Infiltration of salt water in artificial sea inlets in the Belgian dune area

A. Vandenbohede, L. Lebbe, S. Gysens and P. De Wolf

Abstract — In 2004, two sea inlets were made in the Westhoek nature reserve, the latter situated along the French Belgian border. The infiltration of salt water in the fresh water dune aquifer was monitored using electromagnetic bore hole measurements (EM39) and fresh water head and temperature observations in a large number of wells. These data show that salt water infiltration occurs mainly during high water periods around spring tide. With the EM39 measurements, the downward movement of the salt water front can be followed in detail.

Index Terms — Belgium, monitoring, salt/fresh water distribution, sea inlets

I. INTRODUCTION

The Flemish nature reserve Westhoek is situated along the French-Belgian border (figure 1) and is one the largest unfragmented dune complexes of the Belgian coast. From the high tide mark to the landward lying polder, the dunes have a width of nearly 2 km. The Westhoek nature reserve has a surface area of 340 ha. The dunes are part of the north-west European coastal dunes which form a long, very narrow dune strip from Calais (France) to the north of Denmark. Ecological value of the nature reserve is recognized to be high. To enhance the biodiversity, more specifically the development of natural habitats of annex I of the European Habitat directive, two sea inlets were made. Therefore the fore dunes were breached in two places so that sea water has access to hinter lying dune slacks. Sea inlets in the dunes are a rare phenomenon along the sandy coasts of the southern North Sea. They usually harbor a highly specialized bird life and salt tolerant flora.

The works were carried out between January and June 2004. The fore dunes and the dunefoot revetment were breached at two locations. The width of the sea inlet is about 20 m. Sand was moved to the second line of dunes. The level of the dune slacks is approximately 5 to 5.5 mTAW (mTAW is the Belgian reference level, being 2.3 m below mean sea level). High sea water levels typically vary between 3.5 and 5.6 mTAW not taking into account extreme conditions. For comparison, mean level of the fore dunes is about 10 mTAW.

For the design, different aspect had to be taken into consideration [1]. The most important aspects were nature development, coastal safety, recreation, landscape conservation and protection of the fresh groundwater. The two new sea inlets have a surface area of approximately 1 ha.

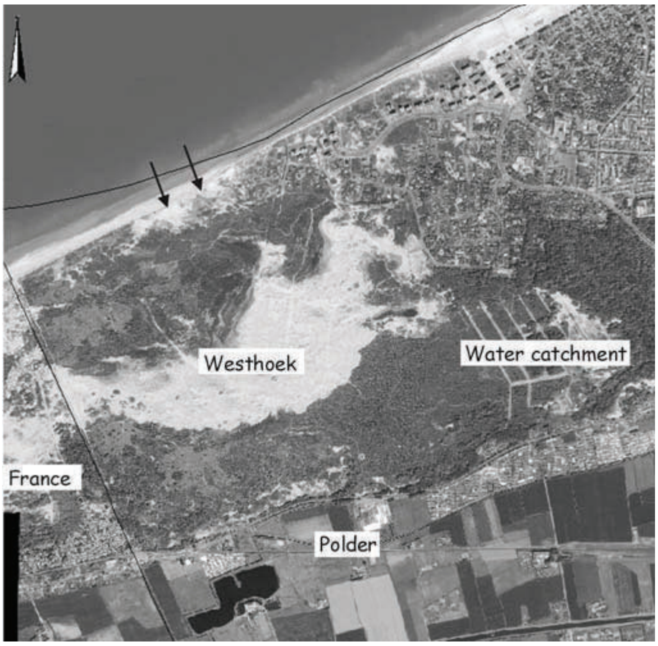

Fig. 1. Location of the two sea inlets (black arrows) in the Westhoek nature reserve along the French-Belgian border.

The effects of the sea inlets on the salinity of the groundwater are monitored by a large number of observation wells. In total 36 observation wells are present around the sea inlets (figure 2). These are arranged in 18 pairs of one shallow and one deep well. 9 of these pairs are placed around the 6 mTAW level whereas the other 9 are placed around the 7 mTAW level. The former are placed close to the area where the salt water infiltrates allowing to follow this infiltration in detail. The latter wells are placed further from the infiltration

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area and allow defining the zone influenced by the infiltration of salt water. Additionally, four wells (again 2 pairs) are placed further from the sea inlets. The infiltration of salt water is monitored by means of borehole measurements and hydraulic head observations in these observations wells. This paper discusses the first results of this monitoring.

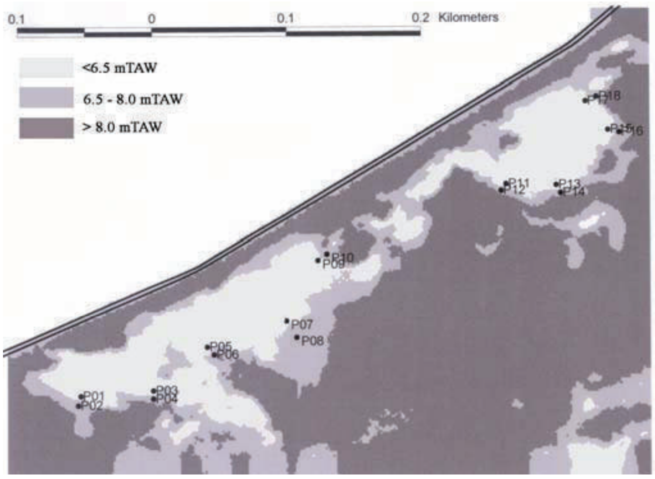

Fig. 2. Location of the monitoring wells around the two sea inlets.

Fig. 3. View of the western sea inlet. Salt water has interred the sea inlet and infiltrates in the dune slack.

II. Fresh/salt water distribution in the dunes

Figure 4 shows a cross section through the phreatic aquifer of the dunes of the Westhoek nature reserve and its surroundings [2]. This phreatic aquifer is bounded below by an approximately 100 m thick clay layer of tertiary age. In the dunes, a fresh water lens is found whereas under the polder, brackish and salt water is present. A peculiar water quality distribution is found under the shore. A salt water lens exists above fresh water.

This water quality distribution is the result of recent geological evolution [3]. 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. This is a low lying area, the mean level is below the high water mark. Water which recharges north of the water divide flows towards the sea. The position of this water divide is influenced by aquifer characteristics, amount of recharge and the water catchment. In the polder a dense drainage system is present to evacuate the surplus of water. This surplus comes from the flow of fresh water from the dunes but also from an amount of rain water which does not infiltrate since the polders consist mainly of less pervious sediments. Therefore, there is only a small amount of water which recharges in the polder. The older salt water is here only partially replaced. Fresh water is only found in the upper part of the polder aquifer.

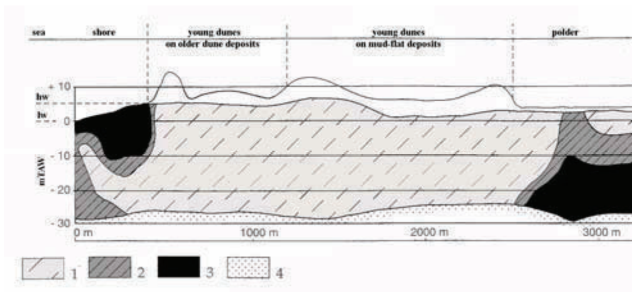

Fig. 4. Distribution of fresh (l), brackish (2) and saline (3) water in the dunes of the Westhoek Nature Reserve. A clay layer (4) forms the lower boundary of the aquifer.

On the shore, there is recharge of salt water on the back shore, mainly during high tide. This salt water flows seawards and discharges mainly during low tide on the fore shore. This small flow cycle results in a salt water lens above the flow of fresh water from the dunes towards the sea. This fresh water discharges around the low water line, distally from the salt water lens. This inverse density distribution is in a dynamical equilibrium [3] [4].

III. Geophysical bore hole measurements

To identify fresh and saline water in the aquifer, bore hole measurements are conducted in all the observation wells. Therefore, a focussed electromagnetic induction tool (EM39, Geonics©) is applied. The EM39 is specially designed for use in wells encased with electrical non-conductive materials. EM39 employs a small internal transmitter coil energised with an audio-frequency current to induce eddy currents in the soil surrounding the well. These eddy currents generate an alternating secondary magnetic field which can be observed by small receiver coils located at some distance from the transmitter. The small secondary magnetic field will be linearly proportional to the electrical conductivity of the surrounding material and the device can be calibrated to read the terrain conductivity directly [5]. The distance between transmitter and receiver coil is 50 cm. With this relatively short intercoil spacing, a centrally located focusing coil must be incorporated to reduce the response from conductive borehole fluid to negligible proportions. This arrangement of coils provides a relatively large lateral range and a high degree of vertical resolution which makes it very suitable for hydrogeological research. EM39 measures the electrical conductivity of the surrounding soil within a distance range from 20 to 100 cm from the well axis while being insensitive to conductivity of the borehole fluid and disturbed material situated near the well axis. The vertical resolution is a few decimeters. This means that detailed vertical profiles of the electrical conductivity can be made in observation wells.

EM39 conductivities σ_b (mS/m) can be readily recalculated in total dissolved solid (TDS, mg/l) values [6]:

$$TDS = 10\ F\ \sigma_b$$

whereas F is the formation factor. This is the ratio of the conductivity of the pore water and the bulk conductivity of the sediments and is typically 4 for the dune sediments [2].

IV. EM39 MEASUREMENTS

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.

Figures 5 and 6 show the EM39 measurements in wells P3 and P9. Both are located in the western sea inlet and are placed around the 6 mTAW line. In P3, two layers of larger conductivity are present, one between -5 and -10 mTAW and the second between -10 and -15 mTAW. These are lenses of silty or clayey fine sand.

The measurement of 13/01/2005 indicated high conductivities (up to 300 mS/m) in the upper part of the aquifer. This is due to the infiltration of salt water. Maximum concentrations of this layer, taking into account a formation factor of 4 is about 12000 mg/l. The next measurement at 30/05/2006 shows that the aquifer is already influenced over a larger part, up to -0.5 mTAW, by the infiltration of salt water.

In the four and a half month since the first measurement, the salt water has thus infiltrated considerably deeper in the groundwater reservoir. This distance is about 3.6 m, resulting in a mean downward darcian velocity of 3.6 m/y for this period. For comparison, normal recharge velocity in the dunes is about 0.28 m/y. Of notice is also that the salt water zone is not continuous. It consists of zones of high conductivity and zones of slightly lower conductivity.

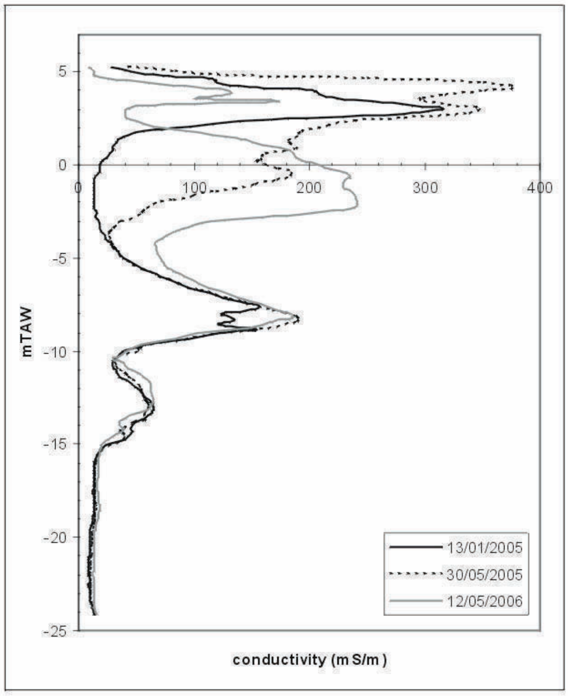

Fig. 5. Electrical conductivity measured in P3.

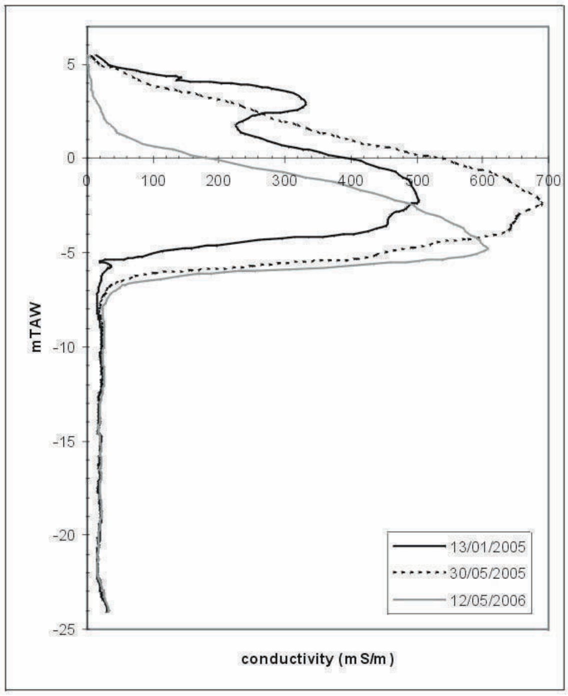

Fig. 6. Electrical conductivity measured in P9.

This is due to the fact that there is no continuous infiltration of salt water. Only during certain high water periods, salt water can enter the sea inlet and infiltrate. During other periods, the high water level is not large enough to enter the water in the inlet and no infiltration occurs. Maximum conductivities measured are 377 mS/m corresponding with a TDS of about 15000 mg/l. The measurement of 12/05/2006 shows two distinct zones of salt water divided by a zone of fresh to slightly brackish water. The maximum concentrations decreased since the last measurement to about 9600 mg/l. The conductivity of the most recent infiltrated salt water (upper salt water zone) is remarkably smaller than the measurement of 30/05/2005. From the second half of 2005 there were less regular flooding of the sea inlet than in the previous period. The infiltrated sea water is then quicker diluted by infiltrating rain water. This is also evident when calculating the mean downward darcian velocity over this period. This is 0.72 m/y or 5 times slower meaning that less salt water infiltrated in the vicinity of P3 than in the period 13/01 – 30/05/2005.

In P9 (figure 6) no layer with clay lenses is present. The observation well is located closer to the inlet of the western sea inlet than P3 but more or less the same trends can be distinguished. Notice that on the first observation (13/01/2005) salt water is found deeper in the aquifer than in P9. The mean downward darcian velocity for the period 13/01 – 30/05/2005 is 1.4 m/y which is much smaller than for P3 for the same period. The infiltration of salt water is thus also function of the location. The last measurement of 12/05/2006 shows almost fresh water in the upper part of the aquifer. This is due to the already mentioned smaller infiltration of salt water from mid-2005 onwards. On the location of P9 this salt water infiltration must have been minimal in this period. Also, the lower saline zone moved only marginally deeper.

Figure 7 shows the EM39 measurements in P15, situated in the eastern tidal inlet. Here the influence of a horizon with clay lenses is very well seen. The first measurement on 13/01/2005 shows a pattern already discussed. A zone of salt water is seen with maximum conductivity of 300 mS/m, corresponding with a TDS of about 12000 mg/l. Again there are different pulses of infiltration of salt water visible. Between -5 and -8 mTAW there is a layer with clay lenses. The two next measurements show that the salt water has moved lower in the aquifer up to the level of these clay lenses which form a semi-permeable layer. The salt water, however, has not moved lower than this semi-permeable layer.

Wells placed around the 7 mTAW line are located further from the inlet and are used to delineate the spatial influence of the salt water infiltration. Some of these wells show very little influence of the salt water infiltration. An example is given in figure 8. In P6, the semi-permeable layer is very distinct. The measurements on 30/05/2005 and 22/12/2005 show only a small increase of the electrical conductivity in the upper part of the aquifer.

Figure 9 shows a different type of response. Electrical conductivity does not change in the first two measurements. In the third measurement, there is a sharp peak with a large conductivity, corresponding to a TDS of about 12000 mg/l. This can not be due to a direct infiltration on this location. Therefore, the conductivity is too high and as mentioned before, infiltration from mid 2005 onwards was rather limited. Here the influence of horizontal flow is seen. As the salt water infiltrates, it has a strong vertical flow component.

Additionally it also has a, although smaller, horizontal flow component. The infiltration water thus flows mainly downward but also sideward from the sea inlet. It is this sideward flow which is seen in P8. This means that the salt water also flows towards the centre of the dunes in the vicinity of the sea inlet. But this zone is relatively small because of the general seaward flow north of the water divide

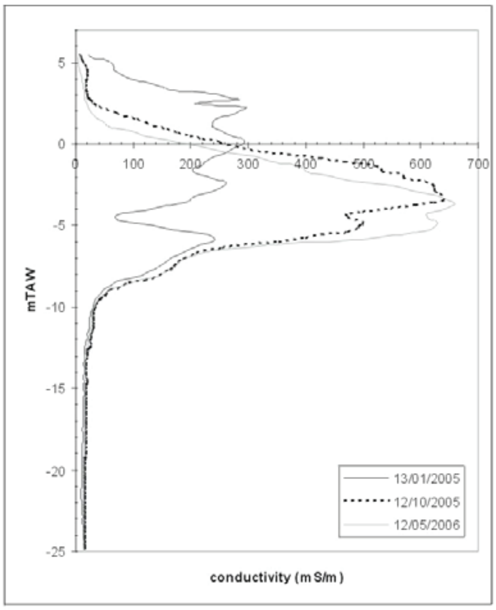

Fig. 7. Electrical conductivity measured in P15.

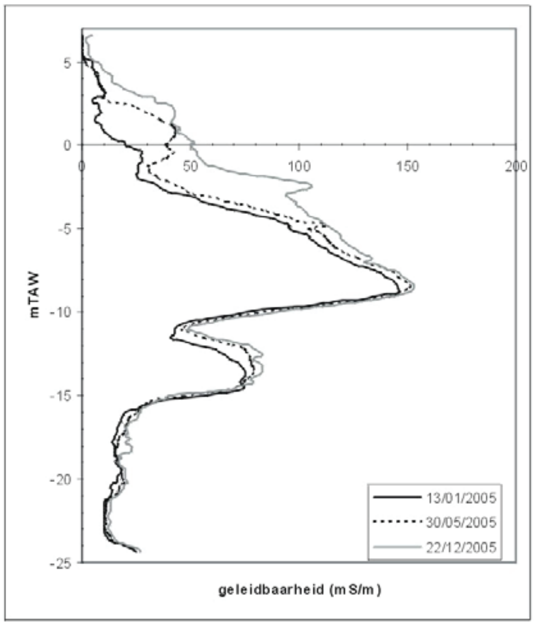

Fig. 8. Electrical conductivity measured in P6.

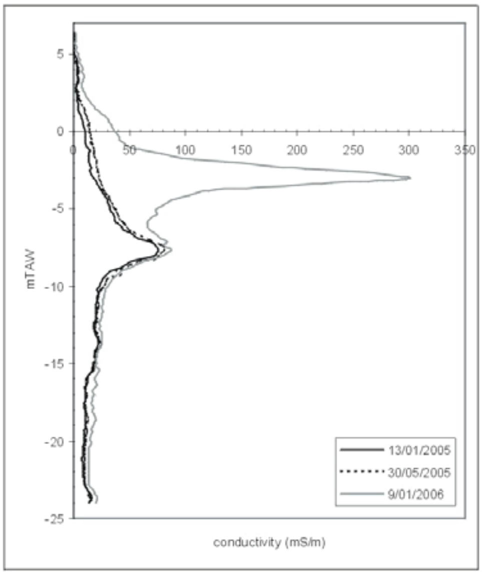

Fig. 9. Electrical conductivity measured in P8.

V. HYDRAULIC HEAD MEASUREMENTS

During several months divers were placed in a number of wells. These recorded the hydraulic heads every 10 minutes. Figure 10 for instance shows the fresh water heads in P11F1, P11F2 and the sea level during 60 days starting from 25/01/2005. Figure 11 shows for the same period the precipitation, reference evapotranspiration and recharge for the same period. Reference evapotranspiration was calculated using daily meteorological data measured at the nearby Koksijde air force base. The Penman-Monteith approach was used [7]. Water balance is then calculated by comparing the potential evapotranspiration with the precipitation.

P11F1 has a filter between 6 m and 6.5 below the surface, P11F2 has a filter between 33.5 and 32.5 below the surface. The deepest well shows the tidal fluctuations very well. The tidal influence in shallow wells, however, is very limited [8]. This is due to the large storage coefficient near the water table which is about 0.165 [9]. The water table in the dunes fluctuates because of seasonal variations. High frequency variations such as tidal variations are subdued by the large storage coefficient near the water table.

The fluctuations of the fresh water head of P11F1 are due to the infiltration superposed on seasonal fluctuations. The sea inlet around the observation well was flooded during high water in two periods. These periods occur around spring tide and caused an increase of the fresh water head of respectively 65 and 60 cm in P11F1. This is not the case during every period around spring tide. For instance around the second spring tide in figure 10 no important infiltration of salt water is observed in P11F1. For the period considered in figure 10 a sea level larger than 5 m is needed to cause infiltration of salt water in the vicinity of P11F1.

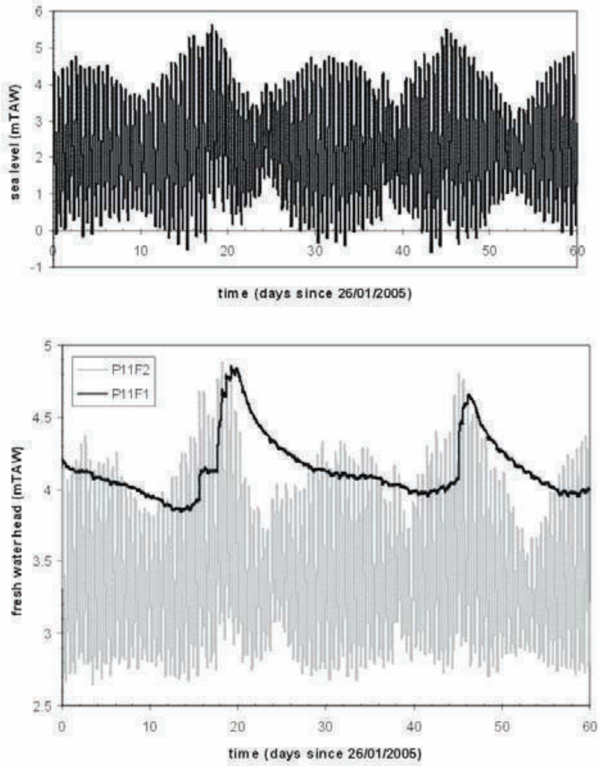

Fig. 10. Sea level fluctuations and fresh water heads in P11F1 and P11F2 from 26/01/2005 onwards.

Notice that before the first major increase in fresh water head, there is a smaller increase of 25 cm. This coincides with a south-western storm. The effects of this storm are visible in the sea level graph and also cause an increase in the fresh water head in P11F2. An increase in daily precipitation (16 mm) is measured and a subsequent higher recharge (12 mm) is calculated. This higher recharge and perhaps also a flooding of the sea inlet caused an increase in the fresh water head in P11F1 just before the import increase during the subsequent period around spring tide. After the increase around spring tide, the fresh water head slowly decreases in P11F1. This pattern is due to the fact that the sea inlets are flooded during the high tides around spring tide whereby a large volume of salt water inters in a relatively short period. During this period, a large volume of salt water infiltrates, hence the increase in fresh water head. Afterwards, only a minimal of extra salt water enters the sea inlets and the water still present infiltrates. This infiltration becomes smaller with time, hence the decreasing fresh water head.

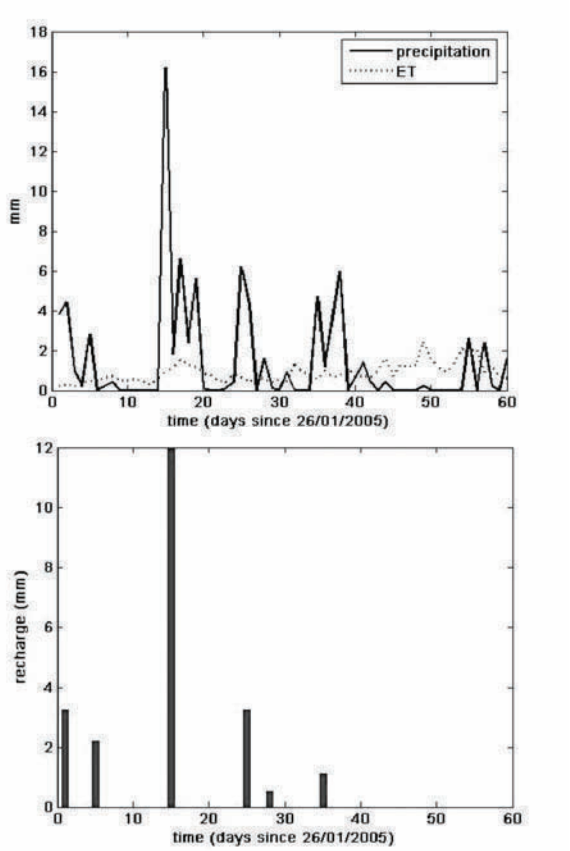

Fig. 11. Daily precipitation, evapotranspiration (ET) and recharge from 26/01/2005 onwards.

VI. TEMPERTURE MEASUREMENTS

Temperature measurements were also performed in a number of wells during several months. Measurements were also made with divers. Figure 12 gives an example of wells P11F1 and P11F2 for the same period shown in figure 10. The temperature measured with the diver is more or less representative for the aquifer temperature on the level the diver is located. For P11F2, the deep well, this is approximately 7.5 m deep whereas this is approximately 3.5 m deep for P11F1. P11F2 shows a continuous decrease in temperature. This is part of the seasonal groundwater temperature fluctuation. Super posed on this, a small fluctuation due to the tidal fluctuations of the head in the well is visible. This temperature fluctuation is largest during spring tide. In general, a decline is also seen in P11F1 but the signal from the infiltration of salt water is super positioned on it. When there is infiltration of salt water, there is a drop of temperature. This drop is 1.4 and 0.9°C respectively for the first and second infiltration period. During winter, sea water has a lower temperature than groundwater which explains the drop in temperature. During the period of measurement, sea water is about 6.5 to 7°C whereas this is 10 to 11°C for groundwater. Afterwards, temperature increases slightly but never recovers to the value before the important infiltration around spring tide.

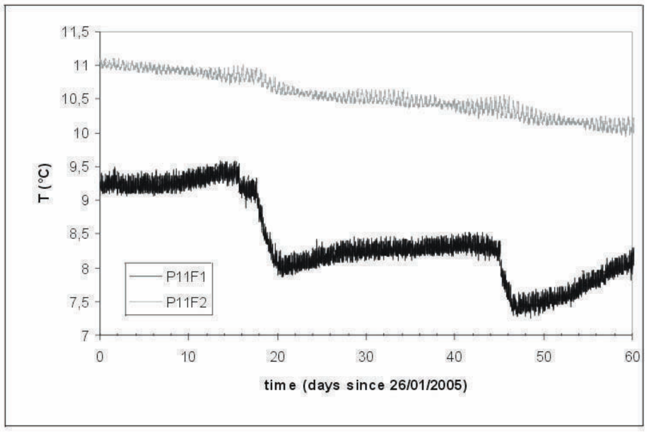

Fig. 12. Temperature fluctuations in P11F1 and P11F2.

VII. CONCLUSION

Infiltration of salt water in two sea inlets in the Westhoek nature reserve was monitored using bore hole measurements and hydraulic head and temperature observations. Fresh water heads and temperature measurements illustrate that there is an important infiltration of salt water, mainly during the high water periods around spring tide. EM39 bore hole measurements show the downward movement of salt water in the aquifer. There is a large vertical velocity in the immediate vicinity of the sea inlet. This velocity is highly dependeds on the position of the observation wells but is several times larger than the recharge velocity of rain water in the dunes. From mid 2005 the frequency with which the sea inlet is flooded, decreased. The downward moving salt water front therefore decreased and the top of the aquifer became fresher again. In wells placed further from the sea inlets, the lateral movement of salt water was observed. Until now, salt water has not moved below a semi-permeable layer in the dune aquifer. Furthermore, the infiltration of salt water is also observed with fresh water head and temperature measurements in observation wells.

ACKNOWLEDGMENT

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