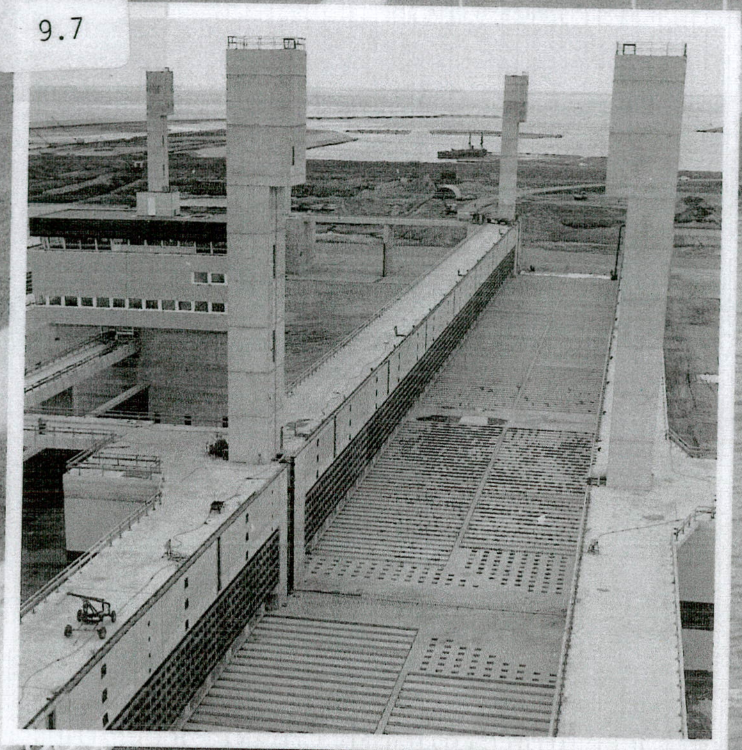

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PREVENTION OF SALT AND FRESH WATER EXCHANGE

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Prevention of Salt- and Fresh Water Exchange

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Contents

Preface

This publication provides an overview of research done on the separation of salt and fresh water at ship locks in the Netherlands. The knowledge was obtained through studying many realized projects and the scale models that preceded them.

The objective of this publication is to provide deeper insights that could prove beneficial for the application of future projects. Where possible, results of research with scale models, theory and real life experiences are noted so as to provide choices in studies and planning. At the same time, too-specific details were omitted in order to maintain a reasonable standard of readability.

The original Dutch version encompasses a second part that looks at existing Dutch systems specifics. This second part, however, is first and foremost concerned with background information concerning management and maintenance of the systems, and is not relevant to their design.

This publication is a joint effort of the Ministry of Transport, Public Works and Water Management, Directorate Rijkswaterstaat and Delft Hydraulics (Waterloopkundig Laboratorium). The authors* co-operated closely in designing and developing these systems to reduce salt-fresh water exchange at navigation locks. However, the total planning and design process of all complicated systems has been performed by many others, forming teams of varied constitutions. They all contributed to these innovative designs.

*J. Kerstema, project engineer, P.A. Kolkman, adviser and H.J. Regeling, project engineer, Delft Hydraulics; W.A. Venis adviser, Rijkswaterstaat.

List of symbols

a	distance ship to adjacent chamber wall (m)
b	distance ship to distant chamber wall (m)
C	concentration of salt (salt content)(kg chlorion/m^3)
C_B	average concentration of salt in the inland basin (kg chlorion/m^3)
C_{inland}	salt content of basin (kg chlorion/m^3)
C_{outside}	salt content of water outside the basin (kg chlorion/m^3)
C_o	salt content at the lock side of the basin (kg chlorion/m^3)
C_o	salt content at the lock, fresh-water basin side (kg chlorion/m^3)
C_s	salt content of sluiced water (kg chlorion/m^3)
C_r	salt content of feeder or river discharge (kg chlorion/m^3)
C_t	maximum salt content allowance (kg chlorion/m^3)
C_z	salt content of salt harbour mouth (kg chlorion/m^3)
d	height slot (opening) in wall or culvert height
D	dispersion (m^2/s)
D	height of slot (m)
F_i	$u/\sqrt{\varepsilon gh}$ internal Froude number
g	acceleration in gravity (m/s^2)
h	water depth (m)
h_1, h_2	height of salt-fresh water interface in Section I and II (m)
K	$Q \cdot C$ = salt transport (kg chlorion/s)
SCO	short compartment of subdivided chamber
L	length of lock chamber (m)
L	length (m)
LCO	long compartment of subdivided chamber
$100 \cdot n$	percentage of fresh water flushed along
p	measure for salinity decrease related to distance (m^{-1})
p_1, p_2	pressure in the salt- and fresh-water, respectively (kg/m.s^2)
q	discharge per unit of width (m^2/s)
q_a	interchange discharge (per layer) per m′ (m^2/s)
q_{air}	air discharge per m′ (m^2/s)

q_{air_o}	theoretical discharge of air needed to prevent interchange (m^2/s)
q_L	discharge through left wall slot (m^2/s)
q_R	discharge through right wall slot (m^2/s)
q_s	sluicing discharge per m′ (m^2/s)
q_w	water discharge per m′ in under or upper layer (m^2/s)
Q	(water) discharge (m^3/s)
Q_d	net discharge flowing through (m^3)
Q_{sluice}	sluicing discharge (m^3)
Q_i	interchange discharge (m^3)
S	relative lockage prism (Lockage prism volume/$V_{chamber\ fresh}$)
t	time (s)
T_a	interchange time duration (s)
u	current velocity (m/s)
u_a	(horizontal) velocity of interchange current (m/s)
u_{ri}	rising velocity of air bubbles (m/s)
u_w	water velocity in under or upper layer (m/s)
$V_{chamber\ fresh}$	chamber volume belonging to the water level ‘fresh’ basin (m^3)
$V_{chamber\ salt}$	chamber volume belonging to the water level ‘salt’ basin (m^3)
V_s	relative vessel volume (in relation to $V_{chamber\ fresh}$)
V_{ship}	vessel volume (m^3)
V_1, V_2	velocities in Sections I and II (m/s)
x	ordinate (or distance to lock) (m)
X_O	distance between irrigation admission point and lock (m)
z	vertical coordinate (m)
Z	depth under water surface (m)
Z	water level difference on both sides of the vessel (m)
Z	penetrated of salt (kg chlorion)
Z	quantity of salt (kg chlorion)
α	resistance over the slot (s^2/m^3)
ΔE_{pot}	difference in potential energy (kg m^2/s^2)
ΔE_{kin}	difference in kinetic energy (kg m^2/s^2)
Δh	water level difference (m)
Δh_L	water level difference over left wall slot (m)
Δh_R	water level difference over right wall slot (m)
ΔL	distance travelled (m)
$\Delta\rho$	density difference in liquid (kg/m^3)
Δp	difference in pressure ($kg/m.s^2$)
Δt	time (s)
ε	relative water density $=(\rho_{salt} - \rho_{fresh})/\rho_{fresh} \simeq (\rho_{salt} - \rho_{fresh})/\rho_{salt}$
ρ	density of water (kg/m^3)
ρ_{HT}	density during high tide (kg/m^3)
ρ_m	density of air-water mixture (kg/m^3)
ρ_{fresh}	density fresh water (kg/m^3)

ρ_{salt}	density salt water (kg/m^3)
θ	actual volume interchanged/volume of completed interchange
θ_o	volume interchanged without vessel influence as related to volume of completed interchange

CHAPTER 1

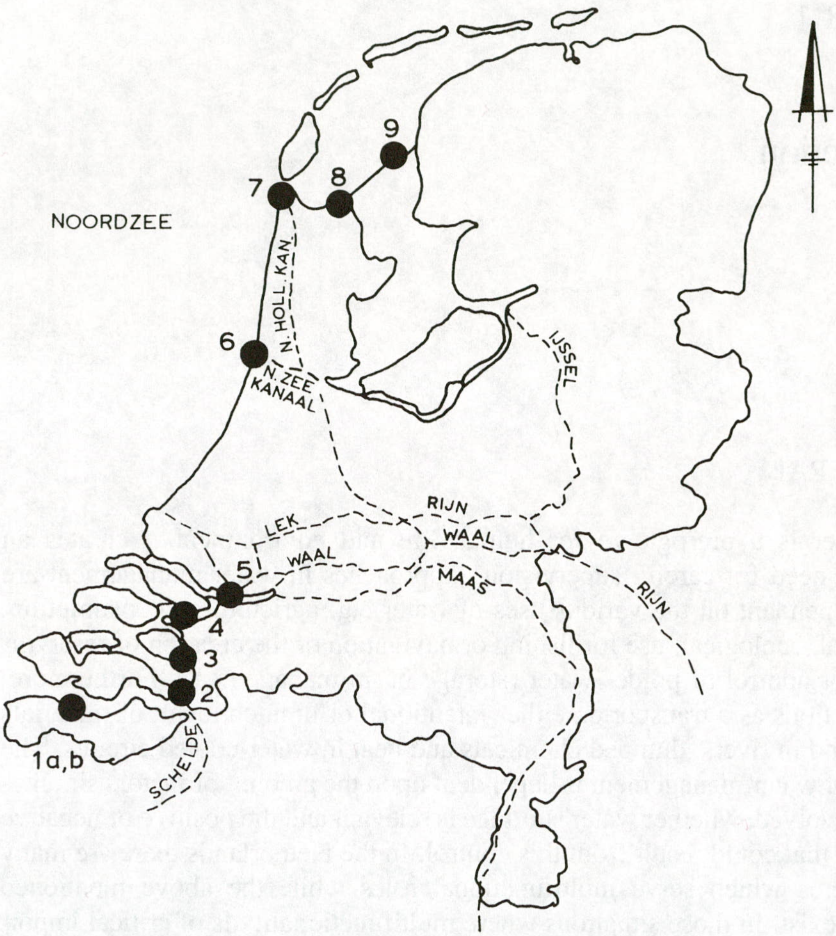
Introduction

1.1 GENERAL

Since water is a prerogative for human life and environment it creates an increasing need for careful supervision. Approaches in water management are heavily dependent on the various uses of water e.g. agricultural, consumption, recreational, ecological, use for fishing or navigation or the creation of reservoir systems for control of polder water (storage basin management). Furthermore, water functions as a transporter, either intentional or unintentional, of materials such as sand in rivers, dumped chemicals and heat in water-cooled circuits. The intensity of water management is dependent upon the amount of factors simultaneously involved, whether water shortage is relevant and the positive or negative influences that could result from this control. In the Netherlands there are many watersystems which serve multifunctional roles while the above mentioned situations exist. In those situations where multifunctionality is of critical importance, a need for precise demands of water quality and quantity arises. Obviously, management of multi-functional systems is a complex and delicate matter, especially when demands are incongruent to a certain degree.

Consequently, analysis of the system and its functions becomes necessary to form a strategic management plan that is comprehensive and effective seen within the totality of presented factors.

The objective of this publication is to point out the technical possibilities of one of the means which have become available in quality improvement of water management. This device is the realization of segregating salt and fresh water at shiplocks. The examples given in the publication are drawn from experiences with salt- and fresh-water segregation that became necessary on the edges of the Zoommeer, the Oosterschelde, Terneuzen, IJmuiden and Den Helder (see Figure 1). The publication's structure is as follows: First, the functions of water in the Netherlands and how these functions conflict with and influence each other. Also, the different sources of water in the country are summed up. This introduction is meant to note and underline the complexity involved in the decision making



1a Ship lock Terneuzen for ocean navigation (system Terneuzen)
1b Terneuzen inland navigation locks (air curtain)
2 Kreekrak locks
3 Bergsediep lock (Zoommeer lock)
4 Krammer locks
5 Volkerak lock (featuring a temporary air curtain for the period in which the Volkerak contained salt water and the Haringvliet fresh water)
6 IJmuiden lock (air curtain and pumping station), air curtain now out of use
7 Den helder lock (selective draining at the pumping station)
8 Den Oever lock (air curtain)
9 Kornwernerzand lock (air curtain)

Figure 1a. Locations were salt- fresh water separation systems are operative.

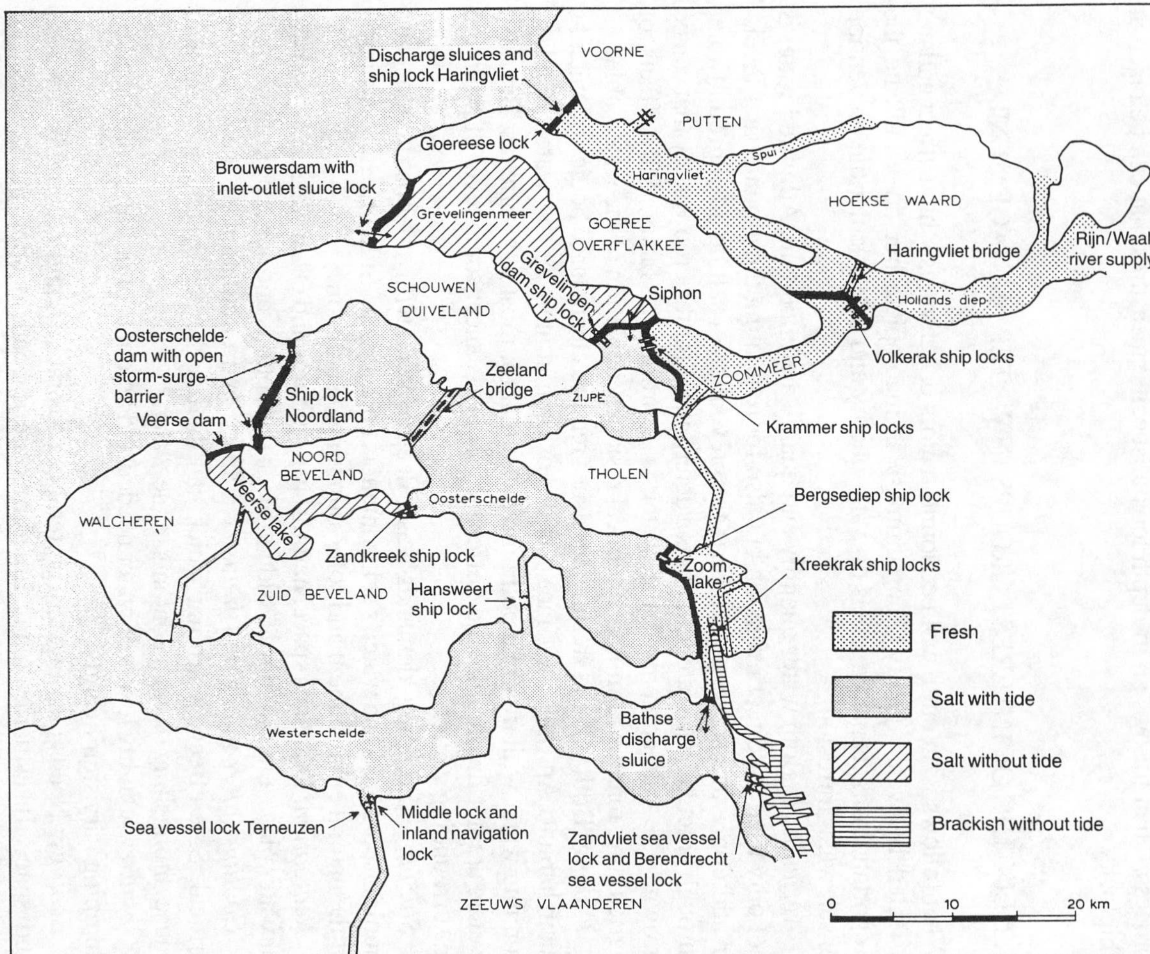


Figure 1b. The situation in the Delta area in more detail.

process. Then follows an in-depth look at specific measures that can be taken at shiplocks.

1.2 LISTING OF INTEREST GROUPS IN WATER MANAGEMENT

What follows is an outline of economic sectors or activities which affect and are affected by water quality. The summary is incomplete but does indicate the importance of acceptable levels of water quality and in particular the prevention of salt water intrusion.

Agriculture: Both water quantity and quality are important. Admitted water is not only used for direct irrigation but also for regulating the groundwater levels. In addition, water serves a purpose in the prevention of salting up of groundwater through perculation. Water quality is a determinant for the crop variety that can be grown. The salt content of the water is a prominent factor. Side-effects of agriculture: manure dumping, chemical residues, depletion of the water table.

Fishing: Both salt and fresh water fishes require clean, large bodies of water as their habitat. An important factor is the oxygen content of the water. Shallow, running water with minimal pollution is optimal for most fish varieties. Brackish waters are not favourable. Side-effects of fish existance: some level of pollution in surrounding water.

Shipping: Shipping demands vast, deep waters with no obstructions and minimal currents. The water's salt content is not an issue. Side-effects: disruption of the natural environment and some dumping, usually oil.

Recreation: Demands space, natural surroundings and clean water. Salt content of water plays a minimal role. Side-effects: disruptions and some pollution.

Cooling (*of reactors and industry*): Space and circulation of the water are critical. Side-effects: warming which can disrupt the eco-system and can also cause diminishing oxygen contents in the water.

Industry: Quality levels of water needed and amounts of pollution produced by dumping vary significantly.

Ecology: Needs clean water (preferably not brackish and preferably running) and space. In estuaries many life forms are dependent upon the presence of vertical tides (with alternating dry banks and plates) in these tidal marshes. Side-effects: a necessity for vast space, excess manure production by inhabitant birds.

Drinking water: Demands very clean water with a low content of salt and other aromatic matter, as well as no chemical or biological pollution. In most cases free surface water cannot be used directly for consumption purposes. Sometimes, the levels concerning chemical pollution and salt content are met at higher discharge conditions of rivers. Side-effects: decrease in groundwater levels.

The sources of fresh water in the Netherlands are rain water and water supplied by the rivers Rijn (Rhine) and Maas (Meuse). During periods when the discharge is low, the Rhine already holds a relatively high salt content at the location it flows into the Netherlands, at Lobith. Consequently, a large area of Dutch agricultural lands suffers. The problem is intensified in those areas where other salt water sources are also present. Rhine water is also used for irrigation of the northern part of the country; the IJsselmeer has several points where the polders let in water. For a overview of locations, refer to Figure 1a.

1.3 PREVENTION OF SALINISATION IN THE NETHERLANDS

From the last paragraph it has become evident that water-quality control has high stakes. Preventing salinisation of surface waters plays a principal role. In the country, both management of reservoir systems for storage of irrigation water and for superfluous polder waters ('boezems') as well as control of the fresh-water supply basins IJsselmeer and Zoommeer are critical. From the agricultural perspective, profits are highest in the horticultural and bulb growing branches. In the horticultural area Westland, percolating salt water in the ground (seepage) has to be fought by flushing the soil. Irrigation of the area is increasingly performed with costly drinking water. In the northern part of the province Noord-Holland the situation was much improved when the canal and 'boezem' system was more intensely flushed and a system for retarding the salinisation process was installed at the ship locks and at the large pumping station at Den Helder. Both these factors, combined with the particular characteristics of the soil, made bulb growing activities possible. Consequently, the value of the soil was much increased.

Figure 1 shows that at strategic places along the coast line or other locations in contact with both salt- and fresh water, special measures were taken to prevent salt water entering at ship locks. The methods used will later be explained in detail. With a look at history the choice of systems for separating fresh- and salt water becomes clear. In existing ship locks the only preventive method available would be installation of an air curtain. This system retards salt water incursion. It became available in the latter part of the '50s and was the first of its sort. With the building of new large pumping stations to flush the polders, use was made of 'selective withdrawal'; it was taken into account that heavier salt water has a tendency to sink beneath the lighter fresh water. Only in the '60s more advanced systems of water separation at ship locks were introduced, which are an especially worthwhile investment with intensive use of the locks.

CHAPTER 2

Management of a basin related to the problem of saline intrusion

2.1 COMPARISON OF THE SITUATION IN AN ESTUARY BEFORE AND AFTER CLOSURE

Prior to deciding to close off an estuary we will have to examine the consequences for water quality. A number of factors are of critical importance in the decision-making process: The need for safety from floods, increasing the water level for shipping purposes, the possibility of creating a fresh-water basin and/or preparation for land reclamation in the future.

Closed-off basins will never be considered for use as a brackish basin. From an ecological point of view it creates a decrease in the variety of living species and the water would become 'dead', i.e. will hold inadequate variety of species. An option is to leave the created basin a salt-water basin. This has occurred at the Grevelingenmeer, which has created an area of high ecological and recreational value.

Is opted for a fresh water basin, then the necessity arises for a short transitional period from salt to fresh water. This is to ensure the (marine) eco-system dies off only once, and the process will not continue into an eco-system of brackish water. The process produces matter which pollutes the water and gives off stench. The fresh water eco-system starts off very one-sided. To obtain more variety in the eco-system cleaning actions could be necessary.

In comparison with the situation before closure a stagnant bay will pollute faster and will hold a lower oxygen level. In the original situation, i.e before closure, tides cause the salt water not to penetrate too far inland even if the river discharge is rather low. Of course, stronger tides cause more violent movements of salt and mixing of waters through the velocity created. It is this mixing (in particular the vertical mixing), however, that makes that horizontal salt penetration can only occur through turbulent diffusion. Without the mixing, the two water varieties will not mix into a completely homogenous mixture and the situation will remain layered, with the heavier water spreading more horizontally. Salt penetration caused by this spreading is much stronger than the penetration

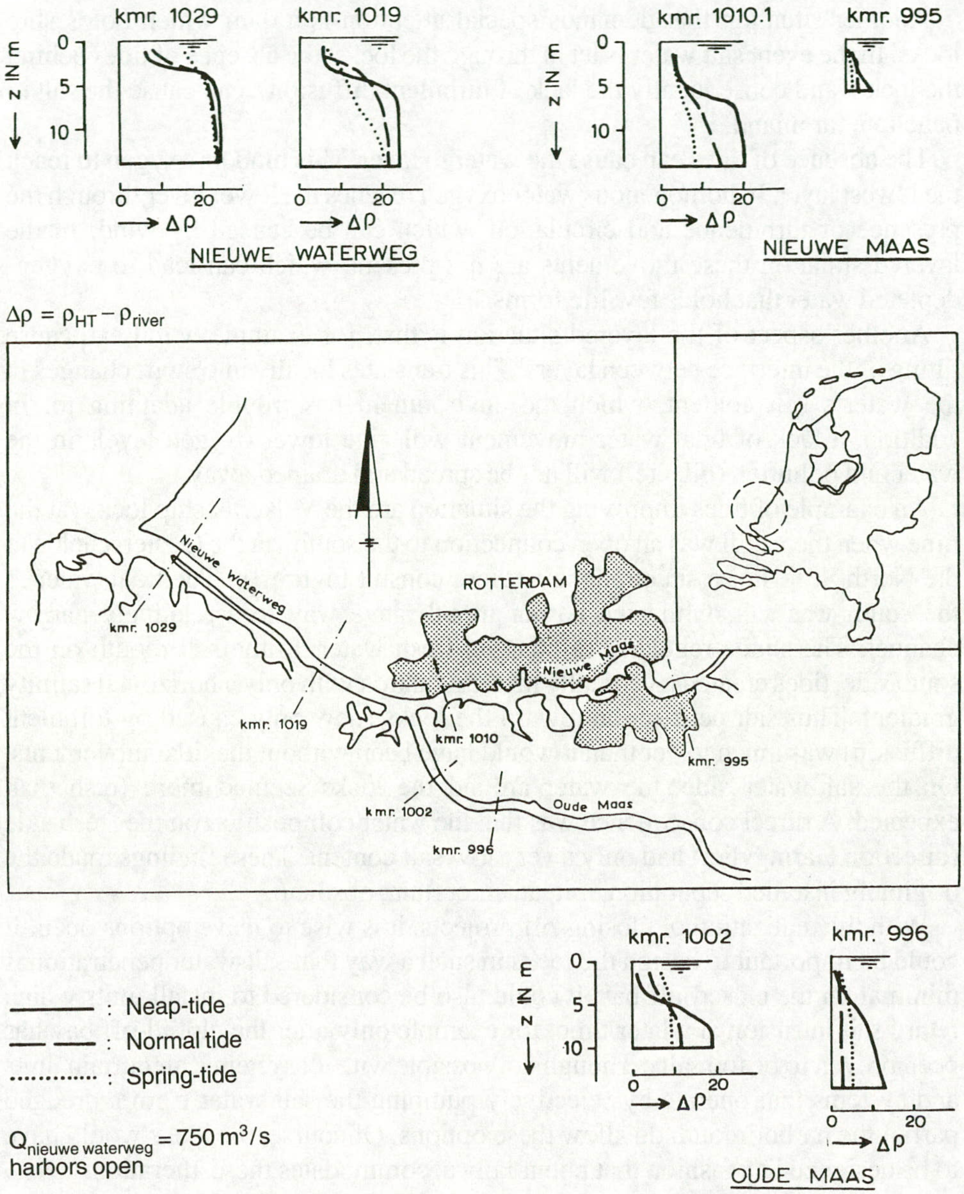


Figure 2. Degree of blending in and around the Nieuwe Waterweg at Rotterdam, taken from Abraham et al. 1986.

caused by turbulent blending. Figure 2 illustrates this phenomenon: at the Nieuwe Waterweg and in particular a little more inland at the Oude Maas and the Nieuwe Maas the most mixed situation occurs during springtide. At this tide the average salt content in the Nieuwe Maas is lower. Figure 2 indicates water density during high tide.

Another situation that demands special attention is a dam which holds ship locks. In the event salt water is let in through the locks, the absence of tides behind the locks (and consequently the lack of turbulent diffusion), can cause the salt to penetrate far inland.

The absence of tides can cause the water to layer. This hinders oxygen to reach the lowest layer. In homogenous water oxygen reaches the lower layer through the presence of turbulence and circulation, which can be caused by wind. In the layered situation these movements are not present, which can lead to oxygen-depleted water that holds few life forms.

Another aspect of the layered situation is that, for example, wind can cause tilting of the interface between layers. This translates locally into swift changes in the water's salt content, which the environment has trouble adapting to. In addition, a lack of tidal water movement will give lower oxygen levels in the water and pollution (oil, etc.) will not be spread and drained away.

An example of tides improving the situation are the Volkerak ship locks (at the time when there still was an open connection to the south via the Oosterschelde to the North Sea). For a situational overview, consult Figure 1b. The tidal water to the south was salt, while the harbor mouth gave way to a relatively narrow channel. The sluice regularly discharged fresh water. In the salt mouth on the south side, tides created a vertically mixed situation with only a horizontal salinity gradient. Thus salt penetration toward the locks (now only caused by turbulent diffusion) was much lower than it would have been without the tidal movements. On the salt-water side, the water around the locks seemed more fresh than expected. A direct consequence was that the water composition on the fresh side (direction Haringvliet) had only a very low salt content. These findings made the originally installed separation unit, an air curtain, obsolete.

With the realization of closing-off projects, it is wise to leave options open. It could be important to design the locks in such a way that salt-water penetration is minimal on the closed-off bay. It could also be considered to install units which retard salt intrusion at a later time, for example only after the closed-off bay has been proven to be too salty. Though not possible with all systems, air curtain units and systems that operate by selectively pumping the salt water from a dredged part of the harbor mouth do allow these options. Of course, the locks would have to be designed in a fashion that potentially accommodates these alterations.

2.2 QUALITY CONTROL OF A FRESH-WATER BAY: PREVENTION OF SALT INTRUSION

Figure 3 shows a situation in which a fresh-water basin is bordered by a dam with ship locks. Scetch A indicates the location of feeding points and draining points. Some of these locations are determined by the natural conditions, others reflect human interests. The discharging sluice is necessary to drain excess water.

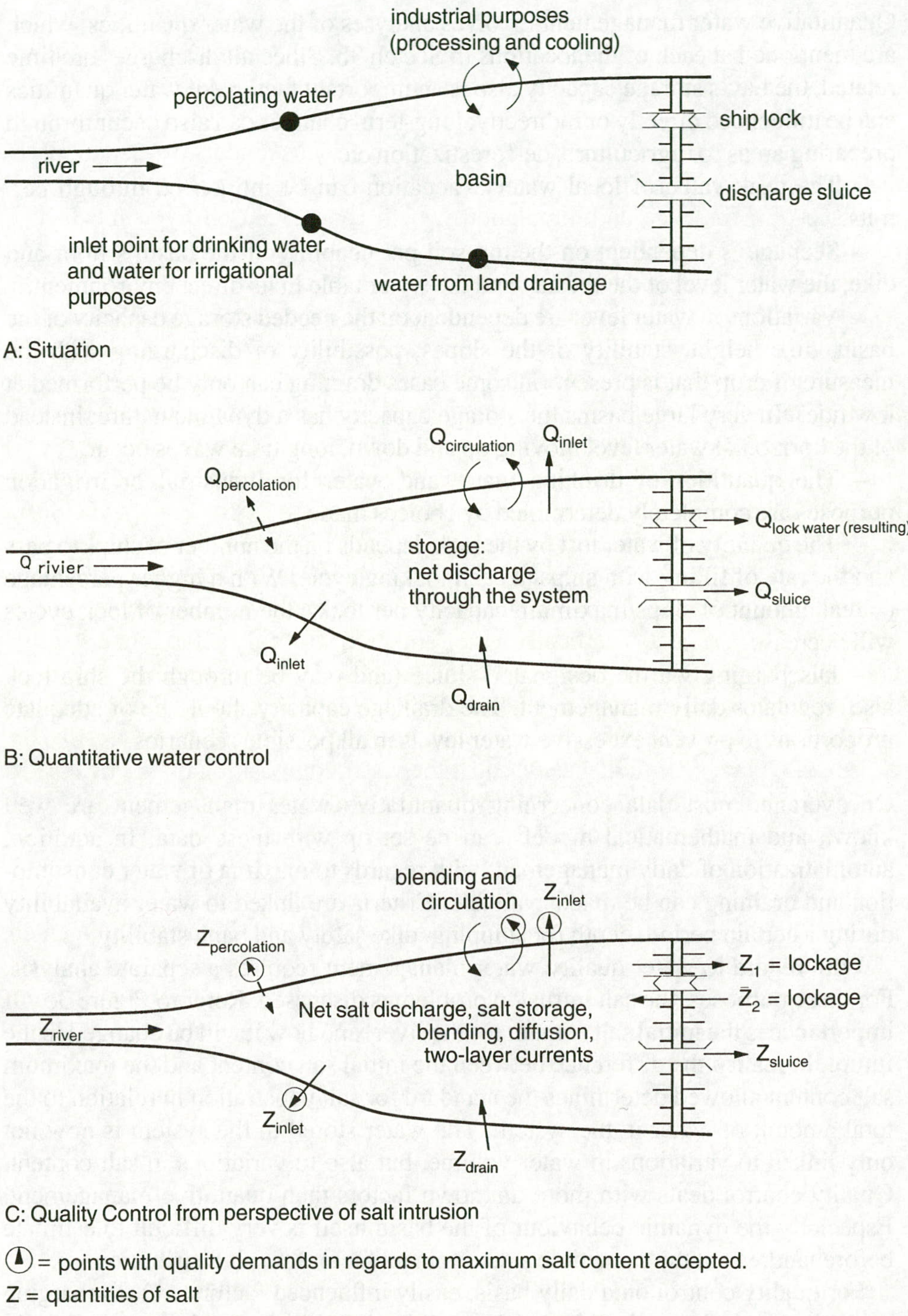


Figure 3. Basin management from the viewpoint of quantity of water and water quality in relation to the perspective of salinity.

Quantitative water management involves analyses of the water quantities, which are mentioned at each of the locations in Scetch 3b. Since all discharges are time related, the bay's storage capacity also is an important factor. All water quantities can be influenced directly or indirectly; long-term changes can also occur through preparing areas for agriculture, de-forestization etc.

– The peak value of local water evacuation can be influenced through permits.

– Seepage is dependent on the top soil permeability of the basin's floor and dike, the water level of the the bay and the water table in its direct environment.

– Variations in water level are dependent on the needed storage capacity of the basin, dike height, stability of the slopes, possibility of discharging with the measure of drop that is present (in some cases draining can only be performed at low tide). In very large basins the storage capacity has a dynamic nature; instead of the horizontal water level moving up and down, long tidal waves occur.

– The quantities of drinking water and water for industrial or irrigation purposes are completely determined by choices made.

– The quantity of water lost by the lock depends on the number of ships to pass and the rate of filling with ships at each locking cycle. With a higher percentage (= real amount of ships/maximum capacity per lock), the number of lock cycles will decrease.

– Discharging via the designated sluice (and may be through the ship lock also) regulates daily management. The drainage capacity should be of adequate proportions to prevent excessive water levels in all possible scenarios.

On average, most data concerning quantitative water management are well known and mathematical models can be set up with these data. In addition, automatization of daily management with regards to maxima of water consumption and draining can be made available. Criteria are linked to water availability during a certain period, depth for shipping, dike safety and bank stability.

With regard to water quality, water management requires a separate analysis. For these purposes, the salt intrusion problem is discussed. Refer to Figure 3c. Of importance is the initial salt content (of the river) and how it will be changed in the future. In reality, the difference between the initial salt content and the maximum salt content allowed determines the standard for salt penetration in relation to the total amount of water in the system. The water stored in the system is now not only linked to variations in water volume, but also to variations in salt content. Quality control deals with more unknown factors than quantitive management. Especially the dynamic behaviour of the basin itself is very difficult to estimate beforehand, yet at the same time a determinant factor for salt distribution.

For quality control on a daily basis, easily influenced factors are: discharging through the designated sluice and possibly the ship lock (during periods in between formal operation) and the salt-fresh water exchange which occurs at the latter during formal operation. Use of the water in the ship lock, in the event it produces a net outward flow, is also accounted for in this model. The outflow of salt with discharging is dependent on the salt content in the basin near the opening used for discharge operations. If the basin's water is layered it is important that this opening lies deep.

Given that the basin's inflow higher up is fresh water (although the salt content of this water is certainly not zero) and given the various sources of salt water, the salt content in the basin will decrease in relation to distance from the lock. Some sources of salt might be affected by the salinity of the basin itself. This particularly seems to be the case with salt penetration at ship locks. Knowledge of this distribution in the basin is important, as it enables us to make certain predictions of the water quality at the various locations water is admitted.

To make an estimation of the longitudinal salt gradient we have to study (at every location) the balance between the salt that will be sluiced into sea (local water discharge multiplied by concentration level) and the inward salt transport (by mixing and diffusion), or, in the event of a more layered situation, the velocity of penetration over the path travelled by the lower salt layer. The velocity of the salt can be relatively high in a layered situation (several tens of centimeters per second) whereas velocity of discharging is often minimal (cm/sec). Mixing breaks up the layered situation and salt penetration velocity subsequently decreases dramatically. Factors which enhance blending are wind and ship movements. In some situations, intermittent discharginging can be useful, because it produces a momentary higher outflow discharge. Uncertainty concerning the degree of blending and the degree in how far a layered situation exists makes it tough to determine salt content distribution over the basin.

This distribution can also vary sharply with the seasons, or even shorter time periods. Therefore, no breakthrough has been made in realizing a mathematical model that could support an automated managerial system of the basin. What could be realized is a mathematical model with input data based on a continuous flow of salt-content data coming from certain locations in the area.

Criteria for adequate quality control in relation to salt intrusion are:

- Adequate quality of drinking water and water for irrigation;
- Sufficient quality of cooling and processing water;
- Low salt content of seepage in the proximity of agricultural and grazing lands, and
- Absence of layering in deeper wells which causes a left over of stagnant, oxygen depleted water.

Although prediction of the salt content in the basin with mathematical models is complicated by several uncertainties, analyses of various salt water sources have concluded that ship locks are an important source of salt intrusion. In the Netherlands, the many experiences gained in this field have been incorporated in the design of mathematical models. These models bear upon both water quantity as well as quality.

If the margin between the river's salt content penetrating the basin and the maximum salt content allowed at admission points for e.g. irrigational use, is small then salt incursion by the greatest salt source has to be decimated. Most likely, one of the systems for separation of salt and fresh water (as they will be described hereafter) will have to be applied at the lock. These systems will be discussed in following chapters.

In addition, discharging can be made more effective. The basin floor can be dredged locally at the designated discharging sluice, with the discharching conduits opening placed at increased depth. It may be possible to discharge for longer periods of time and with lower velocities (which translates into broader suction nozzles). In the event the location of this sluice is less than optimal (i.e. too high or too far from the salt to be sluiced), then discharging as a preventive measure will be less effective.

2.3 SHIP LOCKS AS A SOURCE OF SALT INTRUSION

To get an impression of the salt volume flowing into a fresh-water basin per locking procedure we will now look at a relevant situation, where the lock borders on fresh- and salt-water basins. Figure 4 shows a longitudinal section of the lock and the fresh-water canal. In this situation the salt-water level is higher. We

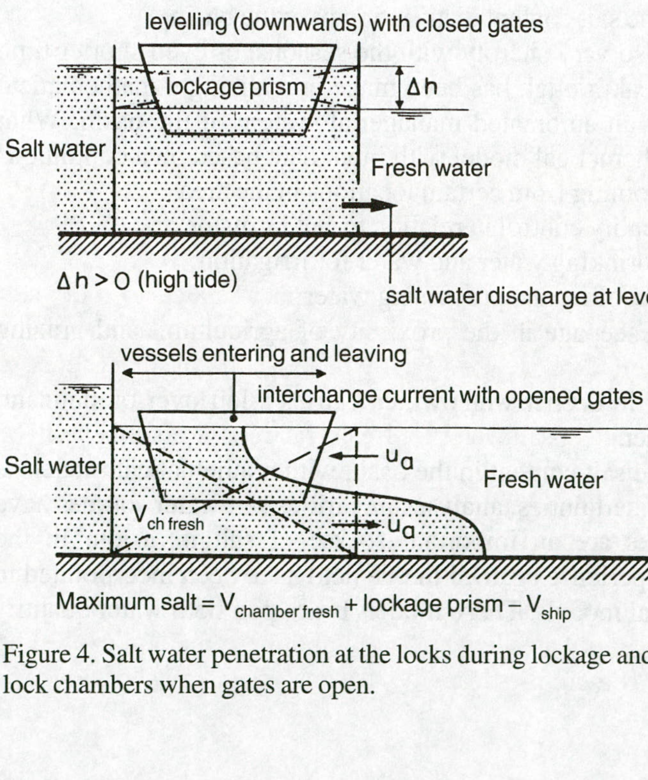


Figure 4. Salt water penetration at the locks during lockage and by interchange of water from lock chambers when gates are open.

assume a ship has entered the lock from the (salt) sea, the gate has been closed and the lock chamber is completely salt. In the next stage of operation the water level in the chamber will be lowered until it equals that of the fresh water basin. The volume of water in the lock prism, which equals the chamber's surface times the drop, will now flow into the fresh-water basin. The lockage prism volume times the salt content also gives the salt load into the fresh water basin. To which degree incoming water will mix with the fresh water or will spread over the basin's floor, depends heavily on the location and shape of the lock's outflow nozzles. When the main lock gates facing the fresh-water basin canal are now opened, the heavier salt water will immediately sink to the bottom and the potential energy released becomes kinetic energy. The study of the energy balance can give the velocities of the stratified flows, i.e upper and bottom layers, (U_a in Figure 4) in a situation without vessels (refer to Section 4.1).

When the ship leaves the lock, the departure produces a returning water current, which will cause a temporary velocity decrease in the bottom layer and an increase in the surface layer. When the front of the fresh water current reaches the closed gates wave reflections occurs. The front of fresh-water reaches the closed gates and reflects. The fresh-water layer on the surface thickens and this thickened 'wave' propagates towards the opened lock. In the reflected wave zone, water velocity will be low (with a velocity of zero at the closed gate). In the rest of the chamber we will find a current in both the salt and the fresh water layer. Consequently, when the gates facing the canal are opened for a sufficient time the entire chamber will fill with fresh water. In other words, the chamber will completely change its content. In the lock a certain salt-water volume was present, which equalled: $V_{\text{chamber fresh}} - \text{V}_{\text{ship}}$. The total volume of salt penetrating the (fresh) canal or basin then equals:

$$\text{Lockage prism} + V_{\text{chamber fresh}} - V_{\text{ship}}$$

This in turn equals:

$$V_{\text{chamber salt}} - V_{\text{ship}}$$

in which $V_{\text{chamber salt}}$ is the water volume in the chamber related to the water level of the sea. Even if the water level of the sea is lower than that of the basin, a salt-water volume ($V_{\text{chamber salt}} - V_{\text{ship}}$) will incur the basin, whereas a ($V_{\text{chamber fresh}} - V_{\text{ship}}$) fresh-water volume will enter the seaside harbor mouth.

From now on, this exchange of salt water for fresh water in the chamber will be expressed as a function of the chamber volume $V_{\text{chamber fresh}}$. This choice has been made since the canal's water level generally varies little, whereas the sea's water level varies drastically due to tidal effects.

Following this train of thought, the volume of salt water which penetrated the canal, as well as the fresh water that flowed into the harbor mouth, thus equals 100%, given the difference in water levels is zero and the reduction caused by vessel volume is omitted. If there is a drop, the lockage prism has to be added: it

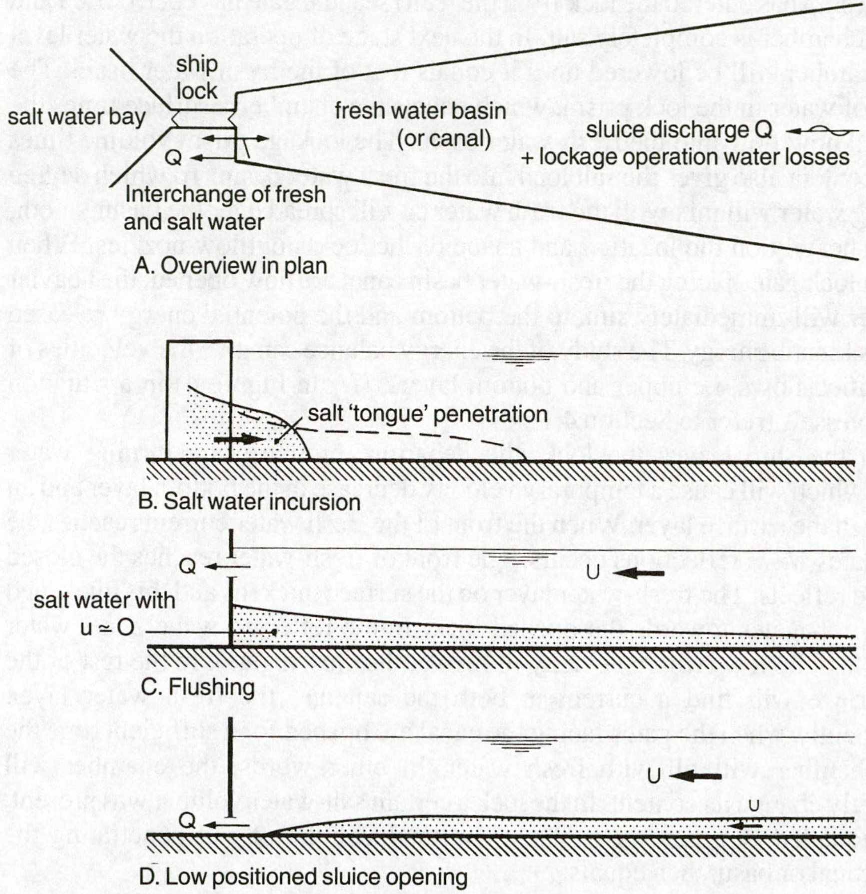


Figure 5. Schematic presentation of salt incursion and sluicing effectiveness on the basin side.

will either be withdrawn from the canal volume and enter as fresh-water volume in the salt harbor mouth, or be withdrawn from the sea water volume and penetrate as salt-water volume in the canal.

The total lockage prism together with the total discharging volume make up the net water transport in the system. Even though there are some factors which enhance mixing, salt-water admitted through the locks will undoubtedly layer and spread out over the basin's floor, and consequently penetrate very far up, even if operation of all ship lock procedures and sluicing cause a net water flow towards the sea.

In salt intrusion prevention, the effectiveness of a net water flow to the sea is dependent on the depth level at which the water is drained and the degree of mixing (refer to Figure 5). At any rate, a multiple of the chamber's water volume will be needed to flush back one chamber volume of sea water.

2.4 SALT-CONTENT DISTRIBUTION OVER THE BASIN

If the salt contents of all sources are known, the question arises what the salt content in the basin itself would be. Even under steady conditions in which the salt content would not vary, calculation of the salt content in a closed basin is only possible by introducing a number of simplified assumptions. A prerogative is knowledge of the quantity of salt Z (expressed in kg chlorion), which enters the basin, as a function of the salinity of the water in the basin (expressed in terms of the difference in density between the inland water and the sea water). The salt burden will decrease when the density difference decreases, for example when the basin's water becomes saltier. Now assume the salt content outside is known. Then it is true that:

Z is a function of the density difference (for instance across the lock),

$$Z_{\text{influx}} = f(\rho_{\text{outside}} - \rho_{\text{inland}}) \tag{1a}$$

Since the density difference is proportional to the difference in salt concentration this can also be expressed as:

$$Z_{\text{influx}} = f(C_{\text{outside}} - C_{\text{inland}}) \tag{1b}$$

where C_{inland} signifies the salt concentration in the basin (expressed in kg chlorion per m^3) and C_{outside} the salt concentration of the outside bay.

Although it is realistic to write Z as a function of $(C_{\text{outside}} - C_{\text{inland}})$, often it is sufficient to approximate Z as independent of C_{inland}, since C_{inland} is much smaller than C_{outside}. This is also true with regard to the salt penetration at ship locks.

In the calculations all salt contents are viewed with respect to the influx concentration at the river flow entering at the upstream side of the bay (as a background value). This salt content value will have to be added to the calculated results.

In steady conditions the salt influx will equal the discharged salt volume. The outflow of salt from the system equals the discharging volume times the concentration C_s of the discharged water. Then it follows that:

$$Z_{\text{influx}} = Z_{\text{outflow}} = Q_{\text{discharge}} \times C_s \tag{2}$$

If we now assume that the bay is completely blended, i.e. the water has the same concentration C_B throughout the basin, then it will hold that:

$$C_B = C_s \tag{3a}$$

Combining Equations (2) and (3) gives that the salt concentration in the bay is proportionate to the salt influx. In reality however, the salt content is distributed unequally. If the discharging sluice is located near the principal salt sources (for example near the lift lock), then:

$$C_s > C_B \tag{3b}$$

The relative salt content of the discharge water can increase by draining salt water at a greater depth (this is in a situation with a certain degree of stratification). Because C_s is directly linked to Equation (2), C_s will not increase, rather C_B will decrease.

The concentration in the basin will decrease in the direction of the upper current. If x signifies the distance to the lock, then the salt content will be:

$$C = f(x)$$

Caused by a discharge Q, a certain quantity of salt K will be transported towards the lock at distance x:

$$K = Q \cdot C(x) \tag{4a}$$

This is called 'convective' transportation since this conveyance of salt is linked to the water transportation. In Equation (4) the direction of K and Q is positive flowing towards x, while in reality Q will be negative.

Equation (4a) expresses that, with Q being constant but C varying with distance, salt transport, which is linked to Q, also varies with distance. Thus the salt content at a certain location increases with:

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} \tag{4b}$$

with A being the cross-section of the canal or basin.

The salt content increases when at distance x more is added than lost at a distance $(x + \mathrm{d}x)$. This holds when $\partial C/\partial x$ is negative. Moreover, Equation (4b) also holds when Q is negative.

On the other hand, turbulence causes the water at a distance x to blend with surrounding water at a distance $(x + \mathrm{d}x)$, where concentration is less. We now have an (opposite) 'dispersive' transport with a dispersion factor D*. Factor D can also be viewed as a compilation of all factors which enhance salt penetration, salt travelling over a path in stratified flows included. Transportation from the lock will now be:

$$K' = -D\frac{\partial C}{\partial x}A \tag{5a}$$

The minus sign shows that dispersion occurs in direction x (travelling up the canal) when the concentration at the lock is highest (then $\partial C/\partial x$ will be negative).

*Also refered to as the *diffusion coefficient*. Since this expression also implies the physical sense of transportation linked to molecular interchange of the particles, here the term *dispersion* is used.

Since the salt transport over distance x varies because of dispersion, the concentration will increase at a certain point over time:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{5b}$$

In a steady condition the total salt content increase will be zero, which results in:

$$\frac{-Q}{A}\frac{\mathrm{d}C}{\mathrm{d}x} + D\frac{\mathrm{d}^2 C}{\mathrm{d}x^2} = 0 \tag{6}$$

Equation (6) works out as (given D is constant):

$$C = C_o e^{+px} + C_r \tag{7a}$$

$$\text{with } p = \frac{Q}{DA} \tag{7b}$$

Because Q is negative, it will be found that the salt content decreases with distance. C_r signifies the salt content of the influx discharge (which is the limit value of C for $x \rightarrow \infty$ and $C_o + C_r$ agrees with conditions at the lock.

Figure 6 shows the situation in which there is an inlet point for irrigation at distance *Xo*. Salt concentration at this point should not exceed a normative value, C_t. It seems the maximum salt allowed is linked to the available discharge for discharging. The larger the discharge flowing through Q_d, the more salt is accepted at the sources of salisination (in our study these are the locks). In Figure 6, a ship lock with a salt/fresh water interchange discharge Q_i at an average time value, is introduced as a salt source. We now add this condition at the lock to Equation (7): Salt influx (interchange discharge Q_i times the salt concentration difference between water inside and outside) equals the volume of salt discharged (Q_d times ($C_o + C_r$)). Now the lines in Figure 6 can be determined mathematically. Equation 7 gives:

$$C_o = (C_X - C_r)e^{+Q_d x/DA} \tag{8a}$$

Of which we note that as in Equation (7b) the sign convention is that $Q_d = -Q$. It is now evident that with a given value C_X the allowed concentration at the lock, $C_r + C_o$, becomes larger as the discharge flowing through increases. The maximum salt influx by salt/fresh water interchange at the lock allowed follows from a continuity observation of the salt:

$$Q_i = \frac{Q_d C_o}{C_{\text{sea}} - (C_o + C_r)} \tag{8b}$$

If we set a norm for C_X, being C_t, then C_o and Q_i can be calculated at each value of Q_d. Combining Equations (8a) and (8b) gives:

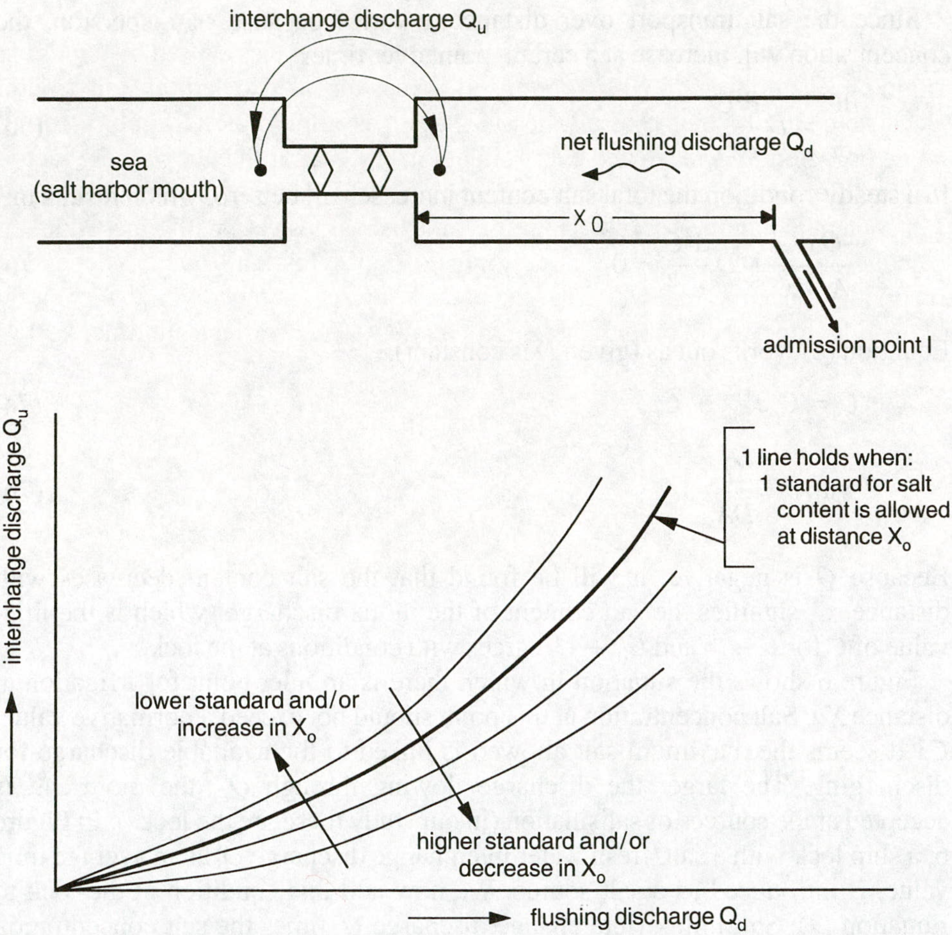


Figure 6. Lines illustrating the qualitative relation between the needed flushing discharge and the degree of interchange allowed with a set salt content limit at distance X_o.

$$\frac{Q_i}{Q_i + Q_d} = \frac{C_t - C_r}{C_{\text{sea}} - C_r}\, e^{Q_d x/DA} \tag{8c}$$

Such a one-dimensional calculation is applied quite often but its complexity is much greater than in this example. In reality, the calculation is only applicable in a vertically blended situation, in which D does not vary too much. In all other cases C will have to be assigned a meaning (in general this will be the average vertical concentration) and it will have to be known in what manner D is dependent on the degree of stratification. At the Zoommeer (refer to Figure 1), the transition from the original salt situation to the present fresh situation was calculated through in a one-dimensional model with D being 20 as well as 500 m^2/s. The latter value agreed best with actual observations.

Because D is not really known, the equations provided only hold a limited degree of accuracy. Dispersion intensifies with winds, waves caused by winds and shipping. In addition, the discharge itself causes turbulence and thus dispersion. Because of the influence of all these factors it is impossible to apply a certain value of D blindly to each and every situation, since the influence of these factors might differ significantly. It is best to determine D by gauging the dynamics of the salt content in nature. Because salt influx and discharges vary with time, complete calculations should encompass the 'storage' of salt. This salt storage is dependent on fluctuations in water level times the basin's surface (in other words, increase in water quantity), but in particular on a salt content which varies with time.

CHAPTER 3

Overview of possible measures to reduce salt-fresh water exchange at ship locks

This chapter provides an overview of measures to limit natural exchange of salt and fresh water at shiplocks. The next chapter will further analyse each of these measures. The measures may be sub-divided into a number of categories. Reference is a situation in which no measures are taken.

A. Management. It could be possible to operate the locks less frequently with more ships per locking operation. The salt burden would then decrease more than proportionally with the number of operations, since the volume of salt water in the chamber would be reduced by the increase in vessel volume. It can also be considered to operate more often at low tide; this will also decrease the salt water volume in the chamber. From the perspective of limiting salt intrusion it would also be favourable to partition off the chamber into several smaller ones, which reduces the volume of salt water per locking operation and increases the relative filling factor of the locks.

B. Flushing the basin. Effective especially if the salt water which penetrated the basin is received in a dredged part, from which it is selectively pumped. Also if there is reason to expect the salt will be vertically blended to a satisfactory degree by wind and shipping, flushing still has a certain effect.

C. Pumping back the salt water lockage prism into sea. This measure is very effective since the pumped water has a high salt content. The measure is also effective if used in combination with any of the following systems.

D. Retarding the natural salt-fresh water exchange-current combined with soonest possible closure of the main lock gates. It appears that fast closing of the gates is sensible only if there is a very slow interchange current of salt and fresh water. This is the case with shallow, long locks, with little density differences between the water at both sides and artificial retardation of the interchange-current with air curtains. Planting the bottom with artificial 'reed', with a lighter intrinsic weight than that of water, so it will stand up, is a possibility of retardation that has once been investigated. If the planting is dense enough, retardation is accomplished, yet only towed ships will be able to pass. Self-propelled ships will be hindered by the reed. Thus the practical application becomes void.

E. Flushing back salt water immediately at the lock. Efficient flushing back of salt is possible if suction nozzles are positioned where salt concentration is highest, i.e. deep and in the vicinity of the source of salt. The following measures can augment results:

– Dredging of a pit near the inner lock gate, so as to intercept the salt flow and hoze it back immediately.

– Dredging part of the canal floor near the lock to store the salt in this deeper basin. This 'salt basin' should preferably be pumped out at low suction speeds with a broad nozzle located at considerable depth, to ensure selective pumping. Both methods are combined in the system at Terneuzen (refer to Section 4.6).

F. Pumping out or draining by use of the natural drop, of the salt lock chamber and simultaneously replacing it with fresh water before the gates are opened. (Draining and filling of the chamber will have to be performed simultaneously. Otherwise, the ships would fall dry, which is only acceptable for small vessels). During this operation it is crucial to produce minimal blending: fresh water will have to be added carefully on top and salt water drained from the bottom. To add fresh water the entire circumference of the chamber should preferably be used, whereas draining operations should preferably be performed over the basin's entire (perforated) floor. In reality, only wall apertures are used for admittance of fresh water (this is called crosswise interchange). When the fresh water loss has to be limited, the system can be used in reverse also. Then the fresh water will be substituted for salt water while gates are closed. Then, too, the discharge should not be too large. For small locks an interchange over the length through apertures in the gate facing the fresh basin should be considered. It can also suffice to have apertures in the wall on one side of a small lock's chamber. Crosswise interchange was first developed in France* (system Dunkerque) and was later developed further in the Netherlands for application with the very large inland navigation locks (Kreekrak locks and Krammer locks). Interchange over the length (known as system Hansweert) has not been applied yet, but scale-model versions have been studied.

G. System 'salt lift trough'. This system features a broadened and deepened chamber in which an inner chamber filled with salt water moves up and down

*P.A. Kolkman, one of the authors, had the opportunity to assist with studies of the model and further development of the lock at the consulting of consultance firm Sogréah in the early 1960s.

(refer to Figure 39). The lock itself is always filled with fresh water and adjustment of the chamber's water level to that of the water outside is done by gravity or with pumps. When the inner chamber (the salt lift trough) is on top, the lock seen from a ship seems to have a salt chamber. Is the trough on the bottom, ships will pass through a fresh lock over the salt trough. During operation three actions are performed, (which can to a certain degree take place simultaneously):

1. Increasing or lowering of the fresh water level in the broadened lock;
2. Lifting or lowering the salt trough;
3. Correcting the salt water volume in the trough. This is necessary to correct the influence of the vessel's volume, in the case it differs when locking takes place in the other direction.

Obviously, this system is very complicated and special solutions will have to be found to assure a rather tight fit of the salt trough on both sides. The system has been designed in the past, but the plan was never realized. Studies in scale models have taken place at Waterloopkundig Laboratorium (Delft Hydraulics).

Characteristic for systems A, C and D is that unwanted salt penetration is reduced without an additional loss of fresh water. Systems F and G also do not use extra fresh water, but these two systems' performance improves dramatically with the use of this additional fresh water. Even with an advanced system like F some loss of fresh water will occur, when the ship travelling seawards leaves the chamber. This is also the case with G, although this system needs even less fresh water than F.

Characteristic for systems A through E is that the gates can be opened immediately after levelling. With systems F and G the interchange stage has to be completed before the gates can be opened.

CHAPTER 4

Futher analysis of measures reducing salt-fresh water exchange with systems allowing the gates to be opened immediately after levelling

4.1 ANALYSIS OF THE REFERENCE SITUATION WITHOUT SPECIAL MEASURES

4.1.1 *The various stages of operation*

The specific currents and forces acting on the vessel in a lock with salt-fresh water differences are compared with the homogenous situation, where density differences are absent.

In the following analysis the sea level will be lower than the water level in the canal. Since steps of operation are repetitive, any stage can be chosen as Stage 1. Here, it is assumed that the gates facing the sea are open and the ships have just entered the chamber.

Stage 1

The gates facing the sea are closed and the chamber is filled. Fresh water from the canal is let in through an aperture in the gate or bottom perforations. The water either forms a surface layer, or is blended with the salt water in the chamber. If the fresh water is admitted through perforations in the floor it will also tend to float, but will blend when rising through the salt water flow. Filling the chamber through openings located in or near the upstream main gates will initially cause much blending. However, the water tends to settle into a (two-layered) stratified situation, with the bulk of the ship resting in the fresh water which flows to the back. Hence filling through an aperture in the door causes a surface current going from this door, and an extra force on the vessel in this direction. Vrijburcht (1991) explains how this force can be calculated. In salt-fresh water scale models, the forces exerted on mooring cables were measured to double those in a homogenous situation.

The fresh-water filling discharge is linked to pressure variations over the gate, which are not exactly equal to the pressure variations caused by differences in the water level. If an aperture is located at depth Z in the lower water flow, then the

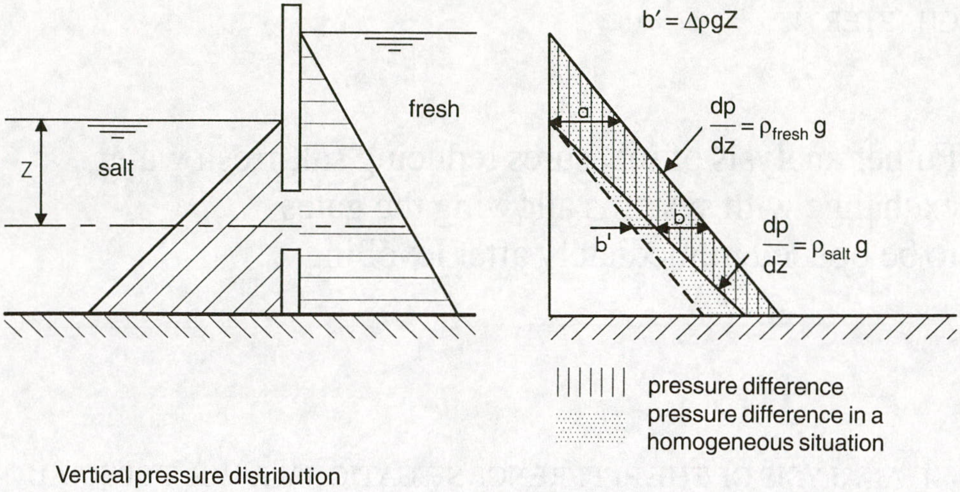


Figure 7. Pressure distribution over the lock gate during filling of the salt chamber.

pressure on that side would be ($\rho_{fresh}gZ$) in a homogenous fresh situation. However, the actual pressure on the salt side is ($\rho_{salt}gZ$). The pressure deviation is $\Delta\rho gZ$ (value *b*' in Figure 7). Filling will stop when the water pressure is equal on both sides of the aperture. The water level on the fresh water side will be slightly higher. Therefore, the chamber cannot be entirely filled.

Stage 2

The gates facing the canal are opened. Through the pressure difference related to the (slight) difference in water levels, ships will experience forces exerted in the direction of the salt water. Translation waves will also be present because of the difference in total water pressure on both sides of the gate just before opening. (With apertures in the gate it is possible that the total water pressure on both sides of the gate is equal after levelling, but only when these apertures are positioned half-depth). After the translation waves have travelled away on both sides, the total water pressure in the salt and fresh water will be equal. Vertical pressure gradients in the two water varieties will, however, still differ (refer to Figure 8). This difference will cause an interchange-current: Fresh water floats up and flows into the chamber at the surface, salt water streams out of the chamber. When vessels are still moored in the chamber, the interchange current can exert great force on the moorings (refer to Vrijburcht, 1991).

The heavier salt water streams out of the chamber up the broader channel across the floor: The salt water 'tongue' broadens and initially spreads out in all directions. For the situation in the chamber, vessel movements are crucial. During this stage ships leave the chamber (moving against the fresh-water current on the surface), followed by others entering the chamber (along with the current).

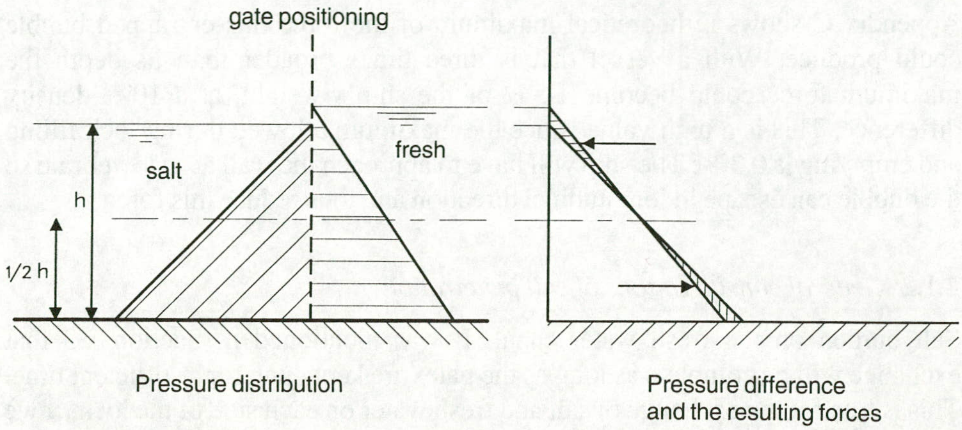


Figure 8. Pressure distribution in that situation where total water pressure is equal on both sides of the gates.

Flowing along with the current impedes vessel manoeuvrability. The volume of ships leaving the chamber is replaced by fresh water. Some blending will occur if the vessel's propellor is near the interface of the stratified flows. Ships entering the chamber push water away, and in particular the upper flow will enter the canal as mixed fresh water. This volume should have been pure fresh water, but blending caused it to dilute with salt. Ship movements strongly reinforce the exchange currents. Incoming ships strenghten the salt-water current up the canal by the piston effect they create.

Stage 3
After all ships have left and entered, the lock gates facing the fresh-water basin are closed. The chamber is levelled downward and the salt-contaminated fresh water from the chamber spreads over the salt water in the harbour mouth, as oil does. Because of this, measures designed to improve water-flow conditions in a homogenous situation (e.g. changing the direction of the current and creating a discharge along the shores to minimise the burden of shipping), seem of no use in situations where density differences exist.

Stage 4
The gates facing the sea are opened and ships leave and enter the chamber; these occurrences of two-layer currents are completely analogous with Stage 2. The process ends up with some fresh water in the upper layer. This poses a problem for the incoming vessel. A fresh water bubble is trapped beween the chamber wall and the incoming ship and cannot adequately flow away under the ship. The bubble will thicken as the vessel tries to reach the wall; making mooring of the ship a problematic operation. The water will have to spill away over the length.

Appendix C shows a theoretical maximum of the force this entrapped bubble could produce. With a vessel that is three times broader than its depth the maximum force could become 1.5‰ of the ship's weight, at a 10‰ density difference. This is a high value, since the maximum allowed during lock filling and emptying is 0.3‰. The ship will have to approach the wall at a slower rate so the bubble can escape in longitudinal direction and thus reduce this force.

4.1.2 *General considerations of salt penetration*

Salt burden on the fresh water canal: It was mentioned in Section 2.3 that exchange will be complete as long as the gates are kept open for a sufficient time. This is true for the exchange of salt and fresh water on each side of the lock. If we express the salt quantity flowing into the fresh water basin as an undiluted volume of salt water, then this volume will equal the chamber's volume belonging to the sea water level, minus the vessel's volume. This has also been mentioned in Section 2.3. Because of blending, realistically the canal receives a greater volume of mixed water. Since by definition the salt penetration is related to the fresh water volume in the chamber (and because the sea level is again assumed to be lower than the water level in the canal) the relative salt water penetration is:

$$\frac{V_{\text{chamber salt}} - V_{\text{ship}}}{V_{\text{chamber fresh}}} = \frac{V_{\text{chamber fresh}} - \text{Lockage prism} - V_{\text{ship}}}{V_{\text{chamber fresh}}} = 1 - S - V_s \quad (9)$$

In the event the water level on the salt side is higher than the fresh side, salt incursion will be:

$$\frac{V_{\text{chamber salt}} - V_{\text{ship}}}{V_{\text{chamber fresh}}} = \frac{V_{\text{chamber fresh}} + \text{Lockage prism} - V_{\text{ship}}}{V_{\text{chamber fresh}}} = 1 + S - V_s \quad (10)$$

in which:

$$S = \frac{\text{Volume of lockage prism}}{\text{Volume of chamber at water level canal}} = \text{Relative volume of lockage prism} \quad (11)$$

and

$$V_s = \frac{\text{Volume of ship}}{\text{Volume of chamber at water level canal}} = \text{Relative volume of ship} \quad (12)$$

In reality the exchange process will be less complete since the gates might close before the last volume of water is interchanged. Exchange currents can be reduced further by applying a bubble shield (or air-curtain). The reduction in local interchange can be expressed as factor θ (with $0 < \theta < 1$), with θ only relating to the interchange on one side. θ on one side also influences the interchange process on the other side. This influence on reduction of salt penetration is calculated in

Appendix A and the results thereof are illustrated in Figure 9. With the calculations the following was assumed:

- The harbour mouth on the canal side is completely fresh;
- The harbour mouth facing the sea is completely salt;
- The drop is constant;
- Vessel occupation is constant during all operations.

In Figure 9, the volume of the prism (horizontal axis) is presented as the dimensionless parameter S. The vertical axis reads the rate of salt penetrating into the fresh basin (as a volume of salt water with a 100% concentration in relation to the lock chamber volume at the water level of the fresh basin). Lines are plotted for the various values of θ and V_s. In the event of complete exchange at both sides and no vessel occupation the upper line coincides with Equations (9) and (10).

In addition, we can distinguish between salt by the lockage prism and by the exchange process at both sides, per operation cycle. It would make sense to do so if the water balance and the salt balance of a cycle are to be determined separately. If the water level in the salt basin is lower than in the fresh basin, then the salinisation rate from Figure 9 relates only to the exchange process. Also by this exchange an equal volume of fresh water is taken from the fresh basin. The lockage prism is withdrawn from the basin as additional fresh-water volume and ends up in the sea. When the water level of the salt basin is higher, then the salt burden in Figure 9 consists partly of the exchange process, and partly of a (salt) lockage prism. Only the exchange volume is drawn from the fresh-water basin.

Before Figure 9 can be used in a quantitative sense, the value of θ will have to be known. The interchange percentage each time a gate is opened depends on:

1. The fluid density difference over the gates before these are opened and the time a lock door remains open;
2. If an air curtain is applied and if so what the air discharge is;
3. Ship movements.

ad 1: This difference in densitiy in turn depends on all other factors. As a practical approach it is recommended to use an estimated value for θ (between 0.6 and 0.9) and look up the density difference over the gates (as part of the density difference in the harbour mouth). In Appendix A the density differences over the lock gate just before opening are discussed, and this value is an element in reaching the θ value in Figure 16. At the end of calculations the estimated value can be reviewed.

ad 2: Since this section discusses the reference situation, this subject will be discussed further in Section 4.5 (where in Figure 16 also the situation without an air shield is presented). The estimation of density difference over the gates that was made under *ad* 1 is used. Figure 16 gives a value of θ_o, which is the reduction factor, without accounting for the influence of ship movements.

ad 3: Appendix A gives an estimation for the increase of θ by ship movements:

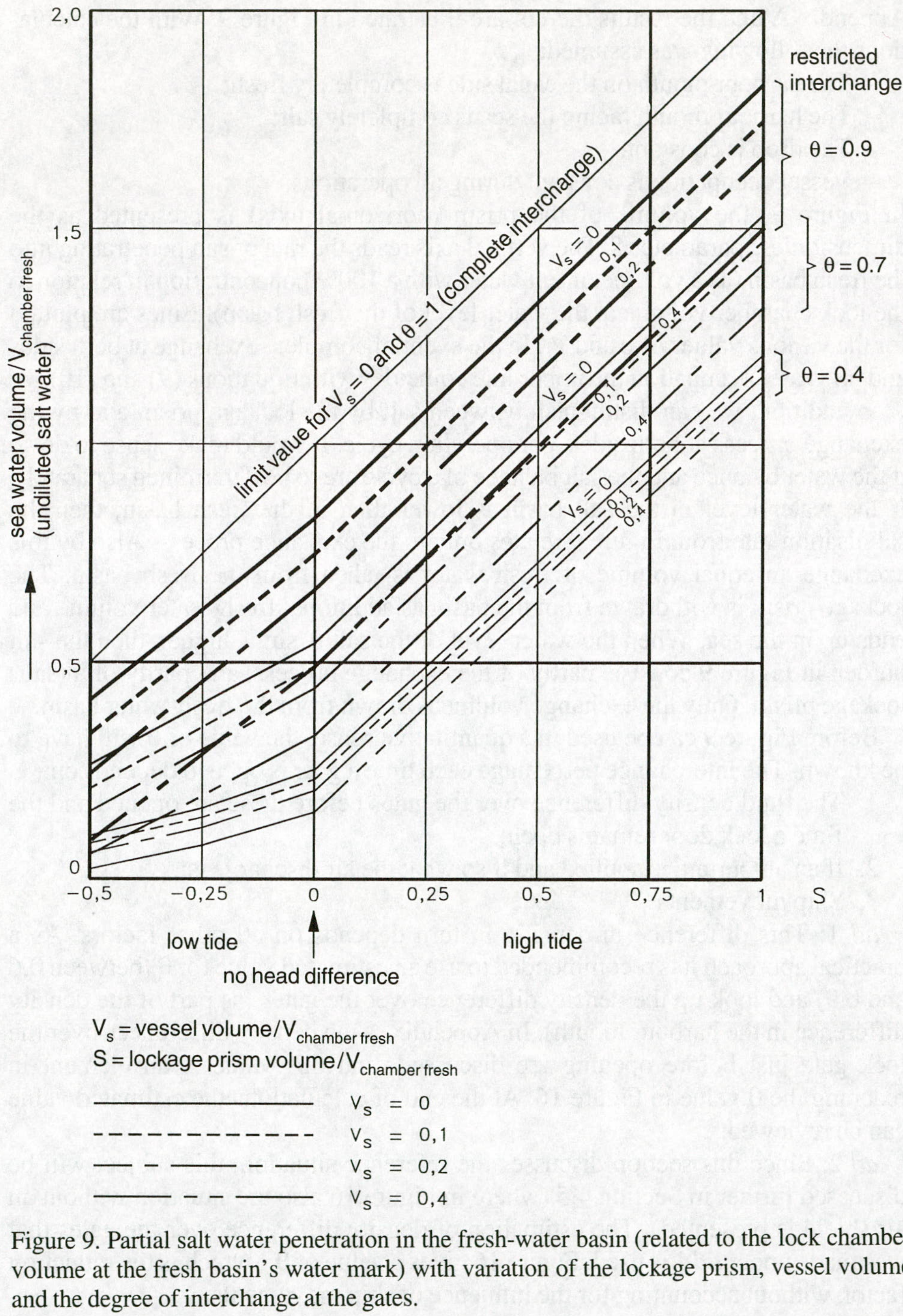


Figure 9. Partial salt water penetration in the fresh-water basin (related to the lock chamber volume at the fresh basin's water mark) with variation of the lockage prism, vessel volume and the degree of interchange at the gates.

$$\theta = \theta_o + 0.8\,(1 - \theta_o)\,V_s \tag{13}$$

with V_s in turn defined by Equation (12).

This correction is especially important with smaller values of θ which occur with the use of an air curtain.

These calculations are not exactly precise, but several factors do not weigh too much in the end result. The total salt burden should be computable with an accuracy margin of around 25%.

To get an impression of the interchange process's duration, Figure 10a shows the situation shortly after gates have been opened. With equal water levels, the salt water holds a higher vertical pressure gradient. The resulting (arced) pressure difference at the floor level has the value $\Delta p = \Delta\rho g h$ ($\Delta\rho$ = density difference between salt and fresh water). In reality there exists a symmetrical situation with a pressure difference $\frac{1}{2}\Delta\rho g h$ on the floor as well as at the surface. This situation (Figure 10b) follows from the initial situation since the total salt water pressure surplus translates into an external translation wave. This wave further has little influence on the creation of the two layerered current.

The two layered current is symmetrical in both layers, caused by the equality in the pattern of pressure (although counter-directed), which in turn also causes the velocity and discharge in both layers to be symmetrical. We will now now further examine the value of U_a.

Figure 10b indicates the interface between salt and fresh water at time t (drawn line) and at time Δt, a little later (dotted line). The latter holds an equal salt volume

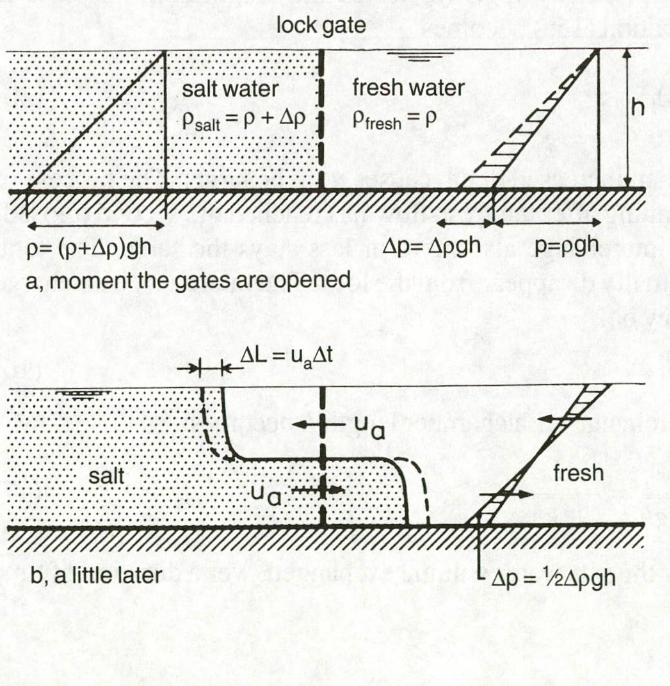


Figure 10. Salt/fresh interchange shortly after opening the gates.

to the left as the former, but at the dotted line some water has sunk down. It concerns a water volume of

$$\tfrac{1}{2}\,\Delta L = \tfrac{1}{2} h\, u_a \Delta t$$

of which the point of gravity has been lowered by height $\tfrac{1}{2}h$. This volume has been replaced by fresh water. The potential energy of the salt water has so been reduced and that of the fresh water has increased. The resulting decrease is

$$\Delta E_{pot} = \tfrac{1}{2}\, h\, u_a\, \Delta t\,(\rho_{salt} - \rho_{fresh}) g\, \tfrac{1}{2}\, h = \tfrac{1}{4}\,(\rho_{salt} - \rho_{fresh})\, g h^2\, u_a\, \Delta t \quad (14a)$$

The kinetic energy has now increased, since the zone in which the water moves has increased in lenght by

$$\Delta L = \Delta L_{fresh} + \Delta L_{salt} = 2 u_a\, \Delta t$$

The increase in kinetic energy is

$$\Delta E_{kin} = \tfrac{1}{2}\rho\, u_a^2 h\, \Delta L = \rho u_a^3 h\, \Delta t \quad (14b)$$

Equalization of the Equations (14a) and (14b) gives:

$$u_a = \tfrac{1}{2}\sqrt{\frac{\rho_{salt} - \rho_{fresh}}{\rho} gh} = \tfrac{1}{2}\sqrt{\varepsilon g h} \quad (15a)$$

Empirically, a 10% smaller value is found because of the differing shapes of the salt-influx in reality and friction on the bottom and the interface between the layers.

Remark. When making use of the internal Froude number, defined as the water velocity (in this case u_a) divided by $\sqrt{\varepsilon g L}$ (in which the length L in this case is water depth h), then Equation (15a) becomes

$$F_i = \frac{u_a}{\sqrt{\varepsilon g h}} = 0.5 \quad (15b)$$

From this it follows that an increased depth causes u_a to be larger. The process of interchange keeps continuing after the fresh flow has reached the second (closed) flood gate. The rate of interchange also more or less stays the same. The total amount of salt will eventually disappear from the lock. The interchange discharge per unit of width will now be:

$$q_a = \tfrac{1}{2} h\, \tfrac{1}{2}\sqrt{\varepsilon g h} \quad (16)$$

And the duration of interchange with chamber length L becomes:

$$T_a = \frac{2L}{u_a} = \frac{2L}{\tfrac{1}{2}\sqrt{\varepsilon g h}} = \frac{4L}{\sqrt{\varepsilon g h}} \quad (17)$$

According to this theory the salt-water volume exchanged over a duration of time

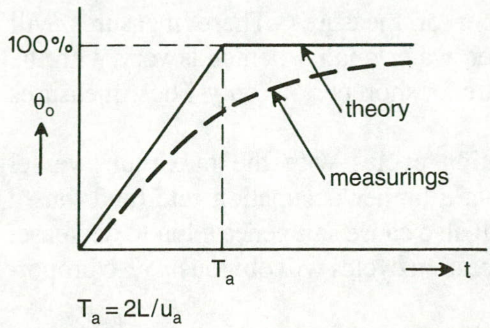


Figure 11. The interchanged volume over a time interval from Abraham et al. 1962.

elapses as indicated in Figure 11. A not too-extreme example gives:

$L = 250$ m,
$h = 5$ m,
$\varepsilon = 2.5‰$,
$u_a = \frac{1}{2}\sqrt{\varepsilon g h} = 0.56$ meters per sec,
$T_a = 2L/u_a = 893$ s $= 15$ minutes.

To obtain an incomplete interchange, the gates will have to be opened for a shorter period, but this is nearly impossible.

The rate of exchange will actually be lower with the presence of ships in the lock. However, the entering and leaving of ships usually exceeds the time as computed above, so we should take a completed exchange process into account. Only with small density differences can the exchange be limited by swiftly closing the gates.

The interchange actually never is 100%. Figure 11 shows a broad connection between salt penetration and the time period gates are opened. The results were obtained through measurings and presented together with the theoretical curve based on the above-mentioned theory (Equations (16) and (17)). With definition of the percentage of the exchange process, the chamber volume with no vessel occupation (and with regard to the water level of the fresh basin) is taken as reference volume. This reference volume also relates to the salt penetration into the fresh basin. If penetration shows to be smaller than 1, the cause could be either a smaller volume, or a lower salinity level of the salt-water influx as compared to the water in sea. When we, in Figure 11, assume that gates are opened for 30 minutes ($t/T_a = 2$), then the interchange percentage will exceed 90%. Figure 9 shows salt penetration will be 0.66 (undiluted salt water volume related to a fresh water volume in the chamber), with a 20% vessel volume. Further refinements such as Equation (13), do not play a prominent role.

4.2 MEASURES FOR MANAGEMENT

Lock management with an eye on fast and convenient vessel traffic as well as salinisation, can make use of a number of measures. These measures will somewhat limit lock operation. However, water quality demands vary with the seasons, so that limitations for shipping are for short periods only. These measures can be:

– Minimising the number of operation cycles with the maximum vessel occupation possible. Figure 9 shows that a higher occupation rate (and thus a higher percentage of vessel volume), will also cause salt penetration to decrease. Furthermore, lowering the number of operation cycles will obviously also proportionally decrease the salt burden.

– Using those locks that have a salt/fresh water-separation system, even if using these locks will cause a detour for the ship.

– Operating as much as possible during low tides, when the salt-water level is low.

– With small density differences, considering to close the gates as fast as possible (refer to Figures 9 and 11 for potential results).

– Using partition chambers instead of the entire lock (smaller chamber volume and relatively higher vessel volume).

– If fresh water supply is abundant, it could be considered to sluice with the ship lock in between periods of formal operation, not allowing the salt water to penetrate deeply up the canal.

Optimal management is only possible when lock personel and boatmen are well motivated and will provide their cooperation. Some essential factors are: Continuity in management; (modifications are difficult to carry through), continual information, sound preparation before implementing the above-mentioned measures (educational courses).

From this summation it becomes evident there also are critical factors in the design and building of the lock, such as installing partitions so partition chambers can be used. Another example is the lock Bergsediepsluis. When construction of this lock equipped with the 'salt lift trough' system could not be realised for financial reasons, it was decided to build a small lock based upon classical design. It could only allow recreational vessels to pass through. This meant merchant ships would have to detour. In this ship lock, arrangements have been made for installation of an air curtain, if this should later be necessary.

4.3 FLUSHING THE BASIN TO PREVENT SALT INTRUSION

To ensure maximum effectiveness of sluicing (i.e. maximum salt drainage), discharging should take place there where salinity is highest. This means in the vicinity of the salt source and, if stratification is to be expected, as deep as possible. When the floor of the canal or basin is locally dredged to create a receptor basin, the salt will nestle there.

In the receptor basin or salt pit, the pumping station's suction nozzles or

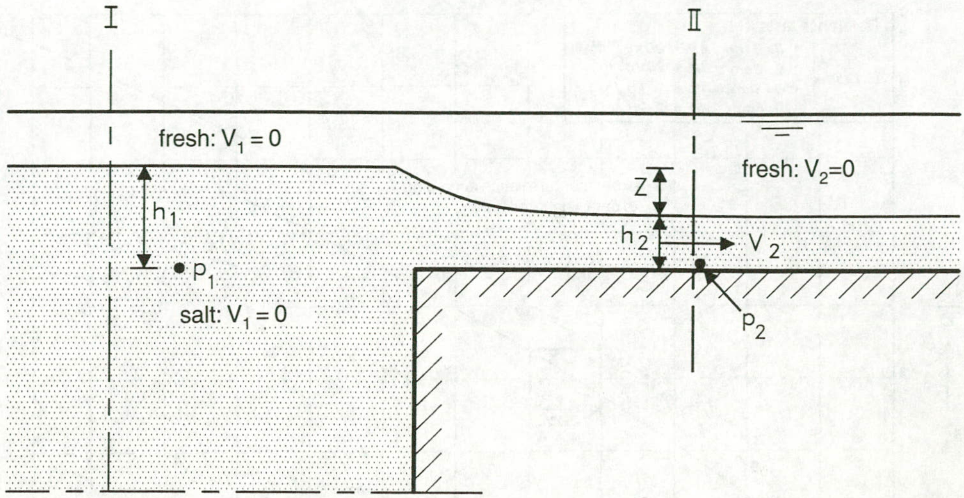


Figure 12. Situation where the salt underlayer streams over a sill.

discharging tube should be placed at a certain depth below the interface of the two layers. The maximum discharge pumped free of any upper layer fresh water can be determined theoretically. Note that actual upper limit discharges are about 20% lower than the calculated values. The computation assumes that with a permanent water flow the pressure decreases with increasing velocity (*Bernoulli*). Decreases in pressure translate into a thinner salt layer (the fresh water on top is assumed to be tranquil, which gives a hydrostatic distribution in the upper layer).

Figure 12 illustrates this situation schematically. From it we can derive a number of relations. The pressure difference $p_1 - p_2$ is entirely determined by the weight of the liquid that is present directly above these locations. Only the disparity in height Z is relevant because at that height at section I salt water is present, whereas at section II fresh water is present. Above this area the water pressure is hydrostatic with a vertical pressure gradient related to the densitiy of the fresh water. Hence, the pressure difference I-II is:

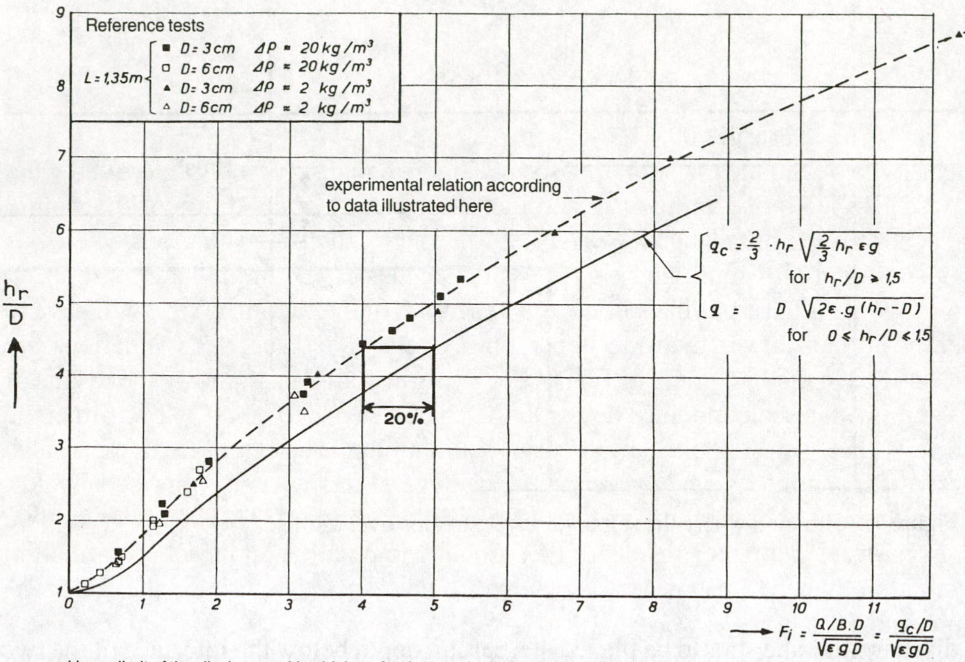
$$p_1 - p_2 = (\rho_{\text{salt}} - \rho_{\text{fresh}})\, gZ = \Delta\rho g Z \tag{18}$$

The velocity increase in the flow allows us to apply the *Bernoulli equation*, which holds that:

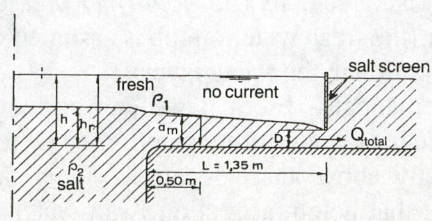
$$\frac{\rho_1}{\rho g} + \frac{v_1^2}{2g} = \frac{\rho_2}{\rho g} + \frac{v_2^2}{2g} \tag{19}$$

We are examining the salt-water situation with $V_1 = 0$ (Figure 12)

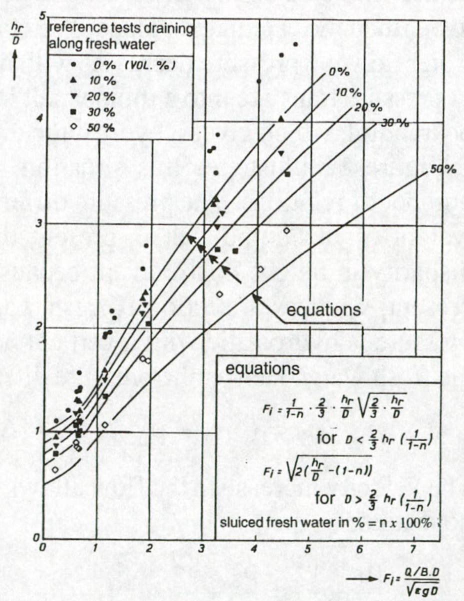
So it is valid that (by introducing $\varepsilon = \Delta\rho / \rho_{\text{salt}}$)



Upper limit of the discharge with which no fresh water is drained along



Defining illustration for tests, with L = 1.35 m



Comparison theoretical approach and test results when fresh water is drained along

Figure 13. Test results selective withdrawal of salt water, Delft Hydraulics 1973.

$$V_2 = \sqrt{2gZ\varepsilon} \tag{20}$$

and

$$q = (h_1 - Z)\sqrt{2gZ\varepsilon} \tag{21}$$

This type of equation is similar to the discharge equation of a broad-crested weir. Here also, with one value of H_1 similar to the free flow condition of the weir, q reaches a maximum when $Z = H_o/3$. Furthermore, there are situations where q is smaller than maximum and also Z is smaller than $H_o/3$. In the latter case, if no fresh water is to be pumped along, the upper part of the suction nozzle will have to be positioned lower than the upper limit of the salt layer. Both situations are described in the first graph of Figure 13. This illustration also shows the results of testing with a scale model. The border discharge seems to be 20% lower than the results that were obtained by theory. With similar considerations one can also calculate conditions where a certain percentage of fresh water is pumped (Waterloopkundig Laboratorium, presently Delft Hydraulics, 1973). The lower graphic of Figure 13 compares results of theoretical computation and tests performed in situations where fresh water is pumped along. In the reference the theory is presented.

Configurations that ensure drainage of salt with great efficiency can be designed. An example is Figure 14, which illustrates the situation at Den Helder with a salt-receptor basin, before an important pomping station was built. Scale-model tests have indicated that all salt water coming from Den Helder was caught in the salt-receptor basin. This can be seen in the photos; the darker coloured salt water flows into the receptor basin, but not further south into the canal. For this test, part of the canal was initially partitioned off, (a little north of the position where detail A starts). Salt water (defined as holding a concentration of 100%) was stored behind the partition. Then the partition was removed. Tests with initially different salinities gave similar results. Since the salt "tongue" path flows downwards, the potential energy this movement produces is transformed into extra kinetic energy, which in turn causes blending. The water volume which will have to be pumped out, thus becomes greater than the actual influx of undiluted salt water in the basin. The sketch to the bottom right in Figure 13 indicates the salt water's salinity after it has incurred the basin and settled. From the sketch we can make an estimation of the water volumes that have to be drained by the pumping station. It concerns about twice the volume of salt water intrusion. The salt screen, with a slit-shaped opening at depth NAP −10 m (Normal Amsterdam level, Ordnance Datum = normal sea level), which has been placed in front of the pumping station, proves completely effective in retracting the salt influx without draining much fresh water from the upper layer.

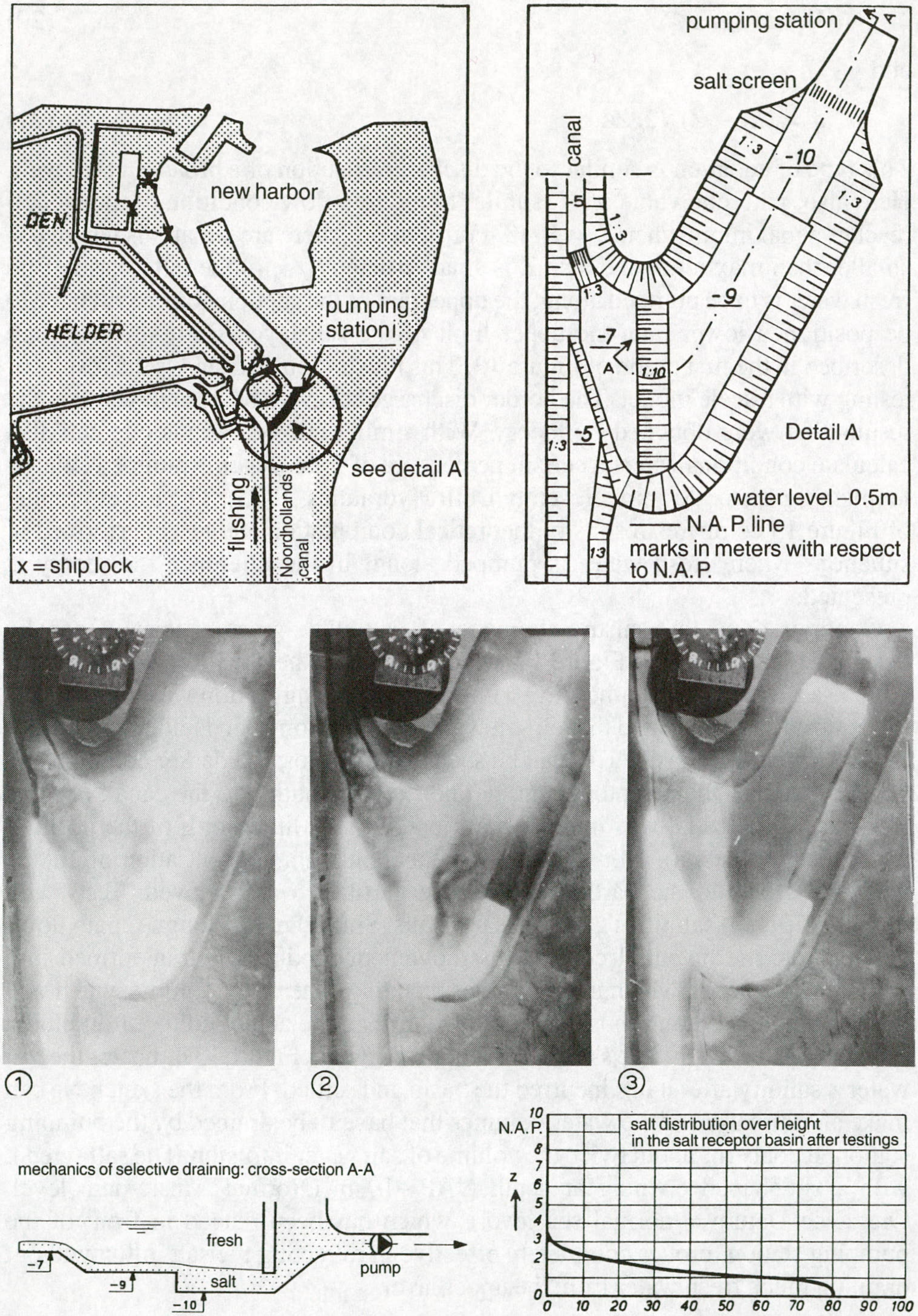


Figure 14. Situation near the old Koopvaarders ship lock with salt receptor basin in Den Helder.

Table 4.4.1. Reduction factor R when pumping the lockage prism volume back to sea.

	$S = 0.25$		$S = 0.5$		
θ	$V_S = 0$	$V_S = 0.3$	$V_S = 0$	$V_S = 0.3$	
0.9	0.78	0.715	0.64	0.56	R = values
0.7	0.74	0.66	0.58	0.495	
0.5	0.67	0.58	0.5	0.41	
0.3	0.545	0.46	0.375	0.295	

V_S = relative vessel volume (in relation to V chamber fresh).

4.4 PUMPING BACK THE SALT WATER LOCKAGE PRISM

Pumping back the salt lockage prism from the lock to sea is to be considered at lock emptying, when the sea level is higher than that of the canal. From Figure 9 we can deduce that the salt burden caused by the prism is close to 100% (as related to the lockage prism volume), at any value for θ and vessel volume. Calculations concerning reduction of the salt when using this method are to be made with Equation (30) in Appendix A. The reduction factor R, to be applied to the results of Figure 9, is mentioned in Table 4.4.1.

When introducing a system to lead the lockage prism back to sea (by pumping or by a conduit connected to an additional reservoir which is continually kept at the lowest water level outside), then it can even be considered to drain the chamber a little more under the fresh-water level, (because it is most effective to discharge that water which holds the highest salinity). With this policy, the chamber will have to be levelled by admitting water from the fresh basin before gates on that side are opened.

4.5 SOONEST POSSIBLE CLOSURE OF GATES IN COMBINATION WITH AN AIR CURTAIN

When air is let in through a perforated tube on the basin floor in non-running homogenous water, the zone above will develop an air/water mixture with a lower density than the surrounding water. We will use the following scheme to determine the (theoretical) discharge of air needed to keep salt and fresh water separated.* There are three vertically separated zones. The blended zone, containing a mixture of water and air, is bordered by a salt zone and a fresh zone. Now assume the desired density of the mixed zone is similar to that of the fresh water. Then a two-layered interchange current will originate at the salt side, and no interchange current at the fresh water side (Figure 15).

* A detailed analysis of currents can be found in Abraham, 1972.

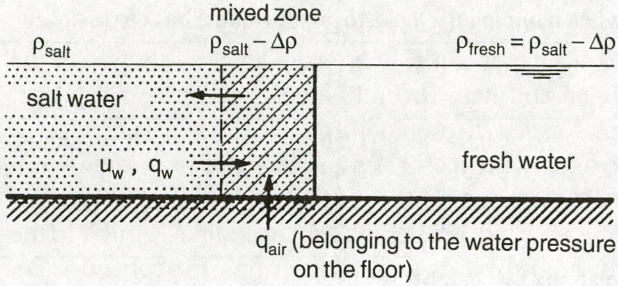
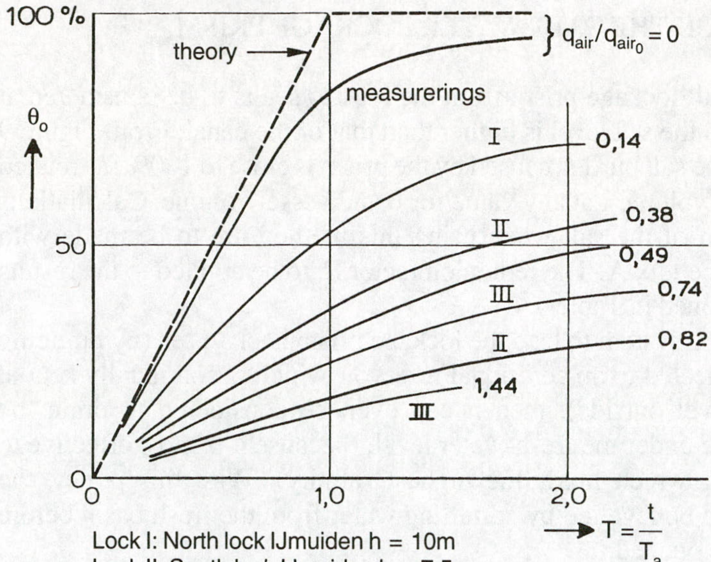


Figure 15. The 'optimal' situation with an air curtain.



Lock I: North lock IJmuiden h = 10m
Lock II: South lock IJmuiden h = 7.5m
Lock III: Lock Kornwerderzand h = 5m

$T_a = 2L/0.5\sqrt{\varepsilon g h}$

$$q_{air_0} = 0.25\,\varepsilon h\sqrt{\varepsilon g h}\left(1 + \frac{U_{ri}}{0.5\sqrt{\varepsilon g h}}\right)$$

q_{air} is the air discharge belonging to the water pressure on the floor

Figure 16. Reduction in interchange with the use of air curtains from Abraham et al. 1962.

The air discharge is indicated by q_{air} (air discharge with an air pressure equal to the water pressure over the basin floor). In Figure 15, salt water penetrates the mixed zone in the lower layer. The necessary air volume to be admitted into the system follows from the requirement that the mixture of penetrated salt water and air will again have to hold a density equal to that of the fresh water. Appendix B presents the complete derivation of the theoretical air requirement per unit of width, q_{air_o}, which will ensure no interchange (theoretically). In Abraham et al.

1973, prototype measurements are presented: The interchanged water volume (as related to the chamber volume) at several locks, is determined as a function of the time allowed for gates to be open and with several values for the air discharge. These measurements are transformed to some dimensionless parameters in Figure 16. This graph can be used with the understanding that it pertains to a situation without vessels. The effectiveness of the air curtain is probably greatest when $q_{air} = q_{air_o}$. The situation when q_{air} is greater than q_{air_o} becomes similar to the situation with an air curtain in homogenous water (described in Appendix B). Since in the mixed zone, water is then sucked from both sides , interchange now increases with the augmentation of q_{air}. We would expect the line in Figure 16 to be positioned higher with $q_{air}/q_{air_o} = 1.44$ than we would find with $q_{air}/ q_{air_o} = 1$. For systems with ships no systematic data are known. We can expect that blocking of the flows by ships causes the interchange process to elapse slower, especially in situations without air curtains.

Figure 16 shows us effectivity hardly increases with greater values of q_{air}/q_{air_o}, from around 0.8 and onwards: Since the air curtain now produces much blending, a new source of salt up has been introduced. The results of Figure 16 show the velocity of the interchange process can be reduced to 0.1 or 0.2 as compared to the situation without an air curtain.

The conclusion from Figure 16 is that an air curtain can much prolong the duration of the interchange process. This makes it possible to close the gates before the entire chamber has changed content. However, to ensure adequate performance by the air curtain, it still is crucial that gates are closed fast.

Experiences from practice are (also in reference to the photo in Figure 17) that:

- Forces on moorings decrease dramatically as a result of exchange currents being suppressed;
- The resulting turbulence and air bubbling pose problems for smaller vessels;
- Air penetrates the engine cooling-systems and vessel toilets (causes an inward flow),
- It is expensive in terms of energy consumption.

An advantage of the system over the drawbacks of other measures to reduce salt penetration (which will be treated hereafter) is that it can be applied at existing locks.

Air curtains should preferably be placed in a groove in the floor, to prevent potential damage by anchors, etc. When the perforations face downward, the tube won't clog and water will be pushed out easily by the air. Projects realized so far featured upward facing perforations. The tube will need a cross-section equal to or larger than the summated area of the perforations. The air-flow loss will have to be calculated. Theoretically the perforations will have to be as small as possible in order to obtain a low rising velocity of the air bubbles. Many small perforations also bring about a more homogenous mixture of air and water. A disadvantage of

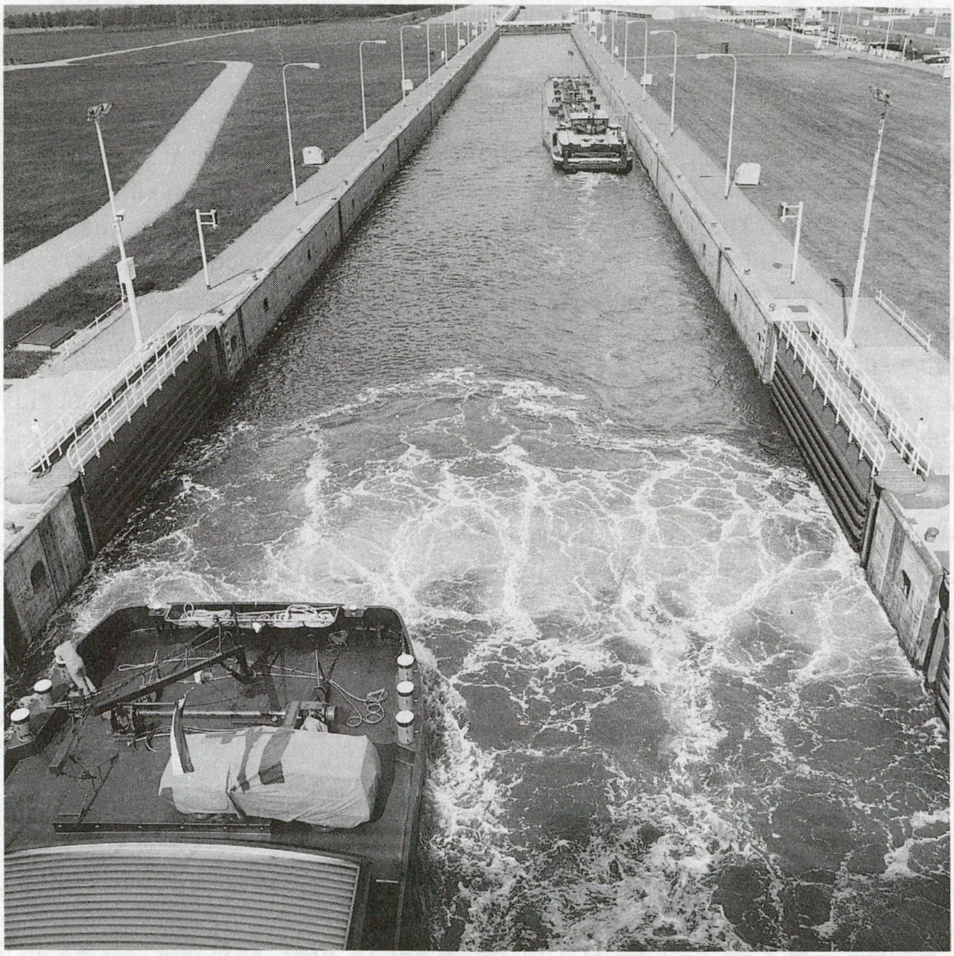


Figure 17. Air curtain in the Volkerak ship locks.

small perforations is that they clog easily. Perforations smaller than 1 mm will demand additional pressure: The surface-pressure of the formed bubbles will also play a role.

An air curtain at both lock gates should be located to the gate as near as possible, at the side of the fresh-water basin. The result is that the (small) volume between curtain and gate is fresh water which will travel towards the sea when the gate is opened. When the curtain is located at the other side of the gate one would get salt contamination of the fresh-water basin.

For calculation of the reduced salt penetration over the entire operation cycle with a low θ, as is the case with an air curtain, Figure 9 provides the necessary data.

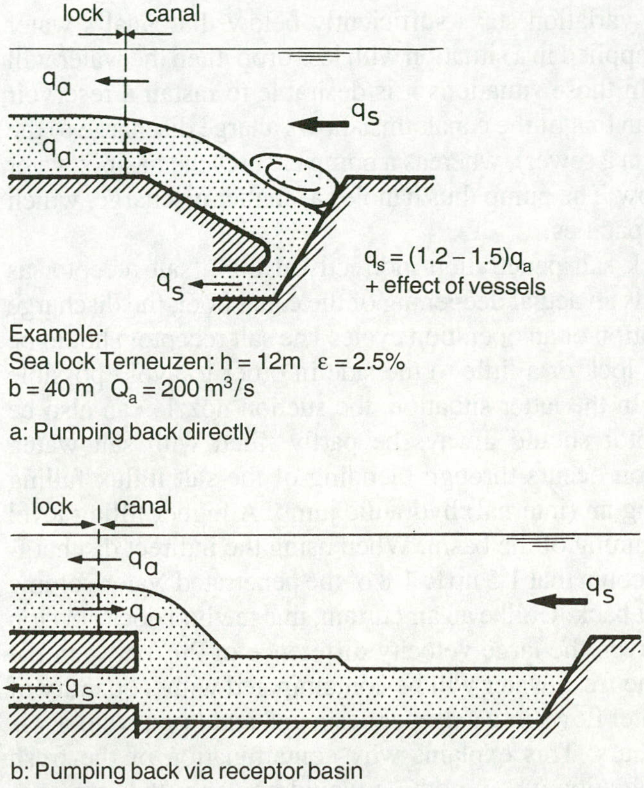


Figure 18. Direct and indirect flushing back or pumping.

4.6 SYSTEM TERNEUZEN (FLUSHING BACK SALT PENETRATION DIRECTLY AND INDIRECTLY)

It is possible to retract salt penetration in the lower layer either directly (Figure 18a), or with use of a salt-receptor basin which receives the influx. Flushing back directly enables the prevention of almost all salt penetration in the canal. The suction opening is at the bottom near the lock gate. The condition is that the discharge $q_{\text{discharge}} = 1.2$ ranging up to 1.5 q_a (refer to Equation (16) for q_a). When ships enter and leave the chamber the under current varies widely and we should count on a factual 1.5 up to 1.8 q_a.

The interchange time duration T_a (Equation 17) is determinant for flushing back the salt undercurrent. T_a is so short that gates cannot be closed any sooner. Since the entire chamber volume enters the canal as salt water, the factor 1.5 up to 1.8 also becomes a measure for the quantitative relation between the discharge volume needed to prevent salt up the net chamber volume. The numeric example in Figure 18a shows that the interchange discharge already is very large. With direct retraction, the discharge of penetrated salt should be larger by a factor 1.5 up to 1.8. At the Terneuzen lock this discharge can be reached with the natural drop, since the sea's tidal variation stays sufficiently below the canal's water level. If the system is to be applied in a situation with less drop, then the water will have to be pumped back. In those situations it is desirable to install a reservoir with a water level lower than that of the canal; this allows a large discharge to the basin by force of gravity (via a sewer), whereas a pump ensures the basin's water level remains adequately low. The pump thus handles a smaller discharge, which allows for smaller pump capacities.

Also when flushing back salt penetration indirectly, using a salt receptor as storage basin, in other words an actual deepening of the canal floor, the discharge can be spread over the duration of an operation cycle. The salt receptor should be positioned in line with the lock or a little to the side in order to avoid possible blending caused by ships. In the latter situation, the suction nozzle can also be placed there. A salt receptor should always be partly filled with salt water, otherwise additional dilution occurs through blending of the salt influx falling down into the basin creating an (internal) hydraulic jump. A higher filling level also simplifies selective draining of the basin. When using the indirect discharging method we should also count that 1.5 up to 1.8 of the penetrated water volume will be necessary to pump it back. Unlike an air curtain, this method does not stop the interchange current. Given the large velocity difference of $2u_a$ between the upper and bottom layers, the fresh water will be contaminated with a quantity of salt water. Since the salt water flows into a deeper basin and additional velocity is gained, more blending occurs. This explains why contamination of the fresh water is higher than in a situation where nothing would be done (the reference situation). Since the bulk of this water will end up back in the chamber it is not very noticeable in the canal, until a vessel pushes this water further up the canal. This additional salt can only be flushed back at a relatively high loss of fresh water.

Figure 19 shows the map of the ship lock at Terneuzen. The flushing conduit

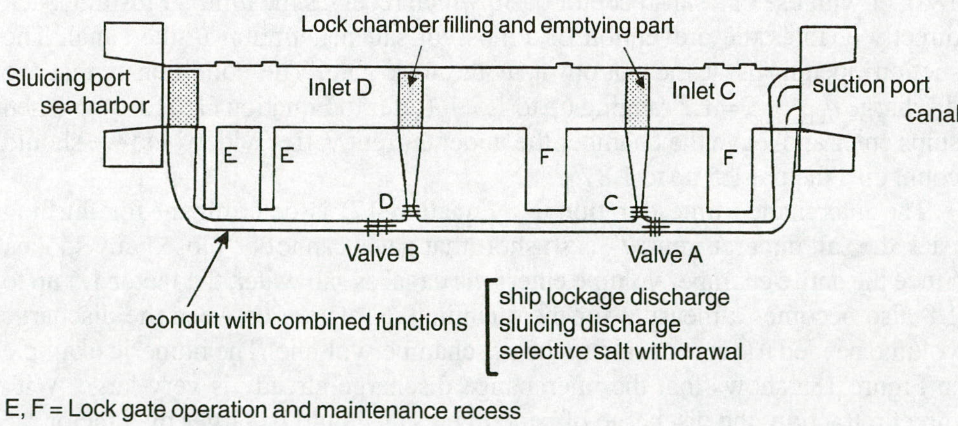


Figure 19. Plan of Terneuzen sea lock.

(with a suction nozzle just past the lock gate facing the canal) is combined with the filling and draining system of the ship lock. At this lock, retraction of the salt influx can be done either directly, or indirectly (by using the salt receptor). For construction details, refer to Jonker and Barentsen, 1968. The lock combines operation with the use of air curtains. On the one hand, air curtains reduce the exchange current, on the other they cause some blending and contamination of the fresh upper layer.

As mentioned before, air curtains reduce the force on moorings while gates are opened; a very positive influence. This is especially important at sea locks: Because of the great depth, u_a is large, whereas sea-going ships allow only small forces to be exerted on their moorings. Flushing back the salt influx directly with a large discharge has, however, not been applied yet at Terneuzen. The underlying reason for this is that flushing discharges exceeding q_a, cause an additional current set towards the lock. In particular vessels entering the lock, experience a loss in navigational ability.

4.7 COMPARISON OF THE VARIOUS SYSTEMS THAT ENABLE THE GATES TO BE OPENED IMMEDIATELY AFTER LEVELLING

In the preceding chapters we looked at measures in situations where the opening

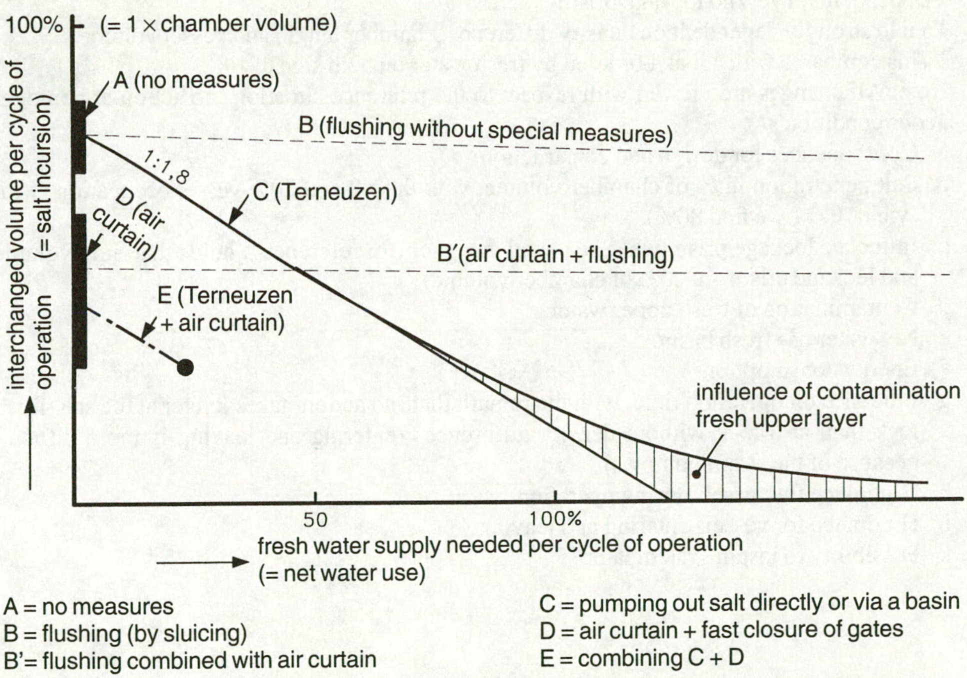


Figure 20. Interrelation between salt penetration and net water use in those situations where the gates are opened immediately after filling or draining the lock chamber.

Table 4.7.1. Comparison of systems interchanging with gates opened.

	No action	Better management	Pumping back lockage prism	Fast closure + air curtain	Flushing back salt penetration
a	None	No influence per operation cycle	Pump/conduit	Preferably grooves	Pump/conduit[1)] + salt receptor
b	72% ($\theta = 0.9$)	Ditto	72%	20-40%[4)]	Minimal
c	20%	Ditto	0%	20%	With salt receptor 5%
d	Yes[2)]	Ditto	No change	Increases	No change
e	None	Ditto	None	None	120-150%[3)]
f	None	Ditto	Yes when pump[1)]	Quite high	Depandant on direction of drop
g	Longer than homogeneous condition[5)]	Less frequent operation; wait longer	Minimal	None	None
h	Yes, with gate filling	Does not change	No change	No change	Probably now floor filling
i	Yes[5)]	Does not change	No change	Decreases	Less advantageous
k	Not relevant	Always possible	Possible, but rebuilt necessary	Small or no rebuilt	Only possible when drainage next to lock

[1)]When tide is seldom higher than canal level, pump can be replaced by buffer basin.
[2)]Caused by two-layered current in chamber.
[3)]Dependent on yes/no lockage prism.
[4)]Yield strongly dependent on density difference, chamber length and vessel volume.
[5)]This compares with a lock bordered by fresh water on both sides.

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

a Consequences for design and construction.
b Salt penetration in % of chamber volume, with drop 0 and 20% vessel occupation (with 'yield' $\theta = 1$ we find 80%).
c Influence lockage prism when sea level is higher (for reference it holds that Ship volume and lockage prism are 20% of chamber volume).
d Contamination of fresh upper water.
e Net water use fresh basin.
f Energy consumption.
g Influence on operation time, with the remark that 'no action' takes longer at the salt/fresh lock than at a lock without density differences (entering and leaving is more difficult because of the stratified flows).
h Hindrance for vessels during operation.
i Hindrance for vessels entering and leaving.
k Possibility to install system later.

of the gates facing the canal caused an interchange current which had to be slowed down (air curtain), or flushed out either directly or indirectly (system Terneuzen). These measures do not pertain to duration of operation, since as soon as gates are opened, vessels can enter and leave the lock. Air curtains can also have a positive effect for vessels by weakening the interchange current.

Table 4.7.1 once more summarizes all factors which can influence the choice of a system. For reference were taken: Situations with equal water levels, 20% vessel volume and an 'exchange reduction factor' θ of 0.9 compared to a lock free of any measures.

Figure 20 plots the salt (expressed as undiluted salt-water volume related to the chamber volume at fresh-water level) as a function of the fresh-water loss. This is expressed as the net water volume withdrawn from the fresh-water basin in relation to the chamber volume. System Terneuzen will not always have an adequate fresh water volume at its disposal to flush back the salt influx. When this occurs, an air curtain will be a positive influence. When an adequate water volume is available, system Terneuzen will be favourable to a system using that water volume as supplemental discharging water for an air curtain. This has been indicated qualitatively in Figure 20 where line *C* lies below *B′*. Combination of both measures is even more effective, but contamination of the upper layer will also be greater.

CHAPTER 5

Further analysis of salt-fresh water separation systems that interchange the chamber's volume before gates are opened

5.1 SYSTEM DUNKERQUE/KREEKRAK/KRAMMER

In the early sixties a new system – system Dunkerque (named after the location it was first applied at) – was developed by the French research institute Sogréah. With this system the chamber's volume is interchanged completely, with closed gates. The salt water is replaced by fresh water or vice versa. Since it is unacceptable for vessels to lie dry, but also to save time and reduce pumping head, the draining and filling processes take place simultaneously. The salt water is drained through perforations in the chamber's floor while the fresh water is admitted through slots in the wall, located near the water surface. This process is called downward interchange. As mentioned, the system can also be operated in reverse order. The chamber's volume will then transform from fresh to salt and the fresh water will be drained through the wall slots back into the canal (the process of regaining fresh water or upward interchange). The system will now be described following the various fases of lock operation. Assumed is the case where the salt sea-water level is higher than that of the canal.

a) Ships enter the canal from sea;

b) Gates are closed and the salt-water level is lowered to that of the canal or basin. The water is pumped into the sea.

c) Further draining with simultaneous admission of fresh water at water surface. Especially in the beginning this should not be done too fast since heavy blending can occur if no fresh upper layer has yet formed in the chamber. This is the downward interchange fase.

d) When the salt water has reached the floor, the interchange stops and after levelling with the water level in the canal or basin, gates are opened.

e) Vessels enter and leave.

f) Now we are confronted with a choice to add a fase of upward interchange. If it is opted for, the salt water will be admitted through the floor while simultaneously fresh water is drained at the water surface. This can be done until a too-large quantity of salt water will be carried in the fresh water (further on it will