Groundwater flow and salinity distribution near a tidal gully in the Zwin remnant, Belgium

Gert-Jan Devriese[1], Jasper Claus[1] and Luc Lebbe[1]
[1]Department of Geology and Soil Science, Ghent University, Ghent, Belgium

ABSTRACT

To understand the hydrogeological processes in tidal flats as the Zwin remnant, the hydraulic heads, the groundwater flow and the salinity distribution near a side branch of the main gully were studied. This was done by collecting hydraulic heads for four months using automatic data loggers, by collecting soil and groundwater samples and by executing electromagnetic induction measurements in six boreholes which were located in a line perpendicular to the coastline near a side branch of the main gully in the Zwin remnant. The collected data were then implemented in a 2D density dependent groundwater model to get insights in the hydrogeological processes. The observations showed that the gullies and their vicinities are very dynamic environments due to the influence of both the tides and the wind direction and wind speed. Both factors induce significant head fluctuations which result in a variable groundwater flow and salinity distribution. The resulting base groundwater flow varies due to longer period variations such as neap and spring tide with a supplementary effect due to the variation in wind direction and speed. Closer to the gully additional variations are present due to shorter semidiurnal tidal cycles. According to the 2D density depended groundwater model, the salinity distribution is less sensitive to the variable hydraulic heads and forms a typical salinity distribution with higher salt concentrations under the gully and intertidal areas and lower salt concentrations under the supratidal areas. Next to this, a typical fresh water tongue arises from the supratidal area towards the gully creating a brackish water lens under the intertidal area.

INTRODUCTION

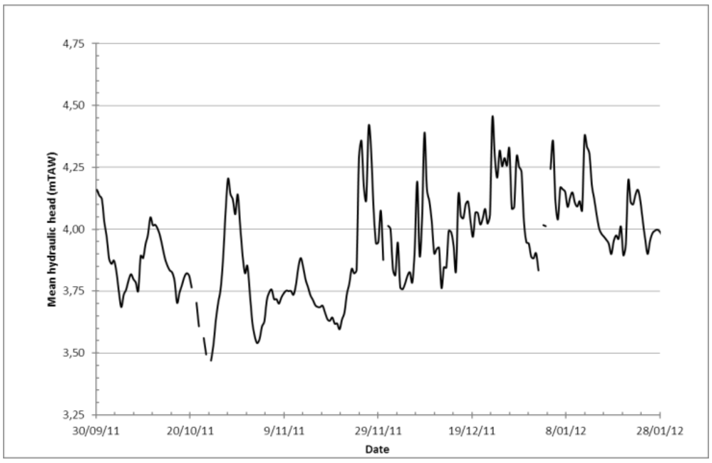
The Zwin natural reserve is an important mudflat and salt marsh area near the Belgian - Dutch border. It consists of a narrow dune ridge which is breached over a length of ca. 250 meters. Through this inlet the seawater can enter the hinterland through a branched network of (narrow) gullies forming a so-called ‘slufter’. In the middle ages the Zwin formed the main entrance to the city of Bruges but since, the Zwin has been silting up due to the reclamation of surrounding lands and, since the 1980’s, due to the sand replenishment at the beaches of Cadzand and Knokke-Heist.

In the past, the groundwater flow near tidal gully’s has been studied by numerous researchers, and although this mostly happened from an ecohydrologic angle and without the incorporation of the salinity distribution insights have been gained about the general groundwater flow near tidal gully’s. Some other researchers (e.g. Mao et al. 2006; Werner and Lockington 2006; Lenkopane et al. 2009) did incorporate the salinity distribution while studying the groundwater flow near tidal gully’s leading to new insights in the contribution of the topography and the tidal fluctuations in the distribution of salt/brackish water near tidal gully’s. We believe however that not all contributing factors have been fully investigated so far. From our observations at the Zwin nature reserve it seems that both the wind direction and wind speed can have a significant influence on the hydraulic heads at different distances and therefore influence the groundwater flow and salinity distribution.

METHODS

For this study six shallow observation wells were placed perpendicular to the coastline near a side branch of the main gully. In these observation wells, hydraulic heads and electromagnetic induction measurements were executed as well as water samples were collected. The hydraulic heads were measured with automatic data loggers for four months and coupled to the registered weather parameters from the same period in order to obtain insights in the relation between both parameters and the periodical inundations in parts of the Zwin remnant. The executed electromagnetic induction measurements allowed us to derive the salinity distribution along a vertical cross-section along the observation wells. Finally, some soil samples were taken to determine the soil characteristics using ROSETTA (Schaap et al. 2001). All collected data were then implemented in a 2D density dependent groundwater flow model. For this model the MOCDENS3D code (Lebbe and Oude Essink 1999) was used. Visual MOCDENS3D (Vandenbohede 2007) was used as a postprocessor.

RESULTS



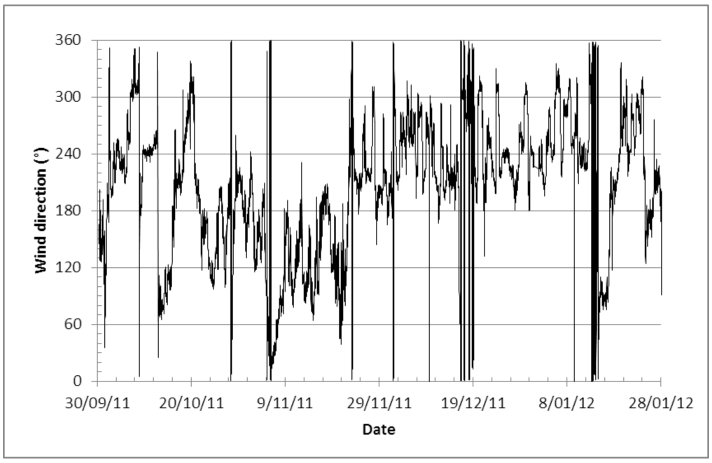


Figure 1 (upper): Mean hydraulic heads of observation well 1.
Figure 2 (lower): Registered wind direction at Zeebrugge.

From the analysis of the mean hydraulic heads of the tidal cycles two dominantly governing processes could be distinguished. The first one, observed during the whole observation period are the tides. During periods of full and new moon the observed hydraulic heads at all observation wells are clearly higher than at first and third quarter. The second process, which is (mainly) observed from 22 November 2011 until the end of the observations, is due the change in the dominating wind direction (Figure 2).

During longer periods of mainly westerly winds the average hydraulic head in the area will rise with up to 50 centimeters. The reason for this uniform rise lies in the fact that the wind forces an extra amount of water into the Zwin during high tide while it hampers water to flow out during low tide. Due to the morphology of the coast before the Zwin remnant parts of the wind generated surface waves are forced into the Zwin inlet during periods of mainly westerly winds therefore strengthening the inflow during high tide while diminishing the outflow during low tide. The relation between the wind direction and the registered hydraulic heads can be seen when comparing Figure 1 and Figure 2 from 22 November 2011 on. With the shift of the wind direction to 210-300° the average hydraulic head in observation well 1 rises with ca. 25-30 centimeters.

The frequency analysis of the observed hydraulic heads showed that the lunisolar synodic fortnightly signal is dominant in the study area with smaller contributions of the principal lunar semidiurnal and smaller solar elliptic signal. These signals have respectively a period of 14.765, 0.518 and 0.499 days. The first one is, together with the wind direction and speed, responsible for the base groundwater flow in the area, while the later ones are responsible for the supplementary variations closer to the gully.

Furthermore the electromagnetic induction measurements in the six observations wells showed that the groundwater reservoir is mainly filled with very brackish water with the exception of the upper few meters. Here, two areas can be distinguished. In the first one, which is located closest to the gully, periodical inundations occur leading to the presence of moderately brackish water in the upper few meters. In the area further away from the gully, the elevation is higher causing it to be inundated only very rarely. In this area brackish to moderately brackish water occurs above the very brackish water.

All collected data were implemented in a 2D density dependent groundwater flow model. For this model, a good fit was obtained with the observed hydraulic heads. The model showed that the hydraulic heads vary greatly within the considered period. Resulting in a clear outflow of groundwater to the gully at periods of low tides and inundations and infiltration at periods of high tide. The initial saltwater concentrations for the model were derived from the EM39 measurements as well as from earlier research by Lebbe and Courtens (2011). Despite the short modeling period (ca. 4 months) some changes in the saltwater distribution could be observed. Due to the mainly draining character of the gully the moderately salt water which was initially present under the gully has almost completely moved towards the gully. Besides this a typical water tongue has developed from the higher non (regular) inundated area towards the gully. This water tongue is similar to the one found under shores with gentle slopes and important tidal fluctuations before dunes with an important fresh groundwater flow towards the sea such as in De Panne (Vandenbohede and Lebbe, 2006).

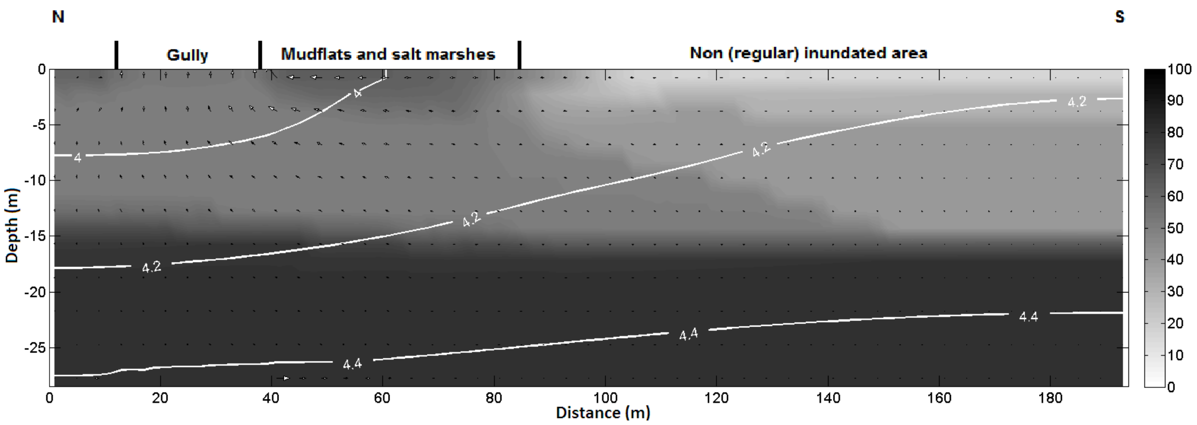


Figure 3: Modelled 2D cross-section through the observation wells. (Colour scale gives the saltwater percentages, black: 100% salt relative to North Sea water, white: 0% salt relative to North Sea water, white lines represent the contourlines of the hydraulic heads.)

CONCLUSIONS

The hydraulic heads at the Zwin remnant are not only governed by the variation in tides but also due to the wind direction and, to a lesser extent, by the wind speed. During longer periods of mainly westerly winds the hydraulic heads in the area can rise with up to 50 centimeters. These changes are due to the morphology of the coast before the Zwin inlet. During periods of mainly westerly winds the wind forces an extra amount of water into the Zwin whereas it hampers the outflow during low tide. During longer periods without, or with very few, westerly winds the inverse occurs. The wind speed strengthens or weakens this process.

The conducted groundwater model allowed the simulation of the groundwater flow in the vicinity of the gully. The heads in the phreatic aquifer showed complex fluctuations which are induced by the water level fluctuations in the gullies and by the periodical inundations of parts of the adjacent mudflats and salt marshes. The head fluctuations result in a groundwater flow which varies strongly in time. The base groundwater flow depends mainly on the longer period variation in spring and neap tide with a supplementary effect due to the prevailing wind direction. This supplementary effect is caused by the drop in the water levels in the gully and the vicinity of the gully in periods where the prevailing winds differs from the dominant (south) westerly winds. Closer to the gully additional variations in the groundwater flow are visible due to the shorter semidiurnal tidal cycles.

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Contact Information: Gert-Jan Devriese, Ghent University, Department of Geology and Soil Science, Research Unit Groundwater Modeling, Krijgslaan 281, S8, 9000 Gent, Belgium. Phone: 09 2644664, Email: gertjan.devriese@ugent.be