DEALING WITH SALT INTRUSION AND WATER SHORTAGE IN THE SEINE SCHELDT WEST CONNECTION

by

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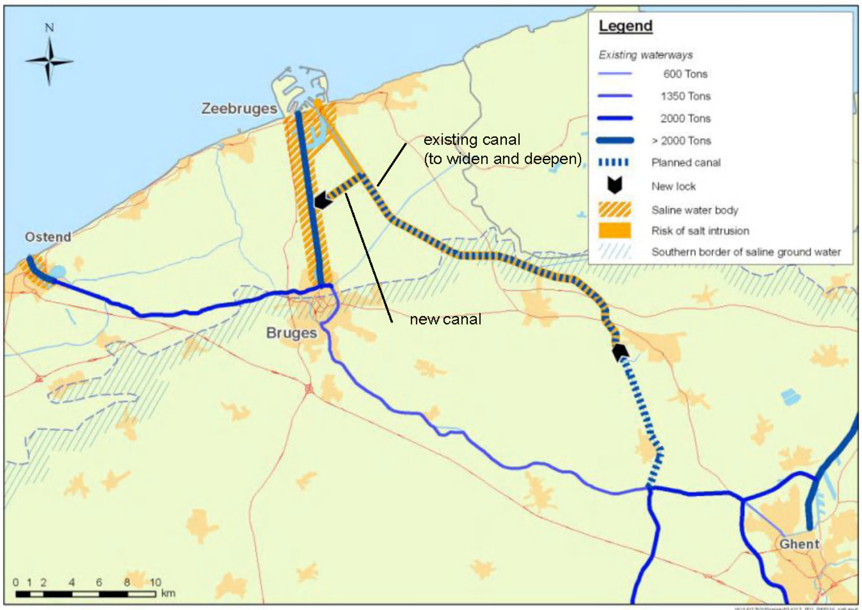
ABSTRACT

The planned Seine Scheldt West canal will provide a viable inland waterway connection of the Port of Zeebruges with the Seine-Scheldt liaison and the (Western) European waterway network. An extensive feasibility study was carried out, showing that from cost-benefit and technical point of view, a connection along the existing Derivation canal of the Lys is the most feasible route. The Lys itself, the most important affluent of the Scheldt, is the backbone of the Seine Scheldt liaison in the Scheldt Basin. This paper is only dealing with the aspects of salt intrusion, which is a consequence of connecting the canal to the Zeebruges Port.

Different mathematical models were used to describe the effects of constructing this canal, allowing stretched Vb convoys on the water system, including the effect of salt intrusion.



Salt flux to the canal was calculated on the basis of a measurement campaign, and used as input to calibrate diffusion and dispersion parameters for a scenario model of the new canal. Assuming reduced fluxes for a Dunkirk type lock, average canal salinity was calculated, which on its turn was used as a boundary condition for a density dependent groundwater model. The surface water model shows that with limited discharges the saline front can be stopped in the polder area where actually already saline groundwater occurs. The groundwater model shows that in the connection area of the Port, where a new canal must be constructed with a much higher canal head than the head of the surrounding groundwater, the deeper saline groundwater levels are mobilized and drained by the hydrographic network. This results in an increase of saline water concentrations near the new canal, while along the existing canal effects are fairly limited.

Measures against salt intrusion imply a certain amount of fresh water use. As the own catchment is limited in size, in periods of drought additional water resources must be addressed in order to supply the necessary fresh water.

Theoretically, these resources can be created and filled up with fresh water of flood events which would normally be diverted through the canal. In fact the canal was built in the second half of the 19th

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century to relieve the area of Ghent from floodings. Through the widening and deepening this function of the canal will even improve. Mathematical models were used to quantify the reduction of risk for flooding, which was included as a benefit in the cost-benefit analysis.

Although the discharges required to prevent saline intrusion are rather limited (in the order of 1 m³/s) and hardly matter on the whole of transfers, the claims on the water resources in the densely populated Scheldt basin are high and still increasing. In the context of the expected dryer summers due to global warming, there is a need to fit any new project in a global water resources management strategy on basin scale, in order to make it socially acceptable.

1. INTRODUCTION

This paper is discussing several aspects of salinization and water shortage as a consequence of the construction of an inland water canal connecting the Port of Zeebruges with the (Seine Scheldt connection and the (Western) European waterway network. As a matter a fact through the canal the saline basin of the inner harbour will be connected with the fresh water bodies of the Scheldt basin.

The study of the salt intrusion and water shortage related to the construction of the canal is part of a feasibility study and was used as input for a Strategic Environment Assessment (IMDC 2008a and 2009, Resource Analysis et al. 2009a and b).

Due to density currents the saline water will migrate upstream causing salinization of fresh water bodies, which is an unacceptable consequence due to the scarcity of fresh water resources particularly in dry periods.

Nevertheless, a salt water environment and living with it, is characteristic for the coastal plains of the low lands (Nord-Pas de Calais, Flanders, the Netherlands). The low lying historic coastal plain is a natural salt water environment. Due to regression of the sea and land reclamation by the associations of Polders and Wateringues, these areas have been excluded from flooding by the salt sea water. Gradually by cultivation, this land is gaining a permanent fresh water character as fresh (precipitation) water infiltrates and is driving out the salt groundwater. However, this is a process of hundreds to thousands of years. Currently, the groundwater still is salt or brackish. Fresh water infiltrates predominantly in the higher sandy dunes and creek ridges. From there the groundwater flow drives the salt water to the low lying depressions. Where man made drainage finally transports the salt water out of the system. Beside the head gradients also density gradients influence the groundwater flow, hence complicating the general flow pattern.

In the low lying coastal plains the surface water is an important steering factor in the salt balance in the ground and surface water system and is critical to the salt and water management of the crop land and pastures. Water level management is used by the Polders to irrigate the land with fresh water and to drain out the salt water.

It is obvious that the construction of a new canal strongly influences this delicate equilibrium between fresh and saltwater in an area where a head difference of only a few cm may result in shift of fresh-saltwater interface with a meter, and may render important stretches of land unsuitable for the current crops and cattle. Therefore a thorough analysis of the effects and possible mitigating measures of the construction of such a canal on the water system is at its place.

On the other hand, in the coastal area, due to the gradual freshening, salt and brackish water dependent habitats are getting gradually under stress and are being replaced by more common freshwater type vegetation. Also the nature sector is concerned and interested in the change of equilibrium as it may not only result in loss but also growth of rare species areal.

1.1 The canal

The concerned canal is largely following the trace of the existing “Afleidingskanaal van de Leie” (Derivation canal of the Lys river). The Lys is the major affluent of the Scheldt and is playing a major role in the future Seine-Scheldt connection.

Currently the Port of Zeebruges is connected with the Scheldt basin through the Canal Ghent-Bruges-Ostend, which has a limited gabarit, and which is difficult to upgrade as it is passing the historical centre of Bruges, which is classified as UNESCO world heritage (Resource Analysis, 2009).

The derivation canal of the Lys, was constructed in the second half of the 19th century, following and connecting existing canals and streams, mainly to protect the city of Ghent (and Bruges) against flooding.

Enlarging the existing canal has several advantages over other possible inland waterway connections, not in the least the saving of work, and territorial planning as the canal already has its place in the protected landscape. Near the Port of Zeebruges the canal, which has to be deepened and widened, must be connected with the harbour basin. For this purpose a stretch of 4 km of entirely new canal must be developed, connecting the Afleidingskanaal with the Boudewijn Canal. The Boudewijn Canal links the inner harbour of the Zeebruges Port with Bruges and the Canal Bruges-Ostend.

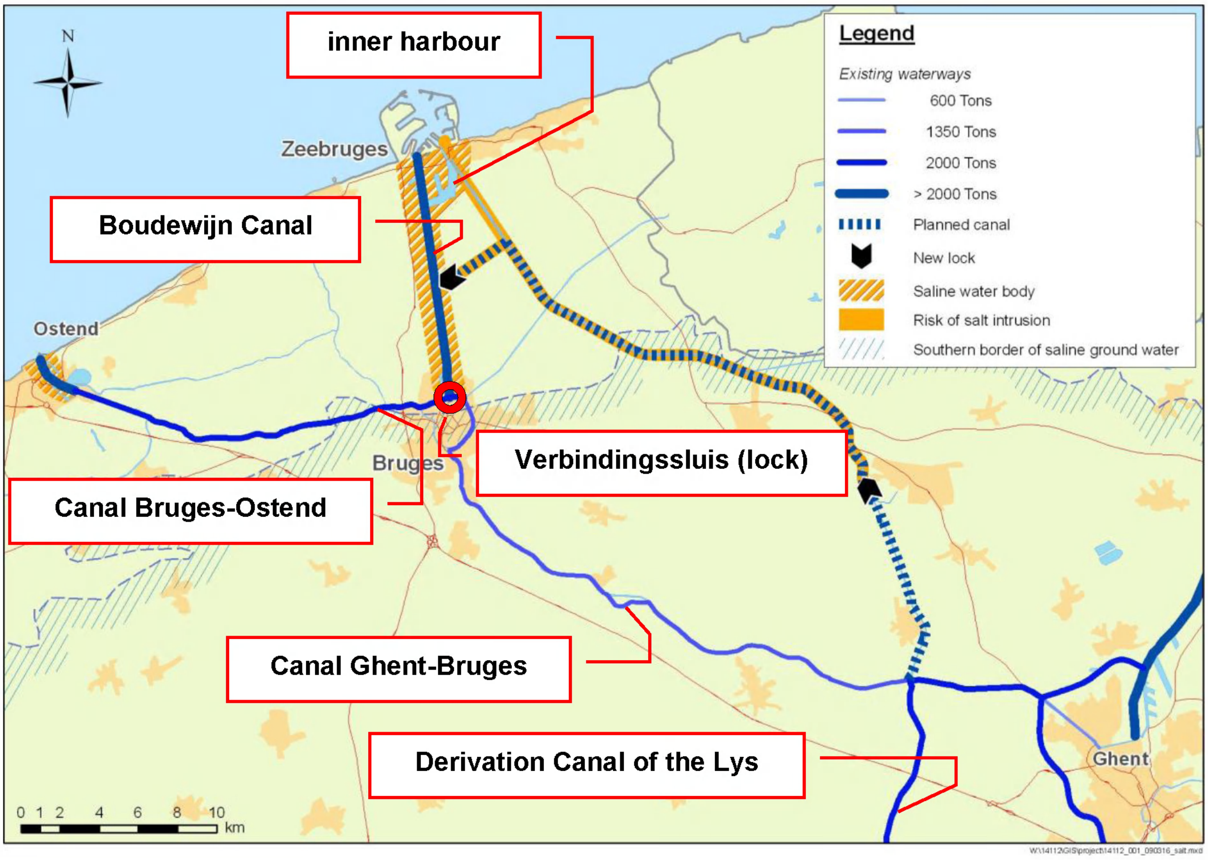

Figure 1: situation map of canals and locks

The inner harbour is connected with the seaside harbour through two locks: the Vandamme and Visaert locks. Locking operations entirely make use of seawater as no catchments are connected to the basin formed by the inner harbour and Boudewijn Canal. As a consequence the entire water body salted up to seawater quality. Despite the connection of the harbour basin with the Canal Bruges-Ostend through the Verbindingssluis, the latter canal stays fresh, as salt water can be diluted and washed away with sufficiently high canal discharges, as locking operations and consequent salt influxes are limited. This will however not be the case for the new canal which has a small upstream catchment and will receive much higher traffic, hence more locking operations and higher salt influx.

Therefore the construction of the new canal will have to be accompanied by adequate measures protecting it against salt intrusion.

1.2 Study

In this study first the salt intrusion through the new canal is studied, without and with measures at the connection with the salt water body of the harbour. The resulting salinity is used as a boundary condition for the study of the effect of the canal on the groundwater flow.

A numerical 2Dv model of the new canal was constructed in Delft3D. As it concerns a new canal and a new situation, calibration is not possible. Therefore first a model was constructed for the Canal Bruges-Ostend, which is also connected with the harbour of Zeebruges through the Boudewijn Canal. The calibration parameters of the latter model are being considered a best possible approximation for the new canal. In order to calibrate the latter model a measurement campaign was organised to study the salt fluxes through the Verbindingssluis between the Boudewijn Canal and the Canal-Bruges Ostend.

A groundwater model was constructed in MOCDENS3D (Lebbe & Oude Essink, 1999), using the Visual MOCDENS3D postprocessor developed by Vandenbohede (2007).

1.3 Prevention of salt and fresh water exchange

In general 4 levels of protection against salt intrusion can be defined, by combining protection at the lock (which represents the connection between two water bodies with different water qualities), and protection along the canal (Table 1). It is obvious that a protection at the connection is the most adequate, and is a minimum requirement for an effective protection of water resources.

Lock protection / **Canal protection**	***No Protection of surface water (at lock)***	***Protection of surface water (at lock)***
No protection of groundwater (at or near canal)	No protection	Canal (partially) protected, groundwater (partially protected)
Protection of groundwater (at or near canal)	Groundwater (partially) protected, canal salted up	Canal (partially) protected, groundwater (partially protected)

Table 1: levels of protection of water resources against salinization

Measures to prevent salt and fresh water exchange (at locks) are well known and described (e.g. Kerstma et al 1994, WL Delft, 2004). All solutions require a certain amount of fresh water to reduce fresh water contamination. The more efficient systems are more costly and result in longer locking cycle times.

Despite these drawbacks several authorities decided the construction of such systems for reasons of water shortage and the need to protect fresh water resources. The most notable examples are the Mardyck Lock in Dunkirk, connecting the fresh Canal à Grand Gabarit with the salt inner harbour of Dunkirk, the Krammer Locks connecting the fresh Volkerak lake with the salt Easterscheldt, and the Kreekrak Locks on the Scheldt-Rhine Canal.

These so-called Dunkirk-type salt protection systems make use of the gravity difference between fresh and saltwater, in which the lighter fresh water is pushed gently up over weirs by the underlying heavier saltwater let in through the lock bottom, and vice versa, the fresh water is gently let in over weirs while the salt water is being removed (by pumping or by gravity flow to lower lying basins) through the lock bottom. The process is executed slowly in order to limit the mixing between salt and fresh water. In order to prevent the mixed layer from flowing into the fresh water body, slightly more fresh water is required. The fresh water requirement is estimated at 10 to 30% of the useful lock chamber volume. Likewise, it is impossible to completely exclude the influx from the mixed layer, resulting in a residual salt water influx. This is estimated at 2 to 5% for the Krammer Locks. The oldest lock, the Mardyck Lock, is operational since the late 1960s, and manages to keep the salinity under 1 g/l at the fresh side (Monadier, 1981). The Kreekrak system was recently replaced by a more adequate system for the low differences in salinity on both lock sides. The original salt intrusion prevention system at the Krammer Locks (operational since the second half of the 1980s) is still successfully used, but currently under debate because of an environmental issue due to blue algae pollution of the Volkerak lake (Projectteam Verkenning oplossingsrichtingen Volkerak-Zoommeer, 2003).

2. MEASURING AND MODELLING THE ACTUAL FRESH AND SALT WATER EXCHANGE AND SALT WATER DISPERSION

A measurement campaign was set up to study 1) the salt flux at the Verbindingssluis (the lock connecting the salt Boudewijn Canal and the fresh Canal Bruges-Ostend), as a function of locking operations, and 2) the development of the salt front or toe in the Canal Bruges-Ostend, as a function of the discharge and the locking operations at the Verbindingssluis. These data are required for calibrating respectively: a conceptual salt flux model of the locking operations, and a density dependent hydrodynamic model of the canal. The calibration parameters of the latter model, viscosity and diffusion, are used thereafter for a scenario model of the new canal. Both have an important impact on the development of the salt front and interface between salt and fresh water.

2.1 Salt flux through the lock

The measurement campaign between 4 and 8 august 2008 allows to analyse the density flow due to lock operation of the Verbindingssluis. 8 CTD-divers were installed down and upstream of the doors in and outside the lock chamber, and at the top and the bottom of the water column (Fig. 2).

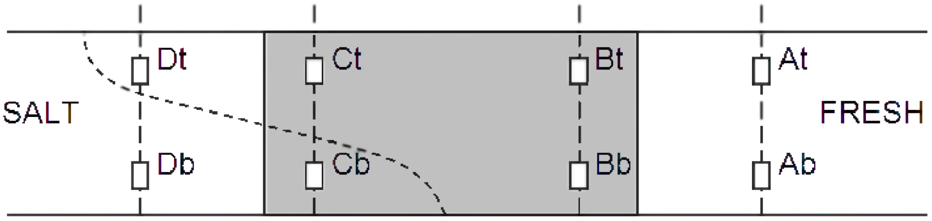

Figure 2: position of CTD-divers; illustration of the intrusion of the salt tongue from the salt basin into the lock chamber with doors open at the salt lock head

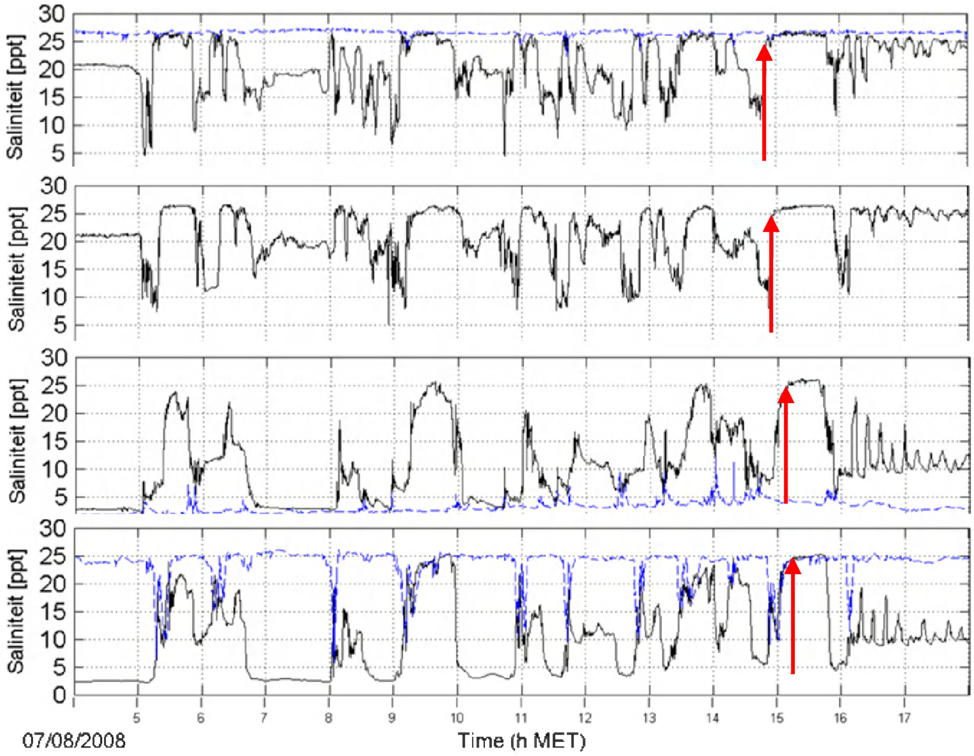

Figure 3: measured salinity in the lock chamber from top to bottom at divers Cb, Bb, Bt and Ct (Fig.2 for positions); the red arrow demonstrates the time shift before obtaining the same salinity at the different positions

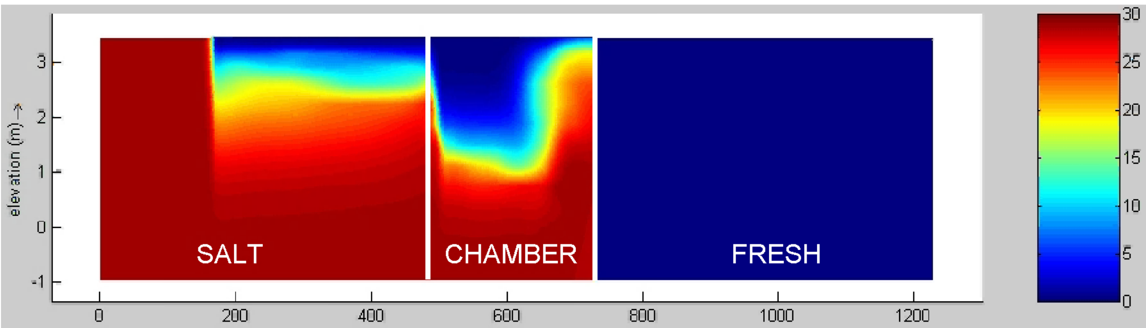

Figure 4: modelled density flow: showing the reflection of the salt tongue against the fresh lock head doors (red: salt water; blue: fresh water)

Figure 3 demonstrates the density flow observed during locking operations. When doors at the salt head are opened salt water flows in at the bottom, closely followed by the salt front near the surface, reaching first the bottom of the opposite lock head, followed by the surface due to reflection against the doors. Figure 4 illustrates the reflection with a model.

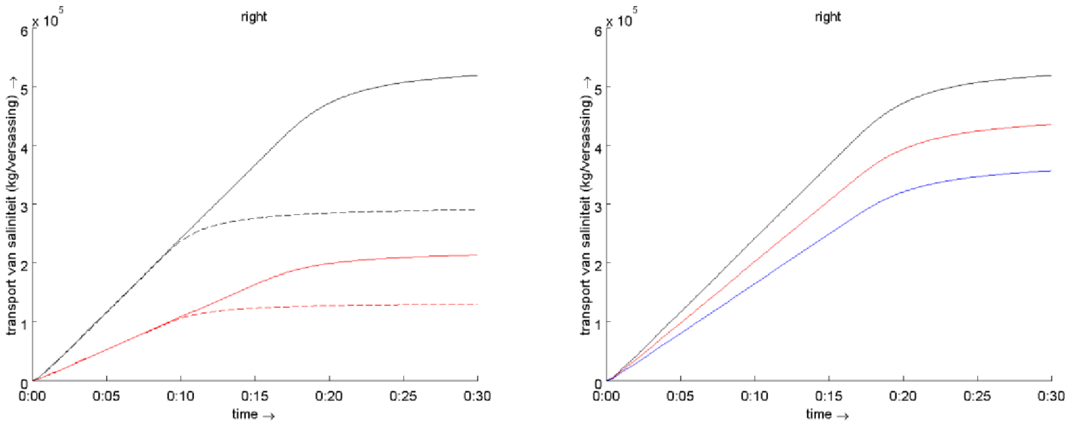

Figure 5: left: effect of lock chamber dimensions on salt infux: black: 25 m wide, red: 12,5 m; full: 230 and 210 m long, striped: 125 m long; right: effect of lock filling on salt influx (black: no ships; red: 12% fill; blue: 24% fill)

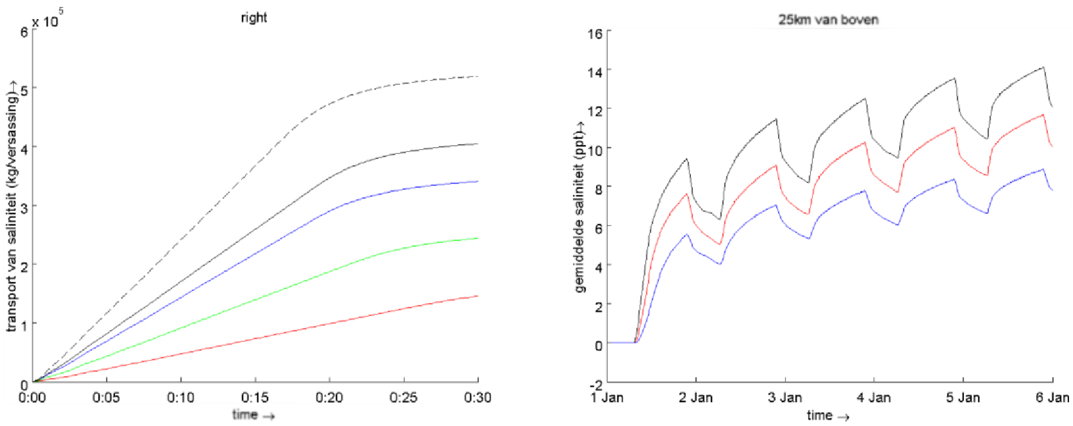

Figure 6: left: effect of difference in salt concentration over the doors on the salt influx (chamber: 12,8% filled, with salt concentration 25 ppt): black: 25 ppt, blue: 20 ppt, green: 15 ppt, red 10 ppt); right: after a few days salinity difference over the doors is evolving to an equilibrium

The analysis of the measurements allowed the definition of a salt influx model able to take into account the lock dimensions (Fig. 5 left), the locking operations, the chamber filling % (Fig. 5 right), with observed salinity difference over the door for the Verbindingssluis (Fig. 6 left), and to make assumptions on the salinity differences over the doors for the new lock (Fig. 6 right). The model calibrated using the measurements is used to generate salt influx boundary conditions representing the locking operation.

2.2 Dispersion in the canal

The measured salinity in the Canal Bruges-Ostend was used to calibrate a model of the canal using the salt influx model at the Verbindingssluis and the discharge at the upstream Dampoort lock as boundaries. The salt influx model calculates salt influx for the given lock chamber dimensions and the observed lock operations, taking into account the filling percentage of the locked ships (ship registration data such as dimensions and charge were obtained from RIS Evergem).

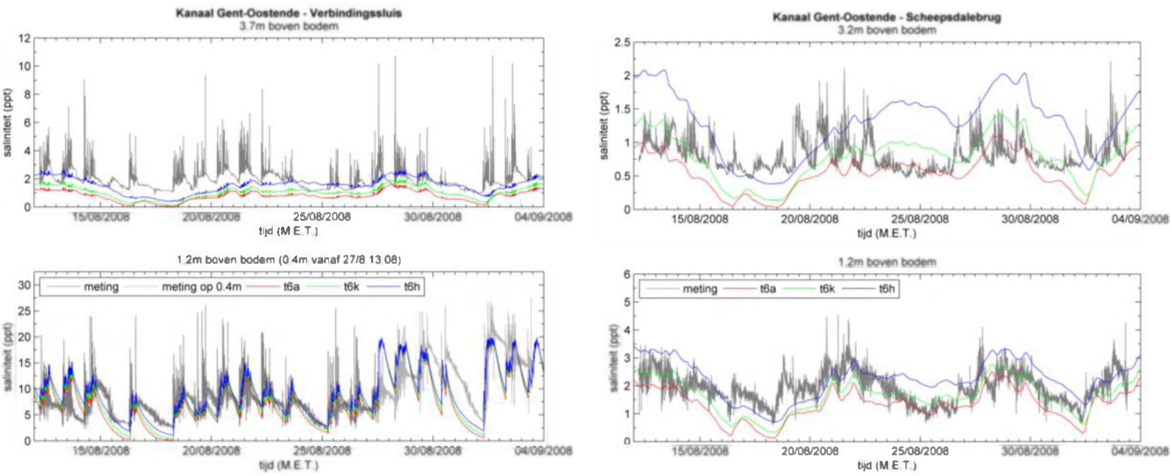

Figure 7: the calibration of the Canal Bruges-Ostend model shows very good results at the lock entrance (left) proving the strength of the salt influx model; despite the uncertainty on the discharge of the canal, results from a downstream location are nevertheless quite satisfactory (right)

The calibration at the lock entrance is extremely good (Fig. 7 left), proving the strength of the salt influx model. Despite the uncertainty on the discharge of the canal (flattened out discharge from a location several km downstream, not taking into account the locking operations of the upstream Dampoort lock, ...), the results on a location downstream of the Verbindingssluis nevertheless are quite satisfactory (Fig. 7 right).

The calibrated vertical diffusion (2E-05 m²/s) and viscosity (1E-04 m²/s) coefficients of the model of the Canal Bruges-Ostend were used for a model of the new canal. Although lock passage and traffic are expected to be much higher and to lead to more mixing by ship movement in the new lock's case, the obtained values for the Canal Bruges-Ostend can be considered as the best available approximation. In Figure 8 the effect of the viscosity and diffusion coefficient on the development of the salt front and fres salt water interface is illustrated with the results of a sensitivity analysis.

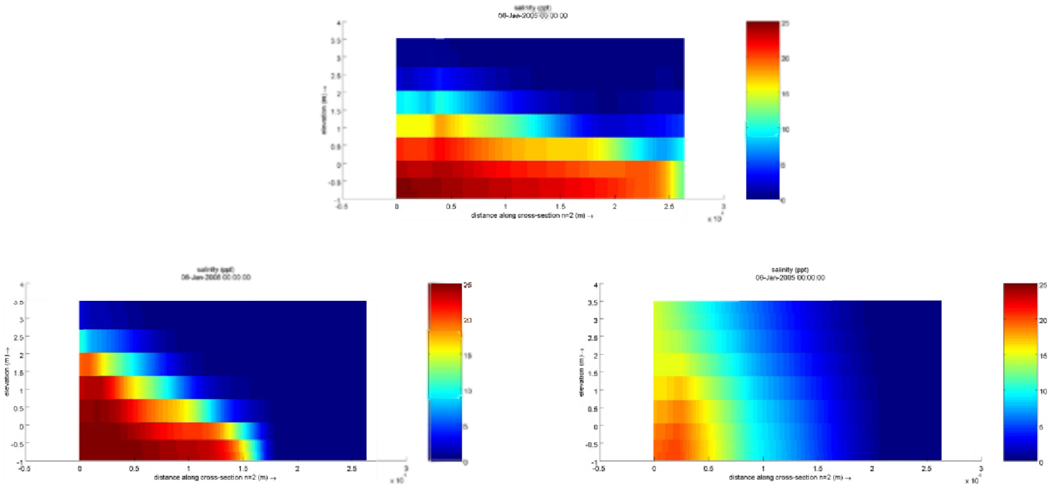

Figure 8: effect of viscosity and diffusion coefficients (m²/s) on the simulation result (top: VicoWW 0,0001, DicoWW 1E-07; bottom left: VicoWW 0,001; bottom right DicoWW 0,0001) (red: salt water; blue: fresh water)

3. MODELING THE FRESH AND SALT WATER INTRUSION IN THE FUTURE CANAL

A 2Dv model in Delft3D was constructed for a future canal situation. The model covers the whole reach from the upstream lock connecting the new canal with the canal system around the city of Ghent to the outlet sluices at the seaside and the lock connecting the canal to the inner harbour of Zeebruges.

The model respects the design geometry of the canal and consists of nine layers allowing the modelling of the density current in the vertical plane.

At the navigation lock a salt influx boundary was defined to simulate the influx due to the locking operation. At the upstream lock discharges (both measured and design) were defined, which were abstracted from the system at the outlet structures.

Model results have been exploited in different ways:

- the effect of salt influx for different lock dimensions, characterised each by different ship groupings and chamber volumes, hence salt influxes
- the effect of upstream discharge on the progression of the salt front: the time for the salt front to reach the upstream lock, the effect of flushing on pushing back the salt front, ...
- the upstream discharge required to control the salinity (to keep the salinity under a specified threshold defined at a specified location)

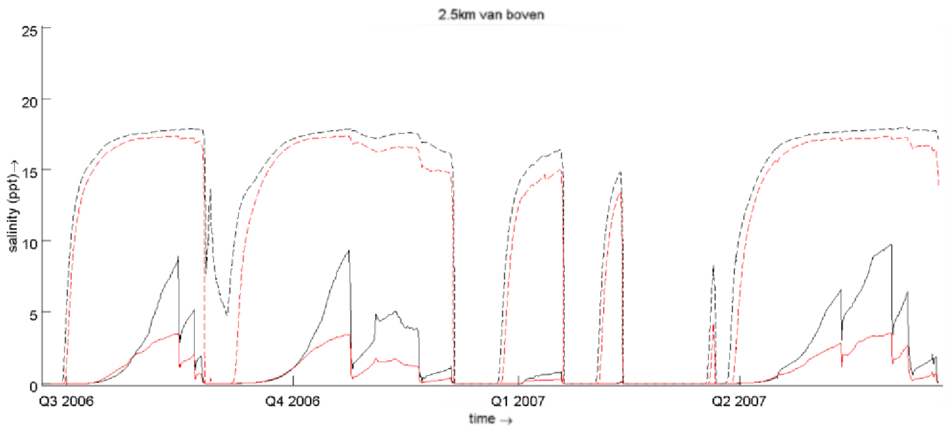

Figure 9: evolution of salinity in the canal 2,5 km downstream of the upstream lock, for a situation without measures: full lines: at the canal's surface; dotted lines: at the canal bottom; the effect of flushing is easily recognisable in the drop of salinity; measured upstream discharge for one year's period 2006-2007 (black), with additional discharge of 1m³/s (red)

Simulations show that current discharges of the canal are not sufficient to control the salinity in the canal to acceptable levels (e.g. Fig. 9). Measures at the lock are required. Salt influxes have been reduced referring to the efficiency of existing salt protection systems of the Dunkirk type.

Simulations with different constant upstream discharges show that to effectively hold back the salinity a constant upstream discharge of the order of the chamber volume is required (Fig. 10 left: 5 m³/s is sufficient to keep the salt front within the limits of the salt ground water body of the coastal plain (Fig. 1), which is located at about 15 km from the upstream lock, whereas the locking operations of the predicted traffic imply a maximum salt influx of about 3,5 m³/s).

With reduced salt influx (in case of a lock equipped with a salt protection system) a much lower discharge is required to hold back the salt front (Fig. 10 right, example of a simulation with a constant discharge of 0,5 m³/s).

The effect of a constant discharge is comparable to that of the mean salinity for a modelled hydrologic year (Fig. 10 and 11). However, it should be noted that a minimum discharge is always required to hold back the salt front in dry periods. Moreover, a minimum discharge is also required to compensate the fresh water losses during the fresh salt water exchange operations of the salt protection system at the downstream lock.

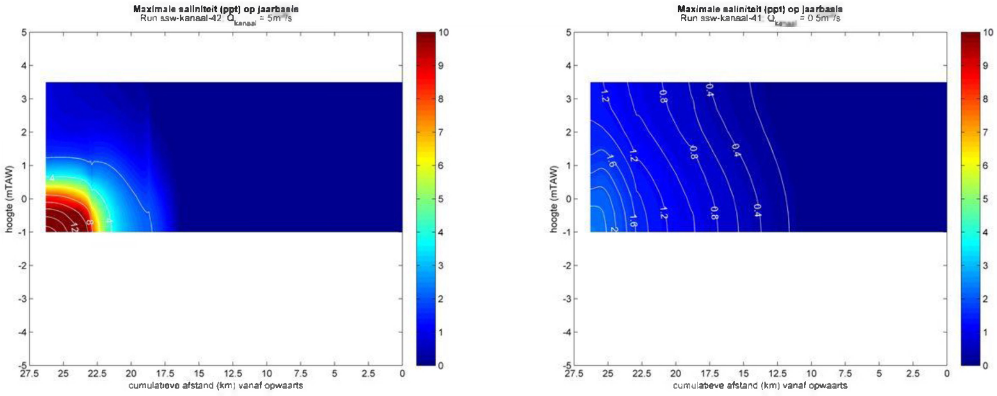

Figure 10: maximum salinity with constant upstream discharge: left: 5m³/s, no measures at the lock, right: 0,5m³/s, measures at the lock (salinity scale in ppt)

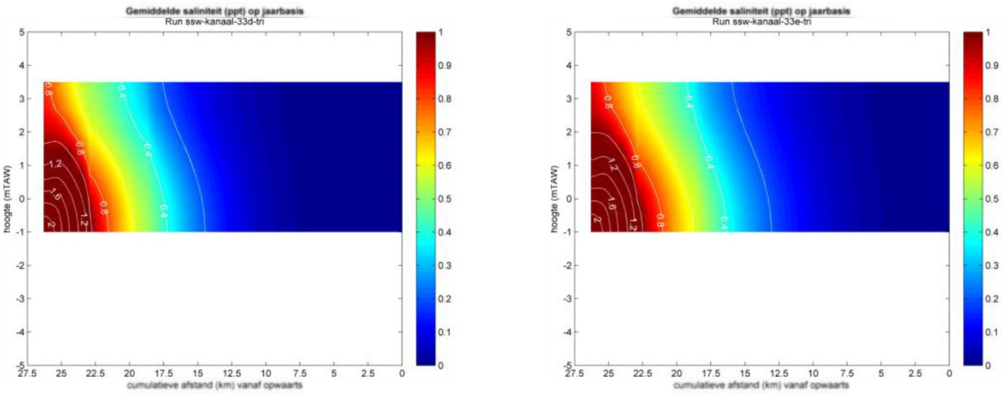

Figure 11: mean salinity over model year 2006-2007: left: a constant discharge of 0,5m³/s added to the normal discharges at the upstream boundary; right: no additional discharge added at the upstream boundary (salinity scale in ppt)

Figure 12 shows the effect of flushing on the salinity (case without measures). It is obvious that in order to effectively flush away the salt: 1) it is required to flush for at least 3 to 4 days, 2) a minimum discharge is required (well above 10 m³/s).

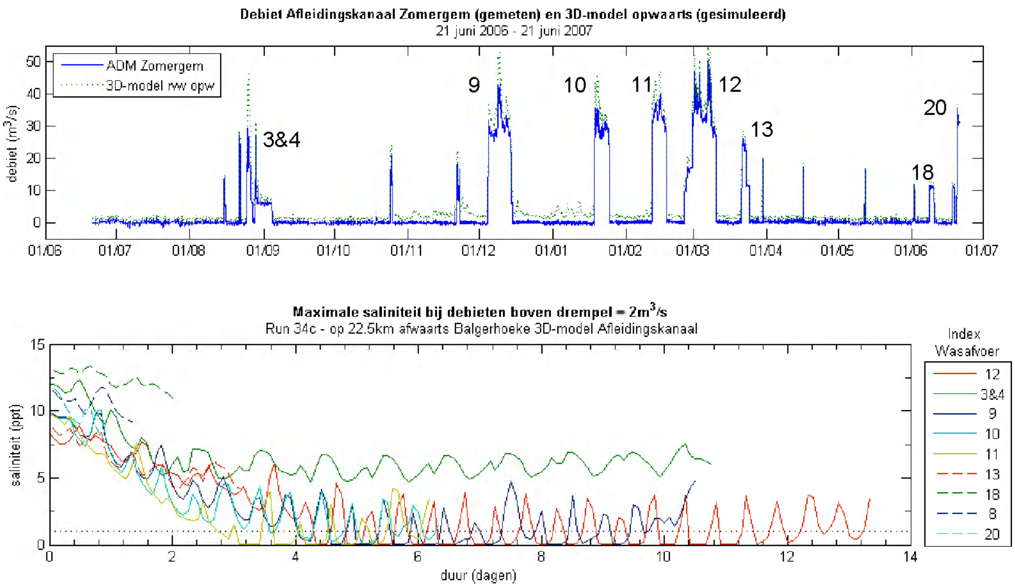

Figure 12: salinity drop for different flushing events; the cyclic course is a result of the interference of the tidal cycle (no flushing at high tide) and the halt of salt influx during night time, when the lock is not operated

4. MODELLING THE EFFECT ON GROUNDWATER FLOW

A MOCDENS3D model was used to study the effect of the canal on the groundwater flow. MOCDENS3D is a finite difference density dependent groundwater flow model combining the solute transport model MOC3D (Konikow et al., 1996) modified to integrate density differences with the groundwater flow model MODFLOW (McDonald & Harbaugh, 1988). The canal head and salinity act as boundary conditions for the groundwater flow. The new canal head is comparable to the actual canal head, but the canal is wider and deeper, therefore the contact factor between canal and aquifer increases. Moreover the new canal will be brackish, at least to some extent, at its bottom over a certain distance. The salinity calculated with the Delft3D model was used as a water quality boundary condition.

The initial condition for the model is the salinity distribution mapped by De Breuck et al. (1975). As the salinity of the groundwater is permanently changing as a consequence of the freshening of the groundwater body by the precipitation recharge driving out the salt water, a simulation was performed of a period to represent today's salinity.

This salinity (green area on Fig. 13) is the reference situation for several simulations corresponding to 1) the autonomous development of the salinity (no canal is constructed, orange line on Fig. 13), 2) the situation with a canal constructed without measures at the lock (blue hatch on Fig. 13), 3) the situation of a canal with measures at the lock (red hatch on Fig. 13). The map shows the 1,6 ppt salinity contour, corresponding to the fresh salt water interface as defined by De Moor & De Breuck (1969).

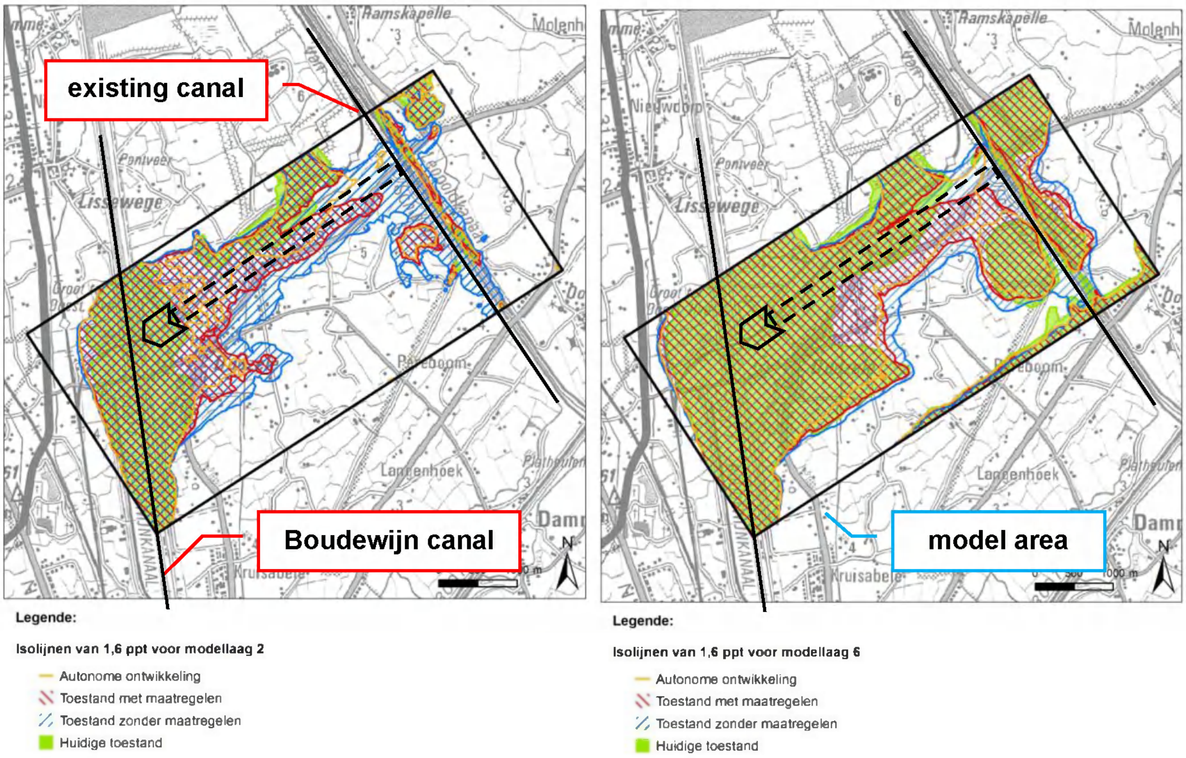

Figure 13: groundwater salinity for different model situations; left: at about 3 m below the surface; right: a about 9 m below the surface; future situations 32 years after canal construction

It is obvious that the canal exerts an effect on the density dependent groundwater flow. The effect is not surprisingly largest near the newly excavated canal (striped line), and relatively moderate along the existing canal, at least for the case with measures at the lock. Along the newly excavated canal the migration of the fresh salt water interface stretches out over several hundred meters.

The effect of the autonomous evolution is quite remarkable in the area south of the harbour (Fig. 13). This can largely be attributed to the increased recharge with fresh water in the raised harbour terrains, where the increased fresh water head pushes away the underlying salt water wedge.

Simulations of mitigating measures demonstrate that drastic measures are required to reduce the impact on the groundwater salinity **in case no salt protection measures are taken at the lock** (Fig. 14, 15, 16). In such a case, an effective drainage canal system must be so deep that the territorial impact of the latter also becomes very important (Fig 15). A pump battery effectively confines the salt migration, but is very costly (Fig. 16).

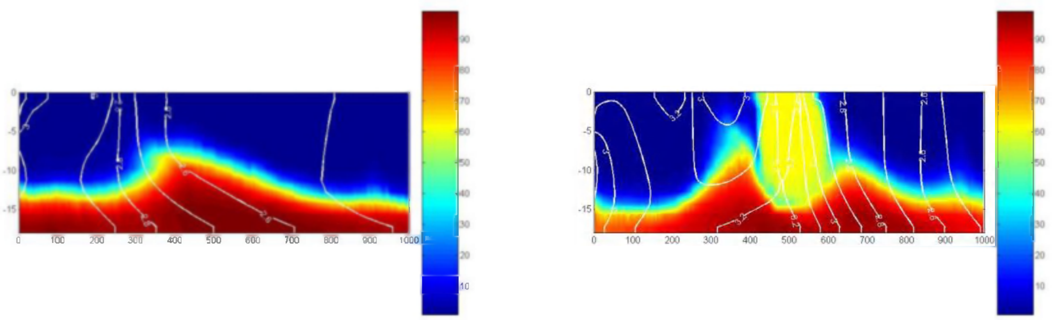

Figure 14: left: today's groundwater salinity in a south-north cross section through the newly excavated canal, fresh water recharge from the raised harbour terrains pushes the salt interface towards the south; right: salinity 16 years after the introduction of the canal (salinity in % between salt and fresh water)

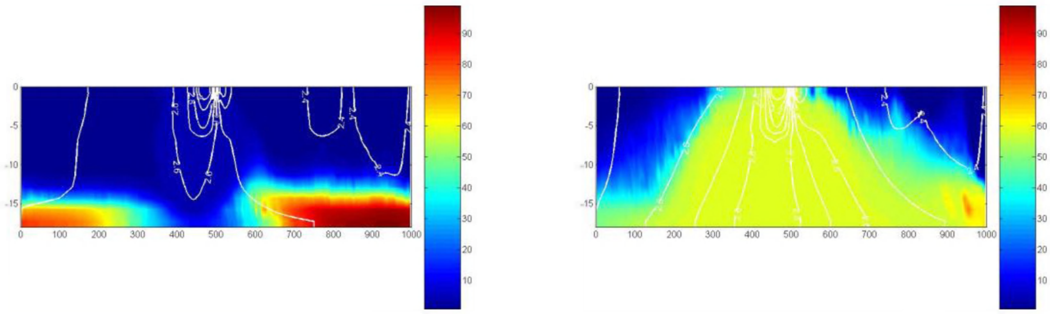

Figure 15: left: today's groundwater salinity in a west-east cross section through the existing canal, shows that the existing canal breaks up the deep salt water layer; right: salinity 32 years after the introduction of the canal (salinity in % between salt and fresh water)

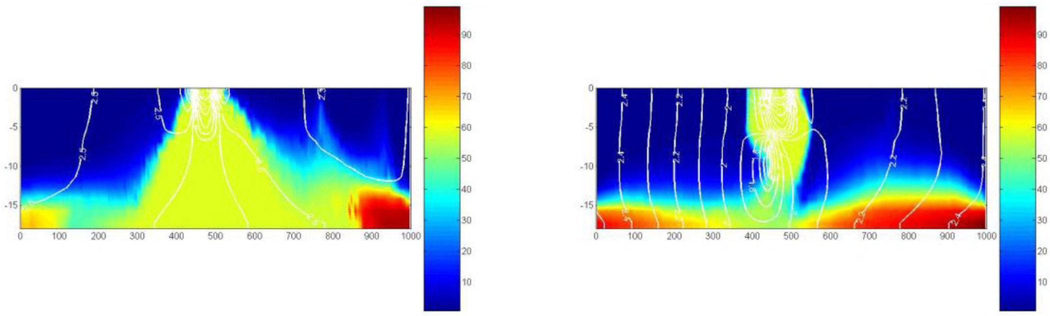

Figure 16: groundwater salinity in a west-east cross section through the existing canal 32 years after canal construction; left: mitigating effect of drainage canals along the navigation canal; right: mitigating effect of a pump battery along the canal (salinity in % between salt and fresh water)

In case **salt protection measures are taken at the lock**, the overall salt water quality of the ground water mass is barely changing. Locally, along the canal, the ground water flow pattern is changing due to the head difference between the canal head and the surrounding ground water head. This will provoke changes in salinity of the ground water in the vicinity of the canal.

Figure 17 shows the process of an apparent freshening in the vicinity of the canal. As a matter of fact the brackish water at the canal bottom will infiltrate following the general ground water flow pattern and will induce a relative freshening of the ground water mass underlying the canal, as the deeper salt water is forced out of the system. Following the ground water flow pattern, the deeper salt water will migrate up and will be removed from the system by the present drainage system of the polders. What is happening here, is the speeding up of the natural freshening process due to the infiltration with fresh precipitation water, and is comparable to the breaking up of the salt water layer as observed under the actual canal (Fig. 17 top right).

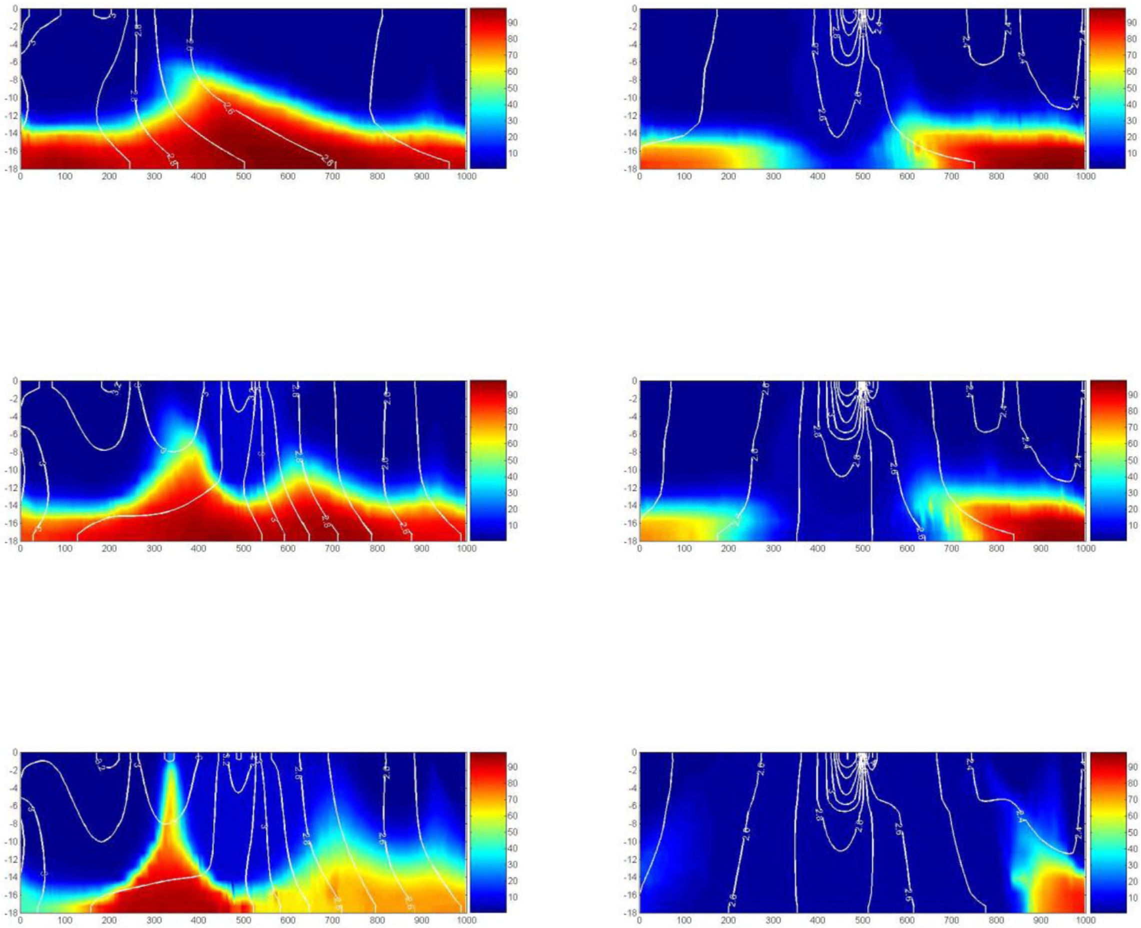

Figure 17: groundwater salinity in south-north (left) and west-east (right) cross sections, from top to bottom: before, 4 years after and 32 years after canal construction (salinity in % between salt and fresh water)

Although the general ground water quality seems to be more fresh than original, the ground water mass below the channel is being replaced with water of brackish quality comparable to that at the canal bottom in an area confined by the drainage system of the polders. This results in a water quality which is close to the actual one. This is translated in the only slight difference between the salt water quality due to autonomous development and the one due to the construction of the canal (Fig. 13).

These results show that the prevention of salt water intrusion at the lock is a very effective and necessary measure to protect not only surface but also ground water resources against salinization.

5. WATER BALANCE

The area around Ghent is characterised by an extensive canal system developed to accommodate many water demands in a highly developed area. The entire system is fed by the Lys and Scheldt rivers, both originating in France and also fulfilling extensive water needs in the French Nord-Pas the Calais Region, before entering the Belgian border (e.g. IMDC 2008b). In Flanders the Lys and Scheldt water is not only required for the Scheldt estuary flowing to the North Sea, but also the Canal Ghent-Terneuzen, the Canal Ghent-Bruges-Ostend, and the Afleidingskanaal.

The flow towards the latter currently is limited. The canal is used mainly to flush peak discharges toward the sea, in order to control the water levels around Ghent (e.g. Fig. 12). Apart from the discharge of its own catchment (which barely measures 12700 ha), a small discharge is flowing in over the weirs and through the current navigation lock at the connection with the canal system of Ghent. As the discharge to the other canals is more or less fixed, the only possible additional source is the discharge to the estuary. However, a further decrease of water towards the Scheldt estuary is under debate for ecological reasons. Therefore, the water required for the new canal must be looked for elsewhere.

A water balance study (IMDC, 2009) shows that it is possible to define solutions using only the currently available resources, by saving water from flood events temporarily in the canal itselves and in the upstream canals, requiring however a strict water resources management.

It may be possible to find a solution for water shortage for this single canal project, however, given the increasing water demand for industrial use, the possible construction of a new lock in Terneuzen and hence increased water requirement to reduce the salt water intrusion there, the tendency towards a more balanced use of water for ecological reasons and the anticipation of longer and more recurrent droughts due to climate change, a more coordinated approach of water resources management should be in place, involving the whole water system rather than the individual management of every single component of the system, because in this case the whole will be less than the sum of its parts.

6. CONCLUSIONS

A new canal linking the Seine-Scheldt liaison with the Port of Zeebruges, requires the connection of a fresh inland water body with the salt water basin of the harbour. Modelling shows that measures to prevent salt water intrusion are necessary to limit the effect on the fresh canal water quality. This is not only necessary to comply with surface water quality standards, but even more to avoid contamination of the fresh groundwater resources.

The prevention of salt water intrusion at the lock is more effective than measures to intercept the salt water recharge of the aquifer through the canal bottom.

Any system to reduce salt water intrusion requires a certain amount of fresh water. This is also the case for the Dunkirk salt protection system, considered in this study. The new canal is situated in a highly developed area with high water demands, where any additional request must be evaluated for its consequences on other demands. A water balance study shows that under current circumstances it is possible to find a solution to accommodate the additional demand by the new canal, requiring however a dedicated water resources management.

Given however the increasing water demand and anticipating more recurrent shortages due to climate change, it would be better to embed this management in coordinated approach of water resources management on the basin scale.

References

De Breuck , W., De Moor, G., Maréchal R. & Tavernier R. (1975). Diepte van het grensvlak tussen zoet en zoet water in de freatische laag van het Belgische kustgebied (1963-1973). Bijlage 1 van de Proceedings of the 4th Salt Water Intrusion Meeting, Gent, Oktober 1974.

De Moor, G. & De Breuck, W. (1969). De Freatische waterlaag in het Oostelijke Kustgebied en in de Vlaamse Vallei. Natuurwetenschappelijk Tijdschrift, 51, 3-68.

IMDC (2008a). Haalbaarheidsstudie Seine-Schelde West. Verkennend onderzoek m.b.t. de verzilting. I/RA/14112/08.054/RAD. Waterwegen en Zeekanaal NV, Afdeling Bovenschelde. 58p.

IMDC (2008b). Etudes techniques et réglementaires pour l'aménagement de la Lys mitoyenne entre Deûlémont et Halluin. Phase 1 – Analyse de l'existant. VNF Direction Régionale de la navigation du Nord Pas de Calais, Arrondissements Etudes et Travaux Neufs (AETN).

IMDC (2009). Haalbaarheidsstudie Seine-Schelde West. Verkennend onderzoek over de waterbeschikbaarheid en verziltingsaspecten. I/RA/14112/08.103/RAD. Waterwegen en Zeekanaal NV, Afdeling Bovenschelde. 302p.

Kerstma, J., Kolkman, P.A., Regeling, H.J. & Venis, W.A. (1994). Water quality control at ship locks. Prevention of salt and fresh water exchange. A.A.Balkema, Rotterdam/Brookfield.

Konikow, L.F., Goode, D.J. & Hornberger, G.Z. (1996). A three-dimensional method of characteristics solute transport model (MOC3D). U.S. Geological Survey. Water-Resources investigations Report, 96-4267.

Lebbe, L & Oude Essink, G.P. (1999). MOC DENSITY/ MOCDENS3D-code (Section 12.11). p.434-439, in Chapter 12. Survey of Computer codes and Case Histories. Eds. Sorek,S. & Pinder,G.F. in Seawater Intrusion in Coastal Aquifers, Concepts, Methods and Practices. Eds. Bear J., Cheng H.-D., Herrera I., Sorek S. and Ouazar D. Kluwer, Academic Publishers.

McDonald, M.G. & Harbaugh, A.W. (1988). A modular three-dimensional finite difference ground-water flow model. USGS, Techniques of Water-Resources Investigations 06-A1, 576p.

Monadier P. (1981). The problem of seawater back-flow through harbour locks. Example of the Mardyck lock at Dunkirk. La Houille Blanche, n°2/3, 121-127.

Projectteam Verkenning oplossingsrichtingen Volkerak-Zoommeer (2003). Verkenning oplossingsrichtingen Volkerak-Zoommeer. Rijkswaterstaat.

Resource Analysis (2009). Seine-Schelde West. Nota Kanaal Gent-Brugge 4400 ton. Waterwegen en Zeekanaal NV, Afdeling Bovenschelde. 23p.

Resource Analysis, Technum, Tritel and IMDC (2009a). Haalbaarheidsstudie Seine-Schelde West. Waterwegen en Zeekanaal NV, Afdeling Bovenschelde.

Resource Analysis, Technum, Tritel and IMDC (2009b). Plan-MER voor de binnenvaartverbinding Seine-Schelde West. Één hoofdrapport en 8 deelrapporten. Waterwegen en Zeekanaal NV, Afdeling Bovenschelde.

Vandenbohede, A. (2007). Visual MOCDENS3D: visualisation and processing software for MOCDENS3D, a 3D density dependent groundwater flow and solute transport model. User Manual. Research Unit Groundwater Modelling, Ghent University.

WL Delft – Saltwater intrusion analysis for Post Panamax Locks (2004)