Interaction of the tides and the shore on the Belgian western coast

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Abstract — The influence of tides on the fresh water heads and fresh/salt water distribution are studied on a sloping shore. The shore and dunes of the Westhoek nature reserve along the French Belgian border are used as a case study. This is done using fresh water head observations in a number of wells and geophysical borehole measurements to study the fresh/salt water distribution. A peculiar fresh/salt water distribution is observed under the shore with a saltwater lens present above fresh water. Fresh/salt water distribution is determined by mean long term hydraulic heads on the shore, flow of fresh water from the dunes and aquifer characteristics. Tides have no immediate effect. The tidal wave, generated on the seabed and on the shore, propagates downward as well as laterally in the aquifer. Its characteristics are discussed.

Index Terms — Belgium, fresh/salt water distribution, modelling, tides

I. Introduction

The interaction between coastal groundwater and seawater is of a unique and dynamical nature. It is the place where fresh and saline water meet and where there is a discharge of fresh groundwater in the marine environment. This distribution of fresh and salt water and groundwater flow in coastal areas can be relatively complex. In the simplest case, there is a salt water wedge under a fresh water lens. Fresh water discharges in the marine environment at the border of the fresh water lens. Under the shore of the western Belgian coastal plain, the distribution between fresh and salt water is more complex, a salt water lens is present above fresh water.

The groundwater flow in many coastal environments is strongly influenced by the tides. The direction of groundwater flow and the location of recharge and discharge zones change constantly during a tidal period. It is usually assumed in studies that the coastal boundary is equivalent to mean sea level ignoring the influence of tides. This results in a simplification of the groundwater flow in coastal aquifers and of the coastal hydrology. The aim of this paper is to study the influence of the tides on groundwater flow, hydraulic heads and fresh/salt water distribution in the coastal aquifer of the western part of the Belgian coastal plain.

II. Study area

The study area is situated in the nature reserve Westhoek, situated along the French-Belgian border (figure 1). The Westhoek is a dune area of about 340 ha in size. It is part of one of the last unfragmented dune areas along the Belgian coast. In the south it is bordered by a low lying hinterland, a so called polder. The Belgian dunes can be divided into young dunes, formed between the 8th century and the present and older dunes formed between 2000 and 5000 years ago. The young dunes have lime-rich, basic or neutral soils resulting in a unique flora. East of the nature reserve, a water catchment is present.

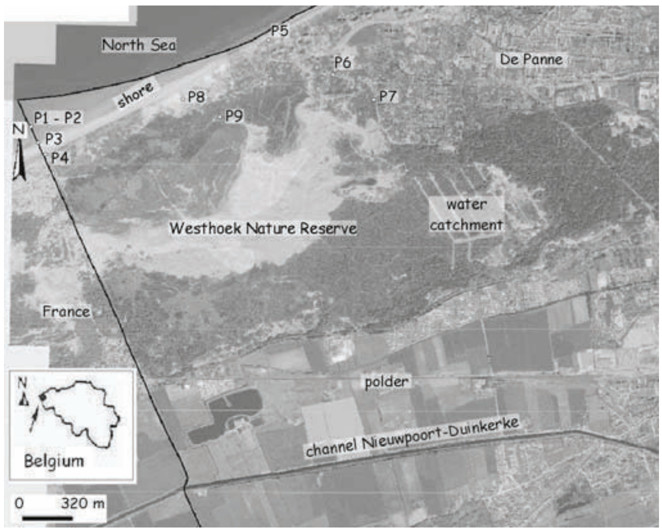

Fig. 1. Location of the Westhoek nature reserve with indication of the different observation wells used in this study.

The Westhoek dunes are part of the north-west European coastal dunes, forming a long, narrow dune strip from Calais (France) to the north of Denmark. The shore before the dunes is one of the widest (300-450) in Belgium. It is a tidal dominated sandy runnel and ridge type of shore. The mean slope of the shore is 1.1% and it is covered by semi-diurnal tides. The difference between the high and low water is at spring tide approximately 5 m and at neap tide 3 m. The sea level reaches its highest point at +5 mTAW and its lowest

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point at 0 mTAW. The mTAW is the Belgian reference level, about 2.3 m below mean sea level. Because the low angle dip of the shore and the relatively large sea level amplitude, the distance between the mean low water and high water line on the shore is large, about 300 to 450 m. The distance between the dunes and the high water line is approximately 50 to 100 m. This part of the shore is only inundated during high sea levels. These characteristics of the shore are very important to better understand fresh/salt water distribution and groundwater flow.

The lower part of the phreatic dune aquifer consists of medium to coarse medium sands of Eemian age. Fine medium sands form the larger part of the aquifer. Lenses of silty or clayey fine sand can occur. The top of the aquifer consists of medium sands. The substratum of this thirty meter thick phreatic aquifer is formed by the clay of the Kortrijk Formation, Ieper group. It is of Eocene age and is considered as an impermeable boundary in this study.

Fig. 2. View of the shore before the Westhoek nature reserve looking towards De Panne. Notice the wide runnel and ridge type of shore, part of the dune belt is visible at the right hand side.

I. FRESH/SALT WATER DISTRIBUTION

In the period 1974 to 1978 a first detailed hydrogeological study was performed in the dune area [1]. One of the results was the indication of salt water above fresh water on the shore in the area of the high water mark. Fresh/salt water distribution was then further studied using geophysical borehole measurements (long normal resistivity measurements) in a number of drillings on the shore and in the dunes [2]. Figure 3 gives a cross-section through the aquifer. It is part of a larger cross-section from the shore to the polder [3].

Fresh water under the form of a fresh water lens is present in the dunes. This fresh water is a $CaHCO_3\varnothing$ water type according to the classification of Stuyfzand [4]. Under the shore, a salt water lens is present above a fresh water tongue, the latter stretching out from the dunes towards the sea. The salt water is of a $NaCl\varnothing$ water type. A $CaHCO_3\varnothing$ water type is present in the proximal part of the fresh water tongue whereas this becomes a fresh to slightly brackish $NaCl\varnothing$ water type in the distal part. The distribution is the result of recent geological evolution.

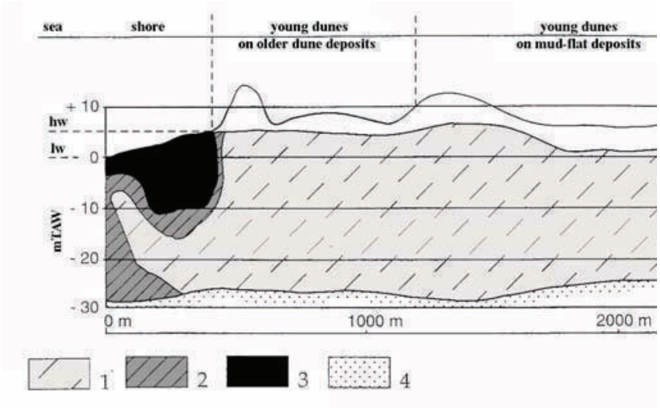

Fig. 3. Distribution of fresh (l), brackish (2) and saline (3) water in the dunes of the Westhoek nature reserve. A clay layer (4) forms the lower boundary of the aquifer.

The current dune belt started to form from the 7th or 8th century onwards. Before, the aquifer was mainly filled with salt water but from then on fresh water started to recharge the dune aquifer and replaced the older salt water. This recharge water forms a fresh water lens under the dunes. A water divide is present in the dunes which dictates the flow of fresh water. Water which recharges south of the water divide flows towards the polder. Water which recharges north of the water divide flows towards the sea.

The occurrence of salt water above fresh water under the shores is due to a combination of different factors [5]. First of all, a relatively large sloping shore is needed covered by semi-diurnal tides. This makes that during high water, salt water can infiltrates on the back shore. This salt water flows towards the fore shore where it discharges mainly during low tide. This cycle of recharge on the back shore and discharge on the fore shore forms a shallow groundwater cycle which results in the observed salt water lens. This salt water lens exists above the fresh water flowing from the dunes towards the sea. Fresh water discharges around the low water line. This inverse density distribution is in a dynamical equilibrium [6]. Similar density distributions have also been studied in the laboratory with sand tank experiments [7] but where first observed in the Belgian coastal plain [2].

The interaction of the tidally fluctuating sea level and the sloping shore thus brings about the inverse density distribution under the shore. There is a mean shallow groundwater flow of salt water from the back shore towards the fore shore. This can also be appreciated by calculating the mean fresh water head on the shore for shallow observation wells. Figure 4 gives for instance the fluctuation of the fresh water head in function of time on the low water line, close to the high water line and midway between the high and low water line. On the low water line, the fluctuation of the fresh water head almost equals the sea level fluctuation, corrected for the density of the pore water. The time average fresh water head on this location thus equals the mean sea level of 2.36 mTAW corrected for the density of sea water. An observation well placed close to the high water mark is only inundated by the sea during high tide. Then the fresh water head equals the sea level fluctuation corrected for the density of the pore water. When the place is not inundated by the sea, the fresh water is slightly less than the elevation head and the slowly decrease of the water table is measured. This decrease is very slow due to the small average interstitial velocity of the groundwater and the large storage coefficient near the water table. The time averaged fresh water head is 3.39 mTAW in the example. This is much higher than the mean sea level. For an observation well placed midway between the high and low water mark, the same reasoning can be applied. When not inundated the fresh water head is slightly less than the elevation head and decreases slowly. The fluctuation of the sea level corrected for the density of the pore water is measured when inundated. This results in a time averaged fresh water head of 2.99 mTAW in the example of figure 4. Thus, there is an average hydraulic gradient on the shore which is the result of the interaction of the tidally fluctuating sea level and the sloping shore. This gradient drives the shallow salt water flow resulting in the salt water lens.

Notice that the fluctuation of the fresh water head with time for a shallow observation well on the shore is asymmetrical. There is a steeper rise and slower descent of the fresh water head. This is the so-called non-linear filtering effect of a sloping shore.

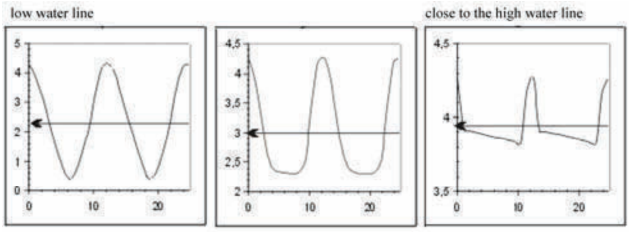

Fig. 4. Fluctuation of the fresh water head (in mTAW) in function of time (h) on the low water line (left), close the high water line (right) and midway between the high and low water mark (middle) on the shore. The time averaged fresh water head of these fluctuations is indicated by an arrow.

The geometry of the salt water lens depends further also on the flow of fresh water from the dunes, aquifer characteristics and tidal amplitude [5]. The less fresh water which flows from the dunes towards the sea, the deeper the salt water lens. This was also observed by the borehole measurements [2]. Figure 3 is the situation observed along the French-Belgian border. More northwards, the fresh water tongue is far less pronounced and a deeper salt water lens occurs. This is due to the present of a water catchment which decreases the flow of fresh water towards the dunes. Modelling showed that if a semi-permeable layer is present just under the shore, the salt water lens is less deep [5]. Modelling also showed that if the width of the shore is smaller, a larger salt water lens is present. This is because the mean hydraulic gradient on the shore is larger. A larger amount of salt water recharges in this situation. If the tidal range becomes smaller, also the salt water lens becomes smaller. The gradient on the shore becomes smaller and less salt water infiltrates.

II. Fresh Water Head Observations

Fresh water head observations were made in the observation wells indicated in figure 1. These are given in figures 5 and 6. P1 and P4 are shallow wells, P2 and P3 have screens located at the base of the phreatic aquifer. The fluctuations in these four wells are highly asymmetric. They are characterized by two abrupt changes of the time derivative of the fresh water head during one tidal period. This is due to the interaction between the tidally changing sea level and the gently sloping shore (non-linear filtering effect) as already discussed. This asymmetry indicates that the shore is filling more easily than it can drain. P2 is located on the same location as P1 but in the lower part of the aquifer. The mean fresh water head in P2 is about 0.7 m higher than in P1. Here the time derivative of the fresh water head follows a more continuous course. The fluctuation of the heads, however, remain typical asymmetric with a slow lowering of the head and a quicker rising. The difference between maximum and minimum is larger in P1 than in P2. P3 shows the same trend as P2 but the difference between maximum and minimum is smaller. Almost no fluctuation is observed in P4 which is situated marginally landwards of the shore-dune transition. This is due to the large storage coefficient near the water table S_0 (being 0.165, [9]). S_0 is the amount of water which is released from storage per unit surface for a lowering of the water table of 1 meter. A large S_0, like is the case here, means that a large amount of water must be released or taken into storage by even small water table fluctuations. This, however, does not happen instantaneous but takes some time depending on the hydraulic conductivity and hydraulic resistance. Long term fluctuations like for instance monthly recharge variations have their effect on the water table position. Short term fluctuations like tides have no effect since the sediments can not release or take into storage large amounts of water over such a small timescale, hence the water table remains fixed and the tidal wave is attenuated. Observations in P1 to P4 show that the amplitude decreases with depth under the shore and decreases also towards the dunes. Note that the lags are minimal.

P5 to P7 are observation wells situated in the dunes about 2 kilometres northeast of the French-Belgian border. The locations are indicated in figure 1. This is close to the water catchment present in the dunes and the observed heads are influenced by it. Therefore, not the absolute values are shown in figure 5 but their fluctuations around their average. All three wells have screens in the lower part of the aquifer and show thus the propagation of the tidal wave in the dunes. P5 is situated, as P4, in the vicinity of the shore-dune transition. In contrast with P4, P5 shows an important fluctuation. The amplitude of the fresh water heads decreases farther in the dunes. In contrast to observation wells placed under the shore, there is also an important lag.

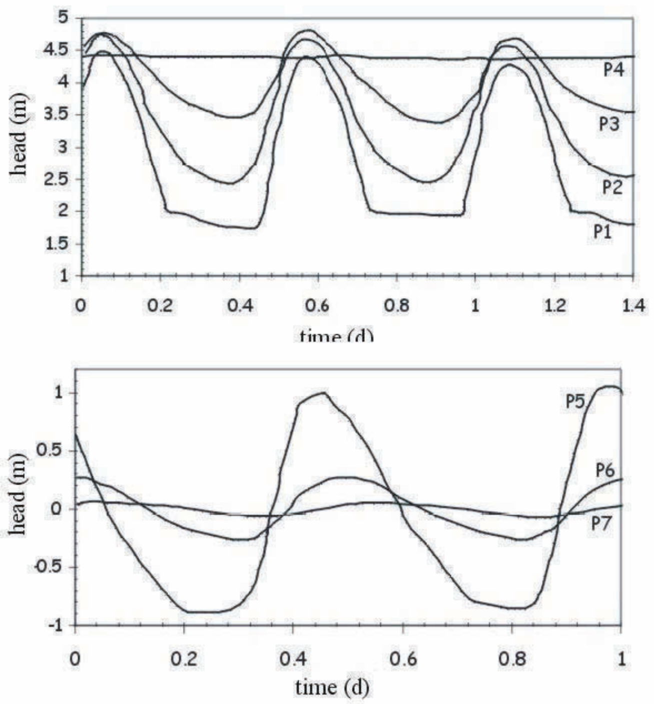

Fig. 5. Fresh water heads in function of time for the observation wells P1 to P7. Fresh water heads for P1 to P4 are given in mTAW, those for P5 to P7 vary about the mean head in the respective well.

Larger time series are available for well P8 (figure 6). P8F1 has a screen in the upper part of the phreatic dune aquifer whereas P8F2 has a screen in the lower part. Figure 6 also shows the sea level variation for the same time period. Fresh water head fluctuations in P8F2 clearly show the semi-diurnal tidal variations. Also, the increasing amplitude towards spring tide is visible. After spring tide the amplitude decreases towards neap tide. Notice that the variation of the fresh water heads occurring during low water are less varied than the fresh water heads occurring during high water. This is due to the non-filtering effect of the sloping shore. The fresh water head on the shore is highly asymmetric (figure 4) and these tidal waves propagate further in the aquifer. The upper limit of the induced wave is determined by the high water level of the sea. The lower limit is highly determined by the elevation head on the shore and therefore varies much less.

Tidal fluctuations in P8F1 are very small. As already noticed the high frequency fluctuations of the tidal variations are attenuated by the large storage coefficient near the water table. Interestingly, the fresh water head shows a small fluctuation with a period which equals the time between two spring tides. Maximum fresh water heads occur a few days after spring tide. Notice that this fluctuation is also asymmetric. The succession of spring and neap tides thus also generates a wave which propagates in the groundwater reservoir. Due to the smaller frequency than semi-diurnal tidal fluctuations, this wave is less attenuated by the large storage coefficient near the water table. Figure 7 shows fresh water head fluctuations in P9F1 which is located further in the dunes than P8. It is a shallow observation well. Here the fluctuations due to the spring tide – neap tide cycle are minimal and are thus already highly attenuated.

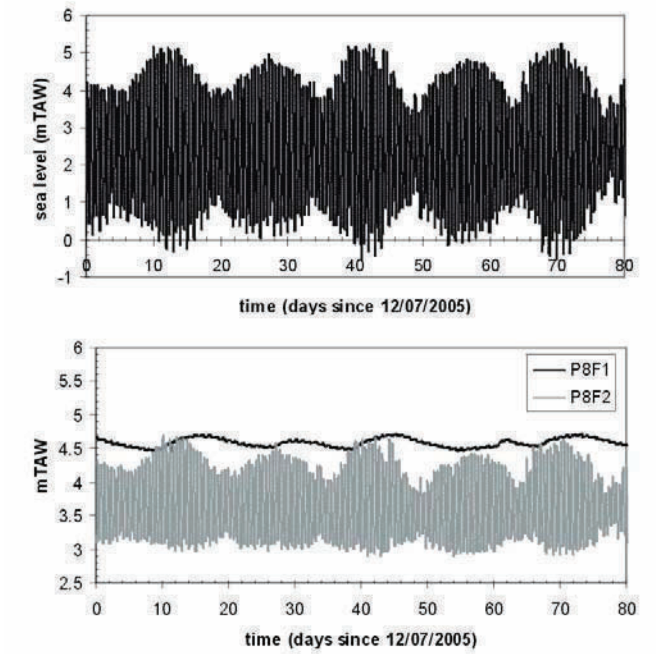

Fig. 6. The upper figure gives the tidal fluctuation of the sea level during 80 days from 12/07/2005 onwards. The lower figure gives the fresh water heads in function of time for the observation wells P8F1 and P8F2 for the same period. All data are given in mTAW.

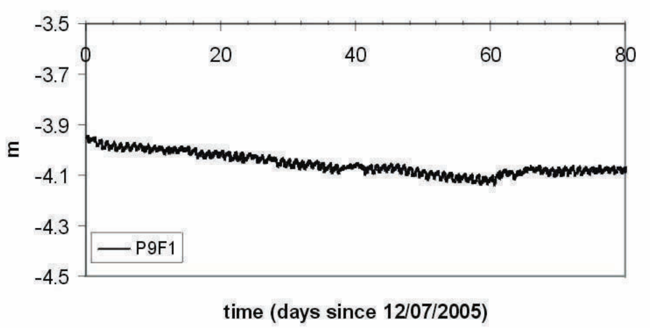

Fig. 7. Fresh water head fluctuations in P9F1. These are given in m below the top of the observation well.

III. Groundwater Flow Modelling

MOCDENS3D [10] was used to model groundwater flow and distribution of fresh and salt water. Details of the model can be found in [11]. First a steady state model was made simulating the observed fresh/salt water distribution in the polder, dunes and under the shore. This was used as the initial condition for a transient state model simulating the influence of tides. This was modelled by altering after every stress period the boundary condition on the sea and shore using the general head boundary (GHB) package. Time steps of 0.1028 h are used and a tidal period of 12 hours and 20 minutes is thus divided in 120 steps. For every time step the hydraulic heads on the shore and of the sea floor change. These heads are calculated using the topography of the shore and a mean tidal sea level change for the Belgian west coast. If a cell located on the shore is inundated by the sea, the fresh water head in the GHB-package equals the sea level (recalculated to a fresh water head) for that time. If the sea withdraws, the fresh water head for this cell is the elevation height of this location minus a decrease of 2 cm per hour to take into account the slow decrease of the water table. This 2 cm per hour decrease is a mean value derived from observations [3]. A constant head boundary is used in the dunes. This simulates the non fluctuating water table as is observed in the dunes during the course of a tidal period. Thus only semi-diurnal tides are simulated, not the spring tide – neap tide cycle.

Figure 8 shows the result of the modelling. The evolution of the fresh water heads during one tidal cycle is given. During low tide, there is a general groundwater flow towards the sea. On the shore there is an important hydraulic gradient which makes that salt water which recharged during the preceding high tide, flows from the back shore towards the fore shore. Also, there is flow of fresh water from the dunes towards the sea. On the back shore, there is discharge of salt water and around the low water line there is discharge of fresh water. During the flood tide, the hydraulic gradient on the shore becomes smaller until at high tide there is a general recharge of salt water. There is even a flow of salt water towards the dunes on the back shore. Notice that during high tide, the fresh water heads in the deeper part of the aquifer are larger than in the shallow part on the back shore and adjacent dune area. This can also be seen in P8 (figure 6). Also of notice is that during high tide there remains an upward flow of fresh water under the fresh water discharge zone around the low water line.

In fact there are two interfering flow cycles [11]. First there is the general flow of fresh water from the dunes towards the sea forming the fresh water tongue. Secondly, there is the shallow groundwater cycle under the shore where salt water recharges during high tide and flows towards the back shore between the periods of high tide. This results in the salt water lens. The two flow cycles are in a dynamical equilibrium as was already indicated by steady state modelling [5],[6] and [8].

IV. Conclusions

Modelling of the influence of tides showed that there is a general groundwater flow towards the sea during low, ebb and flood tide. Only during high tide there is an important recharge of salt water on the back shore. During the tidal cycle, fresh/salt water distribution does not change directly. In the case of the western Belgian shore, the fresh/salt water distribution is determined by the long term mean boundary conditions. Important here is the long term mean hydraulic gradient on the shore which is the result of the interaction between the shore's topography and the fluctuating sea level. Also of importance is the recharge of fresh water in the dunes which flows towards the sea and aquifer characteristics.

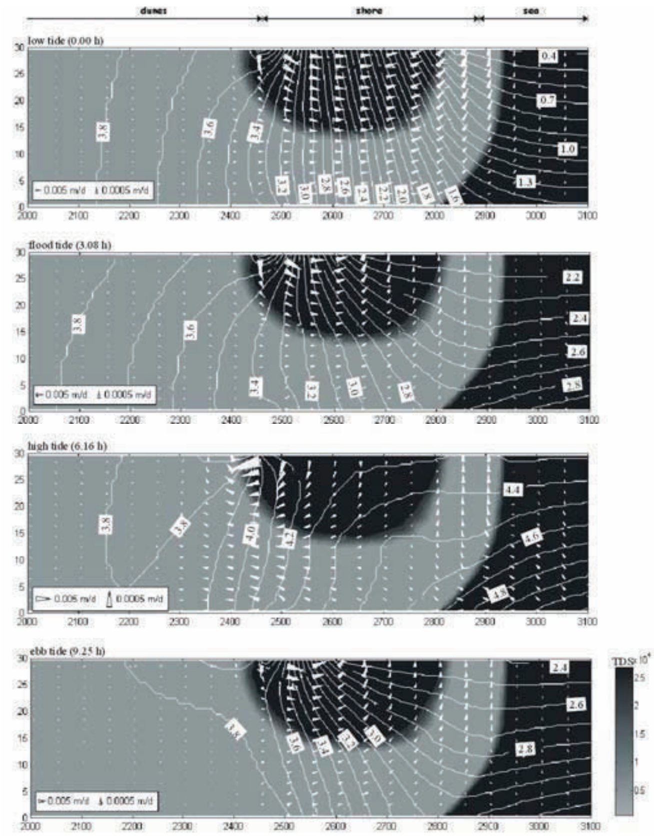

Fig. 8. Evolution of fresh water heads during one tidal cycle. Total dissolved solids (TDS, mg/l) and fresh water heads and effective flow velocities are indicated.

On the shore, the induced tidal wave is of a sinusoidal type on the low water line but becomes highly asymmetric towards the back shore. This is due to the interaction of the changing sea water level with the shore's topography and is called the non-linear filtering effect of a sloping shore. Under the shore, there is negligible small decrease of the amplitude and time lag vertically in the aquifer. The typical asymmetric pattern of the head fluctuations on the back shore evolves towards a more sinusoidal fluctuation deeper in the aquifer. Under the dunes, the amplitude of the head fluctuations decreases further in the dunes but also upward in the aquifer. The latter is due to the large storage coefficient near the water table which makes that the fluctuations in shallow wells are minimal. This has important implications. Shallow wells do show smaller amplitudes than deeper wells. The position of the well screen in the aquifer and the vertical attenuation of the tidal wave must be taken into account in analysing the measurements. The spring tide – neap tide cycle also generated a wave in the aquifer. In contrast with the high frequency tidal variations, this wave is visible in a shallow observation well placed in the dunes close to the high water line.

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