VATTEN – Journal of Water Management and Research 75: 4. 2019

MODELLING WATER EXCHANGE IN THE FLOMMEN LAGOON, SOUTHERN SWEDEN

MODELLERING AV VATTENUTBYTE I FLOMMEN LAGUN, SÖDRA SVERIGE.

Shuwei Wang, Almir Nunes
Department of Water Resources Engineering, Lund University, Box 118, 221 00, Lund, Sweden.

Abstract

The Flommen Lagoon, southern Sweden, is a unique water body of great ecological and economic values. Thus, its protection against flooding and its water quality maintenance has always been a concern. The objective of this study was to investigate the water exchange between the lagoon and the sea with regards to the inlet properties and the existent sluice gate operation. An investigation was also performed about the impact of opening a second inlet on the water renewal. According to the simulation results, the inlet geometry showed no significant influence on the lagoon water level but affected the water exchange rate. For the simulated time period, halve the cross-section area decreases the gross exchange rate by 39.2% and double cross-section area increases the gross exchange rate by 15.3%. The sluice decreases the gross water exchange rate by 31.6%, but it plays an important role in protecting the golf courses around the lagoon from flooding. With two inlets, the gross water exchange rate is 15.3% higher than with one inlet, and the water level is also slightly higher.

Keywords: Water exchange, Coastal lagoon, Numerical modelling, Inlet morphology

Sammanfattning

Flommen lagun i Skåne är omgiven av naturresevat och är ett viktigt miljöområde. Skyddet av detta område inklusive vattenkvalitet i lagunen och översvämning i det angränsande området har alltid varit ett bekymmer. Syftena med denna artikel är att simulera vattenstånd i lagunen och vattenutbyte mellan lagunen och havet med avseende på inloppsegenskaper, sandtransport och driften av slussen (inloppet till Flommen) för att minimera inflytande av mänskliga aktiviteter och nå en lämplig driftsstrategi för slussen. En undersökning om effekterna av att bygga ett andra inlopp mellan lagunen och havet genomfördes också. Enligt simuleringsresultaten är sandtransporten större söder om inloppet än i norr vilket resulterar i sandansamling runt inloppet. Inloppsgeometrin visade inget signifikant inflytande på lagunens vattenstånd men påverkade vattenutbytet. För den simulerade tidsperioden ger en halvering av tvärsnittsarean ett minskat utbyte med 39,2% och en dubblering av tvärsnittsytan ökar ytbytet med 15,3%. Slussen sänker bruttovattenutbytet med 31,6%, men spelar en viktig roll för att skydda golfbanorna runt lagunen från översvämningar. Med två inlopp är bruttovattenutbytet 15,3% högre än med ett inlopp, och vattenståndet är också något högre.

Introduction

Kjerfve (1994) defines a coastal lagoon as "a shallow coastal water body separated from the ocean by a barrier, connected at least intermittently to the ocean by one or more restricted inlets, and usually oriented shore parallel". Lagoons are commonly found in all continents and consist of about 13% of the total shorelines around the world. As a result of the vital location of coastal lagoons, they are usually of significant environmental and economic values.

Water exchange is one of the main factors that control the water quality and physical conditions in a coastal lagoon. Water exchange can be generated by different mechanisms which include tidal currents, wind-generated circulation, wave currents, river discharge, surface runoff, groundwater and seawater influx and outflux and evaporation. The importance of these mechanisms varies in every lagoon and changes over time. In general, tidal currents and river inflow are the dominating factors in most coastal lagoons. Tidal currents have a more significant influence on restricted and leaky lagoons than on choked lagoons as the long narrow inlet has a "filter effect". River inflow decreases the lagoon water salinity and may cause stratification in the lagoon. River discharge is also the main source of nutrient and pernicious substances input.

The Flommen Lagoon is located on the Falsterbo Peninsula in the southernmost part of Sweden (see Figure 1a and 1b). As a famous bird migration site and marine nature reserve, this area is of major environmental importance. It also has substantial economic value for its beautiful beaches and for having some of the most famous golf courses in Sweden. All these factors make it important to preserve the natural environment and minimize the negative impact of human activities.

Water discharged into the Flommen Lagoon from river and drainage is negligible. The water level in the sea together with the inlet channel and lagoon properties determine the water exchange between the lagoon and the sea, thus, the water quality in the lagoon. The Falsterbo Peninsula is a sandy deposit, implying that the coastal area is very dynamic, and the morphology is highly changeable, which affects the inlet properties and the water exchange. The inlet morphology is controlled by both natural processes and human activities which include the coastal sediment transport by waves and currents, the transport by the inlet exchange flow and regular dredging by the municipality. In order to ensure acceptable environmental conditions in the lagoon, it is crucial to estimate the water exchange, which includes the influence of sedimentation on inlet properties. A related aspect is flooding of the areas adjacent to the lagoon that is a potential problem for buildings and infrastructure. To remediate the flooding problem, a sluice gate was installed in the summer of 2016 to prevent inflow during high water levels in the sea; concerns have been raised that this gate has changed the sedimentation at the inlet, increased the tendency towards closure and reduced water exchange.

The overall aim of the study was to investigate the water exchange between the lagoon and the sea using different scenarios. In order to achieve this aim, the work included the following objectives:

- To understand the physical processes governing the water exchange at the Flommen lagoon, including the influence of inlet properties and the operation of the sluice gate.
- To develop and apply a mathematical model for quantifying the water exchange under different conditions with the focus on the influence of changes in the inlet properties.
- To assess the impact of the constructed gate on the water exchange and sedimentation at the inlet to arrive at a suitable strategy to operate the gate.
- To simulate the impact of constructing another inlet on the water exchange.

Physical characteristics of the Flommen Lagoon

In the northwest part of the Flommen Lagoon, there is one opening connecting the lagoon to the sea (inlet in Figure 1(b)). There is a sluice gate on the inlet channel since 2016. The lowest level of this gate is -0.35 m, meaning that when seawater level is below -0.35 m there is no inflow from the sea. And the gate is manually closed when sea level

Figure 1(a). *Location of the Falsterbo Peninsula.*

Figure 1(b). *The Flommen Lagoon along the west coast of the Falsterbo Peninsula and location of the inlet. Source: Google Earth.*

is above 0.5 m, which means no water exchange between the lagoon and the sea when sea level is above 0.5 m.

According to the Swedish Meteorological and Hydrological Institute (SMHI, 2019), the highest hourly rainfall in Falsterbo was 9.9 mm/h from 2010 to 2018, which can be neglected in this context. Therefore, the main water exchange is with the sea through the inlet. The normal tidal range in the adjacent Baltic Sea is typically less than 0.25 m (Hanson, 2007), so the influence of tide in this area is small; similarly, it is not very likely to be affected by tsunamis. Instead, it is the large-scale water movement in the Baltic Sea that determines the water level variation outside the Falsterbo Peninsula.

Water level in the Skanör Harbour and in the lagoon

The sea level variation in the adjacent sea is measured hourly at the Skanör Harbour by SMHI. The sea level data is presented according to RH2000 height system with measuring date and time. This data series records sea level variations since 17th February 1992. This data is used to represent the water level in the adjacent sea of the lagoon.

Longshore sediment transport and inlet morphology change

The coastline of Falsterbo Peninsula is very dynamic and has experienced very noticeable morphological changes both in historic times and during the last few decades, especially the west and south coasts.

Hanson and Larson (1993) applied a model to calculate the net longshore sediment transport rate in the Falsterbo Peninsula. According to them, the longshore sediment transport rate is 35,000 m^3/y along the west coast of Falsterbo, and 61,000 m^3/y along the southeast coast. Wang (2019) also computed the net longshore sediment transport rate along the west coast of Falsterbo. The computed value shows that the net longshore sediment transportation direction is from south to the north along the west coast, which is the same as the result from Hanson and Larson (1993). A larger volume of sediment transport is expected during winter, which is consistent with the wave conditions. According to Blomgren and Hanson (2000), this peninsula has not yet reached a final "equilibrium state" of its coastline.

The twist angle of the shoreline results in a larger sediment transport rate in the south of the inlet than in the north of the inlet. This will result in an accumulation of sand around the inlet mouth. When the water exchange rate between the lagoon and the sea is not high enough to remove the sand, a sandy spit will grow around the inlet and change the inlet geometry, which will further affect the water exchange rate.

Methodology

Background data encompasses bathymetric, topographic, geological, and meteorological conditions (e.g., such as wind speed and direction). Water level data from Skanör Harbour was compiled and analysed. Since the lagoon is rather long and has a complex shape, it was divided into five individual basins connected by channels with different fric-

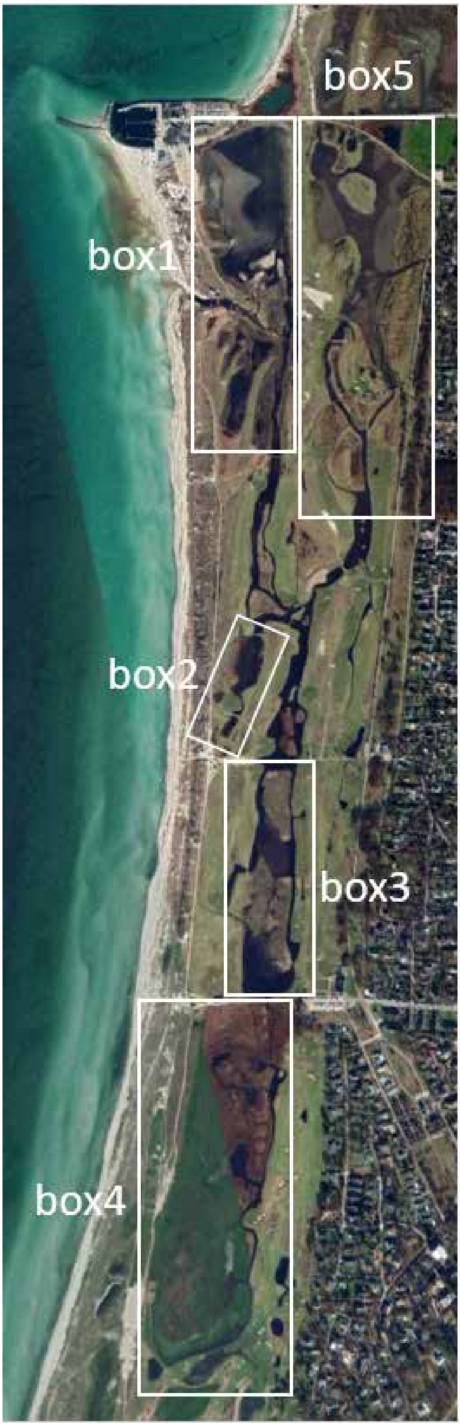


Figure 2. *Division of the lagoon.*

tional properties. The division can be seen in Figure 2. The water level is suspected to be different in different boxes. When water levels in all box are above a certain level, they can be merged. Similarly, when the water level drops below this level, the merged box can split into small boxes again

Two measuring campaigns were undertaken to determine the bathymetry of the lagoon and water levels at 5 locations in the lagoon simultaneously with the level in the harbour to be used for analysis and model calibration and validation since at present very limited information is available on this.

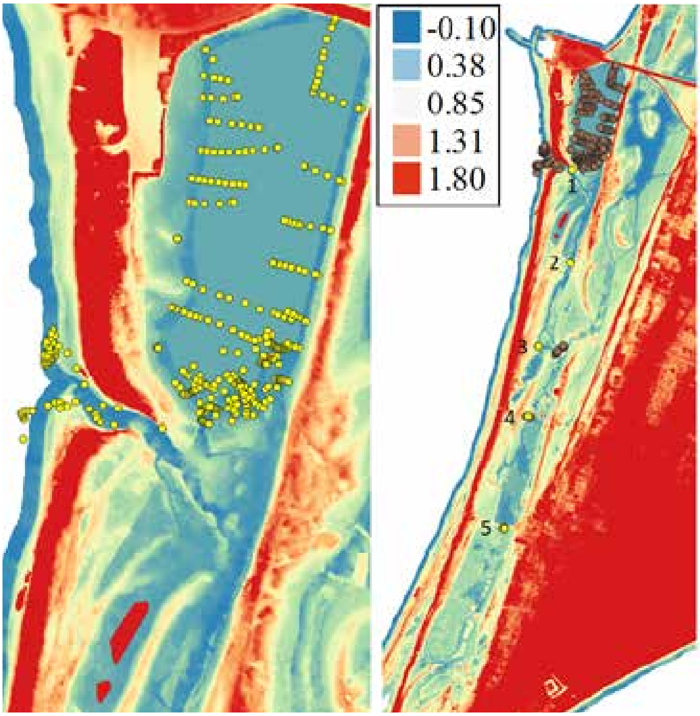


Figure 3. *Map showing topography measurement sites (yellow dots in the left figure) and water level variation measurement sites (yellow dots in the right figure).*

A mathematical model was developed to describe the response of the water level in the lagoon to changes in the sea level. The model was developed based on the classical work of Keulegan (1967). Model parameters were selected following estimates from the literature. Calibration and validation of the model were performed with measurement data on water level variation in the lagoon.

The validated model was employed to simulate the water exchange for different scenarios with regard to the inlet characteristics, determined based on the inlet morphology and its change. The influence of the gate to control the water exchange was also investigated.

Field measurements

A digital elevation model (DEM) of the study area was provided by the Swedish company, SWECO. This DEM, using RH2000 reference system, shows topography data with the elevation above 0.1 m. From this DEM, lagoon surface area of elevation from 0.1 m to 1.5 m can be obtained, with a step of 0.1 m. In order to complete the data with an elevation below 0.1 meters, one field campaign was performed on the 16th of April 2019. The morphology survey was completed using a Topcon GR-3 GPS in Network-RTK mode using the SWEPOS real-time network, with a nominal uncertainty of measurement of ±1-2 cm (95%) in horizontal and 2-3 cm (95%) in vertical. The reference system used was RH2000. Due to the time restriction, this measurement mainly focused on the northwest lagoon and the inlet (box 1 in Figure 2) because from the DEM the channels to other parts of the lagoon have rather a high bottom elevation than 0.1 m. Measurement points can be found in Figure 3 (left). After the topography survey, the results were imported into QGIS and combined with the DEM to analyse the relationship between the lagoon area and water level elevation in the lagoon. The surface area-elevation plot was then generated and used in the mathematical model.

With the aim of collecting water level variation in the lagoon, another measuring campaign was performed on the 6th of May 2019. The instrument used was a foldable wooden meterstick. The water level was measured at 5 different bridges (Figure 3, right) in the lagoon for five hours. A data series of water level variation was obtained. The water level variation measurement data was then calculated according to RH2000 reference system. The sea level variation during the measurement period was approximately 1 decimetre, correspondingly the water level changes in the lagoon was not very significant.

Renewal time and water exchange rate

The water quality in a lagoon is typically determined by the water exchange with the sea that occurs through the inlet. A wide range of parameters has been developed to quantify the water exchange and its characteristic time scales using terms such as "mixing", "retention", "renewal", "residence", and "flushing" time.

The basic idea behind these concepts is to estimate the time it takes to replace the water volume in the lagoon regarding the exchange flow through the inlet. For the simple case of a single lagoon with one inlet, the expression for the renewal time

$$T_R = \frac{V}{Q} \tag{1}$$

where V is the lagoon volume and Q is the exchange flow.

For the case of a tide generating this flow, the tidal prism (i.e., the volume ΔV_T that flows in and out during a tidal cycle) divided by the tidal period (T_T) will yield the mean Q to be used to estimate T_R. For this case, the renewal time becomes:

$$T_R = \frac{V}{\Delta V / T_T} \tag{2}$$

If the tide is not driving the water exchange, but more complex forcing conditions are controlling the exchange, which is the case for the Flommen lagoon system, Q needs to be determined in a different way. Based on a long-time period, the in- and outflow volume to the lagoon should to be the same; thus, the net volume change in the lagoon should be zero, which can be expressed through the flow according to:

$$\Delta V_{LT} = \int_0^{T_L} Q dt = 0 \tag{3}$$

where ΔV_{LT} is the change in the net volume of the lagoon over a long time period T_L and t is time.

If the in- and outflows are separated, then the above equation can be rewritten as:

$$\int_{Q>0} Q_P dt = \int_{Q<0} Q_N dt \tag{4}$$

where Q_p is inflow, for which $Q > 0$ and QN is outflow, for which $Q < 0$.

The proper flow to represent the exchange flow (Q_m) in the renewal time T would be either the integral on the right- or left-hand side in the above equation divided by the time period considered (T_L). Another option to determine Q_m is to simply integrate the absolute value of the flow and divide by $2T_L$ according to:

$$Q_m = \frac{1}{2T_L} \int_0^{T_L} |Q| dt \tag{5}$$

For a discrete time series involving N values on Q, this expression can be written:

$$Q_m = \frac{1}{2N} \sum_1^N |Q| \tag{6}$$

For the study area, a complication when applying the concept of renewal time is to select a representative lagoon volume V, since the surface area varies markedly with the elevation. However, if different conditions regarding inflow cross section are investigated and it is assumed that the representative V does not differ between these conditions, it is sufficient to calculate Q_m for the different options and compare these values. For two conditions (denoted 1 and 2), assuming that V does not vary too much between the two conditions, the definition of the renewal time yields:

$$\frac{d(A_L h_L)}{dt} = Q_I - Q_R \tag{7}$$

Thus, if the exchange flow doubles, then the renewal time is halved. In the model, Q is obtained by (denotes as before):

$$h_0 = h_L + k_f \frac{u_I |u_I|}{2g} \tag{8}$$

Mathematical modelling of water exchange in a lagoon – Keulegan model

Keulegan (1967) introduced a simple mathematical model for water exchange in a lagoon. In his model, the lagoon is represented by a single basin having one representative water level, tidal currents and river inflow are the only factors that influence water exchange and the lagoon is assumed well-mixed.

Water volume in the lagoon is controlled by water exchange between the sea and the lagoon and river inflow, so the water volume conservation equation is expressed as:

$$\frac{d(A_L h_L)}{dt} = Q_I - Q_R \tag{9}$$

where *t* is time, A_L is lagoon surface area, h_L is lagoon water level, Q_I is water inflow through the inlet ($Q_I > 0$ for water flow into the lagoon and $Q_I < 0$ for water flow out from the lagoon) and Q_R is river inflow.

The momentum conservation equation between the sea and the lagoon can be expressed as:

$$h_0 = h_L + k_f \frac{u_I |u_I|}{2g} \tag{10}$$

where h_0 is the sea water level, is the loss coefficient for the inlet, k_f is the acceleration due to gravity and *g* is the water velocity through the inlet (for flow into the lagoon and $u_I < 0$ for water flow out from the lagoon) calculated as:

$$u_I = \frac{Q_I}{A_I} \tag{11}$$

where A_I the is inlet cross-section area. The coefficient k_f is expressed by:

$$k_f = k_{en} + k_{ex} + \frac{f \cdot L}{4R} \tag{12}$$

where k_{en} is the entrance energy loss coefficient, k_{ex} is the exit energy loss coefficient, *f* is the Darcy - Weisbach friction term, *L* is the inlet length and *R* is the inlet hydraulic radius. Here, *f* is expressed as:

$$f = \frac{116n^2}{R^{1/3}} \tag{13}$$

where n is the Manning's roughness coefficient. *R* calculated as:

$$R = \frac{A_I}{P} = \frac{A_I}{B+2d} \tag{14}$$

where *P* is the average wetted parameter, *B* is the width of the inlet and *d* is the depth of the inlet.

Mathematical modelling of water exchange in the Flommen Lagoon

Based on Keulegan model, a mathematic model was developed using MATLAB to simulate the water exchange between the Flommen lagoon and the sea.

Water exchange between the Flommen lagoon and the sea was determined to be the only component of water exchange in this model. The shape of the channel cross-section is usually irregular. To simplify the modelling process, the channel cross-section is assumed to be rectangular. At present, the sluice gate is closed when sea level is above 0.5 m to avoid flooding in the golf course. The lowest level of the gate is -0.35 m. Thus, there is no water inflow from the sea when the sea level is below -0.35 m and no water exchange between the sea and the lagoon when the sea level is above 0.5 m. Assume negligible frictional effect is caused by the sluice gate. When modelling with the scenario where the gate does not exist, the lowest level of the inlet channel was kept at -0.35 m, i.e., when sea level is below -0.35 m, there is no inflow from the sea.

As the Flommen lagoon is very long and has a complex shape, it was divided into five individual basins connected by channels with different frictional properties. Assume quasi-steady flow and uniform response in each box. In the model used in this study, when the water level in the lagoon changes, merge or separation of boxes may happen. Thus, the inflow and outflow of the same box may be different, so the governing equations used in Keulegan model were developed accordingly.

The governing equations were solved using a numerical approach by MATLAB code. At first, an explicit method was introduced to solve new water levels based on the conditions displaced $\Delta t/2$ in time (Δt is the calculation time step). However, when using the explicit method, in case the lagoon starts to fill up again after being dry, i.e., the surface area starts to increase from 0, numerical problems may arise. This means, due to the limitation of the DEM, the next surface area that can be examined after the minimum area is a quite large value. Therefore, during the first time step after a box has dried, the surface area will experience a rapid increase from 0 which will introduce instability in the model. To solve this problem, a minimum area of the lagoon was assumed with regards to the DEM as a third solution. When the elevation in a box drops below h_m, the surface area is assumed to be constant to the minimum area. Thus, in the model, the minimum area method is used in combination with equations from the explicit method.

Parameters and input

This model used sea-level observation data from SMHI as input data. In total, the observation records hourly sea level variation from February 1992 to the latest day. In the model, 10 days data (1st-10th January 2019) was chosen to representatively simulate the water exchange. Model parameters were selected following estimates from Coastal Engineering Manual (2002). The time step was chosen to be 10 seconds in order to get an accurate and stable model output. Thus, the input data was interpolated accordingly.

Calibration and validation

Calibration and validation of the model were performed with measurement data on water level variation in the lagoon.

The loss coefficient (k_f) of the lagoon inlet is the key parameter for calibration because the inlet morphology change is the dominating factor for the water exchange in this model. According to the calibration plots, when k_{en} =0.05 and n=0.016, the simulation results showed the best fits with the measured data point. After calibration, the model validation was performed with calibrated parameter values and the same measurement data. After calibration, the model shows a good ability to simulate the water level variation in the lagoon even though at some data point time or phase lag between measured data and simulation values was observed.

Results

Inlet geometry

The impact of the inlet (between the lagoon and the sea) morphology change and the spit growth around the inlet is studied by varying the inlet cross-section area in the model. Sea level observation data from SMHI of January 1st, 2019 to January 10th, 2019 was selected as input. The cross-section area was halved and doubled.

As is shown in Figure 4 and 5, the cross-section area changing has no significant influence on the water level in the lagoon, but it affects the water exchange rate. Larger cross-section area results in larger water exchange. Half the cross-section area decreases the gross exchange rate of 39.2% and double cross-section area increases the gross exchange rate of 15.3%.

Effect of the sluice gate

In this section, the effect of the sluice gate is discussed regarding the water exchange rate and extreme events. As mentioned before, the sluice gate on the lagoon inlet is closed when the water level

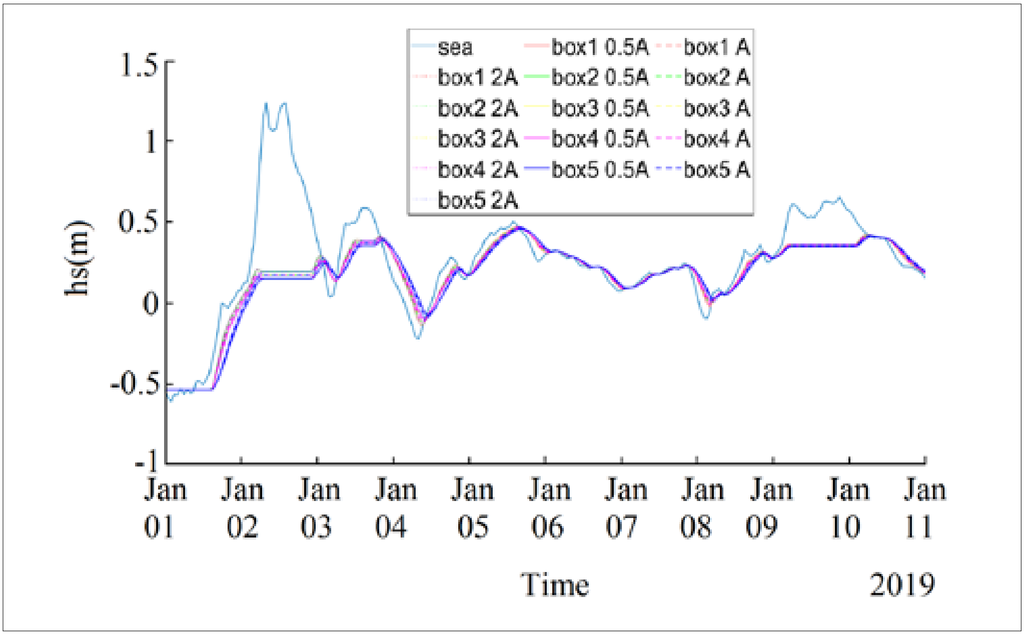


Figure 4. *Simulation results of water level in the lagoon with data from 1st-10th January 2019 (A is the lagoon inlet cross-section area based on inlet geometry from the DEM.)*

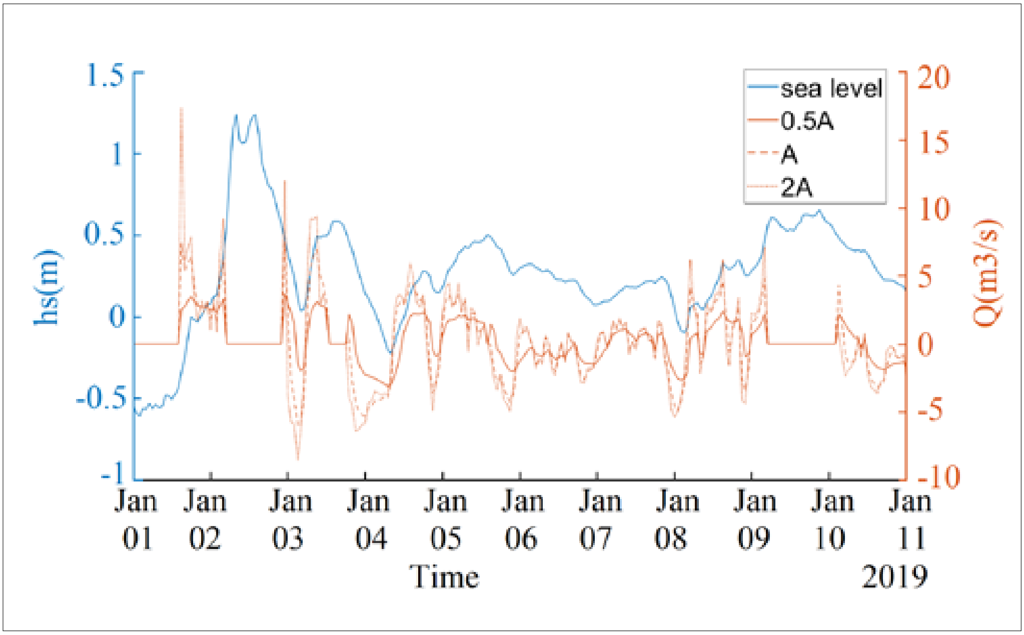


Figure 5. *Simulation results of water exchange rate with data from 1st-10th January 2019. (A is the lagoon inlet cross-section area based on inlet geometry from the DEM.)*

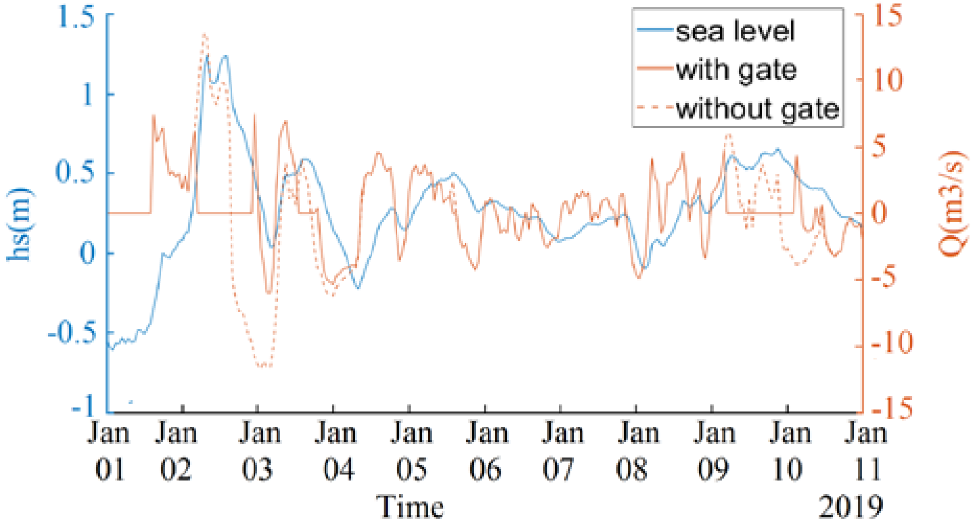


Figure 6. *Water exchange rate with and without the sluice gate. Generated from 10 days data of 1st to 10th January, 2019. Q is possitive when water flows into the lagoon.*

in the sea is above 0.5 m and the lowest level of the gate is -0.35 m.

Water exchange rate

The same data series as in chapter 3.1 was selected to representatively simulate the water exchange between the lagoon and the sea. The results are shown in Figure 6.

In general, without the sluice gate, larger inflow and outflow are expected. This will increase the amount of water exchanged between the lagoon and the sea. Without the sluice gate, gross water exchange rate is 31.6% larger than with the gate under operation. Average net exchange rate in the modelling results is not zero while based on a longer time period, no water accumulation is expected.

Extreme events

There is very limited data record about extreme events in Falsterbo. Therefore, a sinusoidal wave with a large amplitude was used to simulate the effect of the gate when an extreme event happens.

According to Fredriksson et. al (2016), an extreme event with a 100-year return period is calculated to exceed 1.8 m (reference system: RH2000). This value is used in this section to simulate the effect of the sluice gate. The results are shown in Figure 7 and 8.

The sinusoidal wave can be expressed as $hs=80*sin(w*x)+110$; with a period of 12 hours. This will generate a wave with height above 1.8 m for about 2 hours continuously. With the gate being operated at t=0, the water level in the lagoon will gradually increase but remain below 0.5 m. In this situation, no severe damaged will be caused in the golf courses and the adjacent area.

Without the sluice gate, the water level in the lagoon will oscillate between 0.9 to 1.2 m during this extreme event. The water level in the lagoon will exceed 1.1 m for about 4 hours. From the DEM, part of the coastline will be flooded, but

Figure 7. *Lagoon water level and surface area changes during a 100-year return period event, with gate closed at t=0.*

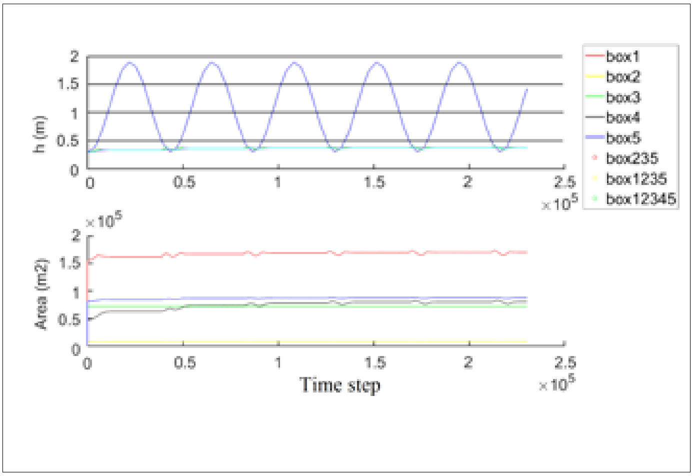
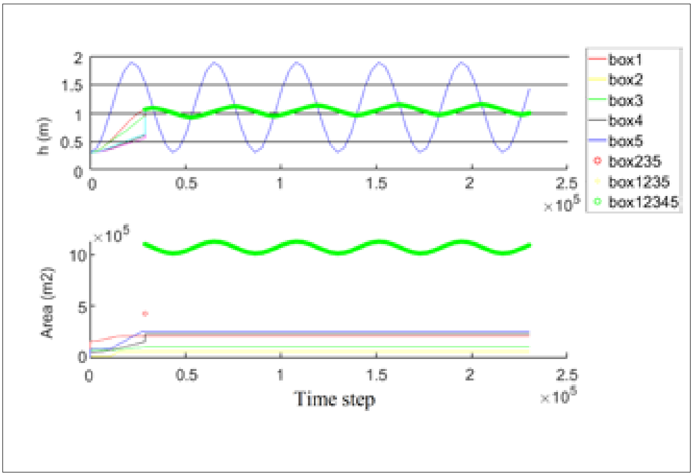


Figure 8. *Simulation of lagoon water level and surface area changes during a 100-year event, without the sluice gate.*



the lagoon still shows a good ability to protect the adjacent inland area from flooding. However, the golf courses will be flooded in this situation.

A second inlet

During years there has always been a discussion about opening a second inlet to the Flommen Lagoon. One suggestion is to dig another inlet between box 1 and the ocean. In this section, the effect of having a second inlet was simulated with data series as in chapter 3.1.

The second inlet was assumed to have the same properties as the original inlet, and they both have sluice gates. This will add another Q_I for box 1 in Eq. 1. In the model, this has the same effect as double the inlet cross-section area of inlet 1.

According to the simulation output (see Figure 9 and 10), with the same incoming wave, a second inlet will result in a slightly higher lagoon water level than with one inlet, and a faster response to sea level variation and a higher water level in the lagoon when the gate is closed.

Simulation results of water exchange are shown in Figure 11. When the gate is closed, the volume of water outflow and inflow are significantly higher with two inlets than with one inlet. When the gate is open, water exchange rates are rather similar to one or two inlets. For this data period, average

Figure 9. *Lagoon water level simulation results with one inlet, with 10-day sea level variation data.*

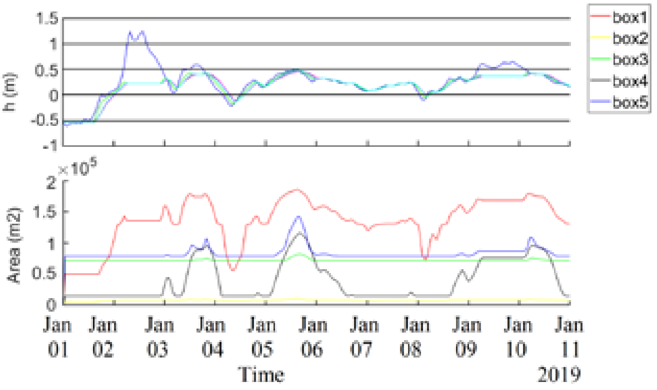


Figure 10. *Lagoon water level simulation results with two inlets. Generated from 10 days data of 1st to 10th January, 2019.*

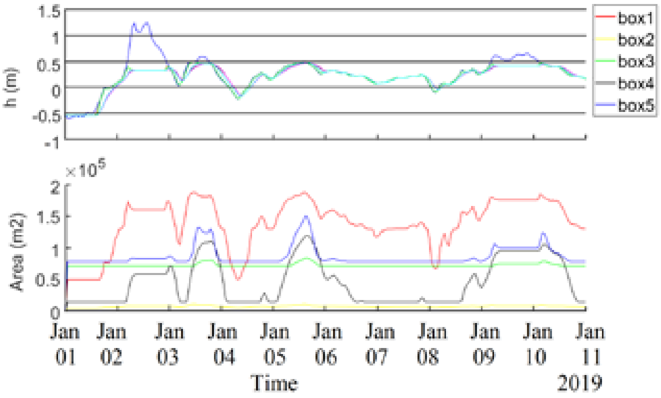
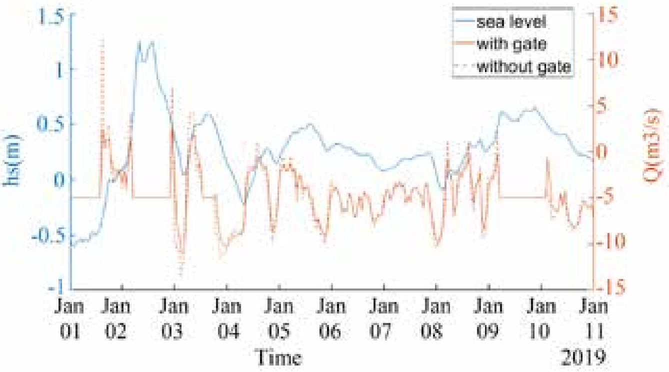


Figure 11. *Water exchange rate simulation results with one inlet and two inlets.*



gross water exchange rate with 2 inlets is 15.3% higher than with one inlet.

Limitations

Due to its complex shape, the Flommen Lagoon was divided into five boxes to model the responds of lagoon water level to sea level. Water level in each box was assumed to be the same at every point in this simplified model. However, during the second field measurement, it was noticed that water level is slightly different at different location in one box. In the future the model can be improved by dividing the lagoon into finer mesh grids if the flow direction can be better defined.

Besides, there is no available data of the water level variation in the lagoon and the bathymetric data from the DEM is rather primitive. Due to the time limitation, only basmetric data of one box and water level variation data for a few hours were recorded during the field campaigns. The model can be better calibrated and validated if more data is gathered in the future.

The influence of groundwater infiltration was neglected in the model whereas it was noticed that in the southern part of the lagoon groundwater infiltration has some influences on the water salinity. This can be studied in the future if more information about groundwater infiltration in this area is collected.

Conclusions

The aim of this study was to study the physical processes governing the water exchange at the Flommen lagoon. These physical processes studied here include the regular dredging of the inlet channel, longshore sediment transport and the operation of the sluice gate. This was achieved by qualitatively analysing the influence of sediment transport on inlet geometry, numerically modelling with different scenarios and quantitively analysing the effects of the inlet geometry and the sluice gate on lagoon water level variation and water exchange rate. Furthermore, the possible influence of constructing a second opening between the sea and the lagoon was also studied.

Inlet geometry has no significant influence on the water level in the lagoon, but it will significantly influence the water exchange rate. Based on the simulation result of ten days sea level variation data, halve the cross-section area decreases the gross water exchange rate by 39.2% and double cross-section area increases it by 15.3%.

The sluice gate on the current inlet generates smaller water exchange than without the gate. Without the sluice gate, gross water exchange rate is 31.6% larger than with the gate under operation. The sluice gate also deceases the threaten of flooding in adjacent areas when an extreme event happens. Without the gate, the golf courses around the lagoon will be totally flooded if an event with a return period of 100-year happens.

A second inlet with the same characteristics as the current one has a similar influence to double the cross-section area. With two inlets, the lagoon water level was modelled to be slightly higher than with one inlet. For the 10-day sea level variation data period, average gross water exchange rate with 2 inlets was modelled to be 15.3% higher than with one inlet.

References

Blomgren, S. and Hanson, H. (2000) Coastal geomorphology at the Falsterbo Peninsula, Southern Sweden. Journal of Coastal Research, 16(1), 15-25.

Engineers, U.A.C.O. (2002) Coastal Engineering Manual. Engineer Manual 1110-2-1100. US Army Corps of Engineers, Washington, DC.

Fredriksson, C., Tajvidi, N., Hanson, H. and Larson, M. (2016) Statistical Analysis of extreme sea water levels at the Falsterbo peninsula, South Sweden. VATTEN—Journal of Water Management and Research, 72, pp.129-42.

Hanson, H. (2007) Falsterbo Peninsula (Sweden). [pdf]. Available at: <http://www.eurosion.org/shoreline/54falsterbo.html> [Accessed 20 April 2019].

Hanson, H. and Larson, M. (1993) Sandtransport och Kustutveckling vid Skanör/Falsterbo. Lund: Lund University. (In Swedish)

Keulegan, G.H. (1967) Tidal Flow in Entrances Water-Level Fluctuations of Basins in Communications with Seas. Technical Bulletin No. 14, Committee on Tidal Hydraulics, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kjerfve, B. (1994) Coastal lagoons. In Elsevier oceanography series (Vol. 60, pp. 1-8). Elsevier.

Wang, S. (2019) Modelling Water Exchange in the Flommen Lagoon, South Sweden. TVVR19/5008.