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Climate change impact on salinization of drinking water inlets along the Campine Canals, Belgium

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ABSTRACT

Study region: Campine Canals, in the north-eastern part of the Flanders Region of Belgium, between the Meuse river and the Port of Antwerp. The region is densely populated with limited water resources and vulnerable for water shortages.

Study focus: The impact of climate change on salt intrusion in the Albert Canal, the area's major surface water source for drinking water production, is studied. Salt intrusion simulations are conducted by means of a conceptual mass balance model for the canal network combined with a solute transport model for the relevant canal reaches. A 110-year long time series of observed discharge at the upstream boundary is applied to simulate reference conditions for the current climate and is adjusted to account for future climate scenarios.

New hydrological insights for the region: Salt water intrusion up to the drinking water inlets is rare under current climate conditions, but its occurrence will increase in the future, up to 1–2 % of the time by 2050, and up to 3–10 % of the time by 2100, for mid- and high-impact climate scenarios, respectively. Chloride concentrations will more often exceed the working limits of water production. These findings illustrate the need for a shift in canal management from the current main focus on inland navigation to a more holistic approach taking climate trends and water quality problems into account.

1. Introduction

Water availability can become critical as a consequence of anthropogenic factors, even for regions with a moderate climate. An example is Belgium, which lacks large natural water resources or reservoirs. Combined with a high population density, Belgium invariably ranks high in lists of country vulnerability for water availability issues. It has for example a 'high baseline water stress' ranking according to the World Resources Institute in 2019 (Hofste et al., 2019). Besides the direct impact on water availability by reducing the catchment runoff and river flow quantities during dry summers, climate change may also affect the water quality. Reduced river flows would lead to increased pollutant concentrations in rivers due to the reduced dilution for the same pollutant load. Moreover, rainfall intensities of extreme rainfall events may increase, leading to increased frequency of floods or sewage overflows, which can further deteriorate the quality of surface waters. Temperature plays another important role, as it has an influence on the kinetics of physico-chemical reaction processes. There are many more mechanisms that can play a role. Delpla et al. (2009) performed a literature review on mechanisms through which climate change can impact the quality of water resources and conclude that there is a

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significant risk of reduced water quality and consequential health issues due to climate change. Leveque et al. (2021) came to similar conclusions when investigating water quality and availability in Quebec as an example for northern regions.

One water quality aspect that can be affected strongly by the impact of climate change, is the increased salinization of both surface water and (coastal) aquifers. When focusing on surface water, a combination of sea level rise and a reduction of upstream discharges in tidal rivers can cause the saltwater wedge to move inland, possibly threatening drinking water inlets or natural systems upstream. These phenomena are commonly studied using physically based models to describe transport of chloride ions. To keep the computational efforts feasible, a one-dimensional approach is often used, in combination with limiting simulations to single reference years that represent for example wet, moderate or dry conditions. Examples of the use of this methodology in Europe are Zwolsman and Becker (2012) and Augustijn et al. (2011). It is, however, often interesting to perform long term simulations that span multiple years to take a wider variety of boundary conditions into account, and to allow for statistical analysis of the salinization risks. Van den Brink et al. (2019) use a one-dimensional modeling approach with 50 years of discharge data for current and future climate conditions to study the risk of salinization of the drinking water inlets of the Lek river in the Netherlands and conclude that the inlet locations will suffer from increased chloride concentrations. A higher fresh water discharge in the river of at least 10 m^3 /s is proposed as a mitigation measure to reduce the risk of insufficient water quality at the inlet locations. It is, however, not studied whether this induces any water quantity or quality issues in connected river branches, as the model is limited to the affected branch of the Lek river. The same argument of high computational cost leads to the indirect effect of climate change on increased salt intrusion being seldom considered. These effects can for example be caused when mitigation measures are taken to reduce the risk of water quantity problems, without taking their effect on the water quality into account. Conrads et al. (2010) use artificial neural networks, trained with streamflow and sea-level time series to study this effect on the risk of an increasing salinity of the Savannah river in the United States. Data-driven models can be very computationally efficient tools for performing long-term simulations, but are often considered not reliable for predictions that lie out of the sample-range of the calibration data. This may be problematic when studying changing boundary conditions such as climate change or the effect of mitigation measures.

Conceptual models can be seen as a compromise technique that describes the physical processes in the modelled system, but on a much more macroscopic scale than physically based models. Their fundamental principle is a representation of the water system by ‘storage cells’, and the use of the continuity equation that describes the change of stored volume in each cell as due to water exchanges with other cells or with boundary conditions to close the water balance explicitly. Conceptual models have successfully been used to model river hydrodynamics for making accurate and fast flood predictions (van Daal-Rombouts et al., 2016; Wolfs et al., 2015), for use in model predictive control of retention basins (Vermuyten et al., 2018) and conceptual sewer systems (Wolfs et al., 2013) and water quality models (Nguyen et al., 2018; Keupers and Willems, 2017; Woldegiorgis, 2017; Praetorius et al., 2012; Mannina and Viviani, 2010).

This work proposes the use of an ensemble of conceptual water quantity models with detailed physics-based models as a suitable method to study the vulnerability of drinking water inlets to increasing salinity in a complex surface water system, with a focus on scenario analyses of climate change and (upstream) mitigation measure impacts. The proposed methodology is demonstrated and tested for one of the major surface water sources for drinking water production in Belgium, the Albert Canal, which is fed by the Meuse river. The models are validated using conductivity observations from two recent dry summers, 2019 and 2020, during which mitigation measures in the canal system were used without taking water quality issues into account. Scenario analyses are conducted with long term simulations to account for the strong temporal natural variability. Climate scenarios are applied to asses future conditions, and statistical analysis is performed to obtain impact frequencies. Final results are changes of critical concentrations at the water inlets under current and planned management strategies of the canal.

The outline of the remainder of this article is the following. The complex hydrology of the case study is described in Section 2, including an explanation of the management practice of the canal’s operators in times of drought, as these management strategies are the main cause for the increased salinization risk. Section 3 describes the proposed methodology, including both the conceptual mass balance for the entire canal network and the detailed physics-based model for the affected reaches. This section additionally explains the used boundary conditions and climate change scenarios. Section 4 presents and evaluates the results of the scenario analyses. Concluding remarks are presented in Section 5.

2. Description of study area

2.1. Campine Canal network

The Campine Canals form a network of navigable waterways in the north-east of Belgium, roughly between Liège and Antwerp, and form a connection between the river basins of the Meuse and Scheldt rivers. The Meuse river is a fresh water river that drains the runoff flows from a large upstream basin of about 35,000 km^2, of which about 16,670 km^2 upstream of Liège (Lambert et al., 2017). This basin is located for a large part in the Walloon region of Belgium, where it receives its highest precipitation amounts in the low mountain range of the Ardennes. Smaller fractions of the Meuse Basin are situated in the northeast of France and in the Netherlands. The river is mostly rain-fed (Ward et al., 2008), which means it has high temporal variability in river flows, from very high flows in wet winter periods to very low flows in dry summer periods. The region was confronted with sequential droughts in 2018–2020, which raised concerns about current and future water availability. The Scheldt is a tidal river, part of the Scheldt estuary along the North Sea. The river receives upstream flows from a catchment area of about 21,800 km^2 which has a rather low gradient (Charriau et al., 2009).

An overview of the canal network is given in Fig. 1. The system is supplied by the Meuse river flows through a complex interaction with an open connection at Monsin (Liège), and several locks and supply channels near Maastricht. It connects with the Scheldt river through a number of locks at the port of Antwerp. The largest canal in the network is the Albert Canal, with a length of 130 km and navigable by ships of CEMT class VI. The canal overcomes a height difference of 56 m by means of six lock complexes, each accounting for about 10 m, except for the most downstream complex at Wijnegem which accounts only for 5.7 m. This has the consequence that for a similar traffic volume at all locks, and when neglecting other water usages in each of the reaches, a water surplus exists in the final reach upstream of the open connection with the docks of the Port of Antwerp. Each lock complex consists of one larger lock with maximum allowed dimensions for ships of 200 m by 23 m, and two smaller locks with allowed dimensions of 135 m by 15 m. The main function of the Albert Canal is inland navigation, but it is also used as a water source for multiple industrial sites along its course, and water is used to a lesser extent for agriculture, nature and recreation purposes. The discharge in the canal at the bifurcation of the Meuse at Monsin is determined by the downstream water demand for this reach, at the different lock complexes and the direct water extractions from this most upstream reach. Next to water usage by the locks, the discharge in the canal network is dependent on bypass channels that are used to manage the target water level in each reach.

The final reach of the Albert Canal, downstream of Wijnegem, ends as an open connection with the docks of the Port of Antwerp. This final reach together with the docks can be seen as a large reservoir where the dominant in- and outflow of water occurs at the large tide locks connecting to the Scheldt river. Additionally, fresh water is supplied from the Albert Canal and the Zoommeer lake in the Netherlands. The docks are managed with the objective of maintaining their target water levels. Surplus water can be drained to the Scheldt river during low tide, while (salt) water can enter the docks through several channels during high tide periods when a water deficit in the docks is imminent. This interaction between the docks and the tidal river Scheldt leads to a high chloride concentration in the docks.

2.2. Drinking water production

The water surplus in the second to last canal reach of the Albert Canal allows using this to produce drinking water. Water production is executed by the water company water-link at two locations: a first production site along the Albert Canal near the Broechem reservoir, and a second site (Notmeir-Walem) along the Nete Canal. The Nete Canal is a side branch of the same canal reach of the Albert Canal and is supplied through the lock of Viersel (see also a sketch of these production locations in Fig. 1, which presents an overview of the study area, and in Fig. 2, which presents a schematized map of the Albert Canal). In 2019, the water captured from both canals amounted to 155,608 m^3 and 258,892 m^3 respectively. Drinking water production from these canals accounts for about 40 % of the total drinking water volumes produced in Flanders (Flanders Environment Agency, 2019).

2.3. Canal management during water shortages

Besides the Campine Canal network in Flanders, the Meuse supplies several major shipping canals and drinking water production

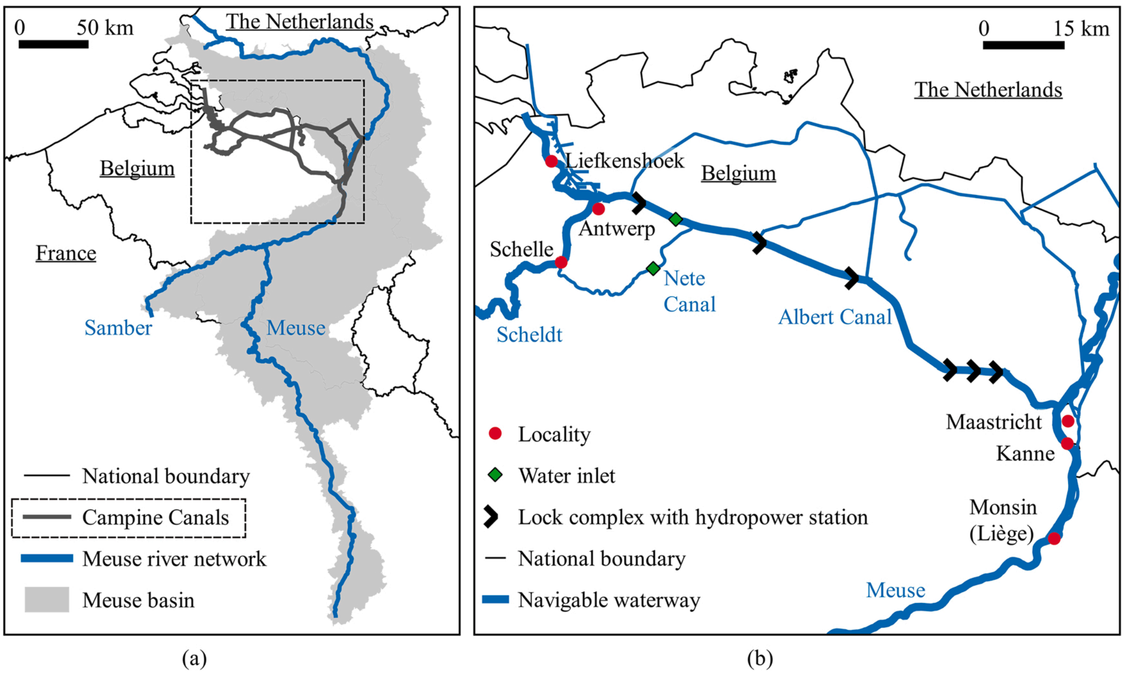

Fig. 1. Overview of the study area of the Campine Canals and their surroundings. Subfigure (a) locates the Meuse river basin, which ranges from France to the Netherlands. The Campine Canals in Belgium are highlighted. Subfigure (b) provides an overview of the Campine Canals in the north-east of Belgium and the relevant locations mentioned in the text.

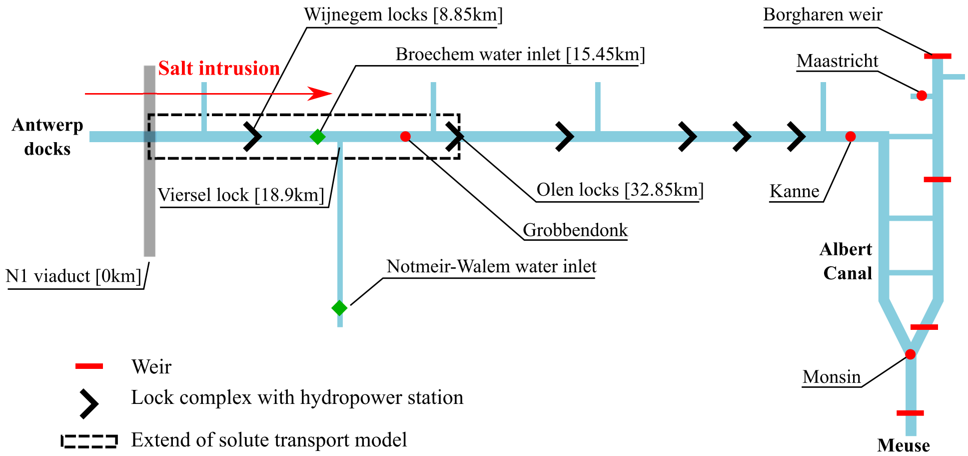

Fig. 2. Schematization of the Albert Canal and the extent of the solute transport model component (not to scale). The distance [km] from the N1 viaduct along the course of the Albert Canal is indicated for important features in the solute transport model.

sites in The Netherlands, and has additionally an important ecological function. A treaty was signed in 1995 between the Netherlands and the Flemish region to regulate the distribution of available Meuse water among those three usages (Flanders, the Netherlands and nature). When the water demand in the Campine Canals exceeds this allowed flow rate, restrictive measures need to be taken while limiting shipping and other water usage as little as possible. In the dry summer months of 2019 and 2020 for example, ships on the Albert Canal were forced to pass the locks simultaneously, leading to higher queuing times but saving the amount of water used per transferred ship. Another measure taken by the canal manager was the construction of hydropower stations at the lock complexes, which can be used as pumping stations to comply with the treaty. These pumping stations bring water from downstream to upstream canal reaches and compensate for the shipping losses and are the cause for the salinization risk of the drinking water inlets along the canal. Water-link monitored the use of these pumps in 2019 and 2020 by performing frequent conductivity measurements along the canal between the docks and their water inlet point. These observations are presented in Fig. 3, along with the pumping flow rate at Wijnegem. From these graphs it can be observed that salt intrusion reached upstream of the complex of Wijnegem in 2019, which entails the risk of having to shut down the production site of water-link. In 2020, intrusion was less critical due to an earlier start of the

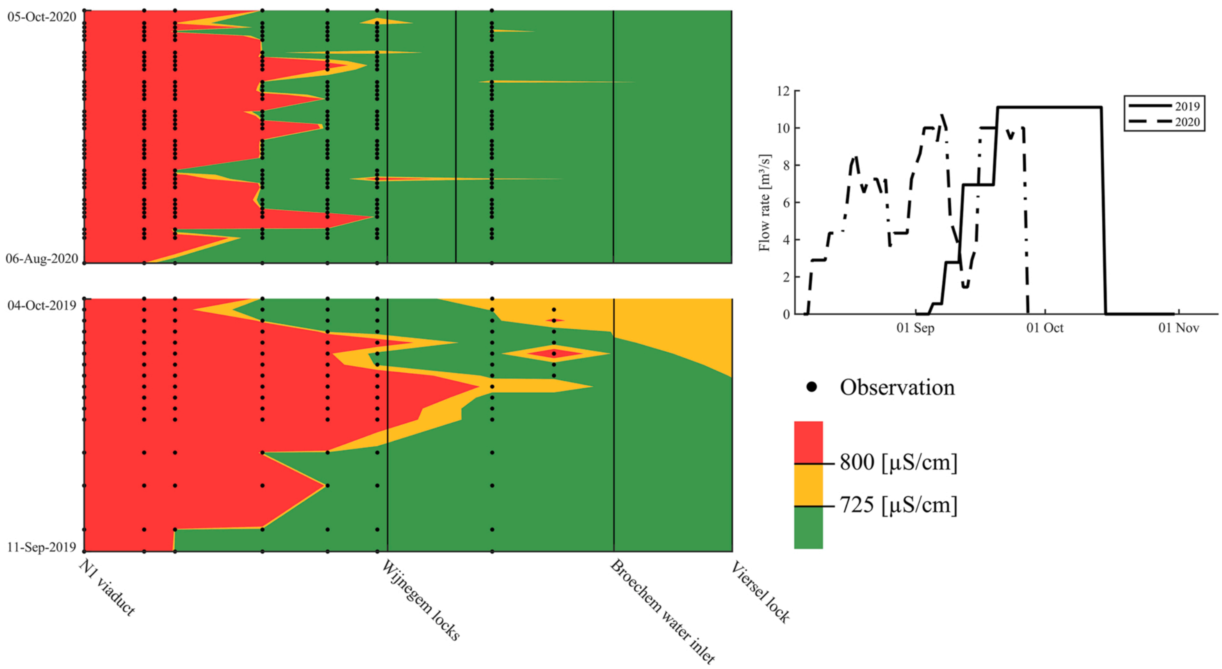

Fig. 3. Left: Observed reference conductivity at 25 °C along the Albert Canal during the pumping campaigns in 2019 and 2020. Observations are marked and linear interpolation in space and time is applied to obtain an estimation of the reference conductivity for the remaining locations and time steps. Right: Flow rate of the temporary pumping station at the Wijnegem lock complex in these periods.

pumping in August, when concentrations in the docks are typically less high. The concentrations in the docks typically reach their highest yearly maxima around early October, since the massive volume of the docks reacts to the higher concentrations in the Scheldt with a delay. This advanced intrusion during the summer of 2019 illustrates how vulnerable the system is for droughts in the Meuse Basin. If similar events will occur more frequently in a changing climate, the water production plant may need to temporary shut down due to too high concentrations in the canal.

3. Materials and methods

3.1. Water balance model of canal network

3.1.1. Conceptual mass balance model

Discharges and water levels in the canal network are simulated using a conceptual model. It is a reservoir-type model similar to a model principle that is used in various hydrologic (Willems, 2014), hydrodynamic (Wolfs et al., 2015), and water quality models (Keupers and Willems, 2017; Mannina and Viviani, 2010). The main principles are a division of the modelled system in reservoirs or storage cells, defining mass exchanges between these cells in function of the system's state and imposing conservation of mass by closing the continuity equation (Eq. 1):

$$\frac{dS_i}{dt} = I_i(t, \boldsymbol{S}) - Q_i(t, \boldsymbol{S}) \tag{1}$$

The time derivative of the volume S_i stored in cell i, equals the difference between the total in- and outflow of that cell, I_i and Q_i respectively. Both I_i and Q_i are time dependent and depend on the state of the system $\boldsymbol{S}$. The division of a river network in storage cells is often an iterative process, where boundaries are located preferably at locations where the mass exchange is known, or are based on insight in the system's behaviour that can change at a certain location, e.g. the reach of tidal influence in an estuary, or locations of bifurcations or tributaries in the river network. The structure and management of the canal network, however, already resembles the principle of a conceptual model as it is divided in reservoirs by the locks and it is managed based on the canal's water levels.

Direct mass in- and outflows in the model per reservoir are based on measurements or permits for water usage. Exchanges between reservoirs are partly known, as ship traffic at the lock complexes or as flow rate registrations from hydropower/pumping stations. The remainder is calculated based on the assumption that the canal is managed to keep water levels between a maximum and minimum value, both to assure shipping traffic and the stability of the banks. The upstream boundary is the observed discharge in the Meuse river at Monsin, while water level observations in the Scheldt river are the downstream boundaries of the model. The total model comprises 34 reservoir cells and data of 43 lock complexes is used. The model is set up with data for 2016–2019 and flow rate and water level observations throughout the canal network are used for model validation.

3.1.2. Model adjustment for scenario analyses

Historical registrations of water usage and discharges along the canal network are not available when performing scenario calculations with the model, which therefore requires to be adjusted. Time series of known water fluxes to and from the canal are replaced by constant values, based on the mean of the most recent data available. An exception is made for discharges of waste water treatment plants (WWTP's) and the extractions for drinking water production, both of which are included based on the average per day of the year to take their strong seasonal variation into account. Water usage by lock operations are averaged per month and per day of the week, to incorporate both their seasonal and weakly variation.

The Meuse treaty limits the total water usage allowed in the canals during extreme low flow conditions. The operators react to this treaty by taking measures to reduce the necessary intake from the Meuse. When using the model to perform scenario analyses, the activation of such drought measures has to be incorporated in the calculation scheme of the model. Restriction measures in the simulation are activated in the following order: sparing lock operations, activation of pumping stations and reduction of other water usage in the canals. This scheme resembles the actual order of the deployment of measures by the authorities during the droughts of 2019 and 2020.

A traffic model is developed for the lock complexes to model spare lock operations: as registrations for transferred ships are available for every individual lock, these can be combined to a list of ships that request to be processed by the lock complex (e.g. consisting of three locks on the Albert Canal), either in upstream or downstream direction, ordered by increasing time of arrival at the lock. The traffic model transforms this list to operations per individual lock of the complex. Pumps at the lock complexes of the Albert Canal are modelled sequentially. When the water level in a reservoir drops, water is attracted from the upstream reservoir. When this is not allowed since this would violate the treaty or simply because the upstream reservoir has a shortage as well, a pump is activated to extract water from the downstream canal reach. Simultaneously, any discharge towards the downstream reach to supply a shortage there is stopped, which could activate the next pump. The pumping stations are set to a flow rate needed to account for the water demand in each canal reach, with a maximum of 12 m^3 /s at the Wijnegem complex, and 15 m^3 /s at the other complexes of the Albert Canal. This corresponds with the actual maximum capacity of the pumps already installed, or the foreseen capacity in the stations planned for construction in the near future. A water reduction for other users is imposed by limiting the total inflow to the Flemish canals to the amount allowed by the Meuse Treaty, and by shutting down al water usage in a canal reach once the water level drops 30 cm under the target level.

3.2. Hydrodynamic and solute transport model

The transport of chloride ions in the Albert Canal is modelled for its two most downstream canal reaches. This study area spans from the lock complex of Olen to the open connection with the Antwerp Docks at the N1 viaduct, as indicated in the schematization of Fig. 2. The water depth, flow velocity and solute concentrations are assumed to be uniform across the channel cross section and vertical flow is neglected so a 1D formulation of the flow and transport equations can be used. This set of equations consists of the fluid mass continuity and momentum equations and the advection-dispersion equation for solute transport. The equations are formulated in integral form for a canal section between longitudinal coordinates x1 and x2 as follows (Eq. 2, Sanders et al., 2001):

$$\frac{\partial}{\partial t}\int_{x1}^{x2} \boldsymbol{U} \quad dx + \int_{x1}^{x2} \boldsymbol{F} \quad dx = \int_{x1}^{x2} \boldsymbol{S} \quad dx \tag{2}$$

$$\boldsymbol{U} = \begin{bmatrix} A \\ AV \\ AC \end{bmatrix}$$

$$\boldsymbol{F} = \begin{bmatrix} AV \\ V^2A + gA\bar{y} \\ AVC - AD\dfrac{\partial C}{\partial x} \end{bmatrix}$$

$$\boldsymbol{S} = \begin{bmatrix} \sum_i Q_i\delta(x - x_i) \\ F_e + gA(S_0 - S_f) \\ \sum_i C_iQ_i\delta(x - x_i) \end{bmatrix}$$

With A the canal's cross sectional area, V the cross sectional averaged flow velocity, C the solute concentration, g the gravitational acceleration, $\bar{y}$ the depth of the cross section's centroid under the free surface, D the longitudinal dispersion coefficient, Q_i the discharge rate of point source 'i' along the canal, C_i the solute concentration of point source 'i', F_c the longitudinal component of the hydrostatic force exerted by the channel walls in a non-prismatic channel, S_0 the bottom slope and S_f the friction slope.

A numerical solution for these equations is found using a Finite-Volume Method (FVM) scheme. In this study, we use the method proposed by Sanders et al. (2001), which applies Hancock's predictor-corrector approach in time stepping in order to achieve second-order accuracy in space and time. This scheme explicitly conserves water and solute mass and is suited for dealing with high concentration gradients.

Cross sections are assumed to be rectangular, characterised by the channel width B, and are defined at the cell interfaces. These section widths are derived from the topographical reference map for Flanders (Agentschap Informatie Vlaanderen, 2020) and vary between 61 m and 120 m in the studied area. Friction slopes are calculated using the Manning formula, with empirical roughness coefficient n = 0.025 $s/m^{1/3}$ which was estimated using the guide provided by Arcement and Schneider (1989).

The dispersion coefficient D is assumed to vary along the channel's course, since some of the various factors that can influence dispersion, e.g. channel width, shipping traffic, industrial activity and others, are not uniform along the canal. D is set as a piecewise linear function of the longitudinal coordinate and is determined using an automatic calibration procedure for intermediate steps of 1 km. The SCE-UA algorithm (Duan et al., 1992) is used to identify the optimal values for D efficiently. The objective function $f(D)$, used in the procedure to evaluate the parameter set's performance, is formulated as follows (Eq. 3):

$$f(D) = \sum_{volumes}\left[\frac{\overline{C}_{model}(x,D) - \overline{C}_{obs}(x)}{\overline{C}_{obs}(x)}\right]^2 \tag{3}$$

Using this function, the calibration should lead to a good correspondence between simulation results and observations, averaged over the calibration period ($\overline{C}_{model}$ and $\overline{C}_{obs}$, respectively). This choice is motivated by the uncertainty on the boundary conditions of the mass balance model on a smaller timescale (hours or days) which could lead to a poor approximation of instantaneous values due to a shift in the timing of the discharge simulations compared to reality. Observations for the summer of 2020 are used as calibration data, while observations for 2019 are used to validate the calibrated model. In both periods, mobile pumping stations were used to compensate losses due to shipping traffic. However, only in 2020, the waterway manager registered the actual usage of the available pumps as well as their pumping rates, while only the installed capacity of the pumps was available for 2019. Since downtime, for example due to fuel shortages or mechanical issues, was not registered in 2019, the total pumping rate is likely to be overestimated in the model. This may cause an overestimation of the chloride concentrations simulated for that period. The model is therefore calibrated using the more reliable 2020 data, while the 2019 data is used for validation purposes with the remark that an overestimation of the chloride concentrations by the model is expected for that period. The SCE-UA method is applied using 6 complexes and the algorithm tries to minimize the objective function until convergence is reached: the procedure is stopped when no reduction of the objective function more significant than 0.1 % is found in ten subsequent optimization cycles, or if the normalized geometric range of the population of points has converged to a value smaller than 0.001 of the feasible parameter space. No absolute threshold for the objective function is defined a priori. The ability of the model to predict the average concentrations in the canal is evaluated by means of the relative error (*RE*) on the time-averaged concentration, as given by Eq. (4).

$$RE = \frac{\overline{C}_{model}(x) - \overline{C}_{obs}(x)}{\overline{C}_{obs}(x)} \tag{4}$$

This *RE* gives an indication on how well the model can estimate the severity of salt intrusion along the canal during an entire summer period. Values closer to zero indicate a good correspondence of simulation results with the observations, positive values of RE would indicate an overestimation of reality by the model, while negative values indicate an underestimation of the chloride ion concentrations.

3.3. Water balance and chloride model of docks

The solute transport model for the Albert Canal is limited to the canal itself, although it has an open connection with the port docks in Antwerp. This choice is motivated by the limited variation in chloride concentration in the docks, and the focus of this study on the water extraction sites for drinking water production along the canal.

Due to this choice, the downstream boundary conditions of the solute transport model are the water level and chloride concentration in the Antwerp docks at the connection with the canal. The concentration in the docks mainly depends on the concentration in the Scheldt through the functioning of the locks and the intake of Scheldt water to compensate losses. A pollutant-mass balance on a monthly timescale is used to account for this interaction. Fig. 4 plots the chloride concentration, calculated using high-resolution conductivity and water temperature observations, in the Scheldt at Liefkenshoek together with the upstream discharge in the river. The salinity of the Scheldt at the location of the locks is estimated with an empirical model that accounts for the variability in concentration due to both the river base flow and the tide.

The concentration gradient to account for the differences in concentrations between the central area in the docks and the boundary of the study area is modelled using a 1D FVM-model, considering the dock cross sections. It is calibrated using observations in the docks for the period 2016–2020. Note that the main goal of this model is to predict the peak concentrations at the downstream boundary during summer, while a good approximation of the lower concentrations is less important.

3.4. Climate change scenarios

The intrusion of chlorides from the port area, and its impact on the production plant's reliability is not only dependent on the Meuse discharge. The duration of the drought, and the antecedent conditions in the canal system are equally important factors. The impact of climate change on the reliability of the production plant is therefore analysed by means long term simulations, based on a 110-years long series of daily discharge observations in the Meuse at Monsin (1911–2020). This time series is assumed to be representative for the current climate. Simulations with these data will yield concentration values that should be interpreted as the response of the current, idealised canal system, and not as historical values. In a similar fashion will the impact of climate change be analysed using perturbed versions of this discharge series, as elaborated in the following paragraphs. No estimations of future shipping traffic, changing infrastructure and water usage, or adapted management of the canals are considered.

For the climate change impact analysis, similar simulations are conducted with the upstream boundary condition (discharge of the Meuse at Monsin) perturbed based on a set of selected climate scenarios. Simulation results for the (perturbed) 110-year long discharge

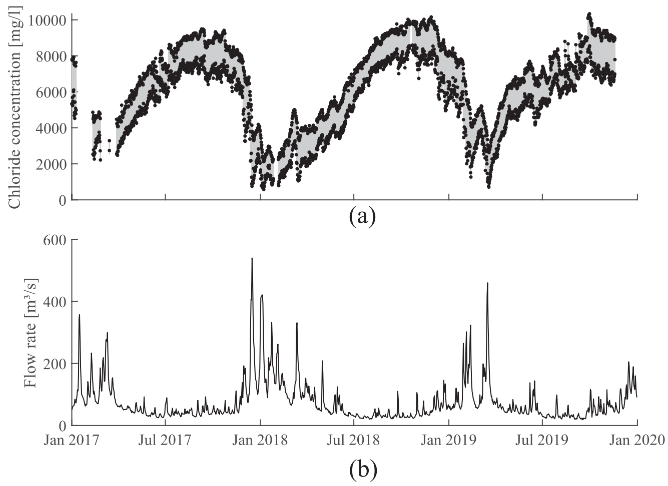

Fig. 4. Top: Time series of calculated chloride concentration in the Scheldt at Liefkenshoek (station zes09x-SF-CM, MOW-HIC, 2021) for 2017–2019, with peaks following low and high tide marked as black dots. Bottom: Upstream calculated discharge in the Scheldt at Schelle.

series per climate scenario are then statistically analysed and the results give predictions for the salinization conditions corresponding with the projected time-horizon and climate scenario. These scenarios were developed by Tabari et al. (2015), following the methodology by Ntegeka et al. (2014). It is based on a statistical analysis of the climate change signals for precipitation and potential evapotranspiration (ET0) obtained from a large ensemble of global, regional and local climate models. These signals consist for precipitation of the changes in the wet day intensities as a function of the empirical return period and the number of wet days per month. For ET0, they consist of the mean monthly changes. The quantile perturbation method (Willems and Vrac, 2011) is applied to alter the available precipitation and ET0 input series of a hydrological model of the Meuse basin according to these climate change signals. This hydrological model is an implementation of the conceptual rainfall-runoff model NAM and was calibrated to daily Meuse river discharge data at Monsin. This was done in the framework of other impact studies in the Meuse basin (Vansteenkiste et al., 2009), following the model calibration methodology described in Vansteenkiste et al. (2014). This involves model parameter optimization based on simulated versus observed peak flows, low flows, and cumulative volumes. Only the mid-impact and high-impact scenarios are considered, corresponding with the median and the upper boundary of the 95 %-confidence interval of the relevant model impact results, minimum discharges in this case, obtained from the full ensemble of climate change signals in the perturbation approach. The future climate scenarios are considered for two time horizons: 2050 and 2100. The results for 2100 are summarised in Fig. 5 where the yearly minimal 7-day averaged discharge is presented versus their empirical return period, for the current climate and the two climate scenarios. The empirical return period is computed as the length of the historical series divided by the discharge rank (1 for the lowest discharge, 2 for the second lowest, …). The recent summers of 2019 and 2020 clearly appear in the more extreme portion of the data, see also Table 1. The most extreme observation occurred during the severe drought of 1976. The same method was applied for the boundary conditions along the Scheldt river, to obtain climate change impact results on the Scheldt low flows. The empirical model presented in Section 3.3 was applied to transfer these in impact results for the Scheldt chloride concentrations.

For the chloride concentration at the Meuse river boundary, it is composed of a background concentration and the result of industrial effluents to the Meuse and its tributaries, which make the concentration at Monsin dependent on the discharge. Van Craenenbroeck (1982) validated a linear relation, and could attribute the majority of chlorides to effluents in the Samber river, an important tributary. This study is limited to an impact analysis on intrusion from the docks due to the shipping-focused management of the canal. Therefore, a fixed concentration of 48 mg/l, based on the long term average, is used as upstream boundary condition in the model simulations, both for current and future climate conditions.

4. Results and discussion

4.1. Model calibration and validation results

The mass balance model of the canal network is evaluated using the discharge observation of Kanne, located upstream in the canal network, see Figs. 1 and 2. The flow rate at this measuring station is representative for most of the water usage in the Campine Canals. The cumulative simulated and observed discharge are compared to evaluate whether the mass balance model is able to approximate the true water demand of the water system. The model overestimates the total cumulative inflow of water in Kanne for the entire period 2016 – 2019 with less than 2 m^3 . It can therefore be concluded that the estimation of water usage along the canal network is sufficiently accurate. The model's capability to estimate the seasonal variation in water usage can be evaluated using Fig. 6(a) where the 30-day moving average of the discharge at Kanne is compared for the model and observation. A Pearson correlation coefficient of 0.92 is found between this 30-day averaged simulated and observed discharge.

The model is validated additionally at the measurement station of Grobbendonk, downstream of the Olen locks and thus located in the area covered by the solute transport model (see Fig. 2). Both the 30-day averaged discharge and the cumulative volume for the period 2018–2019 are considered, given in Fig. 7. Note that only limited observations are available for this location. While the model underestimates the discharge in the canal for the winter period of 2018–2019, the low flow conditions are simulated satisfactory by the

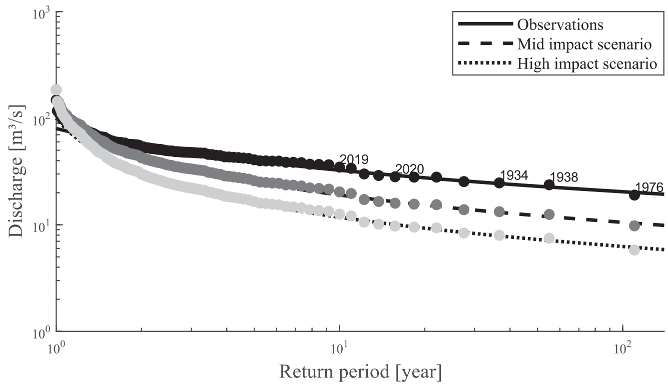

Fig. 5. Yearly minima of the 7-day averaged Meuse discharge at Monsin versus empirical return period, for the current climate and for the 2100 mid-impact an high-impact scenarios, based on the 1911–2020 discharge observations.

Table 1
Observed yearly minima of the 7-day averaged Meuse discharge at Monsin for the most extreme years of the 1911–2020 discharge observations. Years in the most recent two decades are in bold.

Rank	Year	Discharge [m^3 /s]
1	1976	19.0
2	1938	23.7
3	1934	24.7
4	1921	25.4
5	1959	28.0
6	1964	28.0
7	**2020**	**28.2**
8	1943	29.0
9	1947	30.0
10	1991	33.9
11	**2019**	**34.8**
12	1996	36.6
13	**2017**	**36.8**
…	…	…
20	**2003**	**39.8**
21	1953	39.9
22	**2018**	**40.7**

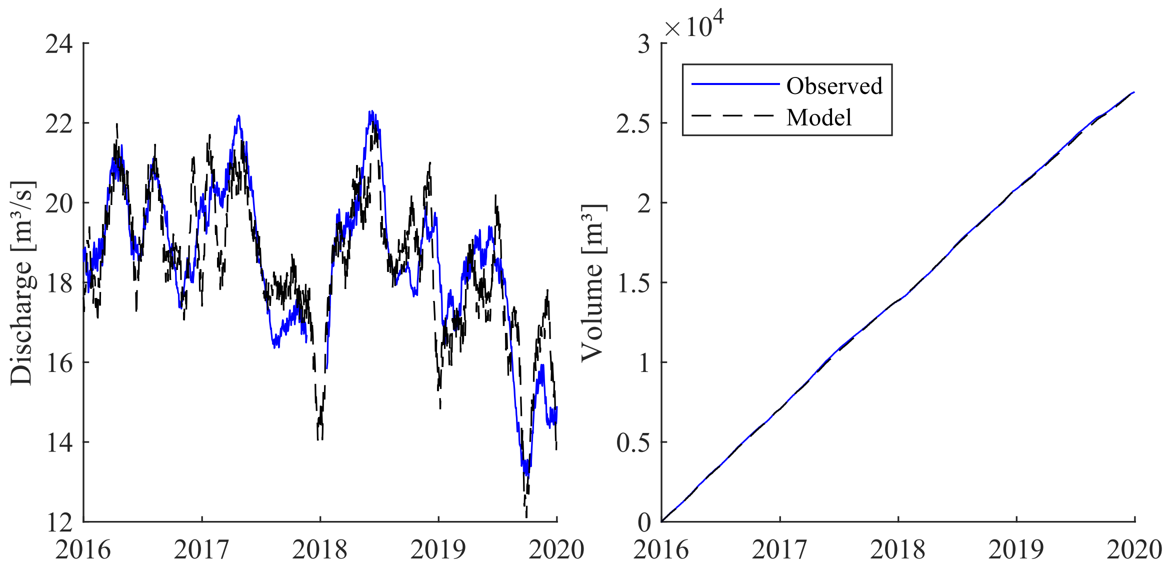

Fig. 6. Left: observed and simulated 30-day averaged discharge in the Albert Canal at Kanne. Right: cumulative volume observed and simulated in the Albert Canal at Kanne. (observations of station abk11a-1066, MOW-HIC, 2021).

conceptual model. A Pearson correlation coefficient of 0.82 is found between the 30-day averaged simulated and observed discharge. The underestimation in the wet period could possibly be explained by a usage of the canal to evacuate excess water in the Meuse. Such excess water is not registered in the data logs of the locks.

As described in Section 3.2, the calibration of the solute transport model intends to achieve a good correspondence between the mean simulated and observed chloride concentrations along the course of the canal. This criterion is evaluated with the relative error RE, whose values are presented in Table 2. To evaluate whether the model can simulate the concentration dynamics, the Pearson correlation coefficient $P r$ is calculated and is presented in Table 2 as well.

The locations of Table 2 correspond with the indicated locations in Figs. 8 and 9, where the simulated concentrations for the calibration and validation periods are presented to allow for a visual evaluation of the model's performance.

The average chloride concentrations along the course of the canal show a good correspondence with the observations for 2020, while the expected overestimation of concentrations in the validation period can be observed in the relatively high positive values for the *RE* in 2019. The calibrated dispersion coefficient ranges between 150 [m^2/s] near the connection with the docks, to around 15 [m^2/s] at the Olen locks. These higher values near the Antwerp area can be explained by the occurrence of salt intrusion in the canal through density currents, a phenomenon not explicitly described in the one-dimensional modelling approach, but implicitly captured by higher values of the dispersion coefficient. Similar values were found by Vanderkimpen et al. (2012): a constant dispersion of 200 [m^2/s] for

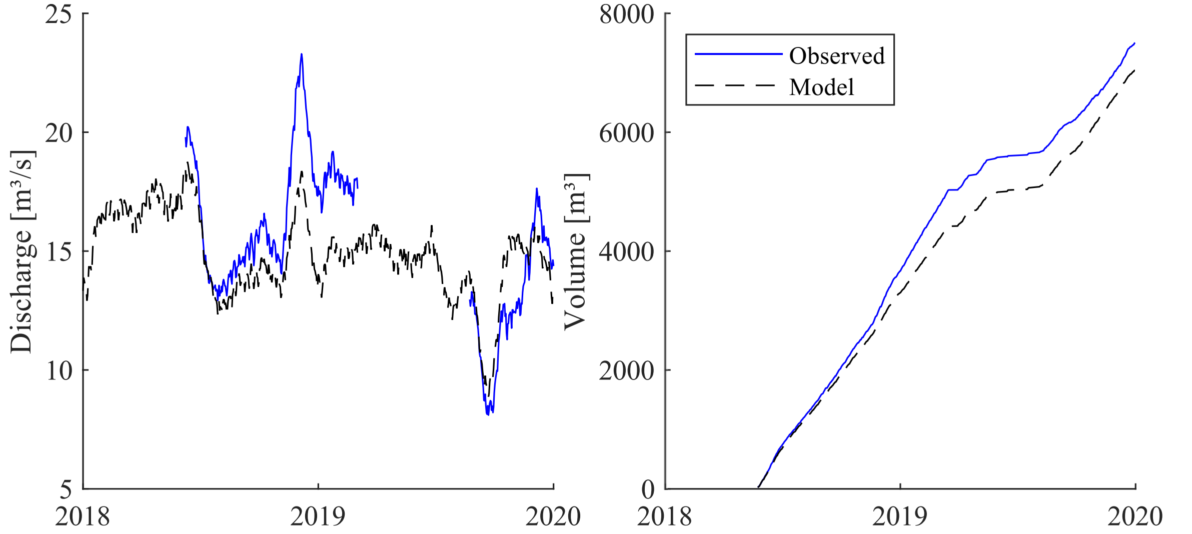

Fig. 7. Left: observed and simulated 30-day averaged discharge in the Albert Canal at Grobbendonk. Right: cumulative volume observed and simulated in the Albert Canal at Grobbendonk. (observations of station abk06a-1066, MOW-HIC, 2021).

Table 2
Relative error on time-averaged concentrations and Pearson correlation for observed and simulated concentrations along the canal.

	RE		P r	
Location	2019 (validation)	2020 (calibration)	2019 (validation)	2020 (calibration)
a	0.229	0.002	0.888	0.858
b	0.365	0.005	0.818	0.838
c	0.218	-0.001	0.862	0.618
d	0.491	-0.007	0.802	$< 10^{-3}$
e	0.770	-0.027	0.612	0.342
f	0.024	-0.072	0.156	0.806

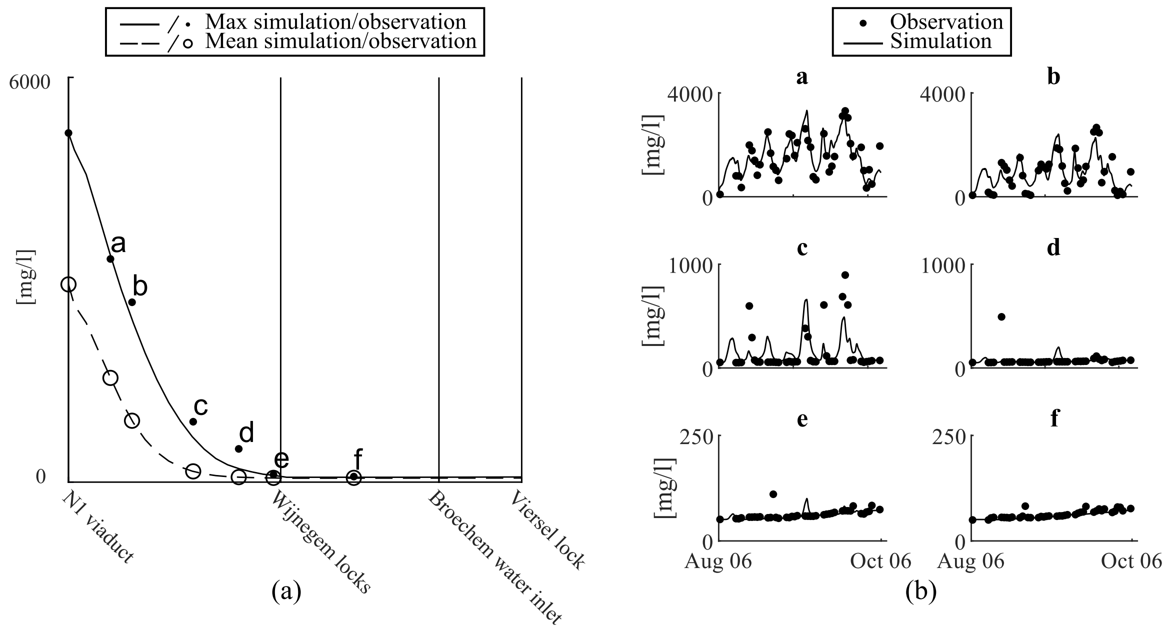

Fig. 8. Simulated versus observed chloride concentrations for the calibration period of the summer of 2020: (a) maximum and mean chloride concentrations along the course of the canal, (b) time series of chloride concentrations at the sampling locations.

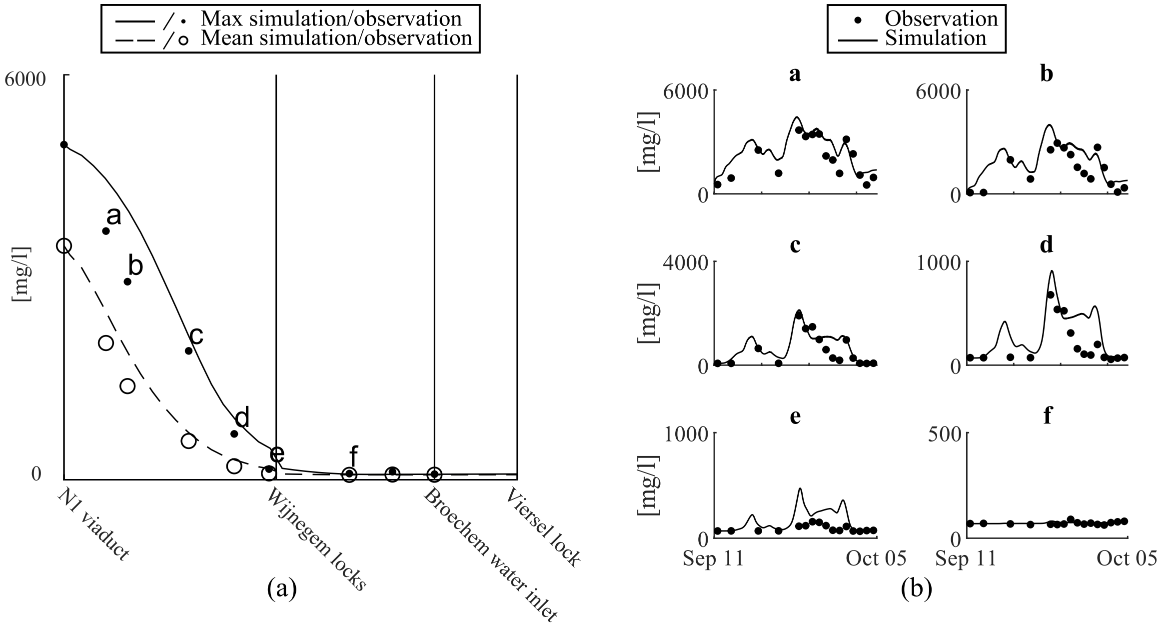

Fig. 9. Simulated versus observed chloride concentrations for the validation period of the summer of 2019: (a) maximum and mean chloride concentrations along the course of the canal, (b) time series of chloride concentrations at the sampling locations.

the canal reach, and Vijverberg et al. (2010): a dispersion coefficient ranging between 55 and 550 [m^2/s], when studying salt intrusion on the Ghent-Terneuzen Canal, a comparable shipping canal between Flanders and the Netherlands. The dynamics of the concentrations are captured reasonably well by the model, especially when the uncertainty in the discharge boundary conditions for the canal network is taken into account. An exception is location **d** where a value for $Pr < 10^{-3}$ is found, and to a lesser extent location **e** with a Pr of 0.342, for the summer of 2020. A single, high peak concentration was observed here that was not simulated by the model. A possible explanation is the occurrence of a high flow rate of the pumping station of Wijnegem combined with lower water use by the

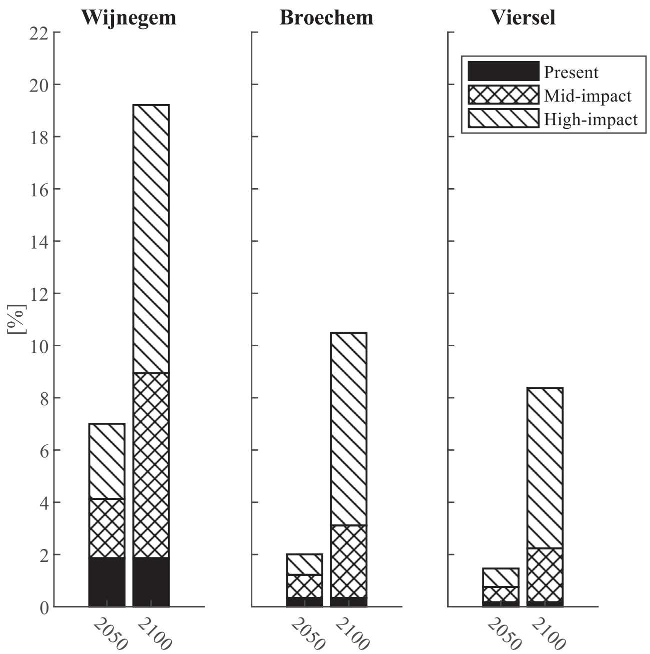

Fig. 10. Percentage of the time that the simulated concentration at the mentioned location exceeds the imposed upstream concentration in the 110 year simulation results: results are shown for the Wijnegem lock complex, the Broechem water inlet and the Viersel lock; for the present climate and the mid- and high-impact climate scenarios, for future horizons 2050 and 2100.

lock complex, however, an erroneous measurement is another possible reason.

4.2. Climate change impact

The occurrence of salt intrusion from the docks can be observed in the simulation results as an exceedance of the imposed constant upstream concentration of 48 mg/l, as every exceedance indicates an influence of chloride ions intruding from the dock area. A threshold value of 1 mg/l is used when evaluating this exceedance, to avoid that numerical instabilities and rounding errors in the simulation results are influencing the interpretation. Three locations were selected for which the percentage of time that intrusion occurs is analysed: the lock complex Wijnegem, the water inlet for drinking water production in Broechem and the lock of Viersel. Fig. 10 presents the results for the present climate and the mid- and high-impact climate scenarios. Under current climate conditions, intrusion up to the locks of Wijnegem is rare as it occurs for less than 2 % of the time. This will rise with a factor 2–4 by 2050 and with a factor 5–10 by the end of the century. The occurrence of intrusion up to the water inlet of Broechem is negligible in the present climate, but can become more frequent, reaching up to 2 % of the time by 2050. By 2100, intrusion reaches the water inlet up to 10 % of the time for the high-impact climate scenario. The total water production is jeopardized when intrusion reaches also the second water inlet. This remains exceptional (less than 2 % of the time) for 2050, but the probability increases (to between 2 % and 8 % of the time) for 2100.

To analyse extreme high impact conditions that can occur along the course of the canal, Fig. 11 presents the 99-percentile of the cell-averaged concentration per simulated year, and for specific return periods. The 99-percentile results are obtained as follows. Simulation years are ordered based on the yearly maxima of the simulated concentration at the location of the water production intake point. This ranking allows to determine the empirical return period of the maximum concentration for each year. As a reference, the maxima of the observations for 2019 and 2020 for each location are shown as well. These figures make clear that the lock complex of Wijnegem acts as a barrier for salt intrusion from the docks. However, it loses its obstructive capacity in the more extreme scenarios when extensive pumping is needed to maintain a sufficient water level in the canal for shipping. In the most extreme years, with empirical return periods higher than 50 years, a combination of high chloride concentrations in the docks and usage of the pumps for long periods of time will lead to an almost uniform concentration in the downstream canal section: there is no longer a sufficient fresh water inflow to the docks from the canal to maintain a concentration gradient. The return period of this situation decreases for 2100 to about 20 years for the mid-impact scenario and even 10 years for the high-impact scenario. These results are also summarized in Table 3, for the three locations discussed above.

Previous results on extreme situations allow to assess the (future) probability of reaching critical concentrations at the production site, but it does not allow to fully evaluate the plant’s reliability. A shorter occurrence of peak concentrations can probably be bridged by using the water reserves or by increasing the production at an alternative site. A long or frequently reoccurring exceedance of the plant’s working limits on the other hand would put more stress on the system since it requires extensive water reserves. The production site at Broechem includes a reservoir that allows to continue production in case of accidental pollution in the canal, which can also be used to bridge periods of elevated chloride concentrations. The reservoir has sufficient capacity to supply water for approximately 27 days. Table 4 summarizes the reliability, calculated as the number of days the simulated concentration at the Broechem water inlet exceeds the working limits of the production installation. It additionally shows the number of periods during which the limit was exceeded for the 110-year long simulation period, and the number of those periods that are longer than 27 days. One can conclude that by 2050, shutting down the drinking water production plant due to salt intrusion up to Broechem is likely to become a realistic threat, but it will still be exceptional. By the end of the century, ceasing production at Broechem can become a recurring event, with 16–50 of such periods simulated. These results are consistent with the findings of van den Brink et al. (2019) and Zwolsman and Becker (2012), who both found that a decrease of river discharges are likely to lead to increased salinization of drinking water inlets along the river branches in the Meuse-Rhine-delta by 2050. Bonte and Zwolsman (2010) come to similar conclusions for the artificial Lake IJselmeer, another important (drinking) water source in the Netherlands, where model simulations predict that a reduced discharge in the Rhine river, combined with increased intrusion of seawater at the tidal closure dam can threat drinking water production by 2050, based on a high climate change scenario.

Drought measures along the canal are imposed when water usage exceeds the limit as determined by the Meuse Treaty. To evaluate whether there is some margin to mitigate acute salt intrusion by violation of the treaty, the impact analysis above was repeated with adjusted models in which the total available Meuse discharge was used as boundary condition instead of the allowed amount. This cannot be interpreted as a feasible scenario, since both inland navigation and drinking water production in the Netherlands depend heavily on the Meuse. It rather is a scenario to assess the minimum of salinization in the canal that will occur for the current water usage and management rules along the canal network in absence of the treaty. The results indicate that– under unchanged water abstractions – there is no acute salt intrusion up to the water inlets if the treaty is not respected. The reliability of the production site at Broechem is in that case 100 % for all scenario’s, except for the high-impact climate scenario for which the reliability drops to 99.72 % (see also Fig. 12 for calculated percentages of the time the upstream concentration is exceeded). This result shows that a temporary violation of the treaty can be considered to resolve acute problems in the future, but cannot be considered a sustainable or robust solution for the salinization problem as it would probably cause water shortages elsewhere in the system. A dynamic control of the intrusion, based on real-time observations to obtain minimal discharges required to maintain the target concentration levels, could perhaps be a more efficient alternative, as demonstrated by Augustijn et al. (2011) for the Volkerak-Zoom lake in the Netherlands.

The above climate change impact results do represent the assessed relative impact of the climate scenarios compared to the current situation, but for the current management of the canal system and water usage. These may also change in the future, and there are several options to further enhance the model and modelling approach. Firstly, the mass balance model of the canal system is an

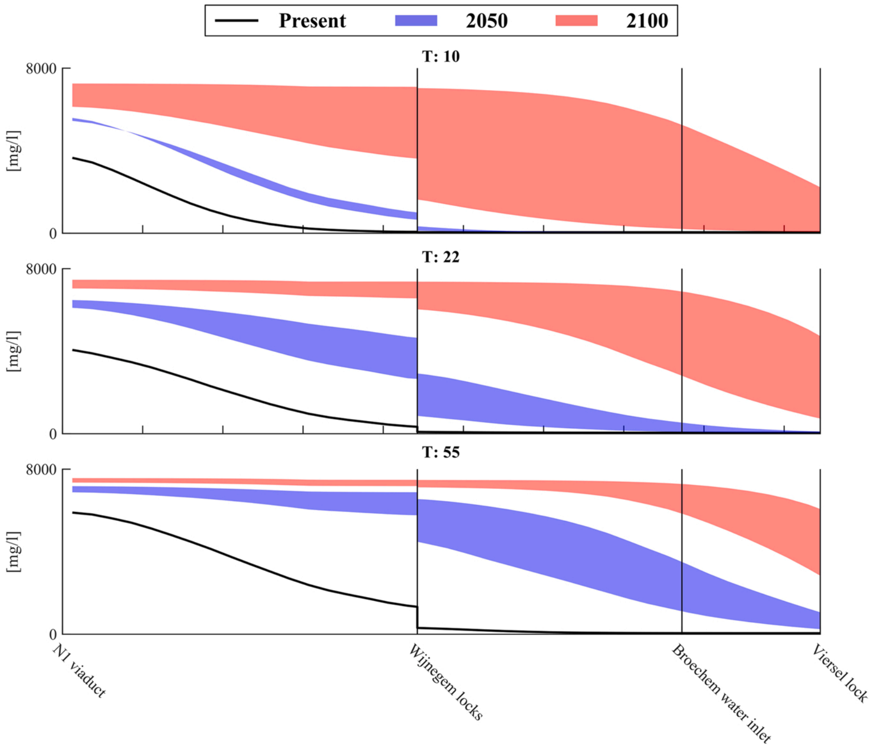

Fig. 11. 99-percentile of simulated chloride concentrations per year with the mentioned return period T in years; for the present climate and mid- and high-impact climate scenarios, for future horizons 2050 and 2100.

Table 3
Yearly maxima of simulated chloride concentrations [mg/l] at three locations, per return period and future horizon; for the present climate and the mid- and high-impact climate scenarios.

Horizon	Return period [years]	Wijnegem			Broechem			Viersel		
		Present	Mid	High	Present	Mid	High	Present	Mid	High
2050	T10	70	440	1470	50	50	60	50	50	50
	T22	340	1960	4400	50	110	610	50	50	110
	T55	940	5260	6730	50	1230	3720	50	250	1130
	T110	5550	7000	7180	1500	5390	6370	290	2340	3640
2100	T10	70	3250	7080	50	260	5560	50	70	2570
	T22	340	6340	7380	50	2930	690	50	800	4830
	T55	940	7150	7490	50	5980	7290	50	2980	6100
	T110	5550	7350	7570	1500	7040	7470	290	5220	6850

Table 4
Reliability of the Broechem-water inlet, calculated as the percentage of time that the simulated concentration does not exceed the maximum for drinking water production. The two rightmost columns display the number of periods during which the concentration does exceed the working limit, and the number of those periods longer than 27 days.

Horizon	Reliability	# unsatisfactory periods	# unsatisfactory periods exceeding buffer
Present	99.84 %	2	1
2050 - Mid	99.37 %	7	2
2050 - High	98.65 %	11	5
2100 - Mid	97.85 %	16	8
2100 - High	92.13 %	50	29

idealized representation of the current canal system and management: Measures to mitigate the impact of drought on shipping are imposed immediately when needed, e.g. the pumping stations, which are partly still under construction and the canal manager relies on temporary installations. Secondly, increased chloride concentrations in the Meuse river is another aspect not considered here, while

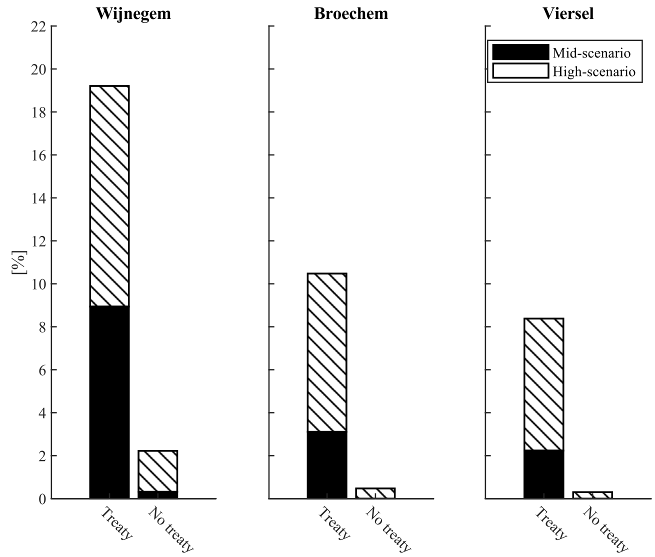

Fig. 12. Percentage of the time that the simulated concentration at the mentioned locations exceeds the imposed upstream concentration in the 110-year simulation results: results are shown for the Wijnegem lock complex, the Broechem water inlet and the Viersel lock, for the mid- and high-impact climate scenarios, for future horizon 2100.

this is expected to contribute as well to an increased chloride concentration at the water inlets during low discharge events. For example van den Brink et al. (2019) studied the possible increase of salinity in the Lek river in the Netherlands due to climate change and found up to 2 % increase due to increased concentration in the upstream water of the Rhine river by 2050. Le et al. (2019) found an increase of the mean conductivity in surface waters in Germany between 10 % and 15 % for the period 2070–2100, attributed to reduced river discharges. It is reasonable to assume similar effects for the Meuse and Albert Canal. Thirdly, an increase in water demand or shipping traffic was not accounted for. Finally, sea level rise is likely to increase the chloride concentration in the Scheldt river, which will consequently impact concentrations in the docks. The modelling tools that were developed for this study are, however, very well suited to further investigate these effects.

5. Conclusions

In this study, a conceptual mass balance model of the Campine Canal system was combined with a detailed physics-based solute transport model of selected canal reaches to study the possible salinization of drinking water inlets. The intention was to obtain a method that can take a wide variety of management decisions in a complex river/canal network into account when performing scenario analyses, while remaining both accurate, robust and computationally efficient. The model ensemble was used to study how climate change can have an impact on the reliability of the drinking water availability of the Flanders Region in Belgium. Discharge observations for the Meuse were perturbed to account for climate change for two future horizons, and for mid-impact and high-impact climate scenarios. This 110-year long time series was used to perform long term simulations with the developed models. It was shown that the salinization risk is small under current climate conditions, as the working limits of the drinking water production plant at Broechem are exceeded twice in the 110-year simulation period. By the year 2050, 7–11 periods with an exceedance of the maximum allowed concentrations at the water inlet location would occur in the 110-year period, depending on the climate change impact scenario. By the year 2100, this frequency further increases to 16–50 occurrences in 110 years. About half of these occurrences are longer than what can be bridged by the water reserves.

This study makes clear that an integrated management of the canal system and surrounding surface waters, focussing on both shipping and other water users, will be crucial to limit the future water shortage risk in the area. The developed models and insight in the effect of climate change can support the operators of the canal network in their planning of future management strategies. Another mechanism that can cause an increased salinity of the drinking water inlets, and which was not considered in this work, is an increased salinity of the Scheldt river due to lower base flow during droughts, and rising sea level as a consequence of climate change. A future increase in shipping traffic in the canal network, as foreseen by the Belgian government (Federaal Planbureau and Federale Overheidsdienst mobiliteit en Vervoer, 2019), would put even further stress on the system. A two-way coupling between the water balance and solute transport simulations, where the water-quantity component of the model takes simulated chloride concentrations into account, would allow for scenario analyses where mitigation measures along the canal take the salinity into account. This is not yet possible in the current one-way coupling of the models where the water balance model is run first, and its simulation results are regarded only as boundary conditions in the solute transport model.

A possible future improvement for this model is to replace the detailed physics-based solute transport model with a conceptualized version. The availability of the detailed FVM-model would allow for an efficient calibration of the conceptual model using simulated rather than observed concentrations. While several authors present methods for conceptual water quality models, further work is required to allow for a robust modelling of the rapid changing of the flow direction in the canal network due to the (de)activation of pumps at the lock complexes. Conceptualizing the solute-transport component could further improve the computational efficiency of the model, which would for example be useful when the model is used for optimization studies to determine optimal strategies of implementing mitigation measures in the canal network.

CRediT authorship contribution statement

Daan Bertels: Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing – original draft**. Patrick Willems:** Validation, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101129.

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