blending between the two water varieties, about twice the chamber volume will have to be flushed back. This system also requires a relatively large volume of fresh water.

The later developed systems both reduce salt-up and the fresh-water loss involved. The latter can be important for two reasons: The availability of fresh water and the unwanted presence of this fresh water in the salt basin. Maximum effectiveness would be achieved with a lock featuring the salt lift-trough device. Unfortunately, the system has never actually been built.

Apart from Dunkerque, at the time an innovative contribution of French engineering (Ribes & Blanchet, 1965), no other developments have been reported on the subject of reducing salt- and fresh-water exchange at ship locks. The other above mentioned development originated most likely all in the Netherlands.

It will be clear to the reader that the higher the effectiveness of the system, the higher the investment in the lock will be. Assessment of the maxima of salt and fresh-water losses allowed, will help the designer to make a choice between systems developed. Figure 44 will be an expedient in the design fase. Furthermore, the internal Froude number has proven itself to play a principal role. From it follows that the velocity with which the water flows in or out of the chamber is crucial. Lock management thus becomes an important factor in the effectiveness of the applied salt-fresh separation system. This is the reason the relations between the salt- and fresh-water loss illustrated in Figure 44, can only be interpreted as indicators.

APPENDIX A

Total salt-fresh water interchange per lock operation cycle when rate of local interchange, θ, is known

DEFINITIONS

$V_{\text{chamber fresh}}$ = Volume of chamber at a water level belonging to the canal.
$V_{\text{chamber salt}}$ = Volume of chamber at water level belonging to the sea.
V_s = Volume of ship/$V_{\text{chamber fresh}}$.
S = Volume of lockage (lift) prism/$V_{\text{chamber fresh}}$.
Ship = Short for vessel volume.

$$S' = \text{Volume of lockage (lift) prism}/(V_{\text{chamber fresh}}\text{-Ship}) = S/1 - V_s \quad (1)$$

$$S'' = \text{Volume of lockage (lift) prism}/(V_{\text{chamber salt}}\text{-Ship}) = S/1 - V_s - S \quad (2)$$

Note: S″is only a relevant factor when the water level in the canal exceeds that of the sea.

θ = local interchange rate, i.e. during that period in which one gate is opened ($0 < \theta < 1$). With $\theta = 0$ no interchange exists and with $\theta = 1$ the entire water volume of the chamber (volume of chamber – vessel volume) is interchanged with water present in the mouth of the harbor.

p = relative concentration

$$p = \frac{C - C_o}{C_z - C_o} \quad (3)$$

In which
C_z = salt concent of salt harbor mouth
C_o = salt concent of fresh harbor mouth
C = variable salt concent

It holds that:
$p_{\text{canal}} = 0$
$p_{\text{sea}} = 1$

PROCEDURE

We will calculate the quantity of salt water that will penetrate the fresh basin and the quantitative loss of fresh water per complete operation cycle. These quantities are seen as water volumes related to $V_{\text{chamber fresh}}$, with the assumptions that filling and draining the chamber is a continuous process with constant head difference over the ship lock, constant vessel volume (equal during both filling and emptying of the lock chamber), a constant density difference and a constant value for θ. Since the process is cyclical, calculations start at a random moment and the condition is that after one completed operation cycle, conditions similar to those at the start are obtained. We assume that in the chamber during filling and emptying complete mixing takes place.

Case A: Sea water level exceeds water level of canal

Assume the water level in the chamber is low and gates have just been closed. In the chamber a concentration p_1 is present and the chamber is now filled with salt water. The new concentration after filling is called p_2. The salt account will now be:

$$p_1(V_{\text{chamber fresh}} - \text{Ship}) + p_{\text{sea}}\,\text{Lockage prism}$$
$$= p_2\,(V_{\text{chamber fresh}} + \text{Lockage prism} - \text{Ship}) \qquad (4)$$
$$(\text{with } p_{\text{sea}} = 1)$$

Now the gates facing sea are opened. Interchange with yield θ signifies that (1 – θ) of the net chamber volume ($V_{\text{chamber salt}} - V_{\text{ship}}$) remains in the chamber and the rest is exchanged for salt water. This results in a post-interchange salt content in the chamber:

$$(1 - p_2)\,(1 - \theta) = (1 - p_3) \qquad (5)$$

(Because this formula is difficult to follow we introduce a check: If $\theta = 0$ then $p_3 = p_2$ and nothing changes, whereas if $\theta = 1, p_3 = 1$, so the concentration in the chamber becomes that of the sea water).

After the chamber is drained the concentration of the chamber water still remains p_3 and now the chamber interchanges with the harbor mouth on the canal side, after opening the gates.

$$(1 - \theta)p_3 = p_4 \qquad (6)$$

(this becomes evident: when $\theta = 1$ then $p_4 = 0$, so a complete interchange makes that pure canal water is present in the chamber after this process).

Moreover, the cycle has been completed, so conditions have to be equal to those at the start:

$$p_4 = p_1 \qquad (7)$$

Now we apply a few mathematical manipulations. By expressing Equation (7) in Equation (6) we get:

$$p_3 = p_1/(1-\theta) \qquad (8)$$

Equation (5) can be transformed to

$$p_2 = -\frac{1-p_3}{1-\theta} + 1 = \frac{p_3-\theta}{1-\theta} \qquad (9)$$

By expressing Equation (9) in Equation (4) (and with $p_{sea} = 1$) we find:

$$p_1\,(V_{\text{chamber fresh}} - \text{Ship}) + \text{Lockage prism}$$
$$= \frac{p_3-\theta}{1-\theta}\,(V_{\text{chamber fresh}} + \text{Lockage prism} - \text{Ship})$$

or, with Equation (1):

$$(p_1 + S')\,(1-\theta) = (p_3 - \theta)\,(1 + S') \qquad (10)$$

With Equations (10) and (8), two equations come about with p_1 and p_3 as variables. From this we can compute:

$$p_3 = \frac{\theta + S'}{2\theta - \theta^2 + S'} \qquad (11)$$

The salt penetration factor (i.e. the quantity of undiluted sea water which penetrates the fresh basin through draining the lockage prism and interchange operations) now becomes:

$$p_3\,\text{Lockage prism} + p_3\,\theta\,(V_{\text{chamber fresh}} - \text{Ship}) \qquad (12)$$

But since from Equation (1) it holds true that

$$\text{Lockage prism} = S'\,(V_{\text{chamber fresh}} - \text{Ship}) = S'\,V_{\text{chamber fresh}}\,(1 - V_s)$$

we now find (all expressed in volume of undiluted sea water):

$$\text{salt penetration} = V_{\text{chamber fresh}}\,(1 - V_s)\,p_3\,(\theta + S') \qquad (13)$$

From the fresh-water basin is drawn a volume equal to the salt penetration volume minus the lockage prism, or, expressed with Equations (12) and (13):

$$\text{loss of fresh water} = V_{\text{chamber fresh}}\,(1 - V_s)\,(p_3\,\theta + p_3\,S' - S') \qquad (14)$$

When we feed Equations (13) and (14) with the value for p_3 as found in Equation (11) this results in:

$$\text{sea water penetration volume} = V_{\text{chamber fresh}}\,(1 - V_s)\,\frac{(\theta + S')^2}{2\theta - \theta^2 + S'} \qquad (15)$$

$$\text{loss of fresh water} = V_{\text{chamber fresh}}\,(1 - V_s)\left(\frac{(\theta + S')^2}{2\theta - \theta^2 + S'} - S'\right) \tag{16}$$

Case B: Sea water level is lower than water level in the canal

Assume the water level of the chamber is low, with a concentration p_1 and closed gates. Now the chamber is filled with fresh water and the concentration becomes p_2.

$$p_1\,(V_{\text{chamber fresh}} - \text{Ship} - \text{Lockage prism}) + \theta = p_2\,(V_{\text{chamber fresh}} - \text{Ship}) \tag{17}$$

After opening the gates facing the canal

$$(1 - \theta)\,p_2 = p_3 \tag{18}$$

After draining the lockage prism the chamber volume with concentration p_3 interchanges at the sea-side with yield θ, after which the concentration in the chamber p_4 becomes:

$$(1 - \theta)\,(1 - p_3) = (1 - p_4) \tag{19}$$

Again it holds that

$$p_4 = p_1 \tag{20}$$

Working back we obtain:

expressing Equation (20) in Equation (19),

$$p_3 = 1 - \{(1 - p_1)/(1 - \theta)\} \tag{21}$$

expressing Equation (21) in Equation (18) gives,

$$p_2 = \frac{1 - \theta - 1 + p_1}{(1 - \theta)^2} = \frac{p_1 - \theta}{(1 - \theta)^2} \tag{22}$$

Equations (22) and (17) give:

$$(1 - \theta)^2\,p_2 = -\theta + p_2\,\frac{(V_{\text{chamber fresh}} - \text{Ship})}{(V_{\text{chamber fresh}} - \text{Ship} - \text{Lockage prism})} \tag{23}$$

If we now introduce a new dimensionless coefficient for the lockage prism according to Equation (2):

$$S'' = \frac{S}{1 - V_s - S}$$

then it holds that:

$$\frac{V_{\text{chamber fresh}} - \text{Ship}}{V_{\text{chamber fresh}} - \text{Ship} - \text{Lockage prism}} = 1 + S''$$

and so Equation (23) becomes

$$p_2(-2\theta + \theta^2 - S'') = -\theta$$

or in other words:

$$p_2 = \frac{\theta}{2\theta - \theta^2 + S''} \qquad (24)$$

Now we can also calculate the quantity of undiluted salt water that penetrates the canal:

$$\text{sea water penetration} = (V_{\text{chamber fresh}} - \text{Ship})\,\theta\, p_2 \qquad (25)$$

or, expressed differently

$$\text{sea water penetration} = V_{\text{chamber fresh}}(1 - V_s)\,\frac{\theta^2}{2\theta - \theta^2 + S''} \qquad (26)$$

Since the water level of the fresh water exceeds that of the sea, no salt penetration has been created by the lockage prism.

The salt penetration is thus purely originated from interchange and an equal amount of fresh water is drawn from the fresh basin. Moreover, the fresh water lockage prism is also withdrawn and ends up in the salt basin. Total withdrawal will now be:

$$\text{fresh-water loss} = V_{\text{chamber fresh}}\left\{S + (1 - V_s)\,\frac{\theta^2}{2\theta - \theta^2 + S''}\right\} \qquad (27)$$

Synopsis

When the salt water level exceeds that of the fresh water, then the volume of sea water will incur the fresh basin as an (undiluted) sea water volume:

With use of the quantity $S' = S/(1 - V_s)$ (1)

we find:

$$\text{sea water penetration} = V_{\text{chamber fresh}}(1 - V_s)\,(\theta + S')^2/(2\theta - \theta^2 + S') \qquad (15)$$

while from the fresh water an equal amount of water minus the lockage prism is drawn. The salt burden thus consists of a salt flow volume (lockage prism), plus an interchange volume. And an interchange volume of fresh water is drawn from the fresh basin.

When the fresh-water level exceeds that of the salt water, we will introduce the quantity:

$$S'' = S/(1 - V_s - S) \qquad (2)$$

we find

$$\text{sea water penetration} = V_{\text{chamber fresh}}\,(1 - V_s)\,\theta^2/(2\theta - \theta^2 + S'') \qquad (26)$$

while an equal quantity minus the lockage prism is drawn from the fresh water.

A first approximation of θ

Figures 11 and 16 provide approximations of the interchange percentages with and without use of an air curtain. The data are relevant for the situation without vessels and can generally be used up till $V_s = .2$. Above this value the interchange process will elapse slower because the vessel partly blocks the current's profile. In this situation air curtains will be less effective (the largest resistance is the relevant factor of measure). Because additional interchange caused by ship movements is not allowed for, the θ is indicated as θ_o.

The difference in density over the lock gate just before opening

For the computation of the interchange with yield θ, using Figures 11 and 16, the difference in density over the lock gate should be known.

When the sea water level is higher than the canal water level, the difference in concentration at the gate facing the canal equals p_3, which follows from Equation (11). At the gate facing the sea this is $(1 - p_2)$, which can be calculated.

When the calculated p_3 value is introduced in Equation (5) and if the fresh water canal level is higher than the water level of the sea, then for the gate facing the canal p_2 is a measure for the density difference which follows from Equation (24).

At the gate facing the sea $(1 - p_3)$ is a measure for the density difference, which now can be computed with Equation (18).

The influence of vessel movements on the interchange process

When ships leave the chamber, a current set inwards the chamber will originate besides the vessel and water from the harbour mouth will incur the chamber. When ships enter the chamber later on, the return current will distribute itself more or less equally over the chamber's water profile, and so only a small portion of water, which entered when the ship left, will in turn flow out of the chamber.

We propose the following correction of θ_o: For the hypothetical case of $\theta_o = 0$, ships entering and leaving will cause an interchange of $0.8V_s$ ($0.2\,V_s$ will return in the chamber from the harbor mouth), so $\theta_o = 0$ gives $\theta = 0.8V_s$. In which θ_o

signifies the interchange expected in a situation without vessels.

With $\theta = 1$ everything is interchanged, the vessel cannot add anything to this quantity. So $\theta_o = 1$ gives $\theta = 1$.

In between the situations with $\theta_o = 0$ and $\theta_o = 0$ we apply a linear interpolation (given the lack of further information), which results in:

$$\theta = \theta_o + (1 - \theta_o)\, 0.8\, V_s \tag{28}$$

The situation in which the sea level is higher and the lockage prism is drained back to sea

In Equation (13) the salt penetration which originates without pumping back the lockage prism is expressed as a volume water $V_{\text{chamber fresh}}\,(1 - V_s)\,(\theta + S')$ times the concentration p_3 present in the chamber before draining was started.

If the lockage prism is pumped back to sea then the volume of water is diminished with the volume of the lockage prism. Thus the decrease in the salt intrusion, expressed as a factor R, becomes:

$$R = \frac{\{V_{\text{chamber fresh}}(1 - V_s)\,(\theta + S')\} - \text{Lockage prism}}{V_{\text{chamber salt}}(1 - V_s)\,(\theta + S')} \tag{29}$$

Since according to Equation (1) it also holds that

$$S' = \frac{S}{1 - V_s} = \frac{(\text{Lockage prism}/V_{\text{chamber fresh}})}{(1 - V_s)}$$

we can re-write Equation (29) as:

$$R = 1 - \frac{\text{Lockage prism}}{V_{\text{chamber fresh}}(1 - V_s)(\theta + S')} = \tag{30}$$

$$1 - \frac{S' \quad '}{(\theta + S')} = \frac{\theta}{(\theta + S')}$$

APPENDIX B

Theoretical approach of the air quantity needed for an air curtain as a salt-fresh separation system

The situation with an air curtain in a homogeneous fluid (Figure B1) can be described as a sucking-in of water in the under layer (with a discharge q_w on both sides) and an outflow down of an equal discharge in the upper layer. In the following derivation of the water discharge three zones are introduced, each with a constant liquid density. These zones are separated by verticals and at each of these verticals there exists a two-layered current, which is related to the density difference on both sides. The middle zone is located above the air curtain. Equation (16) which calculates exchange discharges and which was derived for the two-layered current with density differences in Section 4.1, here theoretically defines the influx discharge in the bottom layer (and also the outflowing discharge in the upper layer).

$$q_a = \tfrac{1}{2}h\left(\tfrac{1}{2}\sqrt{\varepsilon gh}\right) \tag{1a}$$

This now becomes:

$$q_w = \tfrac{1}{2}h\left(\tfrac{1}{2}\sqrt{\varepsilon gh}\right) \tag{1b}$$

For the exchange velocity created Equation (15) holds

$$u_a = \tfrac{1}{2}\sqrt{\varepsilon gh} \tag{2a}$$

which for the situation of Figure B1 now becomes:

$$u_w = \tfrac{1}{2}\sqrt{\varepsilon gh} \tag{2b}$$

Case A: An air curtain is placed on the floor in a homogenous situation

The situation is symmetrical: To the left and right of the air curtain similar conditions exist. Because of blending of the discharge influx in the bottom layer (i.e. $2q_w$) and the air discharge (q_{air}), a mixture with density ρ_m originates:

$$\rho_m = \frac{\rho_{air}\, q_{air} + 2\rho_{water} q_w}{q_{air} + 2q_w} \tag{3}$$

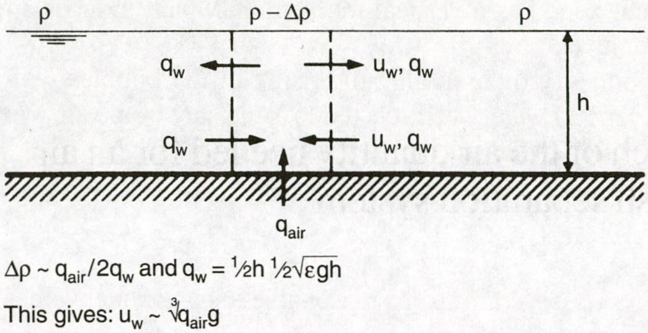


Figure B1. Two-layered current caused by an air curtain.

The relative density difference is now (with the additional assumption that ρ_{air} is negligible)

$$\varepsilon = \frac{\rho_{water} - \rho_m}{\rho_{water}} = 1 - \frac{2q_w}{q_{air} + 2q_w} = \frac{q_{air}}{q_{air} + 2q_w} \tag{4}$$

As long as ε is not too large (in practice this is several percentiles), $q_{air} + 2q_w$ can be approached by $2q_w$, so:

$$\varepsilon = \frac{q_{air}}{2q_w} \tag{5}$$

From Equations (5) and (1b) we can now derive, after eliminating ε, the following relationship between q_w and q_{air}:

$$q_w = ½\, h \sqrt[3]{q_{air}\, g/4} \tag{6}$$

It also holds that:

$$u_w = \frac{q_w}{½h} \tag{7}$$

Combining Equation (7) with Equation (6) computes the following value for the water velocity:

$$u_w = \sqrt[3]{q_{air}\, g/4} \tag{8}$$

Velocities recorded during testing* are a factor 2 larger than would follow from calculations in Equation (8). This is related to the fact that the water outflow only occurs at the upper 25% portion of the water depth. This in turn could be related to

*Bulson, P.S. 'Currents produced by an air curtain in deep water', Dock and Harbor Authority, 42, Number 487, May 1961.

the fact that the mixed water zone has a vertical momentum which induces an extra pressure near the water level.

We can further refine the theory by assuming the rising of the bubbles with velocity u_{ri} (relative to the vertical water velocity) reduces the stay of the air. We take for U_{ri} a velocity of 0.3 m/s. This results in:

$$\varepsilon = \frac{q_1}{2q_w} \frac{u'_w}{u'_w + u_{ri}} \tag{9}$$

Given the patterns of currents observed, it seems reasonable to have equal values for u'_w and u_w, so:

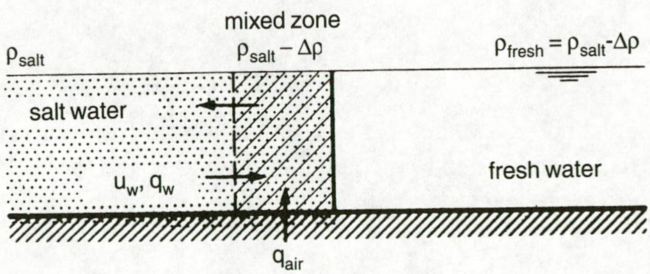
$$\varepsilon = \frac{q_{air}}{2q_w}\left(1 + \frac{u_{ri}}{\sqrt{q_{air}\, g/4}}\right)^{-1} \tag{10}$$

Here U'_w is the increase of velocity of the water. In practice, application of (10) does not alter much in the derivation of u_w. For tests performed with scale models this is different, since u_{ri} will not decrease as much as the water velocities in a small scaled test.

Case B: An air curtain used for salt-fresh water separation

One side of the blended zone (above the air curtain) is bordered by fresh water, the other by salt water (refer to Figure B2 for a schematized illustration). If we assume the water in the blended zone holds the same density as the fresh water, then a two-layered interchange current will develop on the salt side and no interchange will occur on the fresh side. The salt water that penetrates the blended zone at the bottom will mix with air. The quantity of air needed to achieve the abovementioned situation can now be calculated. The salt water will be supplied from only one side, thus the factor $2q_w$ in Equation (10) now becomes q_w.

$$\varepsilon = \frac{q_{air}}{q_w}\left\{1 + \frac{u_{ri}}{\tfrac{1}{2}\sqrt{\varepsilon g h}}\right\}^{-1} \tag{11}$$



$\varepsilon = (q_{air}/q_w)\{u_w/(u_w+u_{ri})\}$

$\rightarrow q_{air_o} = \tfrac{1}{4}h\sqrt{\varepsilon gh}\,\varepsilon(1 + 2u_{ri}/\sqrt{\varepsilon gh})$

Figure B2. An air curtain as salt-fresh water separation system.

By combining Equations (1b) and (11) q_w can be eliminated and the air discharge needed will be expressed as a function of ε and u_{ri}. This (theoretically) needed air discharge is defined as q_{air_o} and when presenting measurings, we use as dimensionless parameter:

$$q_{\text{air}}/q_{\text{air}_o} \tag{12}$$

The value q_{1_o} which can be derived from Equations (1b) and (11) is

$$q_{\text{air}_o} = \tfrac{1}{4}\,\varepsilon\, h\sqrt{\varepsilon g h}\left[1 + \frac{2u_{ri}}{\sqrt{\varepsilon g h}}\right] \tag{13}$$

The prototype measurings indicate to which degree the interchange process is reduced in a ship lock, with gates opened for a certain time interval and as a function of $q_{\text{air}}/q_{\text{air}_o}$. They are presented in Figure 16.

The air discharge values indicated by Abraham v.d. Burgh (1973) are relevant to atmospheric pressure, whereas Equation (12) and Figure 16 deal with the air quantity which is administered at the floor.

APPENDIX C

Calculation of the maximum force athwartships in salt water, with a fresh water bubble situated on one side

A fresh water bubble located on one side of the vessel can originate in two ways: a.) The vessel is, in a situation with a thin upper layer consisting of fresh water, pulled or pushed (by cables and/or rudder) to the nearest lock chamber wall and so the fresh water becomes entrapped between the vessel and the lock wall; b.) fresh water is let in through a wall slot on one side of the vessel (Figure C1 presents the situation and the symbols).

The situation with a maximum of the force athwartships comes about when over the entire draught of the vessel, on one side fresh water is present and salt-water on the other. At the depth of the ship's bottom an equal pressure is present on either side of the boat. Thus it holds that:

$$Z = (\rho_{salt} - \rho_{fresh})\, d_s/\rho_{salt} \simeq \varepsilon\, d_s \qquad (1)$$

The pressure difference left-right that equals $\rho g z$ on top decreases linearly to zero at the bottom.

$$\Delta p_{average} = \tfrac{1}{2}\rho g Z = \tfrac{1}{2}\varepsilon\rho g d_s \qquad (2)$$

In relation to the vessel volume the total force athwartships now becomes:

$$D/\rho g L d_s b_s = (L d_s)\, \tfrac{1}{2}\varepsilon\rho g\, d_s/\rho g\, L d_s b_s = \tfrac{1}{2}\varepsilon d_s/b_s \qquad (3)$$

When

$$\varepsilon = (\rho_{salt} - \rho_{fresh})/\rho_{salt} = 10‰$$

and

$$b_s = 3 d_s$$

then it follows that

$$D/\rho g\, L d_s b_s = (10‰)/6 = 1.5‰ \qquad (4)$$

This value signifies a theoretical maximum. In reality, some fresh water will also surface at the opposite side of the vessel (and certainly in the mooring situation

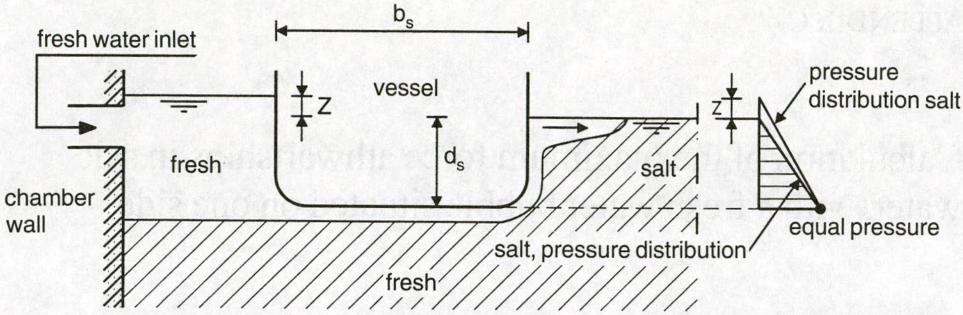


Figure C1. Pressure difference over the vessel while fresh water is admitted through a wall slot.

where the bubble was caused by entrapment of the fresh layer), while additional fresh water will flow down over the length of the ship (at which location an interchange current will originate).

APPENDIX D

Minimum discharge requirement to prevent salt water intrusion in a wall slot

The minimal discharge required to prevent salt incursion follows from a study of a permanent current-situation in which the salt 'tongue' is stationary and the fresh water flows over it. The slope of the fresh-salt water interchange becomes steeper as the fresh-water discharge increases. Theoretically, the slope can even become infinitely steep. With an even greater discharge of salt the interface cannot exist and the salt water tonque disappears.

In the limit situation, when the under layer just stopped flowing, the pressures in the salt can be presumed purely hydrostatical, with no pressure gradient in direction x. This means (refer to illustration to the right) that when z increases and with a given value for p_o at the bottom, the pressure in the upper layer (to be signified as p_1) decreases. In the upper layer it now holds that:

$$\frac{dp}{dx} = -\Delta\rho\, g\, \frac{dz}{dx} \qquad (1)$$

The movement in the upper layer can be defined with Equation:

$$\frac{dp}{dx} = -\rho\, v \frac{dv}{dx} - \frac{(\tau_1 + \tau_2)}{h} \qquad (2)$$

(v and h are the velocity and thickness respectively in the fresh layer and τ_1 and τ_2 are the shear stresses at the interface and the ceiling).

Since q in the upper layer is constant it holds that:

$$v\frac{dv}{dx} = \frac{q\,d(q/h)}{h\ \ dx} = -\frac{q}{h}\frac{q}{h^2}\frac{dh}{dx} \qquad (3)$$

Because

$$\frac{dh}{dx} = -\frac{dz}{dx} \qquad (4)$$

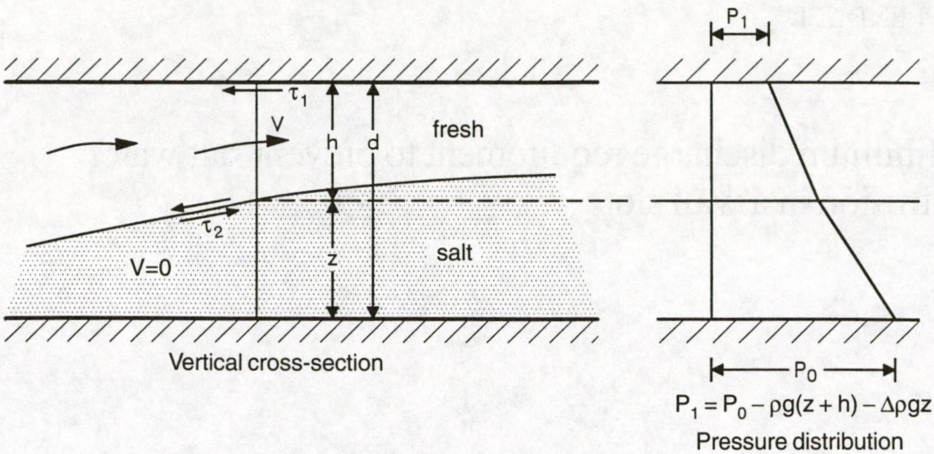


Figure D1. Stationary salt 'tongue' in a closed conduit.

Equation (2) becomes, when we express Equations (1), (3) and (4) as functions thereof:

$$-\Delta\rho g\frac{dz}{dx}=-\frac{\rho q^2}{h^3}\frac{dz}{dx}-\frac{(\tau_1+\tau_2)}{h} \tag{5}$$

Because $q/h=v$, we obtain after dividing by $-\Delta\rho q$ and introducing $\varepsilon=(\Delta\rho)/\rho$:

$$\frac{dz}{dx}\left(1-\frac{v^2}{\varepsilon gh}\right)=\frac{\tau_1+\tau_2}{\Delta\rho gh} \tag{6}$$

The salt tongue is non-existant when at the front it holds that:

$$\frac{v^2}{\varepsilon gh}=\frac{v^2}{\varepsilon gd}=1 \tag{7}$$

In that case,

$$\frac{dh}{dx}=\infty \tag{8}$$

From this the discharge will follow

$$q=d^{3/2}\sqrt{\varepsilon g} \tag{9}$$

This can be re-written. Since $v=q/d$, it follows from Equation (9) that:

$$\frac{v}{\sqrt{\varepsilon gd}}=1 \tag{10}$$

Or in other words, the *internal Froude number* equals 1.

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Salt-freshwater exchange occurs at all ship locks in tidal areas. This is for various reasons unwanted; it reduces the economic value of water for irrigation and industrial purpose and ecologic damage can occur. To prevent or to reduce this exchange several means can be considered: Management of the lock which includes care for water quality; Flushing the inland basin; Pumping back the salt water lockage prism into the sea; Retarding the natural salt-freshwater exchange-current by an air curtain, combined with soonest possible closing of the main lock gate; Flushing back penetrated salt water immediately away from the lock; Pumping out or draining by natural drop the salt water in the lock chamber and simultaneously replacing it with fresh water before the gates are opened; System 'salt lift trough' (a special device).
These systems are described in detail and their efficiency is estimated using experience gained from realized projects in the Netherlands and results of theory and scale-model testing. It is discussed how to estimate acceptable exchange volumes versus demand on water quality and water quantity available for flushing. This relation is needed to judge the cost effectiveness of the measures which are taken to prevent exchange of salt and fresh water at navigation locks.