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Dynamic Control of Salt Intrusion in the Mark-Vliet River System, The Netherlands

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Abstract The Volkerak-Zoom Lake is an enclosed part of the estuarine delta in the southwest of the Netherlands and exists as such since 1987. The current freshwater lake experienced a deterioration in water and ecological quality. Especially cyanobacteria are a serious problem. To solve this problem it is proposed to reintroduce salt water and tidal dynamics in the Volkerak-Zoom Lake. However, this will affect the water quality of the Mark-Vliet River system that drains into the lake. Each of the two branches of the Mark-Vliet River system is separated from the Volkerak-Zoom Lake by a lock and drainage sluice. Salt intrusion via the locks may hamper the intake of freshwater by the surrounding polders. Salt intrusion can be reduced by increasing the discharge in the river system. In this study we used the hydrodynamic SOBEK model to run different strategies with the aim to minimize the additional discharge needed to reduce chloride concentrations. Dynamic control of the sluices downstream and a water inlet upstream based on real-time chloride concentrations is able to generate the desired discharges required to maintain the chloride concentrations at the polder intake locations below the threshold level and

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to reduce the amount of water required by more than 50% compared to a situation with a constant discharge. Other effective measures consist of relocating the most downstream polder intakes more upstream, reducing the downstream cross section of the Vliet to increase flow velocities and measures that reduce the inflow of salt water via the locks. This study shows that dynamic control is a promising technique in regulated streams to alleviate water quality problems by controlled flushing of the system.

Keywords Salt intrusion · Dynamic control · Locks · Hydrodynamic modelling · Flushing

1 Introduction

After the devastating floods of 1953, the Dutch government decided to construct the Delta Works. The Delta Works closed off and compartmentalized the estuarine delta in the southwest of the Netherlands to make it safer and more accessible. As a result several freshwater lakes were created, the Volkerak-Zoom Lake being one of them (Fig. 1). Since its completion in 1987 the water and ecological quality of the Volkerak-Zoom Lake has deteriorated (Breukers et al. 1997). Especially the presence of toxic cyanobacteria is an indication of a disturbed ecosystem and causes problems for

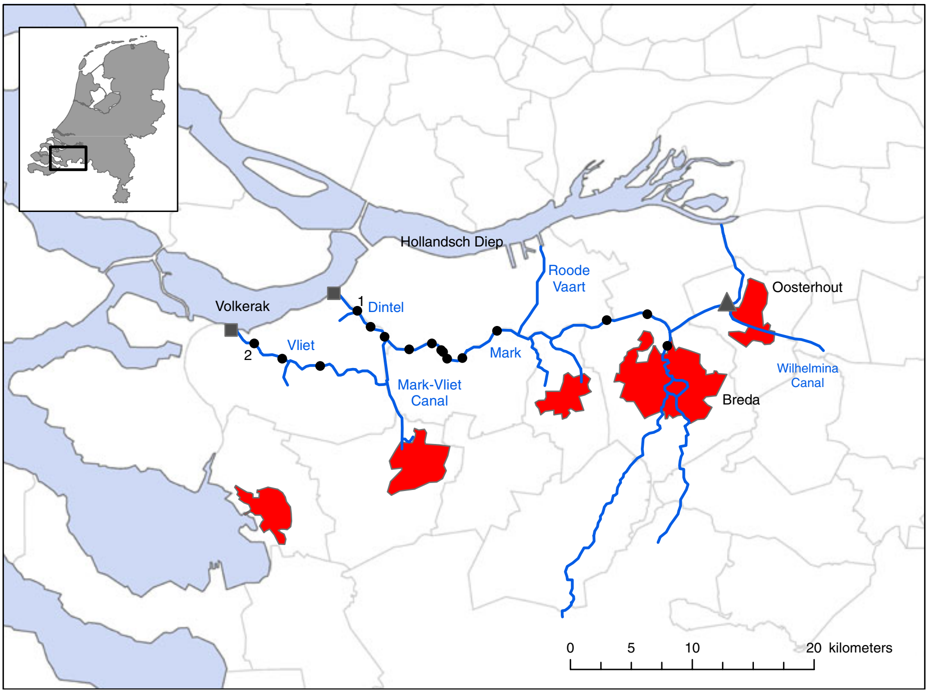

Fig. 1 Location of the Volkerak-Zoom Lake and Mark-Vliet River system. The squares mark the locations of the locks and sluices, the triangle represents the location of the inlet near Oosterhout. The dots indicate polder intake locations. The dots numbered 1 and 2 are the most downstream intake locations in the Dintel and Vliet, respectively

water supply and recreation. Reintroduction of salt water and estuarine dynamics is seen as an important solution to this problem (Verspagen et al. 2006). This fits the current policy of re-establishing salt-freshwater gradients and estuarine dynamics in the region. This policy is partly initiated by the European Water Framework Directive that requires all water bodies to have a good chemical and ecological status by the year 2015 (EC 2000). The plans intend to improve the water quality and ecologic quality of the Volkerak-Zoom Lake, however, it will also have an adverse impact on the freshwater supply for drinking water and agriculture in the region making it a challenging water management issue (Hommes et al. 2009).

The Mark-Vliet River system drains into the Volkerak-Zoom Lake via two branches: Dintel and Vliet (Fig. 1). The Mark-Vliet River system is highly regulated and adjacent agricultural polders rely on it for their water supply in times of water shortages. Both the Dintel and Vliet river branches are connected to the Volkerak-Zoom Lake by a lock and a drainage sluice. Shipping requires the operation of the locks. When the Volkerak-Zoom Lake becomes salt again, salt water will enter the river system through the locks. The larger fluctuations in water level caused by the tidal dynamics will affect salt water intrusion via the locks and the possibility of draining water from the Mark-Vliet River system into the Volkerak-Zoom Lake. Especially during the summer when the shipping intensity is high and the discharge is low, the potential for salt-water intrusion is large. An effective solution to reduce salt intrusion is to increase the discharge, because the extent of salt water intrusion mainly depends on the discharge (Sierra et al. 2004; Nguyen et al. 2008; An et al. 2009). Currently additional water is already supplied via an inlet near Oosterhout (Fig. 1) to maintain sufficient flow velocities and desired water levels during dry periods. A previous model study showed that an increase in discharge indeed reduces salt intrusion in the Mark-Vliet River system (Witteveen+Bos 2008), however, this requires a considerable amount of water that may not be available via the inlet near Oosterhout. A new or additional inlet via the Roode Vaart (Fig. 1) has been suggested. Currently, this inlet could provide a sufficient amount of freshwater from the Hollandsch Diep, however, this could diminish in time due to climate change (Kwadijk et al. 2008).

The objective of this study is to minimize the additional discharge required to manage salt intrusion by dynamic control of hydraulic structures based on real-time chloride concentrations. The hydrodynamic model SOBEK (www.sobek.nl) is used to analyze the dynamic control of the drainage sluices and the upstream inlets (Oosterhout and/or Roode Vaart) in order to maintain chloride concentrations below a certain threshold level near the polder intake locations along the Mark-Vliet River system. Dynamic or real-time control methods have been described for water management as well as urban waste water management (Lobbrecht 1997; Schütze et al. 2002), however, examples of dynamic control in surface water quality management are limited (Xu et al. 2010).

2 Mark-Vliet River System

The Mark-Vliet River system is situated in the west of the Province Noord-Brabant, the Netherlands. The catchment area of the Mark-Vliet River system covers 140,000 ha. The Mark-Vliet River system drains into the Volkerak-Zoom Lake via two branches, the Dintel in the north and the Vliet about 9 km to the southwest. The two branches are connected by the Mark-Vliet Canal. Upstream of the bifurcation the river is called the Mark which is formed in the city of Breda by two smaller tributaries that originate in Belgium. The Mark-Vliet River system has two important functions: water supply for water level management in the adjacent polders and shipping (mainly recreational). The total polder area that uses water from the Mark-Vliet River system is about 20,000 ha. The main land uses in these polders are arable land, pastures, fruit trees and horticulture. Since 1987, when the Volkerak-Zoom Lake was established, agricultural activities in the region have intensified due to the increased availability of freshwater. The dominant soil type is clay of marine origin. The area is flat and partly below sea level. The polders receive seepage water that originates from elevated terrain near the Dutch-Belgian border as well as the Volkerak-Zoom Lake. When the Volkerak-Zoom Lake becomes salt again this will have an adverse impact on the groundwater quality in these polders. Currently, groundwater near the Volkerak-Zoom Lake is still saline as a heritage of the salty conditions before 1987. Seepage of saline groundwater can be reduced by increasing the water level in the polders and the effects can be limited by regular flushing of the drainage ditches in the polders. Both measures require an additional intake of freshwater from the Mark-Vliet River system. During the summer water is let in from the Mark-Vliet River system via a number of (free-flow) inlets and pumping stations. Altogether these inlets and pumping stations abstract an average of $2 \cdot 10^6$ m^3 per month (approximately 10 mm) from the Mark-Vliet River system during the growing season, when the water demand is large. When water levels in the Mark-Vliet River system drop below a certain level, it is possible to supply extra water from the Wilhelmina Canal into the Mark via a culvert near Oosterhout. This is only done when the availability and quality of the canal water is sufficient. Sometimes the water in the Wilhelmina Canal is contaminated by cyanobacteria or the bacteria Ralstonia solanacearum that causes plant diseases known as potato brown rot or bacterial wilt, which makes the water unsuitable for water supply to the polders.

When estuarine conditions are reintroduced in the Volkerak-Zoom Lake, intrusion of salt water will take place via the locks. During the summer months, when agriculture is most vulnerable to salt, the number of lock operations is highest because of the recreational season. The drainage sluices are used to regulate the water level in the Mark-Vliet River system. The estimated amount of salt water entering the system via the locks is based on an exchange percentage. This exchange percentage depends on the size of the lock gates compared to the chamber volume, the time the gates are opened, the density difference between salt and freshwater, the water level difference and water displacement by passing ships (Jongeling 2007). For the lock in the Dintel the exchange percentage has been estimated to be 54%, for the lock in the Vliet 12.5%, which means that for each lock operation this percentage of the volume of the lock is entering the river system. Given the volumes of the locks (being 6,000 m^3 and 10,000 m^3, respectively), and an estimated chloride concentration of 12,500 mg/l in the chamber of the locks, the chloride load entering the Mark-Vliet River system amounts $40 \cdot 10^3$ and $16 \cdot 10^3$ kg per lock operation, respectively. Since salt water is heavier than freshwater a salt water wedge may develop. Whether stratification will occur depends on the level of mixing during lock operation, and the influence of ship movements and wind which is relatively important in shallow water systems such as the Dintel and Vliet (3–5 m deep).

Besides vertical stratification, lateral concentration gradients may also develop near the locks because the size of the locks is smaller than the width of the river branches. Although salt and freshwater mixing in and near a lock is a very complex process, it is assumed here that the intrusion of salt can be described by a simple one dimensional (1D) dispersion process. This assumption is analyzed in the discussion.

3 Modelling Approach

To model the Mark-Vliet River system, SOBEK version 2.11c (www.sobek.nl) was used. In this study the rainfall-runoff, channel-flow, water quality and real-time control module were used. The rainfall-runoff modules calculates the runoff and drainage into the watercourses based on a simple water balance for separate elements. The channel-flow module calculates flow velocities and water depths in 1D based on the Saint Venant equations. The water quality module calculates the transport of substances based on the advection-dispersion equation and reactive processes. The real-time control module was used to simulate strategies with dynamic control. For the rainfall-runoff module daily data of rainfall and evaporation of one weather station in the study area have been used. The river branches depicted in Fig. 1 were schematized in the channel-flow module with a spatial resolution of 50 m. The output of the rainfall-runoff module is used as upstream boundary condition of the river branches and as lateral inflows where non-modelled branches enter the system. The intake or outflow of the adjacent polders is calculated by the rainfall-runoff module based on the water balance and a desired water level in the polders. The water quality module was used to calculate chloride concentrations in the Mark-Vliet River system. For the boundary condition at the Volkerak-Zoom Lake scenario N15, variant 1_100% (Meijers et al. 2008) was used. In this scenario the water level in the Volkerak-Zoom Lake near the lock in the Dintel varies between −0.3 m and +0.3 m NAP[1] and near the lock in the Vliet between −0.35 m and +0.35 m NAP due to tidal dynamics, wind effects are neglected. The chloride concentrations in the Volkerak-Zoom Lake also vary over time, in the summer the chloride concentrations are approximately 13,000 mg/l. Water levels are given for every hour, chloride concentrations in general every 6 h. The calculation method consists of a fully implicit iterative method, with a time step of 5 min.

Salt intrusion is determined by the number of lock operations, the total salt load per operation, the dispersion coefficient and the flow velocity in the watercourses. The latter is most variable over the year. During dry periods there is hardly any flow in the Mark-Vliet River system, allowing chloride to penetrate further upstream into the system. The extent of the dry period and subsequent drop in discharge, is therefore normative for the salt intrusion. Because 1996 had a long dry period the meteorological data for this year were taken as a realistic case for a situation with a high potential for salt intrusion.

In summer (June–October) both locks are operated 56 times per day in the weekend and 20 times during weekdays. The operations are evenly distributed over day

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[1] NAP is Normaal Amsterdams Peil (Amsterdam Ordnance Datum) and is used as an equivalent of mean sea level.

time. In winter the number of lock operations is much lower. For each lock operation, the gates are opened 5 min. The locks are modelled as a lateral inflow having a certain chloride concentration based on the exchange coefficients. To compensate for the inflow of saline water an outflow of the same volume is defined 200 m downstream of the lock. The upstream inlet is modelled as a lateral inflow near Oosterhout

The model has been calibrated for the years 1994, 2003 and 2006 (Witteveen+Bos 2008). For calibration of the rainfall-runoff module the soil drainage, soil storage and average initial groundwater levels were varied. The flow module was calibrated by varying the Manning roughness ($n = 33$ $\mathrm{m}^{1/3}/\mathrm{s}$) and the discharge coefficient over the weirs ($C_d = 1.23$). The results showed good agreement with measured discharges and water levels, especially during the dryer summer months. This is also the period for which salt intrusion is most crucial.

The objective of this study is to develop a dynamic control strategy that minimizes the additional discharge required to prevent adverse effects from salt intrusion. Adverse effects may occur when chloride concentrations of the water admitted into the polders exceed the salt tolerance of crops, hence reducing the yield. The threshold concentration for chloride in irrigation water varies per crop from 16 mg/l for some flowers cultivated in greenhouses to over a 1,000 mg/l (Van Dam et al. 2007). In this study a value of 300 mg/l is taken as a limit.

4 Chloride Control Strategies

Different strategies have been modelled, all based on the data for 1996, to evaluate the effect on the additional discharge required to prevent adverse effects of salt intrusion in the Mark-Vliet River system.

The first strategy is without any measures. It simulates the hydrological situation of 1996, including the measured inflow near Oosterhout, however with a saline Volkerak-Zoom Lake. The drainage sluices are operating when the water level exceeds the desired water level of +0.15 m NAP on the Mark-Vliet River system. The essential difference with the current situation is a saline Volkerak-Zoom Lake and the operation of the locks. In the current situation with a freshwater Volkerak-Zoom Lake the locks remain open most of time, while in the simulated case with a saline Volkerak-Zoom Lake the locks will be closed each time a ship has passed through.

The second strategy has been developed in a previous study (Witteveen+Bos 2008), i.e. the first strategy with a continuous additional discharge of 15 m^3/s, unless the natural discharge was sufficient.

The third strategy includes dynamic control of the drainage sluices and inlet based on real-time chloride concentrations. This strategy was developed in several steps. First the discharge at the inlet near Oosterhout was controlled on the basis of the mean chloride concentration of the most downstream polder intakes in the Dintel and the Vliet (intake locations 1 and 2 in Fig. 1). Here the chloride concentrations will be the highest. When the mean chloride concentration of the two locations exceeded 250 mg/l the upstream inlet was gradually opened allowing more water to enter the Mark with increasing chloride concentrations. The reaction time of the system appeared too slow to sufficiently reduce the chloride concentrations near the most downstream intakes. Lowering the concentration of 250 mg/l at which the additional discharge is initiated introduces an uncertainty, if the chloride concentration does not further increase water may be wasted. Hence, controlling the inlet near Oosterhout based on real-time chloride concentrations at the downstream polder intakes is by itself not adequate.

Since salt intrusion strongly depends on the discharge in the Vliet and Dintel, the next step was to search for an optimal distribution of the discharge over the two branches using SOBEK. A continuous discharge of 3 m^3/s in the Dintel and 7 m^3/s in the Vliet appears to be sufficient to maintain the chloride concentration below the limit of 300 mg/l under the given conditions. Hence, the maximum discharge at the upstream inlet does not need to exceed 10 m^3/s. The discharge in the Vliet needs to be larger because the cross sectional area of the last two kilometers of the Vliet is much larger than the Dintel (720 m^2 vs. 180 m^2), causing a significant reduction of the flow velocity in the downstream reach of the Vliet where intake location 2 is situated.

In the third step the drainage sluices are used to divide the discharge in the desired ratio over the two river branches. In the model, the discharge of the drainage sluices is schematized as an orifice flow. To generate the desired discharge in the Dintel and the Vliet, the opening of the sluices can be calculated based on the following equation:

$$Q = \mu W d \sqrt{2g\left(h_1 - h_2\right)} \tag{1}$$

where Q is the discharge through the gate, μ the contraction coefficient (0.63), W the width of the gate, d the opening height of the gate, g the gravity acceleration

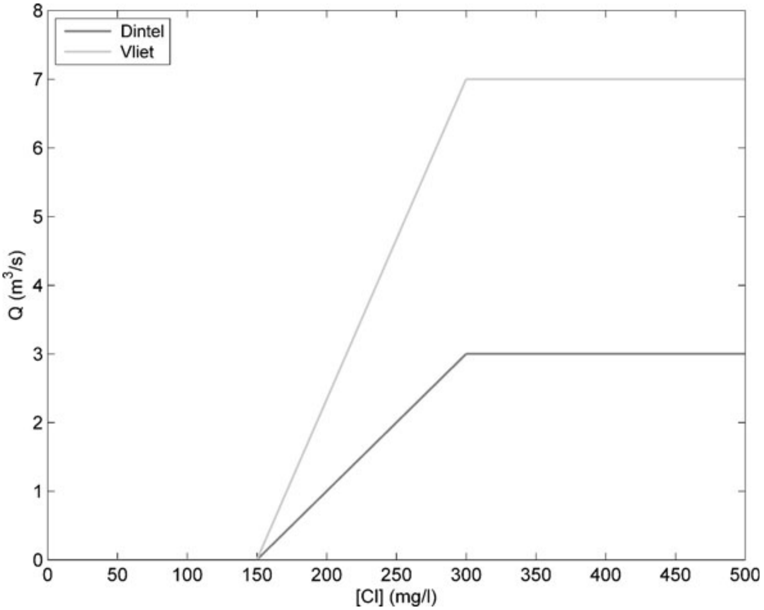

Fig. 2 Discharge generated by opening of the drainage sluices in the Dintel and Vliet as a function of the chloride concentration 200 m downstream of polder intake location 1 and 2 in Fig. 1 according to strategy 3 (dynamic control). The discharge of the inlet near Oosterhout equals the sum of the discharges generated by the sluices in Dintel and Vliet

(9.81 m^2/s), h_1 the water level upstream of the gate (Dintel or Vliet) and h_2 the water level downstream of the gate (Volkerak-Zoom Lake). The drainage sluice in the Dintel is opened as soon as the chloride concentration, simulated in a calculation-node 200 m downstream of intake location 1 in the Dintel, exceeds half the intake concentration limit of 300 mg/l, i.e. 150 mg/l. This value was determined by trial and error and appeared an effective threshold. The gate of the sluice is controlled in such a way that the discharge, calculated by Eq. 1, increases linearly with increasing chloride concentrations up to a maximum of 3 m^3/s at a concentration of 300 mg/l. Above this concentration the discharge remains 3 m^3/s. The same strategy is applied to the sluice in the Vliet, only in this case the controlled discharge increases linearly up to a maximum of 7 m^3/s (Fig. 2). The inlet near Oosterhout is operated in such a way that the inflow of water equals the sum of the discharges generated by the sluices in the Dintel and the Vliet. When the water level in the Dintel or Vliet exceeds a level of +0.2 m NAP the drainage sluice in the particular branch is opened further to control the water level. The additional discharge generated in this way is not compensated for by the inlet. A MATLAB (www.mathworks.com) script was written to perform the real-time control algorithm in SOBEK.

5 Results

When no measures are taken in case of a salt Volkerak-Zoom Lake (strategy 1) the chloride concentration exceeds a value of 8,000 mg/l for a period of three months near intake location 1 in the Dintel. In the Vliet the concentrations are lower, but still exceed 7,000 mg/l in July and August. These months were extremely dry in 1996 and with the locks closed the simulated water level in the Mark dropped below −1 m NAP, where +0.15 m NAP is the target. In reality the water level did not drop in 1996, because the lock gates remained open most of the time establishing a direct connection between the Volkerak-Zoom Lake and the Mark-Vliet River system. The 'natural' discharge in this strategy reduced to zero. The chloride concentration decreases with distance to the locks and sluices, however, even in the Mark the maximum concentration still exceeds 1,000 mg/l. This corresponds to the situation before 1987 when high chloride concentrations also reached the Mark. The total amount of excess chloride (i.e. the cumulative amount of chloride above a concentration of 300 mg/l) entering the polders is in the order of $7 \cdot 10^6$ kg (Table 1). This makes clear that when no measures are taken serious problems for agriculture in the western part of the Province Noord-Brabant will arise when estuarine conditions are reintroduced in the Volkerak-Zoom Lake.

In the situation with a continuous additional supply of 15 m^3/s (strategy 2), the chloride concentration in the Dintel remains below 150 mg/l, however, at the most downstream intake location in the Vliet the daily average chloride concentration varies between 400 and 700 mg/l from June until September. This is because only a small portion (approximately 4 m^3/s) of the additional discharge reaches the Vliet. The routing towards the Volkerak-Zoom Lake via the Vliet is much longer, compared to the routing via the Dintel (Fig. 1). The flow resistance in the Vliet is further increased by a detrimental lay-out of the bifurcations, the smaller cross section and the presence of two abandoned parallel locks halfway the branch of which one is filled with sand. The total amount of excess chloride entering the polders in this strategy is $0.2 \cdot 10^6$ kg. This is a significant decrease compared to strategy 1 (no measures), however the target chloride concentration is still exceeded in the Vliet and a large amount of water is required that cannot be supplied by the inlet near Oosterhout in the current situation.

Figures 3, 4 and 5 show the simulation results for strategy 3 with dynamic control of the drainage sluices based on chloride concentrations and the complementary supply upstream. The results are plotted as daily averages. Figure 3 illustrates that the chloride concentration remains around or below the target concentration of 300 mg/l at the most downstream polder intake locations (indicated by the numbers 1 and 2 in Fig. 1).

In winter the discharge is large and water levels are high (Figs. 4 and 5). At the end of the winter, the runoff and groundwater discharge towards the Mark-Vliet River system decreases due to increasing evapotranspiration. Starting in March the discharge reduces to a level that allows chloride concentrations to rise above 150 mg/l at the downstream intakes in the Dintel and Vliet. At that time the drainage sluices are opened to generate a flow and the inlet near Oosterhout is opened to complement the discharge. Since the concentrations do not exceed the 300 mg/l yet, the inlet is less than the maximum discharge of 10 m^3/s. During this time the discharge in the Dintel is around 3 m^3/s and in the Vliet around 2 m^3/s. Initially, these discharges are sufficient to counteract the salt intrusion. In the beginning of June the chloride concentrations in both the Dintel and Vliet first exceed the threshold level of 300 mg/l because of the increasing lock operations during the summer. The discharge of 3 m^3/s is still sufficient for the Dintel, however, the discharge in the Vliet has to increase to 7 m^3/s, and subsequently the inlet near Oosterhout to 10 m^3/s. To attract more

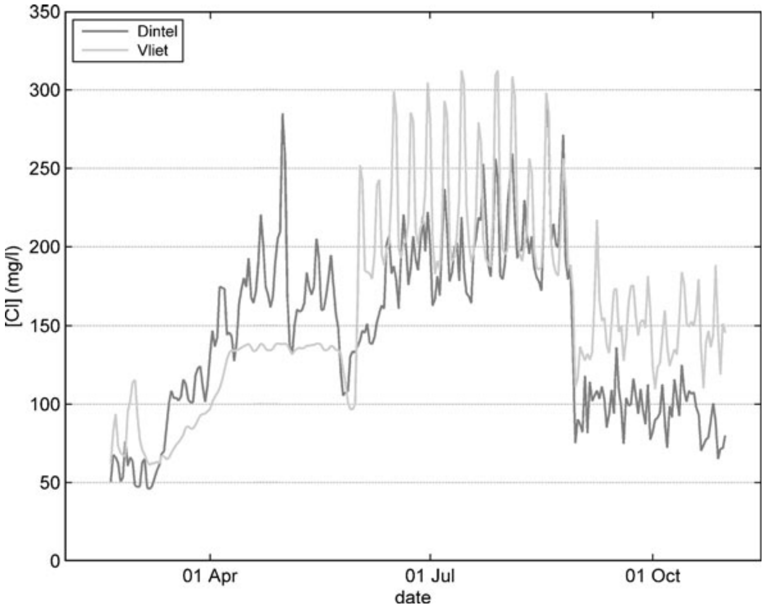

Fig. 3 Variations in chloride concentration for strategy 3 (dynamic control) at polder intake location 1 and 2 in Dintel and Vliet

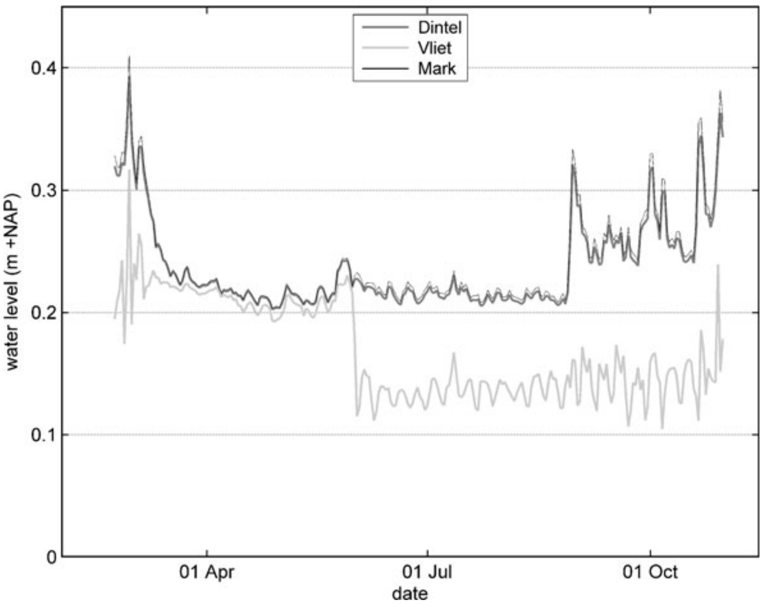

Fig. 4 Variations in water level in the Mark, Dintel and Vliet for strategy 3 (dynamic control)

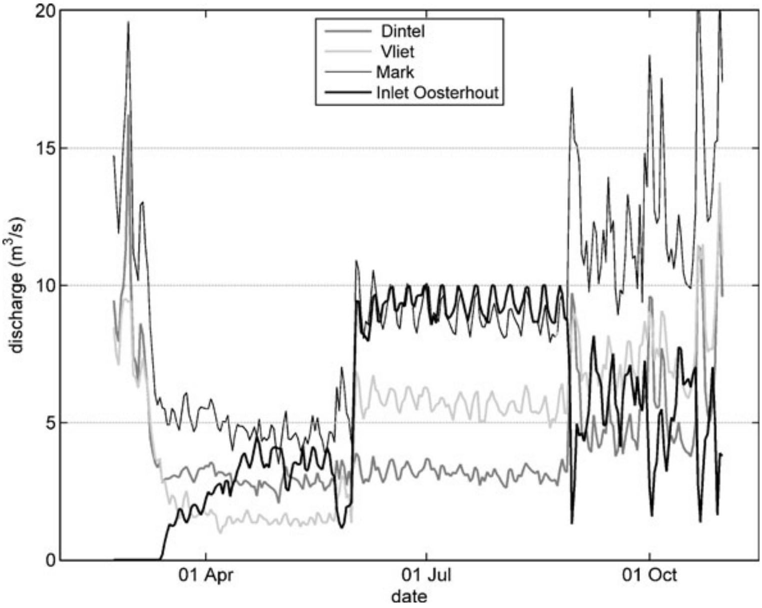

Fig. 5 Variations in discharge in the Mark, Dintel, Vliet and inlet near Oosterhout for strategy 3 (dynamic control)

Table 1 Summary of model results for the three strategies[a]

	No measures	Continuous discharge	Dynamic control
Excess chloride load (10^3 kg)[b]	7,200	221	0.8
Total inlet of water (10^6 m^3)	28	255	120
Maximum inlet (m^3/s)	11	15	10

[a] Given the uncertainties in some of the model assumptions numbers are indicative

[b] Total mass of chloride entering the polders in water with a chloride concentration above 300 mg/l

water to the Vliet the water level gradient is increased by opening the sluice gates further, resulting in a lower water level near the mouth of the Vliet. The water levels and discharge fluctuate because drainage is temporarily hampered during high tides (sluices closed). The concentrations also fluctuate due to the lock operations. In the weekends the frequency of lock operation is larger, resulting in higher concentrations compared to midweek. For the same reason chloride penetrates further upstream into the system during the day and is pushed back at night. The inlet near Oosterhout follows the fluctuations in the controlled discharges in the Dintel and Vliet. At the end of August a large rainfall event increased the discharge and water level in the Mark-Vliet River system, as a consequence the chloride concentrations decrease and the flow through the inlet is reduced. After this event less additional water is required to control the salt intrusion, however, the natural discharge remains insufficient until the end of October.

Table 1 compares the model results for the three strategies based on the load of excess chloride to the polders, the total flow through the inlet and the maximum discharge at the inlet. In strategy 1 (no measures) a minimum amount of additional water is let in just to control the water levels. In this strategy the actual inflow near Oosterhout, as was the case in 1996, was used. Because in the simulation the locks are closed in between ship passages, the water level in the Mark-Vliet River system dropped by more than 1 m. If was compensated for this effect, the discharge at the inlet would have been much higher. With dynamic control (strategy 3) the least amount of salt enters the polders. The total amount of excess chloride in this strategy is 800 kg, which is significantly less compared to the other strategies. It is also the only strategy in which the chloride concentrations at the polder intakes remain around or below 300 mg/l. The amount of additional water required is half the amount needed in the situation with a continuous discharge of 15 m^3/s (strategy 2) and the maximum discharge at the inlet is a third lower.

It can be concluded that dynamic control of the sluices and upstream inlet, based on chloride concentrations, is an effective and efficient measure to reduce salt intrusion. It is able to maintain the chloride concentrations below the desired levels at the intakes of the polders and requires significantly less water compared to a situation with a continuous discharge supplied by the upstream inlet.

6 Discussion

Currently the Volkerak-Zoom Lake is a freshwater lake, hence the model results cannot be verified. By applying the SOBEK model several assumptions were made that lead to uncertainties in the presented results. In Sections 6.1 and 6.2 two important assumptions will be discussed: the assumption that salt intrusion can be described by the advection-dispersion equation and the salt water exchange between Volkerak-Zoom Lake and Mark-Vliet River system.

In this study three strategies for reducing salt intrusion have been analysed, however, other measures may also be effective in mitigating adverse effects. In Section 6.3 some alternative or complementary measures will be discussed. In Section 6.4 some remarks will be made about the implementation of the dynamic control measure.

6.1 Uncertainty in Dispersion Coefficient

The SOBEK model could be used because the assumption was made that salt intrusion can be described by the 1D advection-dispersion equation. It was argued that the opening and closing of the lock gates, together with ship movements and wind effects, causes enough turbulence in the shallow Dintel and Vliet that well mixed conditions could be assumed. This assumption may not be very realistic. Water of different densities does not mix easily. In addition, due to the limited size of the locks compared to the cross section of the river branches lateral concentration differences may develop as well. Even though the 1D advection-dispersion equation may not describe the density driven flow of a salt water wedge or a mixing zone physically correct, it can still be used as an approach to describe the cross sectional-averaged chloride concentration. An uncertainty that remains is the value of the longitudinal dispersion coefficient, which will be different in case of a well mixed system compared to a poorly mixed or stratified system. The value used for the dispersion coefficient in this study was 3 m^2/s. This value is independent of the flow velocity. Due to the discretization of the system also a numerical dispersion is introduced. The numerical dispersion coefficient (D_{num}) for an implicit numerical scheme is equal to (Chapra 1997):

$$D_{num} = \tfrac{1}{2} u \left(\Delta x + u \Delta t\right) \tag{2}$$

where u is the flow velocity, Δx the spatial resolution (50 m) and Δt the time step (5 min). With a discharge of 10 m^3/s, a width of 50 m and a depth of 4 m, D_{num} equals approximately 2 m^2/s. Numerical dispersion increases with flow velocities, like dispersion in reality. The total dispersion coefficient is the sum of the defined longitudinal dispersion coefficient and the numerical dispersion coefficient. A value of 3–5 m^2/s for the dispersion coefficient is common for small streams with low velocities (Kashefipour and Falconer 2002). The model result is rather sensitive for the dispersion coefficient. For larger dispersion coefficients the amount of water required to counteract salt intrusion increases; this is true for all strategies.

6.2 Uncertainty in Estimated Salt Water Exchange

Besides the dispersion coefficient also the amount of salt water that will enter the Mark-Vliet River system is difficult to estimate. In the model, the amount of salt water entering the system depends on the number of lock operations, the exchange percentage and the salt concentration in the Volkerak-Zoom Lake. An increase in these parameters will increase the salt concentration in the river branches and hence the additional discharge required to reduce these concentrations to the desired level. These parameters have been estimated with care based on real data and other studies, but an uncertainty remains.

Given the uncertainties in the dispersion coefficient and estimated salt water exchange, the absolute values presented in Table 1 should be regarded as an indication, and not as the real amount of additional water required. Nevertheless, the relative effects of the three strategies can still be considered reliable. When estuarine conditions are reintroduced in the Volkerak-Zoom Lake, the intrusion of salt water into the Mark-Vliet River system needs to be monitored carefully to be able to optimize the discharge regime.

6.3 Alternative Measures

The total amount of water that is taken in by the polders amounts on average 0.8 m^3/s during summertime, which is a relatively small component in the water balance. The Mark-Vliet water will be diluted by the water already present in the polders. Therefore higher chloride concentrations may be allowed in the intake water. On the other hand, a saline Volkerak-Zoom Lake will in time influence the salinity of groundwater and more freshwater may be required to flush the drainage ditches in the polders situated in the vicinity of the lake. A measure that is considered is to relocate the most downstream intakes more upstream. This allows for more salt intrusion and hence the additional discharge can be reduced.

It is also possible to take measures in or near the locks to reduce salt water intrusion, e.g. by a (movable) sill that blocks the propagation of a salt water wedge upstream, by flushing of the lock chambers during operation or by air-bubble screens (Van der Kuur 1985; Mausshardt and Singleton 1995). If the exchange percentage can be reduced significantly in this way, less inflow from upstream will be required to prevent salt intrusion. However, these measures may require significant investments around the locks. In addition, a reduction in the discharge through the Mark-Vliet River system reduces the flow velocities. Some flow through the river branches is favourable for the water quality as it flushes the system.

In the Vliet a larger discharge is required to counteract salt water intrusion. This is due to the larger resistance caused by the indirect routing, the presence of a closed lock in the middle reach of the Vliet forcing the water through a narrow parallel branch and the fact that the cross section of the Vliet widens at the downstream reach causing a sudden drop in the flow velocity. By opening the closed lock in the middle reach of the Vliet the resistance will decrease and flow velocities will increase at a given discharge. Narrowing the downstream cross section, e.g. by groynes, may facilitate the salt water to intrude further into the system; on the other hand it will also increase the flow velocities pushing the salt water back. Given the large sensitivity of the intrusion length to flow velocities it is expected that narrowing the downstream reach of the Vliet will result in a positive effect. All these measures will reduce the required discharge in the Vliet, and hence the total amount of additional inflow required from the upstream inlet.

The proposed dynamic control strategy may be improved by anticipating to conditions in the near future using model predictive control (Van Overloop et al. 2008). When the intake by the polders and the extent of salt intrusion can be predicted, the operation of the sluices and inlets can be optimized further to the specific requirements. Although model predictive control should be able to save water by a more gradual control of the hydraulic structures, it is expected not to make a big difference compared to the dynamic control strategy evaluated in this study. During the summer months some minimum discharge (in this study calculated to be 10 m^3/s) will always be required to impede salt intrusion effectively, independent of the strategy.

6.4 Implementation

In this model study only the inlet near Oosterhout is considered. Currently the capacity of this inlet is 7 m^3/s, which is insufficient to deliver the maximum discharge required for the strategy with dynamic control. The inlet needs to be upgraded to a capacity of at least 10 m^3/s, but preferably larger, given the uncertainties. Another problem with the inlet near Oosterhout is that water may not always be available and sometimes contains bacteria that can cause potato brown rot. To guarantee a sufficient supply of freshwater, the Roode Vaart could be used to convey water from the Hollandsch Diep to the Mark, however, this requires a much larger investment than upgrading the inlet near Oosterhout (Witteveen+Bos 2008). On the other hand, the Roode Vaart could also be used to drain excess water in times of peak discharges on the Mark-Vliet River, making the system more resilient for future developments.

In this study the chloride concentration is used to control the sluices and upstream inlet. In reality it is difficult to measure the chloride concentration directly. As an alternative, the electrical conductivity (EC) can easily be measured in situ by an electrode and is a reliable indicator of the chloride concentration. In the field sensors (electrodes) need to be installed at multiple locations to measure the EC near the polder intakes and locks in the Dintel and Vliet. In case of incomplete mixing (vertical or lateral) more sensors may be required to obtain a representative concentration. The signal of the sensor(s) is continuously recorded by a computer. When the EC exceeds a certain threshold level, an algorithm as proposed in this study can be used to calculate the opening height of the sluice gate to generate the desired discharge in the particular branch. In this way the sluices in the Dintel and the Vliet can operate automatically and independently based on real-time EC-values. The regulation of the upstream inlet is based on the opening sequence of the sluices in order to balance the upstream inflow with the sum of the discharges generated by the two sluices.

7 Conclusions

The reintroduction of salt water into the Volkerak-Zoom Lake in the southwest delta of the Netherlands for improving its water quality will have consequences for the Mark-Vliet River system that drains into this lake. When no measures are implemented chloride concentrations downstream in the Mark-Vliet River system may increase to over 8,000 mg/l near the locations where water is taken in by adjacent polders to control the water levels, while the tolerance level for crops is around 300 mg/l. To reduce salt intrusion, the Mark-Vliet River system can be flushed by increasing its discharge. In a previous study a continuous additional discharge of approximately 15 m^3/s via the upstream inlet near Oosterhout and/or the Roode Vaart was proposed to counteract downstream salt intrusion. This additional flow reduces the chloride concentrations in the Dintel to desired levels, however, in the Vliet the concentrations still exceeded 300 mg/l for more than 3 months in a dry year such as

1996. This model study demonstrates that dynamic control of the downstream sluices and upstream inlet(s), based on real-time chloride concentrations in the downstream end of the river branches, enables to reduce the concentrations at the polder intake locations below the threshold level with a maximum additional discharge of 10 m^3/s. For the Dintel a required discharge of 3 m^3/s was determined, and for the Vliet 7 m^3/s. For the Vliet the discharge is larger because of a higher hydraulic resistance and a wider downstream cross section. The absolute values of required discharges may be different given the uncertainties. Especially the dispersion coefficient is uncertain and should be verified experimentally. Measures can also be implemented in or near the locks to reduce salt intrusion, reducing the amount of additional water required.

Although this study describes a very specific case in the Netherlands, it shows that dynamic control based on chloride concentrations (or electrical conductivity) is a promising technique to control the adverse effects of salt intrusion in regulated delta regions. The technique can also be applied to other water quality problems that can be alleviated by flushing. It was found that flushing of the system is most effective if the required discharge is generated downstream and balanced by an inflow upstream. To apply this type of control, hydraulic structures need to be in place that can be operated precisely to generate the required discharges. At the upstream inlet enough water should be available of sufficient quality. The algorithm of the dynamic control can be optimized to minimize the operational costs. As shown in this study, complementary measures can often be taken to increase the efficiency of a proposed solution. It is therefore important to understand the system and look for integrated solutions.

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