The influence of an Ecobeach PEM on beach development

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Section: Coastal Engineering

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Preface

When I started an internship at BAM Infraconsult for my study Coastal Engineering at the TU Delft in September 2008, I was introduced to the Ecobeach project. The story behind the tubes in the beach of Egmond was fascinating. A Danish contractor had experienced several times increase of the volume of sand at beaches after the installation of his “Ecobeach system”. This had drawn the attention of Rijkswaterstaat and BAM, leading to a Dutch Ecobeach test near Egmond aan Zee. Meanwhile a heavy discussion was going on about the innovation between the inventor and (Danish) scientists.

My internship started with a scientific workshop of Ecobeach, where scientists from different disciplines discussed about possible working mechanisms of Ecobeach. The Dutch discussions would always be constructive, in contrast to the Danish. I met a lot of interesting scientists at the workshop and during my internship we stayed in contact. I planned experiments to find out the real working mechanism (if there was any) of the system. After the 3 months of the internship, some small experiments and a lot of remaining questions, I went back to TU Delft. In April 2009 I started my MSc Thesis and continued my work for the scientific program of Ecobeach at BAM Infraconsult.

I read a lot of literature about beach (drainage) and swash zone dynamics, worked out the plans I made during my internship and prepared experiments in the field which had to be executed in the summer of 2009. Meanwhile I went to the beach for some pilot experiments, together with Pieter Pauw, a MSc student of VU Amsterdam University. Furthermore I studied the results of the experiments done during my internship (also partly in cooperation with Pieter).

At the end of August and the beginning of September 2009 I went to the beach for over 2 weeks, together with Pieter Pauw and Hugo Ekkelenkamp (a TU Delft student), where we did a lot of measurements of the groundwater behaviour and we collected and analyzed the sediment. And not inconsiderably, we survived 16 days and two autumn storms in a remote area.

After the fieldwork I processed the data collected in the field. It was a tough but inspiring job to find correlations and Ecobeach related phenomena in the measurements of the beach groundwater. The sediment analysis showed a clearly disturbed situation in the southern Ecobeach test area, which increased the interest in the project. Hugo started his MSc thesis and accompanied me at the office, which increased the enjoyment in Gouda and moreover, relieved me that the study should be continued after my graduation.

My MSc Thesis ended like my internship started: with a scientific workshop. I presented the results of last years investigations and we discussed about it with the experts. I went home, feeling satisfied, because my colleagues kept studying for a wider beach, a save coast.

Acknowledgements

During my thesis I stayed in contact, worked with and received help from a lot of people. It is impossible to mentions them all here. Yet, there are some persons I would like to thank explicitly. Foremost I would like to thank my supervisors, prof.dr.ir. Marcel Stive, prof.dr.ir. Theo Olsthoorn and ir. Sierd de Vries of the TU Delft, dr.ir. Vincent Post of the VU Amsterdam and ir. Bas Reedijk of BAM Infraconsult. Theo and Sierd thanks for the Matlab lessons.

Pieter Pauw , student of the VU Amsterdam, accompanied me at the many trips to the beach. He helped me a lot and we had a good cooperation. The VU offered most of the fieldwork equipment and Frans Bakker drove many times over the beach with his Land Cruiser and his everlasting optimism and together with dr.ir. Vincent Post, ir. Michel Groen and prof.dr.ir. Koos Groen we discussed about our measurement results and the Ecobeach system.

It was nice to have conferences with Rijkswaterstaat and Deltares, especially ir. Kees van Ruiten (who had a lot of Ecobeach experience) and dr.ir Anton Gerritsen, who reviewed a part of this report together with my cousin drs. Siebren Ruijg. De Ruiter (ir Bram Bakker, ing. Martin van Velsen and ing. Rene Binkhorst) and Van Essen (ir. Renger Smit, ir. Jeroen Tol and ir. Ronald Ruizenaar) lent us important equipment for the fieldwork and visited us walking, swimming or surfing at the remote fieldwork location.

Ir. Ad van ‘t Zelfde, my inspiring neighbour at the office in Gouda, mister Ecobeach of the BAM, always had time to discuss and brainstorm about the study and the results of the measurements. Ir. Sietsche Eppinga, the Ecobeach project manager, was always involved in my thesis and was accessible for assistance or advice. During the fieldwork Hugo Ekkelenkamp started his MSc Thesis. He helped a lot with the experiments. After the fieldwork he kept me company at the office and during a lot of meetings and conferences and I am glad he continues the Ecobeach study.

Especially thank to my parents Frans Pieterse and Ina Pieterse-Francke for their support during the 6.5 years I studied at the TU Delft.

Abstract

Since the end of 2006 in the Netherlands a test is going on with a passive beach drainage system called Ecobeach. The system consists of vertical draining tubes with a length of 2.0 m called PEMs (Pressure Equalizing Modules). Under the surface level, every 100 m a row of PEMs is installed between the high and low waterline. Ecobeach is a Danish invention and the inventor claims that at beaches at different places around the world the volume of sand is increased thanks to the PEMs. This “drainage system” differs from other beach drainage systems in the way that normally horizontal drains are being placed under the beach, connected by a pump.

When the Dutch test started very little was known about the functioning of the PEM system. For this reason scientific research to the PEMs was being started in September 2008. First the situation in the test area is examined. The beach, and especially the swash zone, is a complex area, influenced by tides, waves, sediment transport and groundwater flows.

Five hypotheses are formulated of the influence PEMs can have on their environment. If a PEM can influence the groundwater behaviour in its direct vicinity, a process can be initiated which has an effect on the total beach. The initial events, caused directly by the PEMs, have to be studied in the field to make clear if the different hypothesised processes are realistic. Moreover consequences of the possible processes initiated by the PEMs should be recognized if anything happens. For this reason a fieldwork is executed in August-September 2009. Measurement results of the groundwater behaviour in the vicinity of PEMs show that some hypotheses are unlikely, and some are still questionable. An analysis of the sediment in and around the test area makes clear that possibly a process is going on in the Ecobeach test area, which could be a result of the PEMs. Because this study will be continued, this report shows an initial study to a very complex system. It shows the setup of a large study, interesting analysis methods and surprising results. Nevertheless it will lead sometimes to new questions.

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1. Introduction

1.1 Problem description

At the end of 2006 the Dutch government started a pilot project for the Ecobeach drainage system at the beach of Egmond aan Zee. The Ecobeach system consists vertical drainage tubes, called PEMs (pressure equalizing modules), of 2 m of length. These are placed under the beach surface. According to Danish experience this passive drainage system positively influences the accumulation of sand on the beach. Although Ecobeach is tested at different locations all over the world, up till now there is no scientific evidence of the working of the system. In September 2008 BAM, one of the parties concerned in the Dutch test project, started a scientific program. Together with Deltares and the universities of Delft and Amsterdam, BAM tries to find possible working mechanisms for the Ecobeach system.

1.2 Research questions

The PEM beach drainage system appears to have positively influenced the volume of sand at different test locations in for instance Denmark and Malaysia. At this moment tests are going on in amongst others the Netherlands, South Africa and Mexico. Every location is different while the configuration of the system is always the same. When a possible working mechanism of Ecobeach can be found, the configuration can be optimized for the natural circumstances at a specific location. Besides that the criticism against it will decrease which makes it easier to set up large test projects and elaborate large scale scientific research to make the system appropriate for large scale implementation. Two important questions have to be answered in the first stage of the Dutch scientific research to Ecobeach. The first question is in which way a PEM can influence its direct vicinity. Besides that the consequences of this small scale effect for the whole beach has to be investigated and tested in practice.

1.3 Objectives

It is important to get familiar with the area in which Ecobeach is implemented. Some experiments and a literature study are done to describe the coastal zone near Egmond aan Zee and the important processes in the swash zone. It has to be found out if possible interaction between a PEM and the surrounding area can cause a disturbance leading to a global change of sediment transport processes at the beach. This is a theoretical approach. Measurements have to be done at the beach, because field test results can confirm or deny the different theories.

1.4 Approach

This study started with a scientific workshop about Ecobeach with a brainstorm session where various ideas about the influence of the PEMs on their surrounding are developed. After this workshop literature about beach drainage projects and processes in the swash zone is studies and the ideas from the workshop are discussed with different scientists. Besides that tests are executed in and around the Dutch Ecobeach test area to accurately describe the situation of this coastal zone.

After a clear picture is sketched of the environment of the PEM system, possible working mechanisms of it are figured out. Different processes which could be the effect of a PEM and possible consequences of them are defined in hypotheses. The initiating processes occur on a small scale in the vicinity of a PEM, while these can lead to a global effect on the beach. A fieldwork is done to measure the groundwater behaviour in the vicinity of PEMs and test the initiating processes. Besides that the global effect of the PEM system is examined because the test system already more than two years in use when the fieldwork is executed as part of the scientific research.

The results of the field measurements are used to examine the different hypotheses of the working mechanism of the PEMs. Hypotheses could be rejected or defined more specific after interpretation of the measurements or processes defined in hypotheses could be proved. Future research can start with fewer hypotheses which are more specific defined. The outcome of the field experiments can also indicate if something “happens” in the test area to give a clear direction to the future research.

1.5 Readers guide

Chapter 2 gives a description of the Dutch Ecobeach test project. After a brainstorm session concerning the possible working mechanisms of the Ecobeach system, different experiments were held. With these experiments, the hypotheses made up during the brainstorm session were tested. This brainstorm session was part of an Ecobeach workshop with a lot of scientists from different disciplines (see Appendix H).

Some experiments were held during the first half year after the scientific workshop, together with a study of literature about the Egmond coast. This resulted in the knowledge about the Ecobeach test area presented in Appendix B. The Ecobeach system consists of vertical tubes, called PEMs (pressure equalizing modules) which are being placed between the high and the low waterline. This area is called the swash zone. Different scientists have studied the characteristics and the sediment transport processes in the swash. A literature study was made to collect the knowledge of the swash zone which might be important to find possible working mechanisms of Ecobeach. Chapter 3 contains the results of this literature study.

Ecobeach is not the first beach drainage project in history. In Appendix G the most important beach drainage projects are being discussed and a comparison with Ecobeach is being made to involve the reader in beach dewatering. After having introduced the Ecobeach system, the circumstances in the test area, and beach dewatering in general, are being described and important facts about sediment transport in the swash zone will be presented, so that the working of the system can be scrutinized. Possible working mechanisms of Ecobeach will be made up and are being described in Chapter 4. In a scheme, possible events and processes, possibly initiated by PEMs are presented. These can interact with each other and may eventually cause changes of the beach. In order to test the hypothesised processes about the working of Ecobeach, measurements have been made in the field. In Chapter 5, this fieldwork will be described. The analysis of the measurement data which are collected in the field are being described the next 2 chapters.

Chapter 6 shows the sediment and morphology of the fieldwork location which are important to interpret the measurements done in this area, while the functioning of Ecobeach will depend on the configuration of the beach where it is being implemented. Furthermore the sediment characteristics along the coast of Egmond, including the southern Ecobeach test area and the reference area, will be discussed An interesting picture is sketched by 28 samples from the intertidal zone over a length of 7 km (which was never done before in this part of the Netherlands). More about the sediment is written in Appedix F.

Chapter 7 contains the analysis of the most important measurements made during the fieldwork, the groundwater behaviour around PEMs by divers. First this kind of measurements at a beach, which are quite unique, will be discussed, and some general results will be illustrated. Afterwards, the obtained data are being used to find out the probability of the hypotheses of Chapter 5. Appendices D and E illustrate the working method of collecting and processing the data. Chapter 8 contains the conclusions for the functioning of the Ecobeach system based on the tests which are being described in this report. In Chapter 9, recommendations for future Ecobeach research are being made.

2 The Dutch Ecobeach test project

2.1 Introduction

2.1.1 Background

In the Netherlands, about 12 millions m^3 of sand are nourished to the beach and the foreshore every year to keep the coastline at its place. This method is efficient, but costs the Dutch society millions of euros every year, and in the future, these costs will even increase. A possible alternative is Ecobeach. This innovative system should lead to accretion of the beach, or at least to reduction of erosion and it consists of PEMS (Pressure Equalizing Modules). The PEM system has a Danish origin and was invented there in the nineties by Poul Jacobsen.

Since 2003 the system has a US patent and there have been several experiments all over the world. The Ecobeach system has been implemented in several areas since 1997. After having gained an apparent successful result in Denmark, the method was implemented in Sweden, Australia, Malaysia, Ghana, South Africa and the Netherlands. The measurement results at the different locations were compared by Egon (2008). In most of the projects accretion of the beach was observed. According to the numbers Ecobeach has a positive influence on the volume of sand on the beach.At the end of 2006 Rijkswaterstaat and BAM together started a pilot project in the Netherlands to test the Ecobeach system for Dutch circumstances at a location along the Dutch North Sea coast near Egmond aan Zee.

2.1.2 Ecobeach system

Ecobeach needs to promote accretion of the beach. During calm conditions more sediment from the sea would be caught while during storms less sediment should be eroded. Placing it at a beach is relatively easy and inexpensive. Figure 1 shows the fundamental idea that the upper part of the beach becomes wider after installation of Ecobeach. The upper beach, which is most of the time above sea level, should become wider if the system functions, as the Danish inventor expected.

The system consists of vertical drainage pipes, called pressure equalizing modules (PEMs), with a length of 2.00 m and a diameter of 6 cm. Only the lowest 1.30 m of the pipes is permeable and in the top there is a filter which makes air transport possible through the top. The PEMs are placed about 25 cm under the surface, in rows from the mean high water line to the mean low water line, at a distance of 10 m from each other. The rows, which contain mostly about 6-9 PEMs, have a longshore interspacing of 100 m.

Figure 1: *Beach development due to Ecobeach [1]*

2.1.3 Dutch experiment at the beach of Egmond aan Zee

In 2006, an Ecobeach test project started in Egmond aan Zee. This project is a cooperation between BAM and Rijkswaterstaat, whereas Deltares assists in analyzing the measuring results of different beach parameters. At the beach near Egmond at two test areas of both 3 km length, the PEMs were installed between November 2006 and February 2007 (see Figure

2). The areas, and also a reference area on the south of the southern test area, are being monitored for 3 years to see if there is any visible effect of the PEMs.

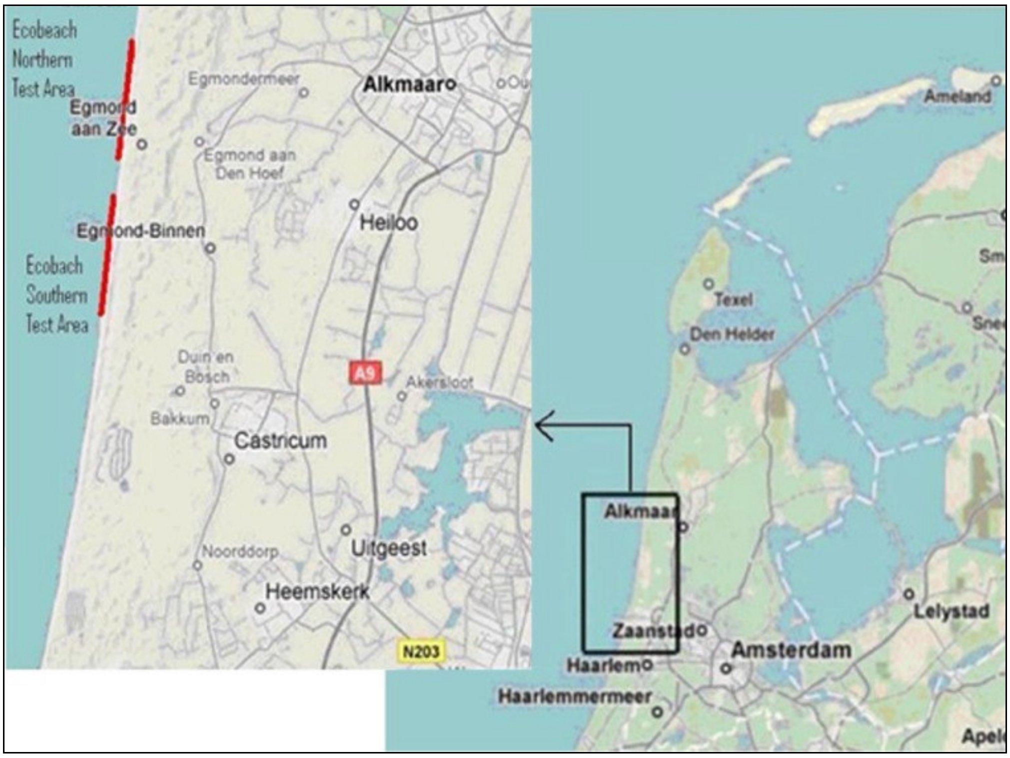

Figure 2: Location of the Dutch Ecobeach test areas

Although Ecobeach has been tested in four different continents since 1997, measurements have only been made on the changes of width and volume of the beach. These measurements in general show positive results, but research including the working mechanism of the PEMs was never done. During the test in Egmond aan Zee, besides extensive monitoring, research was done to the working of the PEMs. This report contains information about the research.

2.2 Monitoring

2.2.1 Monitoring program

The coast near Egmond aan Zee, where the Ecobeach program is located, has been monitored very well in the past and the present. For this reason it is a good location to detect a possible effect of the PEMs on the beach. Over the last 40 years, JARKUS measurements (Yearly Coastal Measurements) were executed. They enable is to detect trends in the development of the beach width and volume and to detect a possible deviation of the trend since the installation of the PEMs. Apart from the JARKUS measurements, a lot of other techniques are being applied on the beach.

The measurement techniques which are applied in the Ecobeach test areas to collect data of the most important Coastal State Indicators (see Table 1) are:

- JARKUS: “Yearly coastal measurements” (since 1964) → Beach width & volume, intertidal beach width & volume, bar location, MCL (mean coastline) position & volume and dune volume are measured.
- dGSP: Once per two months → Beach width & volume and intertidal beach width & volume are measured.
- WESP: Incidentally, just before and after a big storm event → Beach width & volume, intertidal beach width & volume, bar location and MCL position & volume are measured.

- Argus: From 2005 on, camaras make pictures of the beach every hour → Beach width, intertidal beach width and bar location can be measured.

The last mentioned measurement technique is a special opportunity of the beach near Egmond. The northern Ecobeach test area is monitored by the Argus video station at the Jan van Speijk lighthouse, which is located at RSP 3790 and the southern area by the Argus video station at the Coast 3D tower at RSP 4130. The Argus photos are being published on the internet [2] since 2005 every day with a time interval of one hour or less.

2.2.2 Description of the coastal development

All monitoring data enable it to describe the development of a lot of different parts of the coast, such as the foreshore volume, volume of the bars, intertidal beach volume and width, upper beach volume and width and the dune volume. To analyse the Ecobeach system, Deltares yearly publishes the average values and changes of all different parts of the beach of the 3 km long southern test area, and those of a 2 km long reference area just on the south of the southern test area. The costal state indicators, which are described in the yearly reports of Deltares [3], are being explained in Table 1 and Figure 3.

Coastal state indicator	Description of this CSI
Beach width	Distance between NAP +0 m – NAP +3 m
Beach volume	Volume of sand above NAP + 0 m over the width of the beach, measured per linear m
Bar location	Location of bars, which are migrating offshore with a period of about 15 years in Egmond. Important because the position can have influence on the beach width.
Momentary coastline position	The location of the dune foot (NAP +3 m) and the location of the depth contour at level *Mean low water level – (distance from mean low water level to NAP +3 m / dune foot)* are defined. The MCL is located in the middle of these two locations.
Momentary coastline volume	The volume of the grey area in Figure 3 measured per linear m.
Intertidal beach width	Distance between NAP - 0.4 m and NAP + 1.0 m
Intertidal beach volume	The amount of sand under the intertidal beach width, between the levels NAP – 0.4 m and NAP +1.0 m
Dune volume	Volume of the first dune is important, because eaolian transport of sand exists from the beach into the dunes. Transport further landwards is negligible.

Table 1: Coastal state indicators

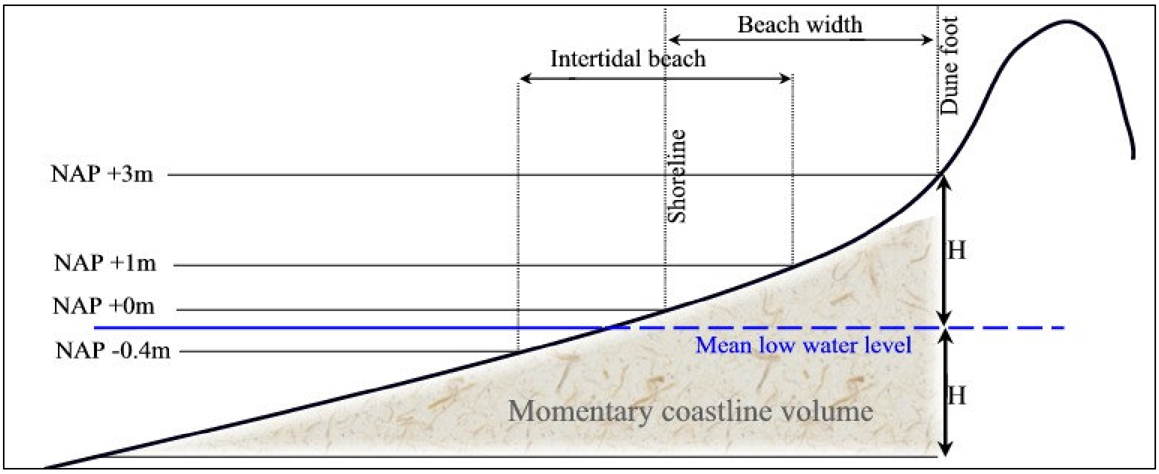

Figure 3: Description of different coastal state indicators

The preferred measurement frequency of all the coastal state indicators is once a month, whereas, for the intertidal beach data, it is also interesting to measure just before and after a storm event. For the Ecobeach study it is important to look at a possible redistribution of material. The beach volume can stay the same, whereas e.g. the beach width grows for instance. At the same time, the dune volume can grow. So, whenever the beach volume stays the same, there can be a positive result for the coastal system in general.

2.2.3 Results of the studies after one, two and three years

The results after one year of investigations are published in the “Year study” of Deltares. Although the results were published at the end of 2007 (one year after the start of the installation of Ecobeach), the data to achieve these results are not collected one year after the system was installed. The installation of the PEMs was completed in February 2007, while some measurements which are presented in the Year study, are done in the spring of 2007. The complete data set for the report was delivered in August 2007, six months after completion of the system.

The changes of the coastal state indicators are within the prediction intervals, which are predicted by a statistical analysis of the measurements of the last 40 years, although most of the data were somewhat higher than the most probable value. No significant difference was found between the test area and the reference area. The most notable difference is the redistribution of sand in favour of the upper beach in the test area. In this area the beach volume is in the middle of the prediction range, whereas the beach width is in the lower part of the prediction range.

One year after the “Year study”, the “Two year study” was published. This report shows data of the beach, after one year and a couple of months having been influenced by the Ecobeach system. This report was published in January 2009. Due to the large natural variability, characterizing the development of the coastal system within the short period of evaluation, it is difficult to detect statistical significant effects of the Ecobeach system. No significant trend break in the long-term and medium-term evolutions of coastal state indicators can be noticed after the installation of the Ecobeach system.

In the “Three year study”, again the long-term development of the coast near Egmond is not raised above the statistical boundaries at the location of the southern Ecobeach test area, although a noticeable development occurs in the seasonal statistics. During the 2nd year of Ecobeach, in the winter period, the amount of removed material from the beach to the foreshore is relative small in the southern test area, compared to the reference area and compared to the statistical predictions. This indicates a more stable beach.

Though the yearly reports published by Deltares show a clear representation of the development of the coastline in the southern Ecobeach test area and the reference area, with useful graphics, the monitoring can be improved. Very frequent (monthly) measurements at the same date every year, in combination with registration of weather circumstances, should be optimal monitoring conditions. The seasonal or incidental (storm related) variations are relative large. If only two or three measurements are executed at random times of the year seasonal and incidental processes are hardly visible, while monthly measurements give a reliable picture of beach development and understanding of short time processes.

To get more understanding, the results should not only be presented as mean variations over 3 km (test area) and 2 km (reference area) length, but also the mean variations of every 100 m alongshore distance should be shown. Namely sediment transport processes and reshaping of the beach occurs often locally and can depend on the shape of the foreshore and dunes. When the beach development is known more locally, PEMs should also be added to the original rows at locations where the beach has grown wider, to make sure that there is enough beach drainage around the low waterline.

3 Theory of sediment transport in the swash zone

3.1 Description of the swash zone

3.1.1 Definition of the swash zone

Different definitions of the swash zone exist. The landward edge of the swash zone is uniformly considered as the point of maximum wave run up. For the seaward edge, where the swash zone borders on the surf zone (see Figure 4), different descriptions are considered. It has been suggested that the seaward edge of the swash zone starts were the bore turbulence begins to significantly affect the sea bed [12], and that the lowest point of backwash is the seaward border [13]. The position of the swash zone will shift permanently, because of tides and changing conditions.

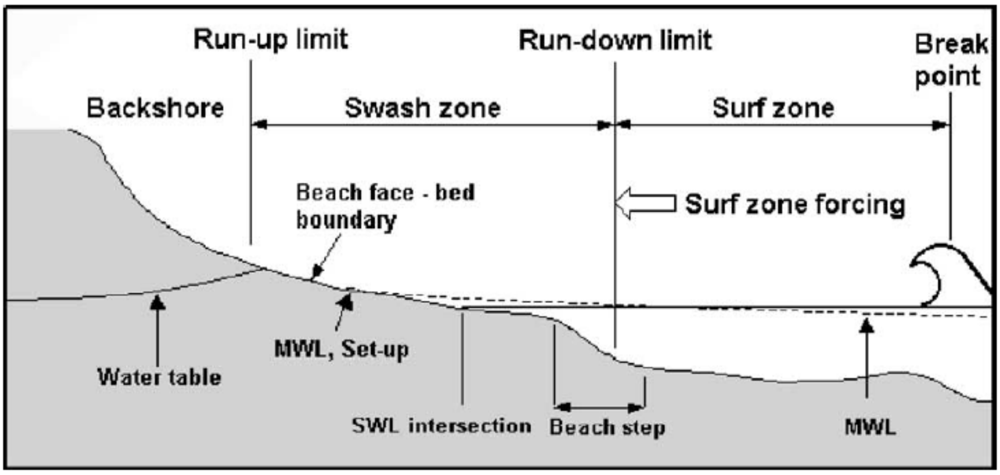

Figure 4: Definition sketch for the nearshore littoral zone [13]

3.1.2 Swash zone characteristics

Important boundaries of the swash zone are wave characteristics, currents, turbulence, beach slope and beach composition (grain size, permeability, degree of saturation). The surf similarity parameter or Irribarren number, $\xi o= \beta/\sqrt{(Ho/Lo)}$ describes if the surf zone is saturated ($\xi o<0.5$) or unsaturated ($\xi o>0.5$). β, Ho and Lo are the beach slope, deep water wave height and deep water wavelength. At Egmond aan Zee these parameters are roughly: $\beta = 0.02 - 0.04$, Ho = 1 – 3 m and Lo =40 – 100 m. Which means that $\beta = 0.10 - 0.30$ and we have to deal with spilling breakers and a saturated surf zone.

3.1.3 Groundwater behaviour in the swash zone

Figure 5 [14] shows the different groundwater processes in the swash zone, interacting with tides and waves. Most of the time the water table under the beach exceeds the water level in the sea, because this level raises quick by infiltration of waves and the groundwater drains slowly during falling tide. During low tide exfiltration of groundwater can occur in the zone between the shoreline and the highest point of saturated bottom.

Figure 5 shows an ideal situation, with a constant beach gradient, and a horizontal scale not matching with the vertical scale. The real situation at the Egmond beach is not this ideal. The shape of the beach varies strongly along the coast. Although the beach of Egmond is not exactly comparable with Figure 5, the phenomena described in this figure are relevant for this beach.

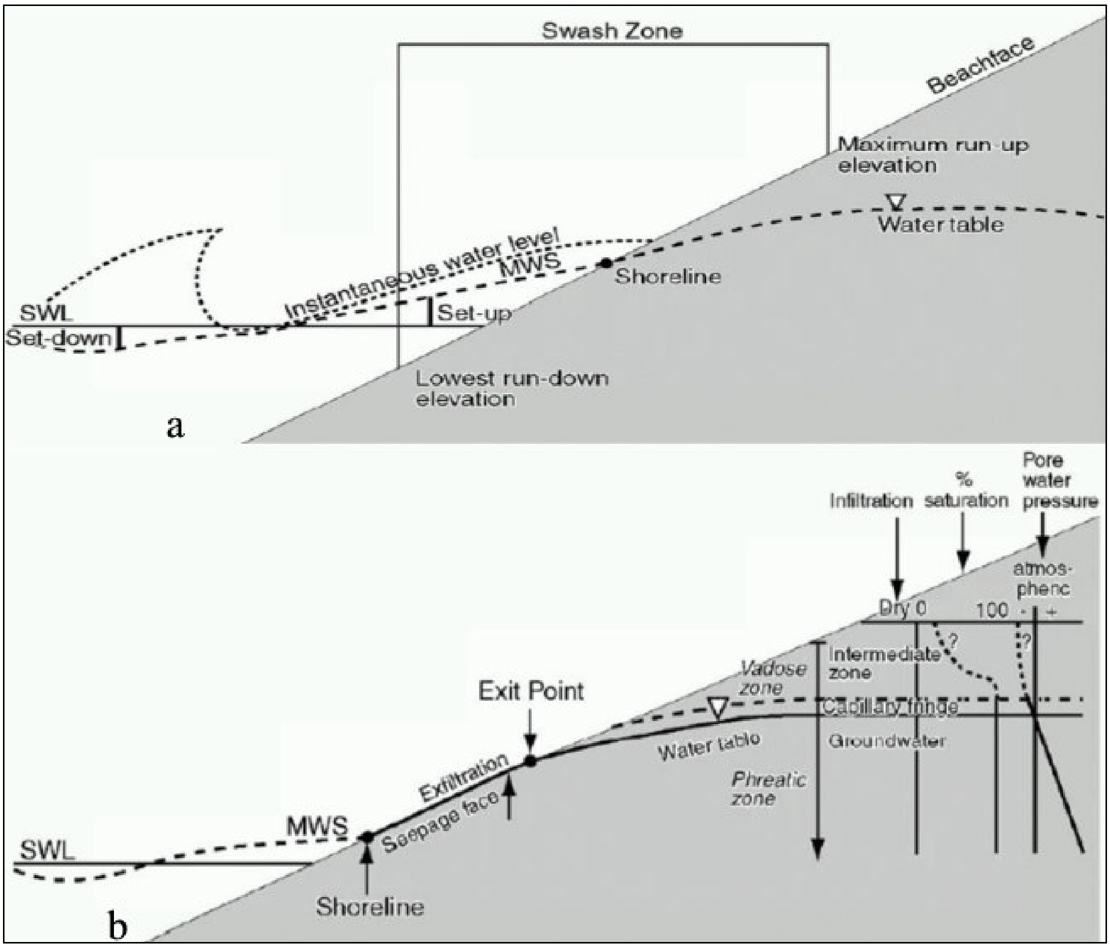

Figure 5: (a) Definition sketch of water levels in the swash zone. (b) Beach ground water zones when the water table is decoupled from the tide [14]

3.1.4 Groundwater behaviour in the Dutch test area

Besides the general groundwater processes occurring in the swash zone, some specific research is done in and around the Dutch Ecobeach test area. Some important facts are illustrated here while, in Appendix C more information is available about the test area. The salinity of the groundwater is measured by electrical sounding, which is explained in Appendix C. It is interesting to know the location of the transition between saline water in the top layers of the beach and fresh water at a larger depth. Moreover, information is gathered about the high frequency pressure fluctuations in the groundwater forces by wind waves.

The relative high groundwater level under the dune area makes fresh water flowing out under the beach by an overpressure. Layers of clay and peat in the bottom, which are not traced exactly, can influence this flow. The upper layer of the beach consists of saline water, filled daily by tides and waves. The transition layer between the fresh and saline groundwater is located at a depth of 7 – 10 m. Near this layer, mixing occurs. Figure 6 shows a cross shore groundwater profile in the Ecobeach test area, measured with CVES (see Appendix C.3). The blue and green colours indicate saline water, while red and purple show the deeper located fresh water.

Wind waves cause pressure differences in the ground. The pressure differences caused by wind waves are measured with divers (pressure transducers) at the Egmond beach. Although the period of the waves is only 3 – 5 s, the waves are noticed very well at a depth of 1.0 m. Pressure differences of 0.50 – 0.60 m water column at the surface are reduced to 0.20 – 0.30 m water column at 1.10 m depth (see Figure 7 and Appendix D4).

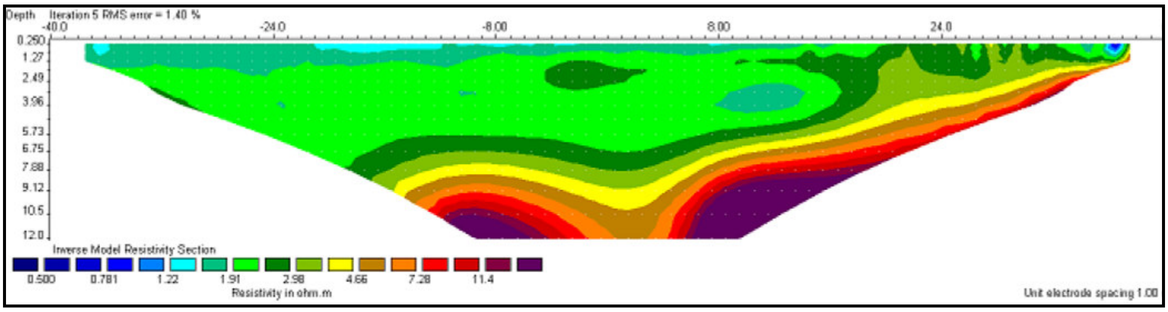

Figure 6: Cross shore groundwater salinity profile, RSP 4200, Februari 2009

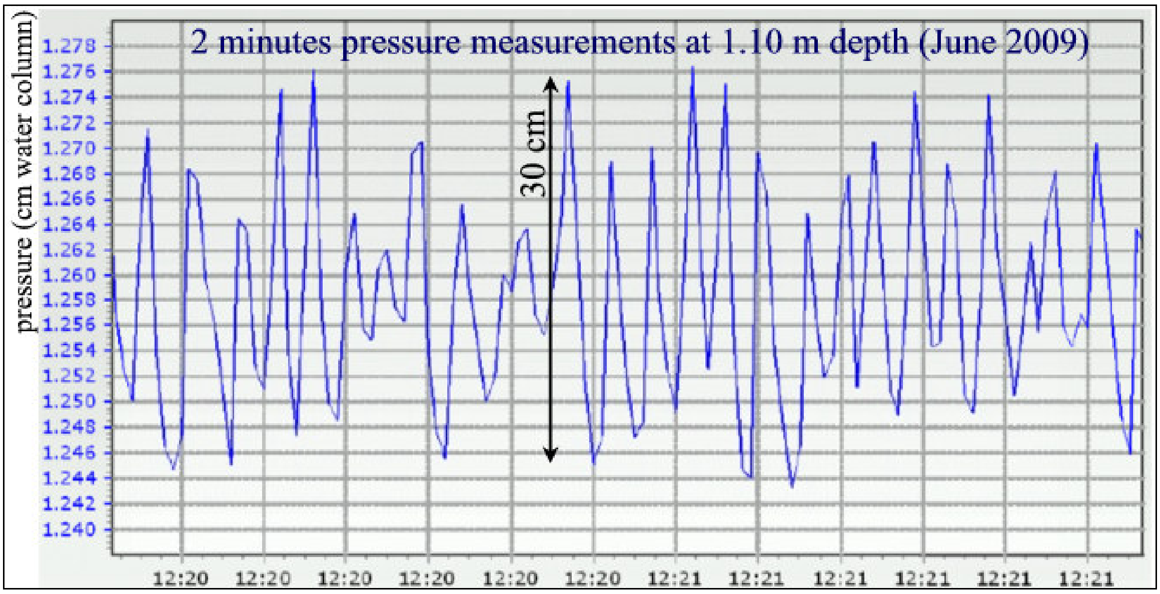

Figure 7: Groundwater pressure variations due to short waves

3.2 Sediment transport in the swash zone

3.2.1 General

The sediment transport in the swash zone can be divided in bed load transport and suspended load transport. Because of the relative large sediment particles (sand, with D50>300 MU) the suspended load transport only can be significant in the presence of bore turbulence. The fall velocity of sediment with D50 of 300 MU is about 3 cm/s [15]. Bed load transport is dominant out of the direct vicinity of the bore, where flow velocities of 2 – 3 m/s have been measured in the swash zone of different beaches [17].

The balance between onshore directed and offshore directed sediment transport can be positive, which means accretion, or negative, which means erosion. If the sediment transport in onshore and offshore direction is exactly the same, the beach is stable. This stable situation does not occur for a long period, because wave conditions change daily.

A net onshore or offshore sediment transport in the swash zone can be a result of asymmetry of the swash, which means that the onshore swash motion is different from the offshore swash motion. Moreover the magnitude of the wave energy determines the direction of the net sediment transport, causing seasonal changes of the beach shape. Infiltration and exfiltration of groundwater also can influence the net transport direction [16].

3.2.2 Initiation of motion

During each swash event (caused by an incoming wave) sediment particles in the swash zone can start to move. Most sediment starts to move during the passage of a bore due to the turbulence in the bore, as suspended sediment. This turbulent motion reaches the bed, without time to develop a transition layer, because the bore suddenly arrives [18].

Besides the initiation of motion due to passage of the bore, sediment can start to move when the flow velocity of the water exceeds some critical velocity. The critical velocity depends amongst others on the sediment size. The Shields parameter indicates at which velocity of the water sediment starts to move [16]. Infiltration and exfiltration of groundwater through the beach face influences the effective weight of the sediment particles and the thickness of the transition layer. For this situation a modified Shields parameter is used [16, 19].

3.2.3 Swash asymmetry

The phenomenon that wave uprush differs from backwash in the swash zone is called swash asymmetry. This asymmetry has influence on the direction of net sediment transport. The asymmetry consists of the following components:

- A difference is caused by the beach slope and gravity. Uprush flow is up slope, while down rush flow is down slope. This causes a decelerating flow during uprush and an accelerating flow during backwash.
- It is generally found that the duration of the uprush is significantly shorter than the backwash duration [20]
- The peak uprush velocities are generally the same or slightly larger than the peak backwash velocities [21]. During constant flow condition the sediment transport is proportional with u^3.
- The uprush flow is a decelerating flow, because the flow in shoreward direction suddenly starts with the passage of a bore front, while bottom friction and the slope of the beach break down the velocity. In contrast with this the backwash current is accelerating. It starts with zero velocity when the water movement turns from shoreward to seaward and is accelerated by the beach slope. This has consequences for the development of the transition layer.
  The transition layer forms the transition between the flowing water above the ground and the still water between the sediment particles. The thinner this layer, the more influence the current has on the sediment particles. During accelerating flow (backwash) the transition layer has time to develop and resist erosion, but during decelerating flow (uprush) this layer is very thin during the highest current velocities, which leads to relative much erosion [17].
- The uprush flow starts with a lot of turbulence due to the bore collapse, before the wave front enters the swash zone: "surface generated turbulence" [17]. At the uprush limit most of the turbulence is disappeared. The backwash flow starts with standing water, which develops into a laminar flow in the direction of the sea. By friction with the bed "bed generated turbulence" exists [17]. When the backwash faces an incoming wave (on top if it), turbulence also develops at the transition between uprush and backwash.

Some components of the swash asymmetry promote erosion (beach slope, duration of uprush and backwash) and others accretion (transition layer development, turbulence). Whether the total effect of the asymmetry is erosion or accretion depend among others on the characteristics of incoming waves, bed material and (infiltration and exfiltration of) groundwater. Figure 8 shows the different processes during a swash cycle [17]. Above the swash velocity is plot. During uprush suspended load is a little more important than sheet flow, while during backwash the sheet flow is a little more important.

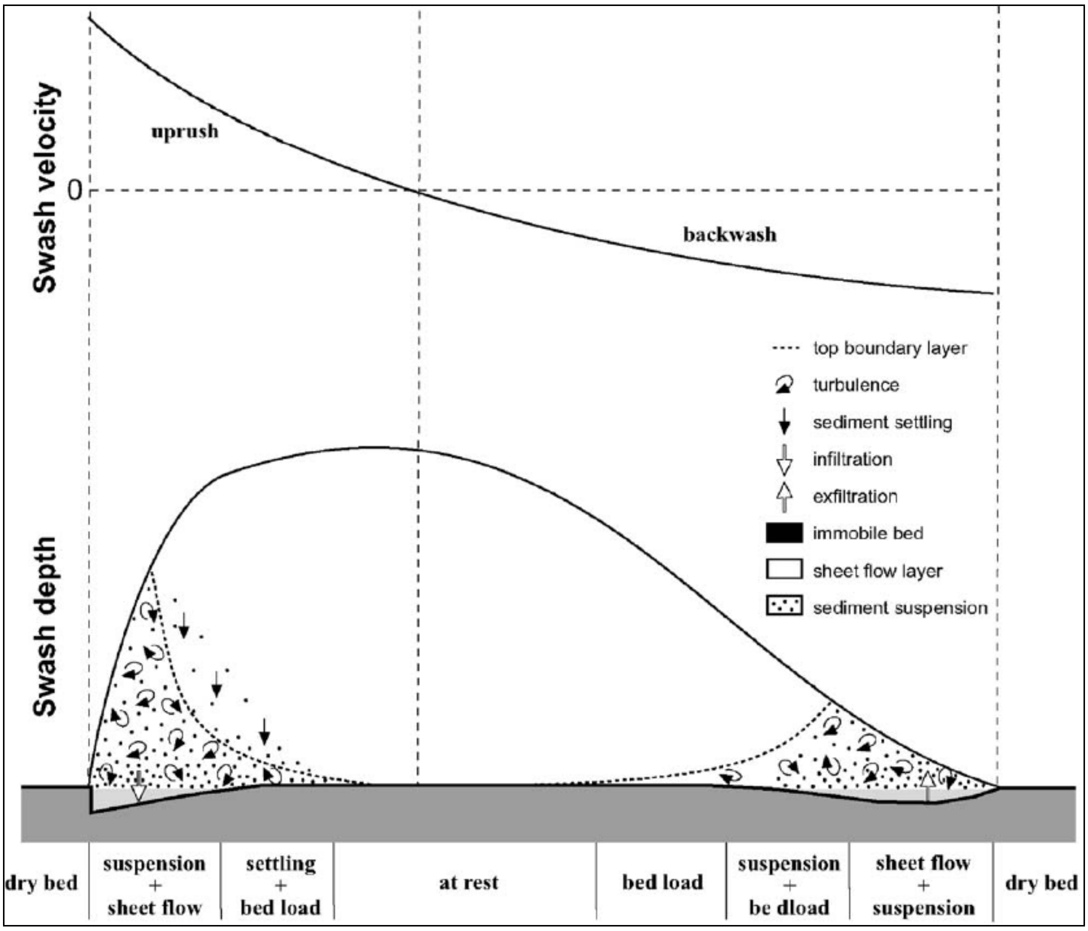

Figure 8: Sediment transport processes during a swash cycle [17]

3.2.4 Infiltration/exfiltration

General

The infiltration and exfiltration of groundwater through the beach face can influence the sediment transport in two different ways: by influencing the critical velocity for the initiation of motion of sediment particles [22] and by influencing the quantities of water transported over the beach during uprush and backwash [23]. The first mechanism has to do with boundary layer modification and vertical forces on the sediment particles. The second mechanism is mainly important at beaches with coarse sediment. A combination of infiltration and exfiltration occurs during the passage of a bore front.

Initiation of motion

The initiation of motion of sediment particles depends on different factors like flow velocity, particle size, shape and density and the viscosity and density of the water, which can be combined in the Shields parameter. Infiltration of water into the ground or exfiltration of groundwater can also influence the process of coming into motion of the particles. Therefore a modified Shield parameter for the situation of infiltration/exfiltration is formulated [22].

In two ways the process of erosion is influenced by infiltration/exfiltration (see Figure 9):

- The transition layer becomes smaller during infiltration because streamlines are directed downward and the current velocities close to the sediment particles become larger. During exfiltration the transition layer becomes larger because streamlines are directed upward and the large current velocities do not reach the upper sediment particles.
- During infiltration a vertical force in upward direction works in the sediment particles which increases the effective weight and counteracts erosion of the particles. The

effective weight of the particles is reduced during exfiltration, which promotes erosion.

There appears to be some critical grain size below which effective weight effects dominate, causing infiltration-exfiltration to bias the transport offshore, and above which modified boundary layer effects dominate, causing infiltration-exfiltration to bias the transport onshore [16]. This critical changeover point of the grain size appears to lie between 0.45 mm (Turner & Masselink, 1998) and 0.58 mm (Nielsen, 1998). According to Butt at al. (2001) the critical grain size is 0.55 mm and Carambas (2003) calculated the critical grain size should be between 0.4 – 0.6 mm. At the beach of Egmond aan Zee the grain sizes (D50) are between 0.27 – 0.38 mm. This means the effective weight effect dominates over the boundary layer effect.

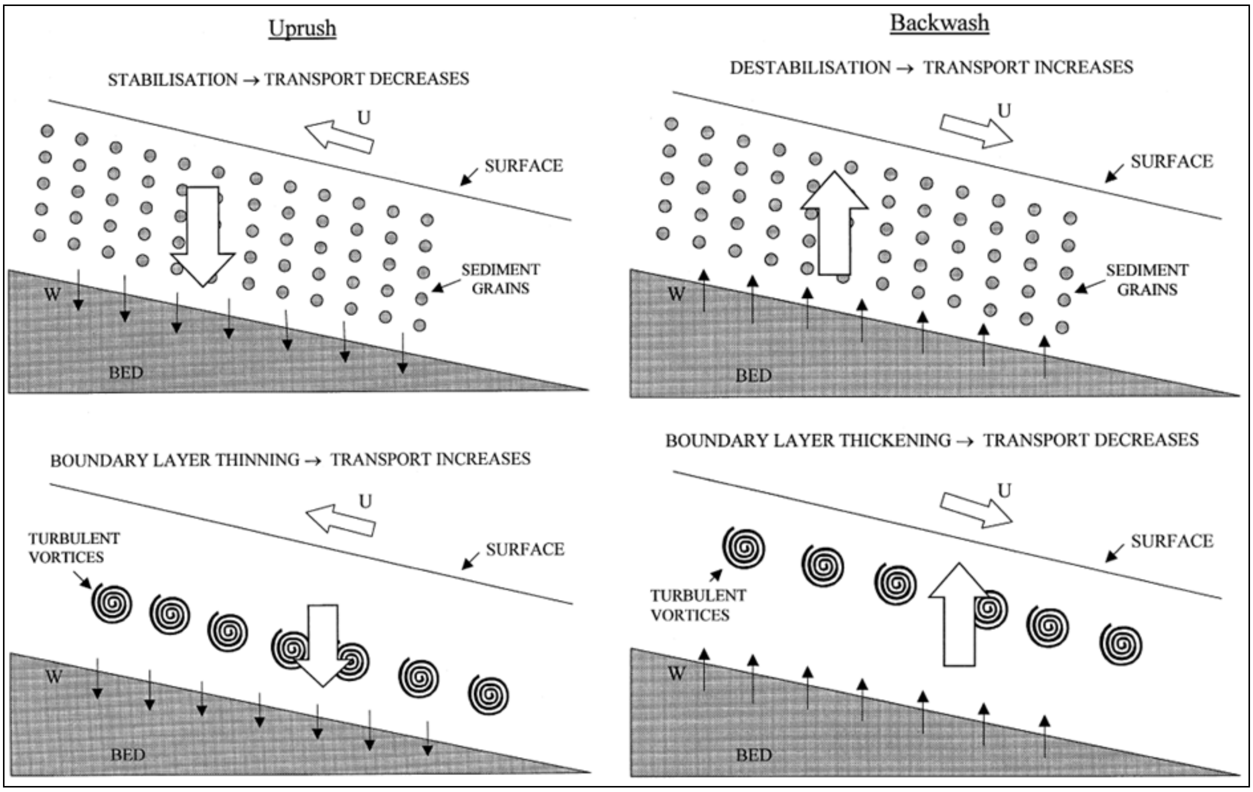

Figure 9: forces on grains and transition layer effects [16]

Influence on the water balance
The backwash volumes can be reduced by infiltration of a part of the uprush volumes. This leads to less energetic backwash compared to the uprush and relative more sediment transport onshore. To be able to notice this accretionary effect at least 2 % of the uprush volume has to infiltrate [23]. To reach this infiltration rate the D50 of the sediment should be more than 1 mm, which is much coarser than the sediment at Egmond aan Zee. This means at the beach of Egmond the sediment transport is not influences by the rate of infiltration in the upper swash zone.

Passage of a bore front
During the passage of a bore front in the swash zone (and inner surf zone) a relative large difference of water pressure exists between the bore front and bore back, see Figure 10. The relative low water level of the bore front causes infiltration into the ground and the relative high water level of the bore back causes exfiltration through the bed [25]. This process has a very short time span (less than 1 second), because the bore moves relative fast through the swash zone and inner surf zone.

The short time period will not limit the process described above. According to measurements with divers at a depth of 1.0 m the pressure waves of a passing bore are almost directly measured at this depth, with an amplitude factor of about 50%. This means groundwater pressure variations move through the ground very fast.

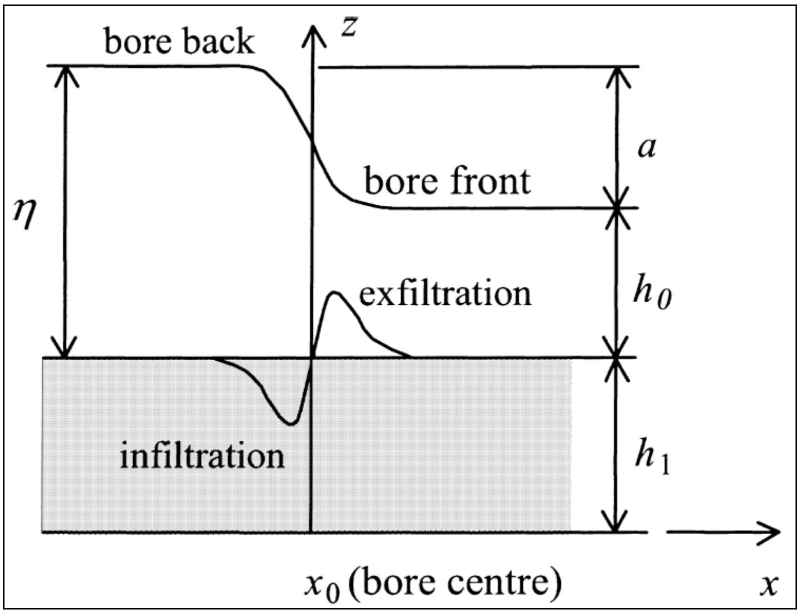

Figure 10: Bore and groundwater flow across a flat horizontal porous bed [25]

Groundwater circulation
Due to the infiltration in the swash zone, near the maximum run-up (RM) and the relative low water level around the breaking point (BP) of the waves a large scale (compared to the infiltration-exfiltration during a bore passage) circulation of the beach groundwater exists [25], see Figure 11.

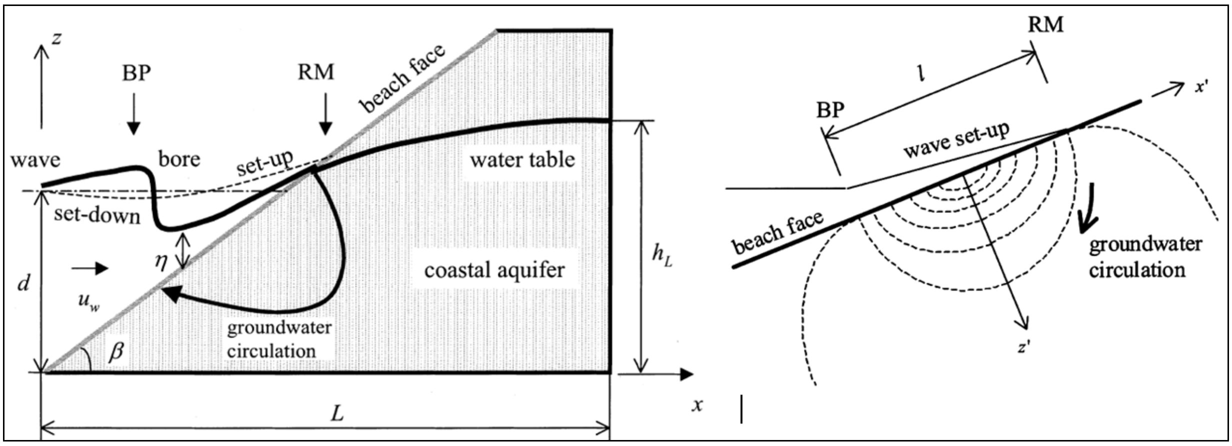

Figure 11: Groundwater circulation under the beach due to wave setup [25]

At the Egmond beach, the exfiltration of groundwater near the low waterline is visible by measuring the salinity of the groundwater. At a depth of 2 m, the groundwater near the low waterline is less saline than 25 m in the direction of the dunes. This means the seawater is mixed with fresh water from the dunes before it exfiltrates.

4 Hypotheses Ecobeach

4.1 Introduction

Based on the appearance of the Ecobeach system, the conditions of the test area (described in Appendix B) and transports mechanisms of sediment on the beach and in the swash zone, assumptions are being made about possible working mechanism of the system. The hypotheses are being tested during a field investigation and the working of the Ecobeach system possibly can be explained by the results of this research Beach dewatering is generally seen as a way to reduce erosion and promote accretion. In the last 20 years, different beach dewatering systems have bean installed in Europe and the United States. Some examples of beach dewatering projects are given in Appendix G.

Ecobeach is called a beach drainage system (see paragraph 2.1.2), but the Ecobeach system is not really comparable with the beach dewatering systems described in Appendix G. All projects from Table G1 consist of one or more horizontal drains under the beach, with an active drainage by a pumping station resulting in a lowering of the groundwater level from some decimetres to more than a meter. In contrast with this, Ecobeach consists of vertical drains which are not connected with a pump and no lowering of the groundwater level of several decimetres to a meter has to be expected. Although the knowledge of the many beach dewatering tests in history is important to analyse Ecobeach. A different view at this system is required to find all possible working mechanisms.

First some basic assumptions are formulated which underlie the study. Afterwards, different plausible processes which might be an effect of the Ecobeach system are put in a scheme. The different processes clearly interact with each other. The steps in the scheme are explained and analysed and research objectives are defined from this analysis.

4.2 Basic assumptions

To find a possible working mechanism of Ecobeach, two basic assumptions are considered as starting point. First, the PEMs which are investigated in this study are presumed to operate. This assumption makes investigating the PEMs of the Dutch Ecobeach test project useful. The operation of a PEM depends on its environment. The sediment and groundwater around it and the forcing by tides and waves have to be measured. The PEMs, which are investigated, were installed in a region where the environment is (during a part of a tidal cycle) comparable with the environment of the already "working" PEMs. Secondly the PEMs are assumed to have a local effect on their environment. The local effects of all PEMs together can lead to a global effect on the beach.

Besides this the PEMs which are investigated are presumed to function "every day". This means during normal conditions a local effect on the beach should be notices. Not only during special condition, like a once-in-a-year storm or an extremely low sea water level. The assumptions described above outline the objective of a field investigation: the PEM's should cause a local influence at the part of the beach where they are installed according to the Ecobeach system definition.

Following from the assumption that the PEMs influence the surrounding beach, the following hypothesis can be formulated: There is interaction between the PEM and its surroundings.
The interaction can have two different appearances.

The first appearance is one of water exchange between the PEM and the surrounding beach. If the bottom exists of different layers the PEM can be a connection between those layers. Difference in (vertical) permeability between the PEM and the surrounding area can give the PEM the character of a drain. It can be a shortcut for water flowing upward or downward.

These "slow" processes could affect the ground water level or the infiltration and seepage which are part of the "beach groundwater circulation" mentioned earlier (see paragraph 3.2.4).

The second appearance is one of "fast" exchange processes between the PEM and its surroundings. Pressure variations caused by passing waves travel through the ground and could influence the packing of the sediment particles or the stability of the surface layer particles (see paragraph 3.2.4). The PEM can be a tunnel with a larger propagation velocity and smaller losses for pressure waves than the ground body. Besides this the PEM could enclose a volume of air during flood, which operates as damping mechanism for fast travelling pressure waves. The "Lisse-effect" is a well known phenomenon for piezometers. It is a large pressure build up in the tube during a rain shower. This phenomenon could occur during the passage of a wave as well.

4.3 Diagram of plausible working mechanisms

Figure 12 shows a diagram with different chains of processes which can be initiated by the Ecobeach PEMs. Different chains interact with each other. This means that some phenomena can be caused in different ways by a PEM. The different processes and chains described in the diagram will be explained in the following paragraphs. Besides these explanations the way to test the phenomena during a field experiment is described in paragraph 4.7.

The approach is partly theoretical (literature study) and partly based on the results of tests which already have been done before August 2009. It is not sure that all start events and the processes brought on really can happen at every kind of beach. The diagram makes clear that a local effect of a PEM can lead to a global effect on the beach by following different steps.

In the scheme of Figure 12 the starting events are indicated by fat bordered rectangles, placed at the flank of the scheme. These are clarified in paragraph 4.4. The measurable phenomena which can occur at the beach as a result of the different mechanisms are placed in the double bordered rectangles in the centre of the scheme. Paragraph 4.5 describes them. In this paragraph the chains of events to reach a measurable phenomenon illustrated by theoretical explanation.

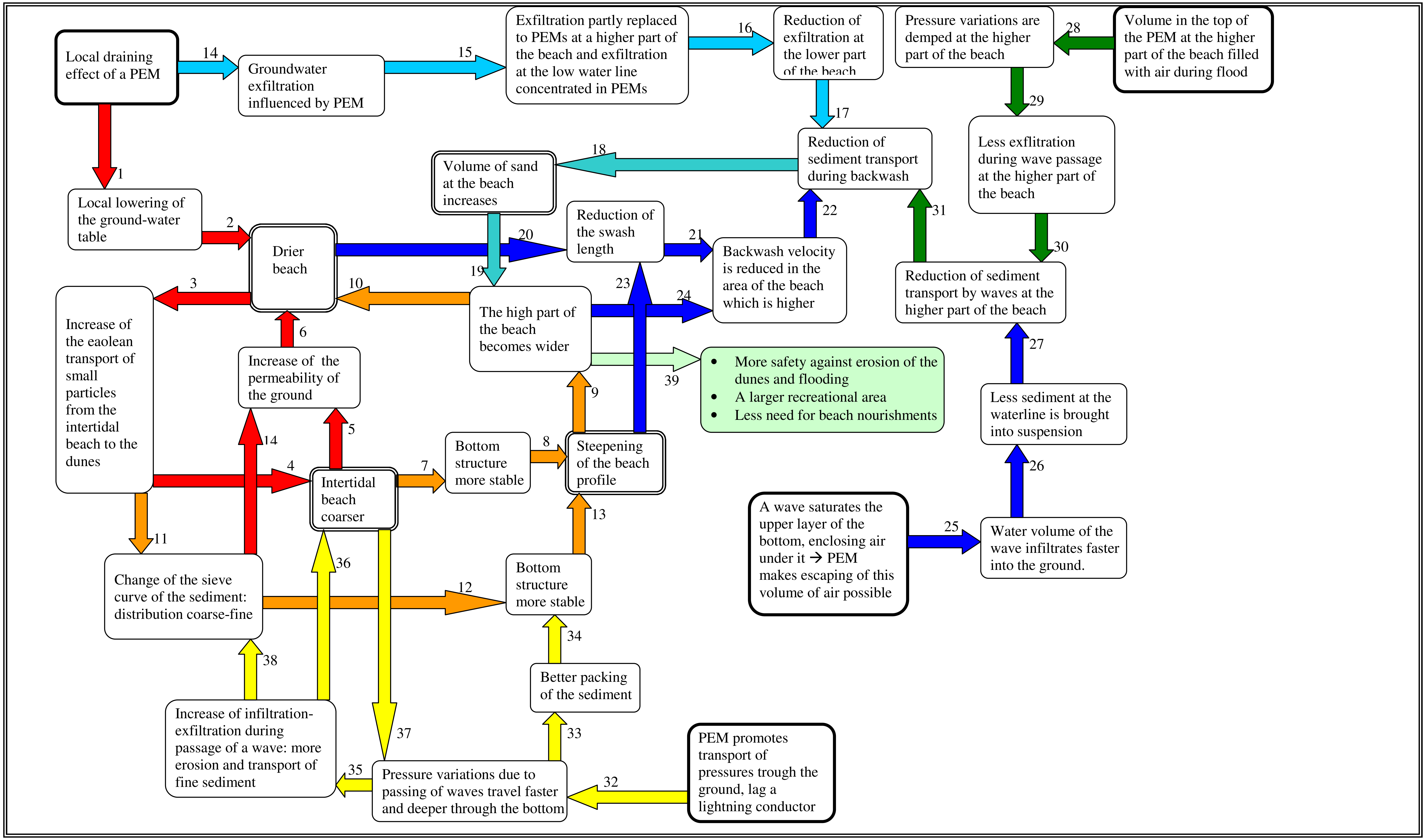

Figure 12: Scheme with an overview of all different hypotheses of the working of Ecobeach

4.4 *Initial events*

4.4.1 Possible starting events

Different events can occur near or in a PEM which can start a chain of events leading to more accretion or less erosion of the beach:

- lowering of the groundwater table
- promotion of (local) exfiltration
- increasing pressure variations in the bottom (by PEM totally filled with water)
- reducing pressure variations in the bottom (by PEM partly filled with air)
- guiding captured air to the surface

4.4.2 Lowering of the groundwater table

The groundwater level under the beach depends on tides and waves. The (asymmetric) tidal variation propagates through the ground under the beach. During this propagation in the direction of the dunes the amplitude decreases, the asymmetry increases (due to the limited permeability of the sand body) and the mean groundwater level increases [12]. Rising of the groundwater table occurs much faster than falling. Waves can let the groundwater table rise very fast during rising tide when they infiltrate into the dry sand and fill the ground with water (see appendix D.4.3).

Because the mean groundwater level around the high waterline is higher than the mean groundwater level around the low waterline a groundwater circulation flow exists under the beach [25] (see Figure 11). A PEM under the higher part of the beach can form a shortcut for the water just under the surface to the deeper groundwater which is transported to the lower part of the beach (see Figure 13). This process can drop down the water level at the higher part of the beach a little bit.

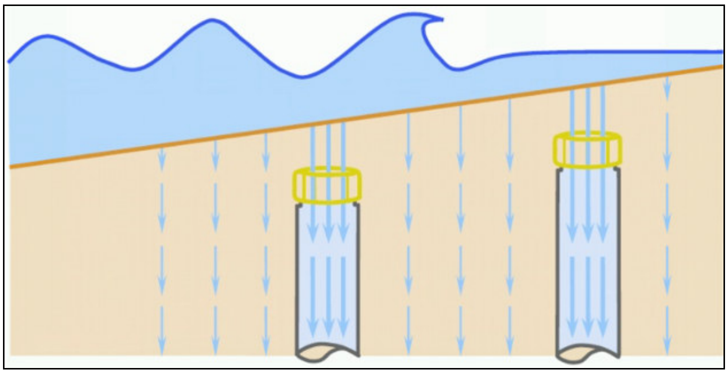

Figure 13: Downward directed water transport trough PEMs

4.4.3 Promoting/decreasing (local) exfiltration

In the natural situation exfiltration of groundwater occurs near the low waterline [25]. The phenomenon is part of the groundwater circulation under the beach (see paragraph 3.2.4 and Figure 11). The PEMs can form a shortcut between the deeper groundwater and the beach surface. This can lead to exfiltration of a part of the circulating groundwater before it has reached to low waterline. Besides this it can reduce the exfiltration volume around the low waterline.

At the natural exfiltration area a PEM can form a vertical flow canal and concentrate the groundwater outflow to a smaller area. This reduces the exfiltration in the area outside the direct vicinity of the PEM (see Figure 14).

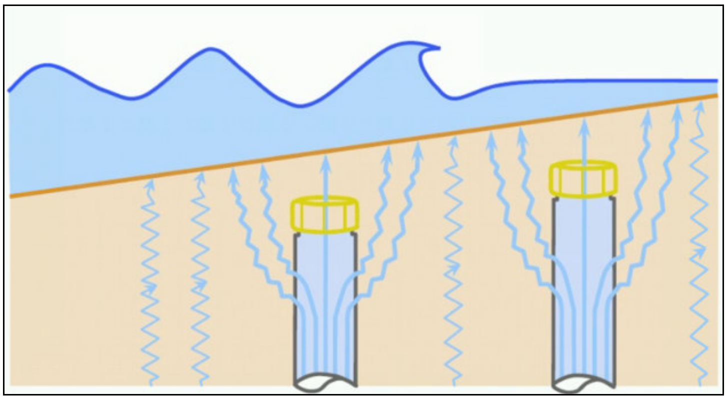

Figure 14: Upward directed water transport trough PEMs

4.4.4 Increasing pressure variations in the bottom

The passage of wind waves over the beach causes pressure variations at the beach face. These variations are transported through the bottom. At a depth of 1.0 m the pressure variation during the passage of a 0.5 m wave are in the order of 0.2 m. This is measured by pressure transducers called divers (see Appendix D.4 and Figure D6).

A PEM can conduct a pressure variation deeper into the ground because of the absence of friction by grains (see Figure 15). Pressure variations at the top side of a PEM probably hardly decrease during transport through the water filled tube.

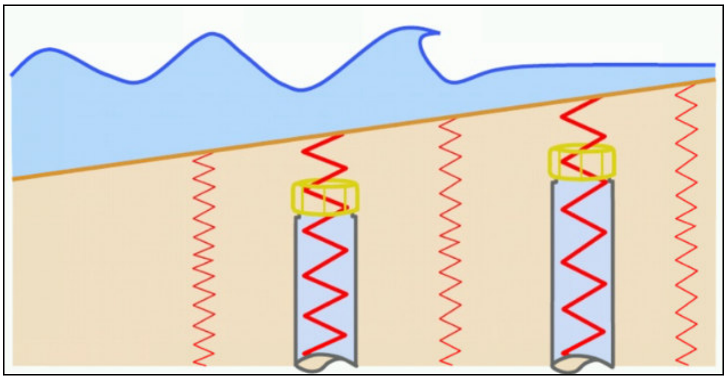

Figure 15: Pressure variations conducted by PEMs

4.4.5 Decreasing pressure variations in the bottom

Pressure variations in the bottom, caused by passing wind waves, can be damped by air enclosed in the saturated bottom. The spring stiffness of air is much smaller than the spring stiffness of water. When a pressure wave is passing a volume of air in the ground, the air can compress easily and the pressure wave weakens (see Figure 16).

The upper 70 cm of a PEM is not perforated, excepting a small air filter in the top. During low water, the upper part of a PEM can be above the groundwater level, in the capillary zone or the dry sand. At this moment the PEM can be partly filled with air. When the phreatic surface rises, due to the rising tide, the air has to leave the PEM through the small air filter in the top. Nevertheless there is very little transport of air possible through the capillary zone where capillary forces between the grains could be strong enough the prevent air to escape to the beach surface. In this way a volume of air can be enclosed in the top part of a PEM.

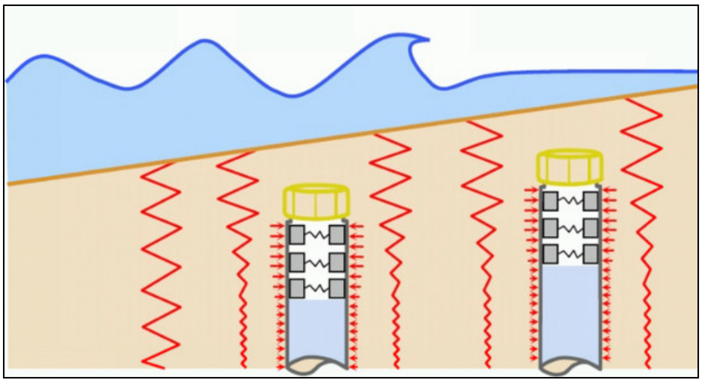

Figure 16: Pressure variations decreased by PEMs

4.4.6 Guiding captured air to the surface

Waves can let the groundwater table rise very fast during rising tide when they infiltrate into the dry sand and fill the ground with water. It is possible that air is enclosed under the upper layer of the beach, which becomes saturated by these waves. A PEM can form an escape route to the surface for this volume of air (see Figure 17).

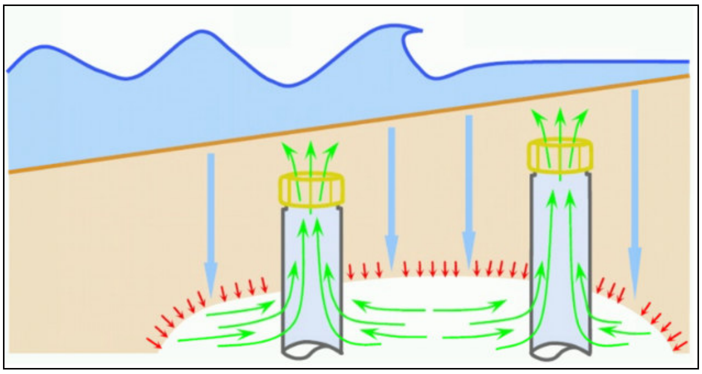

Figure 17:Outflow of captured air by PEMs

4.5 Indicators of the different processes

4.5.1 Drying of the beach

Causes of drying

The diagram of Figure 12 shows different chains of events leading to a drier beach. A simple hypothesis is a local lowering of the groundwater level (*chain 1-2*), caused by a draining effect of a PEM. This lowering of the groundwater level leads to a drier beach. An other hypothesis of the drying is coarsening of the beach (*chain 5-6*). When the sediment at the beach is coarser, the permeability becomes larger and the beach will be more drainable. Most of the time, the groundwater level near the high waterline is higher than the sea water level. The natural drainage by a circulation flow (see paragraph 3.2.4) becomes better when the permeability of the bottom is better. This can drop down the groundwater level especially at the upper part of the beach. Also the hypothesis described by *chain 9-10* is a possible mechanism for drying. When the beach face becomes steeper in the intertidal zone a larger beach width will be above a specific elevation. When the sea water level is under this specific elevation a larger area will dry up than before the widening of the upper beach.

Consequences of a dry beach

The diagram of Figure 12 shows different consequences of drying the beach. The intertidal zone of the beach can become coarser, according to *chain 3-4*, because the aeolean transport of sediment on a dry beach is more than when the beach face is wet. The aeolean transport involves mainly the fine sediments, which are transported from the intertidal to the dunefoot. When the fines are removed by the wind, the composition of the beach becomes coarser.

Besides an increase of the aeolean transport, a drier beach can influence the swash and via this the quantity of sand on the beach (*chain 20-21-22-18*). At a dry beach a larger volume of water will infiltrate during the wave uprush than at a moist beach. When the lost volume of water during uprush becomes larger, the backwash volume of the waves becomes smaller. When the backwash volume is smaller, less sediment will be transported offshore during this backwash. The uprush volume is less influenced by the infiltration in the dry beach, because this infiltration mainly occurs at the end of the uprush whereas the (turbulent bore) transport mainly takes place in the beginning.

4.5.2 Coarsening of the sediment

Causes of coarsening
The diagram of Figure 12 shows different hypotheses of coarsening of the intertidal zone. The intertidal zone of the beach can become coarser, according to *chain 3-4*, because the aeolean transport of sediment on a dry beach is more than when the beach face is wet. The aeolean transport involves mainly the fine sediments, which are transported from the intertidal zone to the dunefoot. When the fines are removed by the wind the composition of the beach becomes coarser.

Also *chain 27-30-31* can cause coarsening of the sediment. When a wave moves through the intertidal zone, the extremely turbulent bore brings a lot of sediment into suspension. This sediment is moved onshore by the wave. An extra mechanism to bring sediment into suspension is the infiltration-exfiltration just behind and in front of the bore. This is described in paragraph 3.2.4 and Figure 10. This exfiltration mechanism is mainly related to the fine sediment particles, because they are light and have small pores which mean large resistance against the exfiltrating water. The presence of a PEM could promote the propagation of pressure variation through the ground (see paragraph 4.4.4) and so the infiltration-exfiltration mechanism. This can lead to more wash-out of fines which are transported to the high waterline by the waves. The intertidal beach becomes coarser according to this hypotheses.

Consequences of coarsening
The diagram of Figure 12 shows different consequences of coarsening of the sediment in the intertidal zone. A consequence of a coarsening of the intertidal zone is drying up of this part of the beach *chain 5-6*. When the sediment at the beach is coarser, the permeability becomes larger and the beach will be more drainable. Most of the time the groundwater level near the high waterline is higher than the sea water level. The natural drainage by a circulation flow (Figure 11, paragraph 3.2.4) becomes better when the permeability of the bottom is higher. This can drop down the groundwater level especially at the upper part of the beach.

Besides a drier beach, steepening of the beach profile can be a consequence of a coarser intertidal zone (*chain 7-8*). The steepness of a beach profile depends amongst others on the sediment particles. The larger the particles are, the steeper the beach face will be [29]. The wash out of fines can also lead to larger open spaces between the sediment particles (*chain 37)*. Groundwater flowing though the pore grid experiences less friction with the sand body. This makes it easier for pressure variation to travel through the bottom.

4.5.3 Increase of the steepness of the beach face

Causes of the increase of the steepness
The diagram of Figure 12 shows different hypotheses of increase of the steepness of the beach face. A coarsening of the beach can lead to a steeper intertidal beach *(chain 7-8),* because the natural steepness of a beach face of larger sediment particles is larger than that of smaller sediment particles [32].

If the composition of the sediment at the beach changes, due to influenced transport processes, the beach face can become steeper according to *chain 12-13*. The strength of a sand body or the angle of repose can be indicated by, amongst others, the sieve curve. The packing of the sand particles also influences the strength of the sand body. According to the third hypothesis (paragraph 4.4.4) a PEM could make it easier for pressure variation to travel through the ground. These pressure variations can vibrate the ground to a higher packing density (*chain 32-33-34-13*). As a result of a better packing of the sand body, the steepness of the beach face will increase.

Consequences of the increase of the steepness
Increase of the steepness of the beach face can be a possible mechanism to achieve a drier beach (*chain 9-10*). When the beach face becomes steeper in the intertidal zone a larger beach width will be above a specific elevation. During low water level a part of the beach will dry up. This part becomes larger when a larger beach width is elevated above a specific level.

An other consequence of a steeper beach can be accretion, according to *chain 23-21-22-18.* When the steepness of the beach face is increased, the length of the swash zone is decreased and the length over which the backwash transports sediment in offshore direction is also decreased. Most of the offshore sediment transport occurs in the end of the backwash, because there the backwash flow has developed the largest velocity. At a less steep beach face the maximum backwash velocity will be a little smaller, but the distance over which the backwash exceeds a specific velocity is larger. When the uprush reaches the top of the steep part of the beach profile the velocity is already small and the last sediment which is still in suspension will settle. The volume of water at this high (almost horizontal) part of the beach will return very slow and does not cooperate with the remaining uprush volume to develop a strong backwash flow.

4.5.4 Increase of the amount of sediment at the beach

Causes of the increase of the amount of sediment
The diagram of Figure 12 shows different hypotheses of increase of the amount of sediment at the beach. One hypothesis is a consequence of the influence of the draining of a PEM on the exfiltration of groundwater (*chain 14-15-16-17-18*), described in paragraph 4.4.3. If the exfiltrating groundwater uses a PEM as shortcut, the exfiltration volume in the surrounding area can become smaller. Canalisation of the groundwater through the PEM occurs. Besides that the exfiltration can be partly replaced from the low water line to a higher located PEM. A smaller exfiltration volume can prevent sediment particles being washed out and picked up by the backwash of the waves. The concentration of exfiltration through a PEM can locally (just above the PEM) lead to more erosion, but reduce exfiltration (and erosion) in a much larger area.

An other hypothesis leading to a reduction of the volume of sediment transported during backwash, is reducing the backwash volume (*chain 20-21-22-18*). This can be achieved by drying the beach, because at a drier beach a larger volume of water can infiltrate during uprush, resulting in a smaller volume of water in the end of an uprush event. The backwash will then be lacking a part of its original volume and develop a smaller velocity. This reduces the offshore sediment transport during backwash which results in an increase of the amount of sediment at the beach.

The third hypothesis leading to smaller offshore directed volumes of sediment during backwash is initiated by an increase of the steepness of the beach profile (*chain 23-21-22-18*). When the steepness of the beach face is increases, the length of the swash zone is decreased and the length over which the backwash transports sediment in offshore direction is also decreased. Most of the offshore sediment transport occurs in the end of the backwash, were the backwash flow has developed the largest velocity. At a less steep beach face the maximum backwash velocity will be a little smaller, but the distance over which the backwash exceeds a specific velocity is larger. When the uprush reaches the top of the steep part of the beach profile the velocity is already small and the last sediment which is still in suspension will settle. The volume of water at this high (almost horizontal) part of the beach will return very slow and does not cooperate with the remaining uprush volume to develop a strong backwash flow.

Consequences of the increase of the amount of sediment
The diagram of Figure 12 shows different consequences of increasing the amount of sediment at the beach. When more sediment is present at the beach a larger area will be above a specific elevation. A consequence of this is a larger vertical distance between the beach face and the groundwater level (*chain 19-10*). This will cause a drier beach.

The goal of the Ecobeach system is to increase the amount of sediment at the beach. *Chain 19-39* shows the desired consequences of this. More sediment means a wider beach, with a larger volume of sediment between the low water level and the dunefoot. This will reduce the wave heights at the dunefoot during a storm and protect the dunes. Besides this the dunes can restore faster after a storm, because more sediment is available. A larger width of the beach increases its recreational function. If the Ecobeach system generates a wider beach, this will save costs of beach nourishments.

4.6 Local influence by a PEM turning on a global effect

In the diagram of Figure 12 some chains of events form a circle. This suggests a process is supposed to be able to reinforce oneself after one event in the chain occurs. In this way a local effect, just in the area of a PEM, can build out to a global effect, in the entire intertidal zone or the entire beach.

The events “drying of the beach” and “coarsening of the beach” can reinforce themselves by the circles of events described below (see Figure 12):

- Drying → *3-4-5-6* → Drying
- Drying → *3-11-14-6* → Drying
- Drying → *3-4-7-8-9-10* → Drying
- Drying → *3-11-12-13-9-10* → Drying
- Coarsening → *37-35-36* → Coarsening
- Coarsening → *37-35-38-14-6-3-4* → Coarsening
- Coarsening → *37-33-34-13-9-10-3-4* → Coarsening

Other events are also part of these circles. More circles exist containing coarsening, but these are mentioned above with drying. Steepening of the beach profile is not mentioned above, but this event is part of most of the circles.

4.7 Testing different hypotheses in the field

It is possible to test the hypotheses of working mechanisms of the Ecobeach system described in this chapter. A lot of events described in the scheme of Figure 12 are measurable at the beach. During a field work, measurements were done at the beach (see Chapter 5) to look for the presence of some of the (starting) events from the scheme. The hypothesis of paragraph 4.4.6 was invented after the field measurements were executed. For this reason no special measurements were done to test this theory.

The groundwater behaviour in was measured, with and without PEMs, at different distances from PEMs and in the top and the bottom of PEMs. Beside the groundwater measurements the sediment was analysed inside and outside the southern Ecobeach test area. This is an indicator of some of the processes described in Figure 12. The next chapters describe the experiment and show the results.

5 Description fieldwork August – September 2009

5.1 Introduction

For the scientific study of Ecobeach a two weeks during field work was executed at the beach near Egmond aan Zee, just to the south of the Dutch Ecobeach test location. Different hypotheses of possible working mechanisms of Ecobeach, mentioned in paragraph 4.4, had to be tested by measurements of the groundwater and sediment analysis. At two locations between the low water line and the high water line measurement instruments called divers were placed in de ground to investigate the groundwater behaviour with and without Ecobeach PEMs. Moreover, sediment samples were taken to study the composition of the bottom and to compare the sediment at the Ecobeach test area with the sediment at the bordering areas. In 2005 a field test was executed in Denmark [5], see Appendix D.6.

5.2 Organization and location

The fieldwork has been done between the 26th of August and the 10th of September 2009 while the net measurement time was 13 days. During this period two researchers have stayed at the beach all day. A site hut was placed as office and a tent to sleep in (see the right hand side of Figure 18). It was necessary to live close to the measurement instruments and to have all equipment at the measurement location. In the end of August the beach becomes less crowded, because holidays are ended. The temperatures of air and water are still nice to work in, and the change of appearance of moderate wind and waves is obvious larger in this period compared to mid-summer. These circumstances were desirable for the measurements.

The groundwater measurements have been executed at a location 250 m south of the southern Ecobeach test area. At this location the beach was expected to not be influenced by the Ecobeach PEMs while the system of beach, dunes and foreshore were comparable to the Ecobeach test area. The southern Ecobeach test area is situated between RSP 40000 – 43000 and the measurements have been done at RSP 43250, in an area of approximately 25 X 60 m (Figure 18).

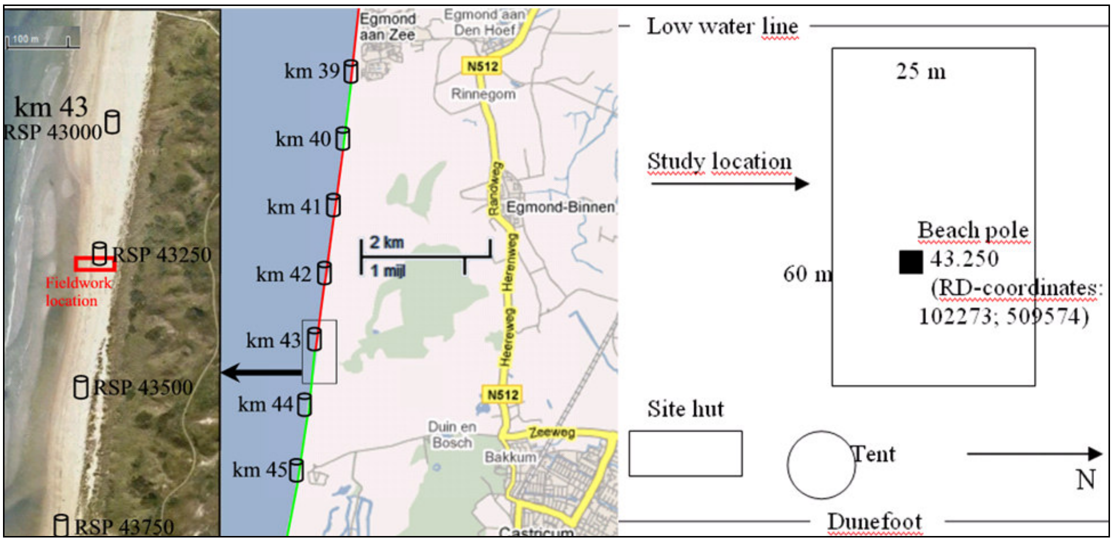

Figure 18: Location of the fieldwork

5.3 Circumstances during the fieldwork

Table 2 shows the daily notes about the weather. Two small storms appeared which were quite heavy for the time of the year. Most of the time, the wind direction was onshore. The temperature in the table is an indication of the maximum temperature, given by the local weather forecast.

Day	Wind direction, force	Temperature	Conditions
28 Aug	SW, 7-8 Bft	18 °C	Thunderstorms
29 Aug	W, 4-5 Bft	18 °C	Showers in the morning
30 Aug	W, 4 Bft	20 °C	Sun and clouds
31 Aug	Z, 3 Bft → 1 Bft	25 °C	Sunny
01 Sept	ZW, 5 Bft → 6 Bft	22 °C	Sun and clouds
02 Sept	ZZW, 4 Bft → 3 Bft	20 °C	Sun, clouds and some showers
03 Sept	ZW, 8 Bft	18 °C	Heavy showers and sandstorm
04 Sept	W, 5-6 Bft	18 °C	Cloudy and some showers
05 Sept	WNW, 4-5 Bft	18 °C	Cloudy
06 Sept	W, 4 Bft	19 °C	Sun and clouds
07 Sept	ZW, 3 Bft → 1 Bft	22 °C	Sunny
08 Sept	ZW, 2-3 Bft	26 °C	Sunny
09 Sept	N, 4 Bft	19 °C	Sun and clouds

Table 2: Weather circumstances during the fieldwork

The significant wave height ($H_{M,0}$) at sea was measured at Stroommeetpaal IJmuiden measurement station. This station is located just offshore, at the mouth of the port of IJmuiden, about 14 km south of the fieldwork location. Figure 19 shows the significant wave height between August 25th and September 11th. Four peaks are visible in the figure: 287 cm on 28-aug-2009 18:00 h, 323 cm on 2-sept-2009 1:00 h, 461 cm on 3-sept-2009 17:00 h and 351 cm on 4-sept-2009 20:00 h. The most heavy wave climate appeared on the 3rd of September.

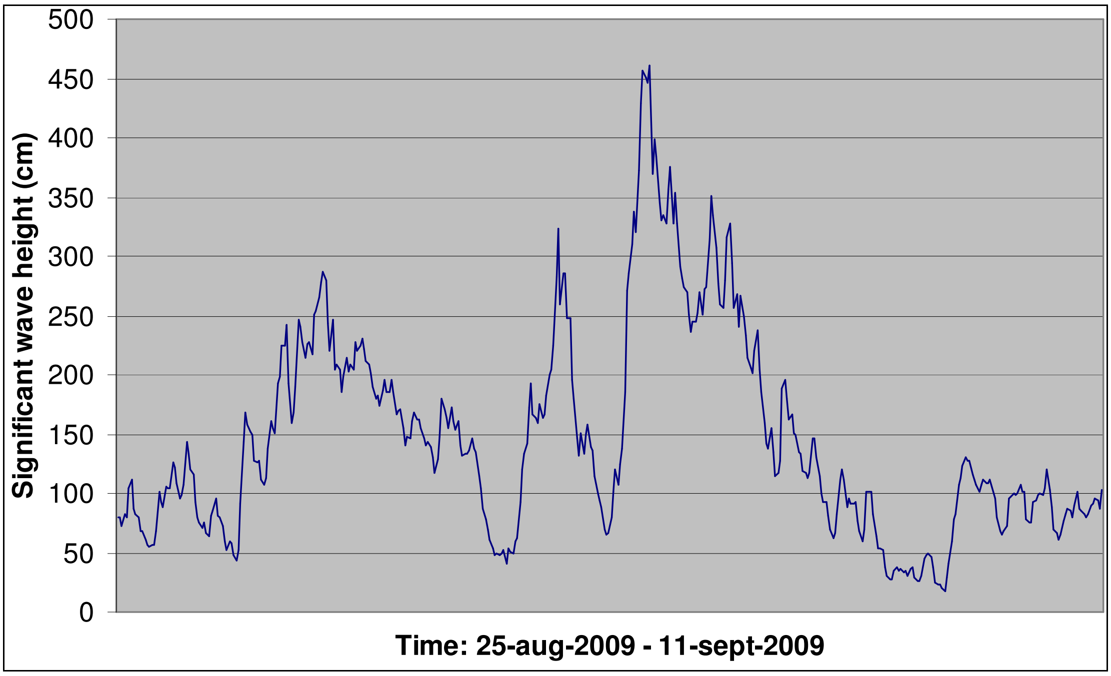

Figure 19: Significant wave height just offshore during the fieldwork (Stroommeetpaal IJmuiden) [7]

The water level at the fieldwork location mainly depends on astronomical tides. Moreover, wind and wave height are important factors. Figure 20 shows the water level at the seaside of the port of IJmuiden. This measurement point is situated about 14 km south of the fieldwork location. The astronomical tide appears at the fieldwork location with a time lag of about 15 minutes compared to the port of IJmuiden. The highest water level of NAP +165 cm (see Figure 20) appeared on the 5th of September 3:40 h.

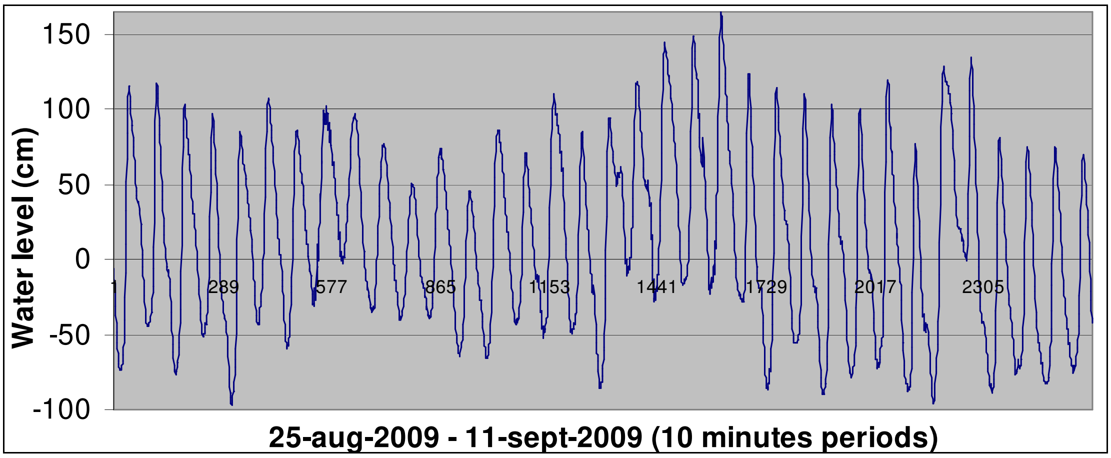

Figure 20: Water level of the North Sea close to the fieldwork location

5.4 Plan of the measurement area

The measurement area is a rectangle of about 25 X 60 m, located between the high and low waterline (see Figure 18). Figure 22 shows the arrangement of the different objects in the measurement area. Besides the exact location of all objects, the dates of placing and removing and the vertical distance to the top of beach pole RSP 43250 are listed in the figure. After about one week of measurements, a 60 m long row of 7 PEMs (named a – g) has been placed. PEM h was planned to be the lowest one, but during the days the PEMs were placed the water level was not low enough to place this tube.

Around PEM b (high waterline) measurements have been done with 2 divers in the ground and 2 in the PEM. Around PEM f (low waterline) measurements have been done with 5 divers in the ground (of which diver 9 and 3 broke down during the measurement period) and 2 in the PEM. Diver 12 broke down during the storm of September the 3rd. Diver 13 measured the wave climate and water level above the surface. The vertical position of this diver has been changed after a lot of erosion had occurred. Around and to the north of PEM e, short period measurements to the pressure variations due to wind waves have been done.

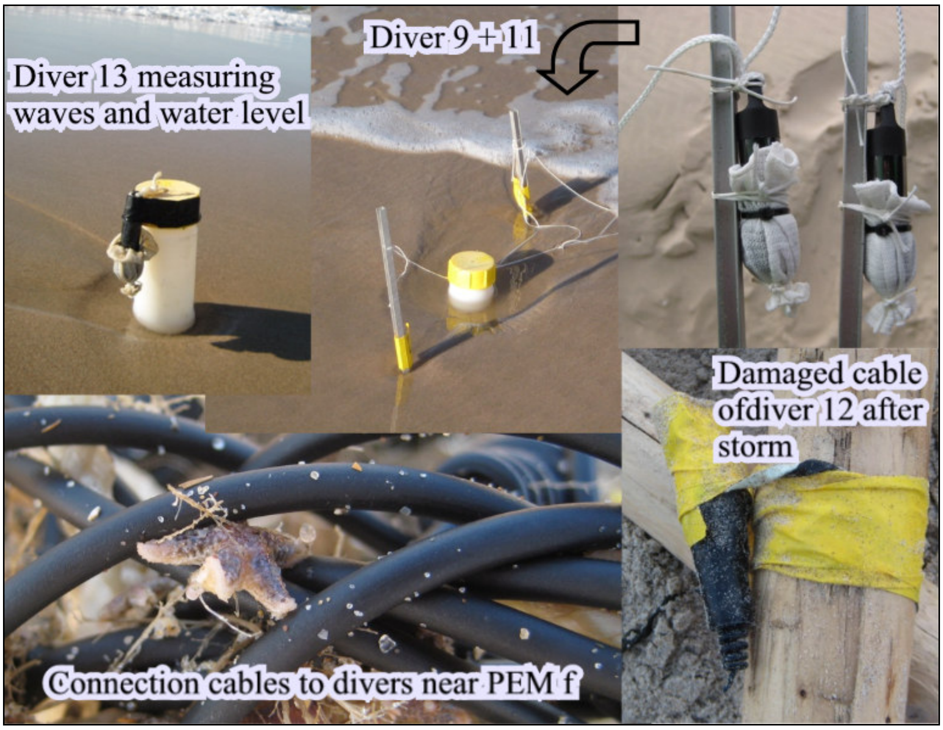

Figure 21: Elements in the measurement area

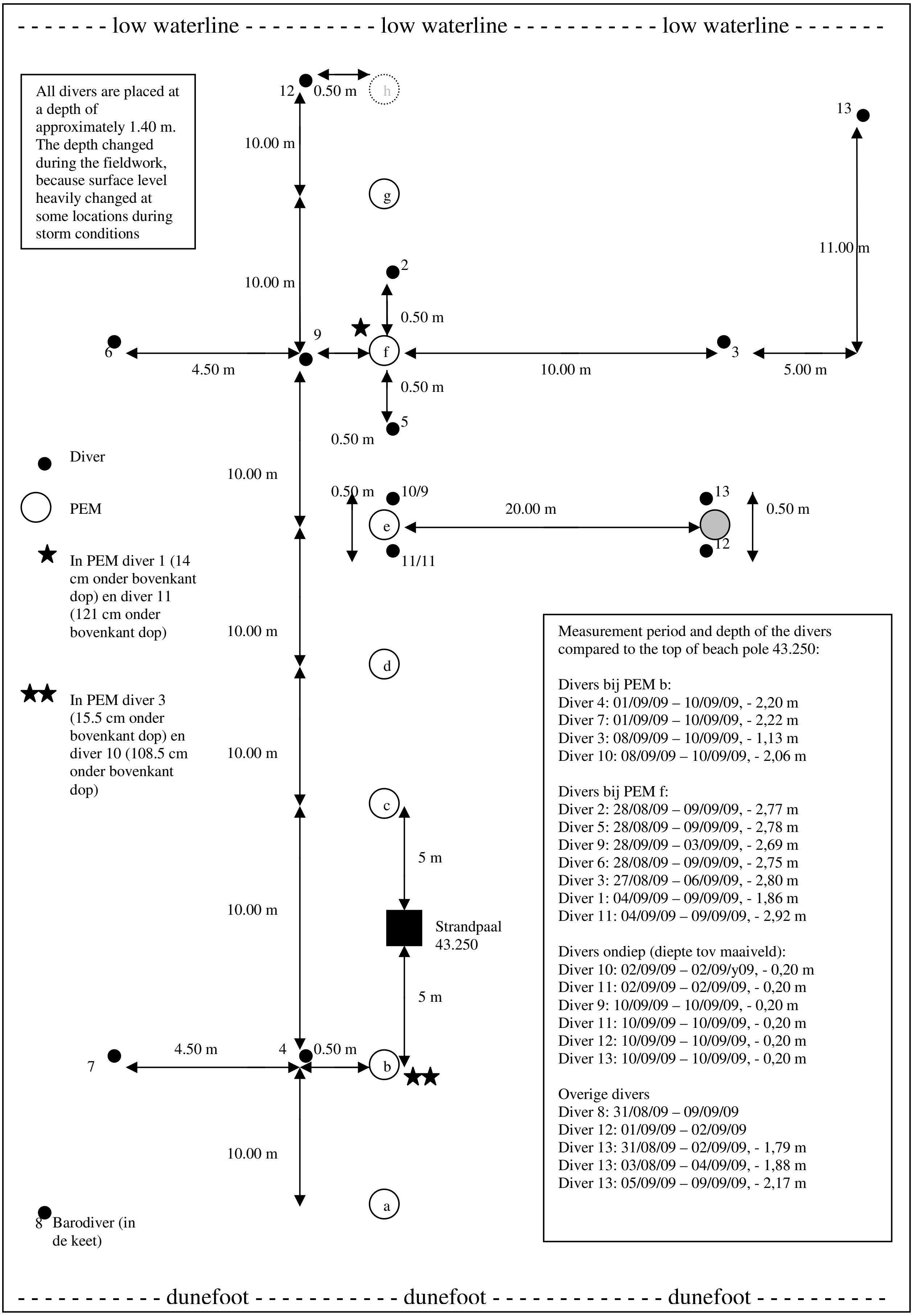

Figure 22: Arrangement of the measurement area

5.5 Diver measurements

5.5.1 Divers used during the field work

To measure different characteristics of the groundwater, divers are used during the fieldwork. Divers are small measurement devices which can be placed under water. 5 Cera Divers and 8 CTD divers have been used (see Figure 23). Cera divers measure pressure and temperature and have a ceramic housing in stead of the standard steel housing. This housing protects them against the saline beach groundwater. CTD divers measure pressure, temperature and conductivity. The conductivity indicates the salinity of the groundwater. In Appendix D more information is available about the divers.

Figure 23: Cera Diver

5.5.2 Installation of the divers

It is common to use divers in combination with a piezometer which is placed in de ground and protects the diver against the surrounding. Measurements with and without a piezometer pipe were done at the beach of Egmond to compare both situations (see Appendix D.4). It has become clear that the diver which was placed without piezometer pipe (directly surrounded by the bottom material) registeres pressure variations, caused by wind waves, the best. Figure 24 shows the protection of a diver, which is placed directly into the sand body.

Figure 24: Protection of a CTD Diver against sand particles

To place the divers in the ground, a hole is made by hand using a pulse drill. Using this drilling technique the disturbance of the bottom is limited. Connection cables to the surface (see Figure 21) make is possible to communicate with the divers.

5.5.3 Data collected with the divers

During the fieldwork, a lot of data about the groundwater behaviour is collected with divers. During low tide the data could be downloaded and the instruments could be set up again. Because the PEMs have been placed halfway the measurement period, the situation with and without PEMs can be compared. Table 3 shows she measurement program of the divers during the fieldwork. In Appendix D.5 more information about the collected data is available.

The different phenomena which were intended to measure with the divers are:

- The groundwater level before and after placing a row of PEMs, at the low waterline and at the high waterline.

- The groundwater level at different distances from a PEM at the low waterline and at the high waterline.
- The pressure variations in the ground before and after placing a row of PEMs, at the low waterline and at the high waterline.
- The pressure variations in the ground at different distances from a PEM at the low waterline and at the high waterline.
- The water level and development of an air bell in a PEM at the high waterline and at the low waterline.
- The waves and water level at the low water line, as reference, and the air pressure to be able to compensate the pressure measurements of the divers in the ground.

Diver	27-aug	28-aug	29-aug	30-aug	31-aug	01-sep	02-sep	03-sep	04-sep	05-sep	06-sep	07-sep	08-sep	09-sep	10-sep
1									blue	cyan	cyan	dark green	dark green	dark green	
2		green	green	green	blue	black	dark green	cyan	blue	green	green	dark green	dark green	dark green	
3	green	green	green	green	green	blue	dark green	cyan	blue	cyan	cyan	black	dark green	dark green	dark green
4				green	green	blue	dark green	cyan	blue	green	green	cyan	dark green	dark green	dark green
5		green	green	green	blue	blue	dark green	cyan		cyan	cyan	dark green	dark green	dark green	
6		green	green	green	blue	blue	dark green	cyan		cyan	cyan	dark green	dark green	dark green	
7				green	green	blue	dark green	cyan	blue	green	green	cyan	dark green	dark green	dark green
8				red	red	red	red	red	red	red	red	red	red	red	
9		green	green	green	blue	blue	dark green	black	black	black	black	black	black	black	blue
10							blue						dark green	dark green	dark green
11							blue		blue	cyan	cyan	dark green	dark green	dark green	blue
12						blue	dark green	cyan	black	black	black	black	black	black	blue
13					cyan	blue	dark green	cyan		cyan	cyan	dark green	dark green	dark green	blue

red	Baro
green	Level (10 s / 1 min)
dark green	Level (mean)
cyan	Wave (1.0 s / 2.0 s)
blue	Wave (0.5 s)
black	Communication error / out of reach

Table 3: Measurement program of the divers

5.5.4 Problems during the measurements

During the diver measurements some problems occurred. Diver 12 was placed next to the intended PEM h (see Figure 22). This diver became out of reach when the low water level became not as low as during the day that the diver was placed (see Figure 20 and Table 3). During a storm at the 3rd of September, the cable of the diver was damaged and no measurements have been done anymore. The relatively high water level made it impossible to place PEM h together with the other PEMs.

After the row of PEMs was placed, with their tops about 25 cm under the surface, a lot of sand was removed by the storm of September the 3rd (see Figure 26). Some of the PEMs were visible above the surface after this storm. Divers 3 and 9 in the area around PEM f gave a communication error after some time. In Table 3, this is visible by the black beams. The connexion between the diver and the cable probably was disturbed by the saline water.

5.6 Sediment analysis

5.6.1 Sampling along the coast

Sediment samples along the coast, about 15-20 m from the low waterline, have been taken during low water on the 6th and 7th of September. These days the weather was quiet (see Table 2) which limited the sediment transport in the swash zone. The sediment has been taken from a depth of 5-10 cm, because the surface can be influenced by aeolean sediment transport while the intertidal beach is dry. The 6^{th} of September samples have been taken between RSP 43000 – 45000 and the next day samples have been taken between RSP 38000 – 43000. The samples have been analysed with laser analyses at the VU University and the results are presented in Chapter 6.

5.6.2 Sampling in the measurement area

Sediment samples at the groundwater measurement location have been taken on the 8^{th} and 9^{th} of September. At 4 locations between the high and low waterline samples have been taken from different depths: the surface, -0.50 m, -1.25 m and -2.0 m. When at an other depth a layer of shelves was found, an extra sample has been taken from this depth. The samples have been analysed with laser analyses at the VU University and the results are presented in Chapter 6.

6 Sediment and morphology at the field site and sediment analysis along the coast

6.1 Introduction

During the fieldwork described in Chapter 5 the groundwater measurements took place in an area of about 25X60 m (Figure 18).. In this area sediment samples are taken from the surface and different depths to have a clear insight into the composition of the bottom. This knowledge can help interpreting the diver measurements. Besides the bottom material the topology of the fieldwork location is measured several times during the measuring period. Significant morphological changes occurred, mainly in the lower intertidal zone, during stormy conditions. Groundwater behaviour can be influenced by the shape of the beach profile and the depth of the divers.

During the winter 2008/2009 some measurements were done at the beach of Egmond aan Zee to get insight into the conditions of the Ecobeach test site. A sediment analyses, (see Appendix F.2) showed interesting results. The sediment in the intertidal zone was coarser at a location in the southern test area (RSP 42000) than at a location in the reference area (RSP 44000). During the field work in september 2009, a new sediment analysis was done. This time the intertidal zone of the total coastline was investigated instead of just two locations. The results enable is to compare the 3 km long southern test area with the bordering areas.

6.2 Sediment analysis at the field site

6.2.1 Composition of the bottom

The composition of the upper 2 m of the bottom is interesting information, because the groundwater measurements are done within this depth and the PEMs are normally functioning in the upper 2.5 m of the bottom. At 4 locations between the high and low waterline sediment samples are taken from the surface, 0.5 m, 1.25 m and 2.0 m depth. When a notable shelf layer is located an extra sample is taken from the depth of this layer.

Figure 25 shows de D50 of all samples in a cross section of the measurement area. In italic the depth of each sample is given and between brackets the weight percentage of particles larger than 2 mm is given. These particles are too large for laser analysis and for that reason they are sieved out of the sample before the analyses. When no number between brackets is displayed the quantity of large particles is very low or not any particle above 2 mm is present in the sample.

6.2.2 Consequences for Ecobeach

The sediment at the surface of the beach gradually becomes coarser between the dunefoot and the low waterline. This phenomenon corresponds with a previous sediment analysis in the Ecobeach test area and the reference area (see Appendix F.2). Everywhere at the surface the sediment is relative fine compared to the bottom material in the upper 2 m of the ground. Around and landward of the beach pole the coarsest sediment is found at a depth of 1.5 – 2.0 m. Seaward of the beach pole the coarsest material is found at a smaller depth: 0.5 – 1.25 m. During storms in the 2 weeks before the samples were taken the area seaward of the beach pole was lowered by more than 0.5 m. This means that the coarse layer was situated at a depth of 1.0 – 1.75 m before this erosion occurred.

In the top layer of the beach very little shelves are found, while in the layer of coarser sediment 10 – 30 % of the weight can be shelf particles larger than 2 mm. This view will not always be through, because sometimes a large quantity of shelves can be found at the surface, but generally at the surface the quantity of shelves is insignificant.

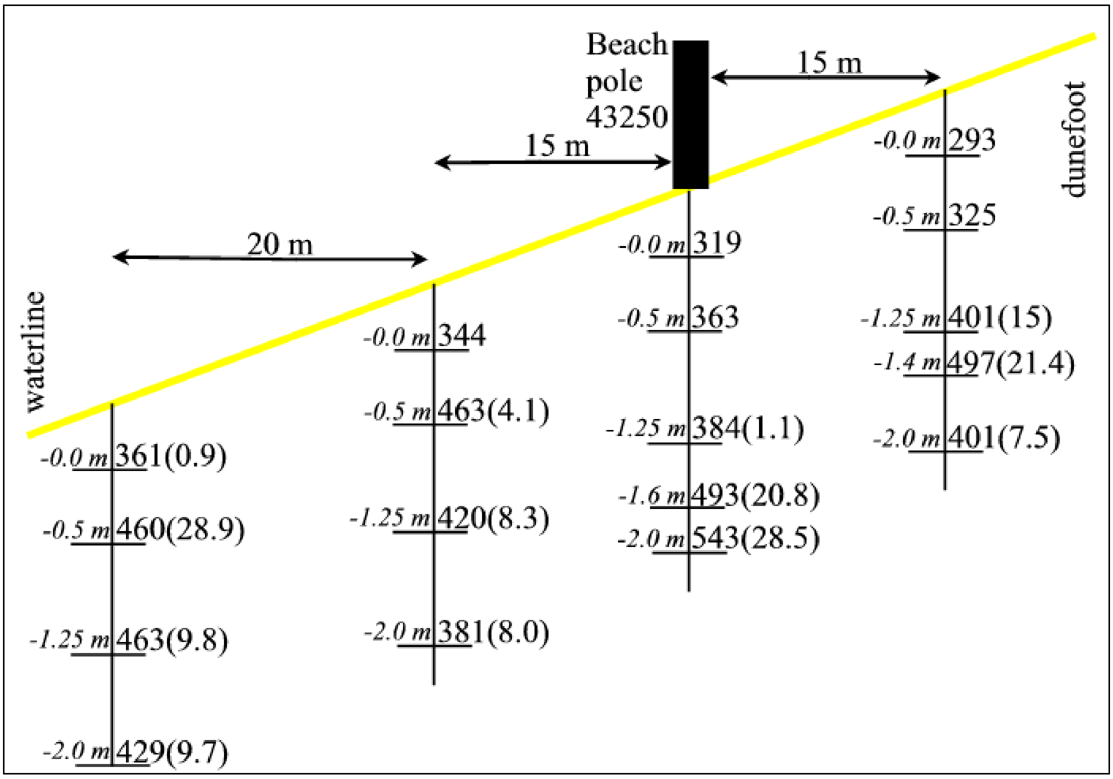

Figure 25: D50 of sediment at the fieldwork location; between brackets: volume % of shelves (>2 mm)

It becomes clear from Figure 25 that a layer of coarser sand particles and shelves exists under a top layer of finer sand particles and very little shelves. Especially near the high waterline the difference between the top layer and the layer at about -1.5 m is significant. De D50 of the coarse layers is about 65 – 70% larger than of the surface. The conductivity of the coarse layer with shelves will be larger than of the top layer while the Ecobeach PEMs are penetrating through the coarse layer. This makes the hypotheses of paragraph 4.4.2 (draining capacity of the PEMs) plausible, because the PEMs can be a shortcut to a layer with relative good draining conditions.

6.3 Morphology at the fieldwork location

During the fieldwork the beach profile was measure 3 times. When the fieldwork started, in the end of August, the beach shape was like the blue line in Figure 26. Between the high waterline and the middle of the intertidal zone the beach slope was constant: 1:30. The lower part of the intertidal zone consisted of a bank and the slope at the low waterline was 1:15.

During a moderate storm in the beginning of September a lot of sand disappeared between the low waterline and the middle of the intertidal zone. The original bank disappeared totally and the beach slope became more constant: 1:28 – 1:35. The days after the storm a little bit more material disappeared and the total erosion was 45 - 70 cm over a length of 25 m. At the high waterline the surface rose 5-10 cm by sediment which was transported by wind from the original bank in the direction of the dunes, but most of the sediment was transported to the foreshore by waves. Divers which were placed at a depth of 1.4 m measured after the storm at a depth of 0.7 – 1.0 m and PEM which were placed 25 cm under the surface became visible after the storm (see Figure 27).

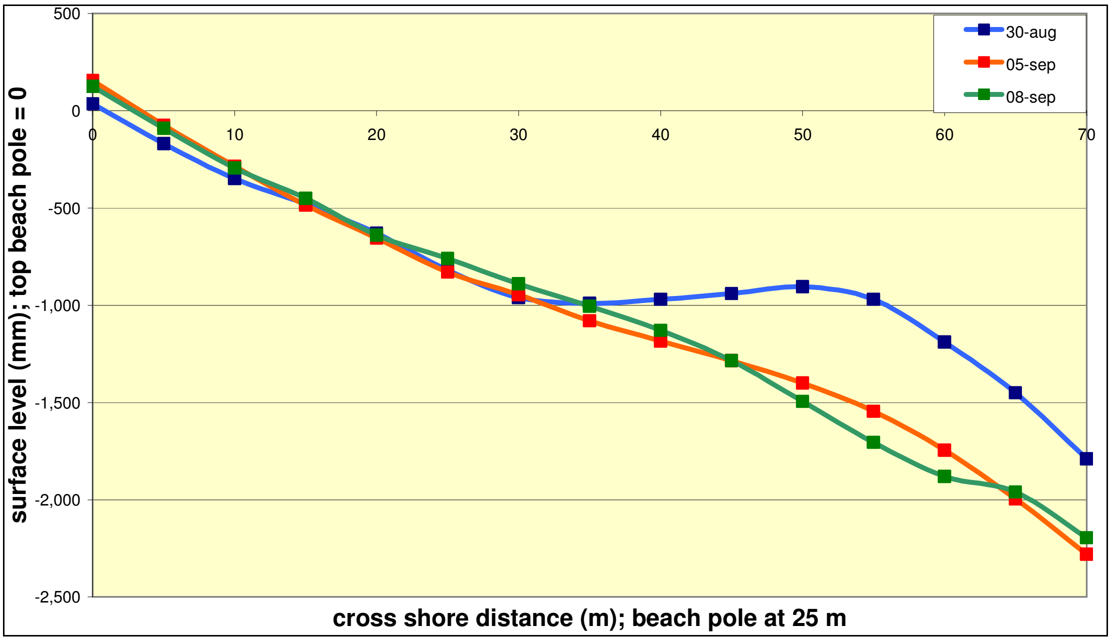

Figure 26: Development of the beach profile during the fieldwork

Figure 27: PEMs are visible at the fieldwork location after erosion

6.4 Sediment analysis along the Ecobeach coast

6.4.1 Design of the experiment

The execution of the experiment is described with the following points:

- In a 7 km long section of the coast (RSP 38000 – 45000) 29 sediment samples are taken from the intertidal zone.
- The spacing between the samples is 250 m. In the Ecobeach test area (RSP 40000 – 43000) every 100 m a row of PEMs is installed which means not all samples can be located just above a PEM.
- The samples are taken during low tide at about 20 m from the low water line.

- Time of sampling: RSP 43000 – 45000: 06/09/2009 14:30 – 15:30, RSP 38000 – 43000: 07/09/2009 15:30 – 16:30. Between these days the circumstances were very calm, with little sediment transport in the swash zone.
- The sediment of the samples is taken from just under the surface of the beach: 5 – 10 cm depth, because the top layer is sensitive for aeolean sediment transport while the sediment at a small depth is stable during low tide.
- A lot of characteristics (like sieve curve and particle shape) of the samples are investigated by laser analysis at the VU University (see Appendix F.5).

6.4.2 Measurement data

Table F1 of appendix F.3, shows the distribution of the particles of all samples over different size classes. To make it easy to interpret the numbers plots are drawn of the analysis results, see Figure 28, Figure 29, Figure 30 and Figure 31.

Figure 28 shows the D50 of each sample. From this figure is becomes clear that in the southern Ecobeach test area (RSP 40000 – 43000) the samples are relatively coarse, with D50s between 342 – 532 MU. Outside the test area the D50s vary between 308 – 435 MU. Because the difference between neighbouring samples is considerable the difference between D50s in the intertidal zone along the coast becomes clearer from Figure 29 where the mean of every km coast is calculated and shown with bars. The blue bars indicate the southern Ecobeach test area.

The distribution of sediment sizes in the intertidal zone is visualized in Figure 30 and Figure 31. For the readability the numbers are averaged over lengths of 1 km in Figure 31. The extensive sieve curve of the sediment analysis is simplified to four size classes: fine (< 230 MU), moderate coarse (230 – 325 MU), coarse (325 – 460 MU) and very coarse (460 – 2000 MU). The particles above 2000 MU are filtered out of the samples because they are too large for the laser analysis. The weight % of this filtered material can be read in appendix F.4.

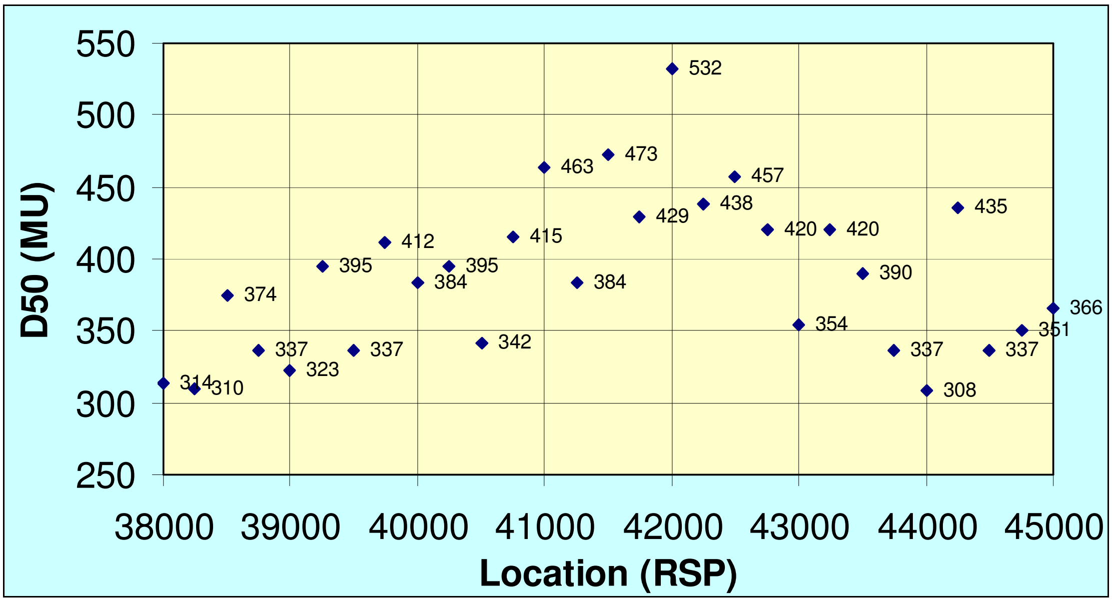

Figure 28: D50 of sediment samples in the intertidal zone between RSP 38000 - 45000

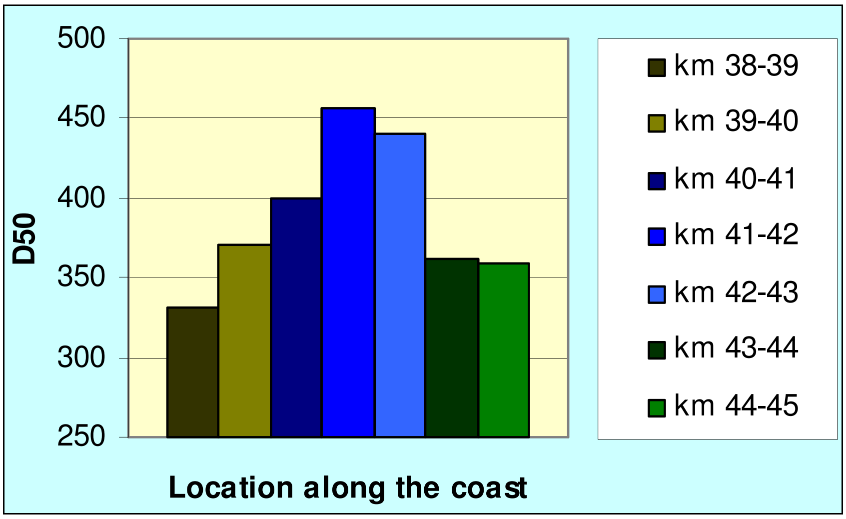

Figure 29: Average D50 per km coastline, blue bars indicate the southern Ecobeach test area

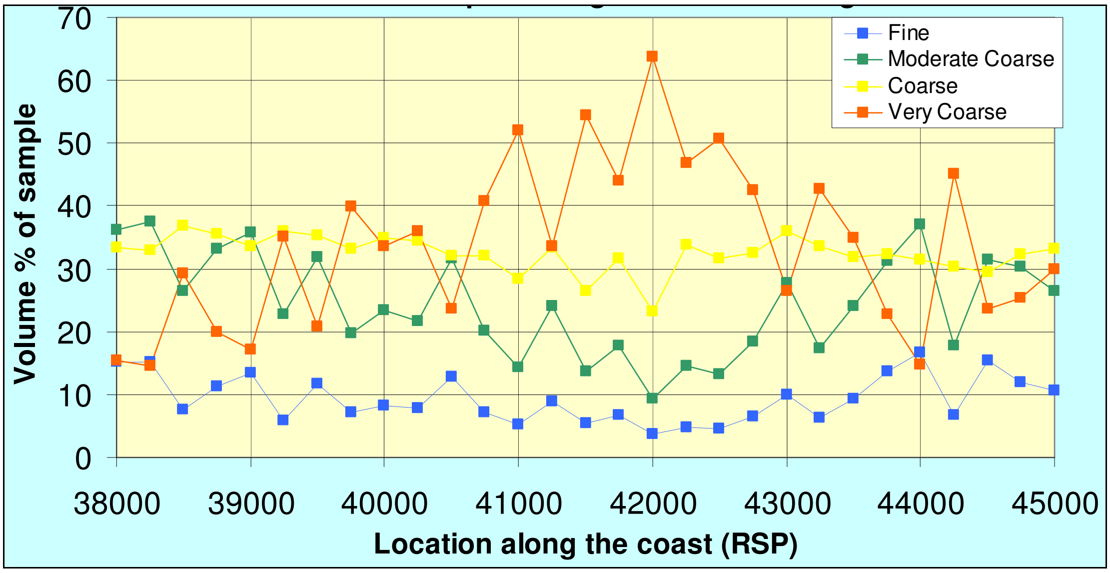

Figure 30: Size distribution of sediment samples in the intertidal zone between RSP 38000 - 45000

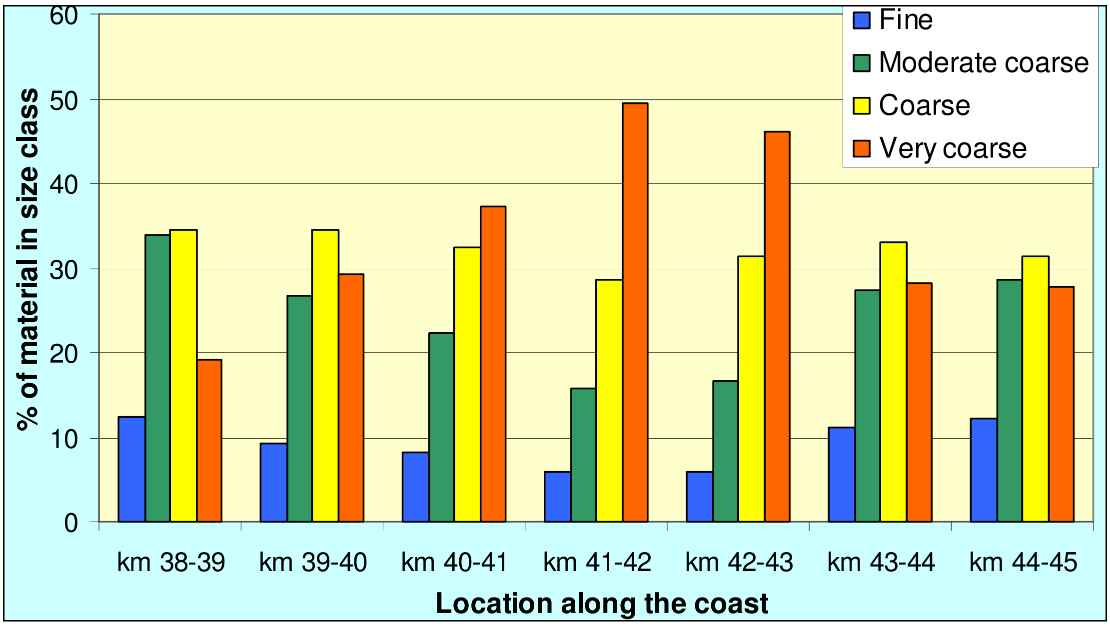

Figure 31: Size distributions of the sediment samples averaged per km coastline

6.4.3 Conclusions and recommendations

The hypotheses of coarser sediment in the Ecobeach test area compared to the reference area, which followed from the first sediment analyses, was the starting point for this study. At a location in the Ecobeach test area (RSP 42000) the mean D50 of the sediment in the intertidal zone was 347 MU, while at a location in the reference area the mean was 289 MU.

In the test described in this paragraph it becomes clear that this remarkable difference between the two locations was not accidental. A pattern is visible of coarser sediment in the southern Ecobeach test area, compared to the areas just north and just south of this beach. The coarsest sediment is found around the centre of the test area.

Although a clear trend of coarser sediment between RSP 40000 - 43000 is visible the difference between the neighbouring samples, with an interspacing of 250 m, is significant (see Figure 28) inside as well as outside the test area. Although scatter appears the quantity of samples (29 samples over 7 km coast length) is large enough to proof the difference in coarseness between the test area and the reference area.

Compared to the small analysis of November 2008 (see Appendix F.2) the D50 measured in September 2009 is relative large. This can be caused by the weather circumstances in the weeks before the sample were taken (see paragraph 5.3). During the first week of September and the last days of August two storm events appeared which can have transported a lot of sediment away from the area just above the low water line. Because fines are better transportable than coarse material this can be the cause of the observed difference.

These very interesting results are a reason to continue the study of sediment properties in the Ecobeach swash zone. Besides a comparison between the test area and bordering areas it is important to compare samples from the test area taken close to a row of PEMs with those taken just between two rows. Besides that the same experiment should be done at other Ecobeach test areas which are not disturbed by for instance nourishments to see if this phenomenon appears at different kinds of beaches where Ecobeach is implemented. During the publication of this report, new sediment samples are being analysed. The first analysis results confirm the results of September 2009 (see Appendix F.4)

7 Analyses and synthesis of the groundwater measurements

7.1 *Introduction*

During the fieldwork described in Chapter 5 the beach groundwater behaviour was measured. Near the low and high waterline divers measured the water pressure, temperature and sometimes the conductivity. Figure 22 shows the setup of the fieldwork location. Much data was collected, with and without PEMs and at different distances from PEMs. In this chapter the data are analysed. At first they are interpreted. Because these kinds of measurements are quite unique, different phenomena which are observed are analysed and the opportunities and restrictions of the measurements are considered. Afterwards the hypotheses of possible working mechanisms of Ecobeach from Chapter 5 are evaluated against the data. The chapter is finished with conclusions about the probability of the different hypotheses and suggestions for further research to the Ecobeach PEMs.

For the analyses of the diver data Matlab is used. This program is appropriate for calculations with large data series. In Appendix E the procedure is described resulting in some of the graphs and results that can be found in this chapter. Moreover Appendix E contains some graphs which can clarify the explanation in this chapter.

7.2 *Pressure measurements on tidal scale*

7.2.1 Tidal variations at different locations

One of the phenomena observed is a pressure variations in the ground caused by tidal variation at sea. The tidal water level near IJmuiden shows a behaviour as in Figure 32 [7] for an arbitrary period during the fieldwork. At the fieldwork location the tide is delayed approximately 15 minutes as compared to IJmuiden. (Ground)water pressures at the field site are measured simultaneously at different locations: above ground at the low waterline, at a depth of about 1.0 m just above the low waterline and at a depth of about 1.4 m at the high waterline. The original diver measurements included pressure variations caused by wind waves. Nevertheless, these are filtered out in Figure 33 (Appendix E shows the filtering procedure).

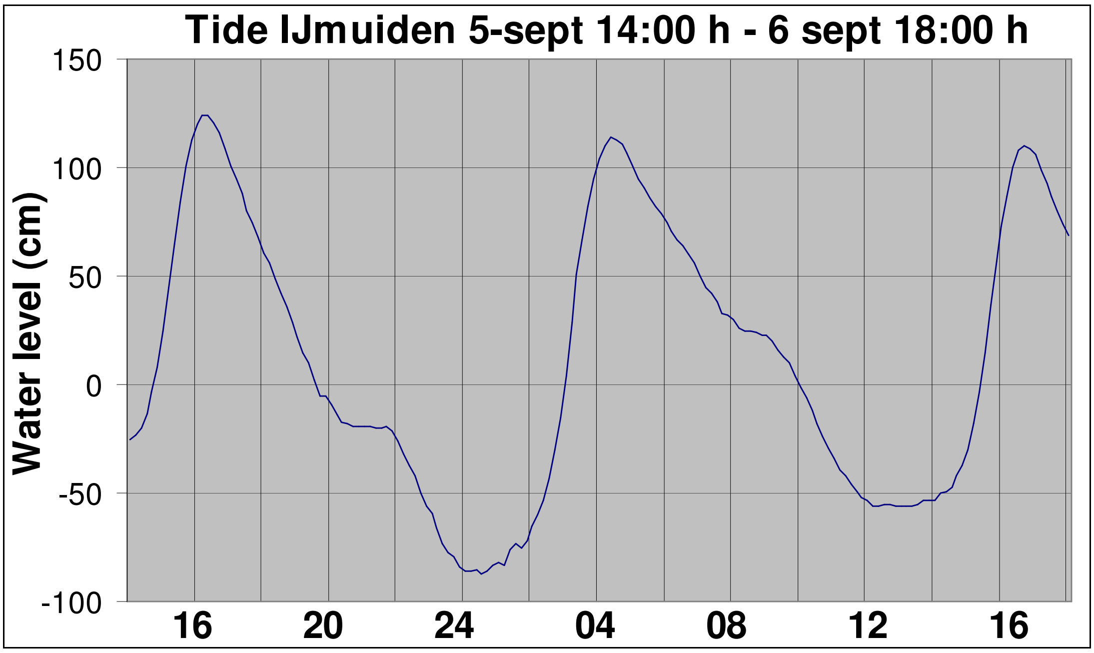

Figure 32: Water level near IJmuiden during over 2 tidal cycles [7]

The blue line in Figure 33 shows the pressure above the ground at the low waterline. Diver 13 (see Figure 22) measured at this location. This line should resemble the tide chart of Figure 32, with a phase lag of about 15 minutes. Near IJmuiden the difference between the highest and lowest point in the first tidal cycle is about 210 cm, while this is less at the fieldwork location (blue line in Figure 33). This difference is mainly caused by the fact that diver 13 is not submerged anymore during low tide. Between 22:30 – 4:00 h diver 13 measures the barometric pressure. During the second tidal cycle in the graphs the tidal measurement of diver 13 does not resemble the tidal graph of Figure 32 totally. The water level difference between the second top and the small step during ebb tide is 84 cm in Figure 32 and 72 cm (74 cm water column = 72 cm salt water) in Figure 33.

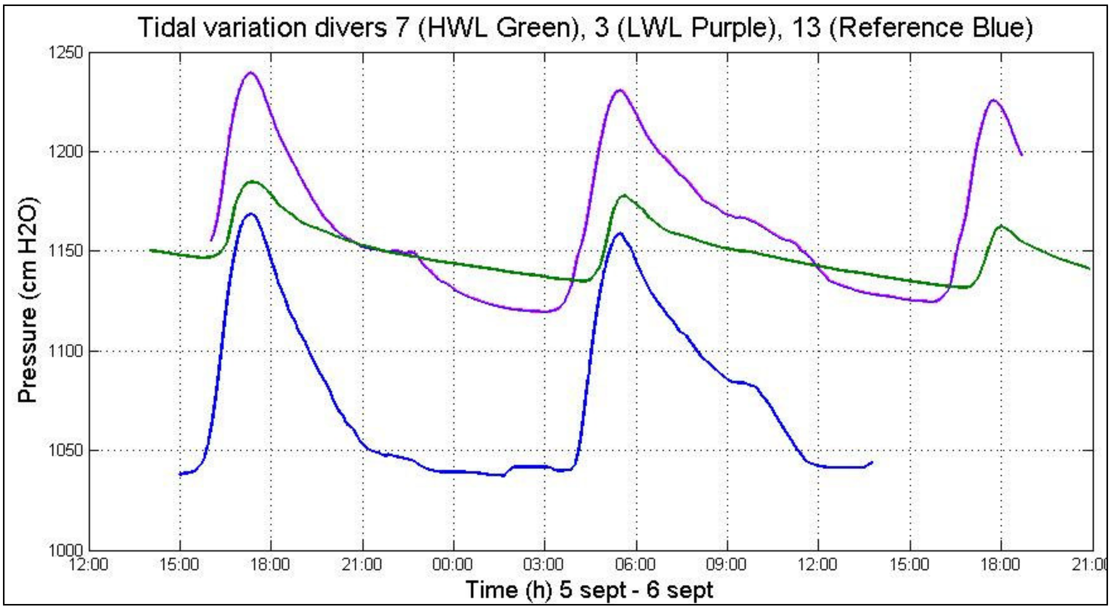

Figure 33: Water level at different locations above and under the beach surface

During the first tidal cycle, visible in Figure 32 and Figure 33, also a small difference between the tidal variation at sea near IJmuiden and near the low waterline at the fieldwork location is visible. During the same time-interval of 1:25 h before the highest water level is reached the level rises 1.18 m at the fieldwork location and 1.22 m near IJmuiden. The differences are quite small, but the water level difference near IJmuiden seems to be a little bit larger than at the fieldwork location.

It is difficult to explain this small difference, because it may be scatter. Otherwise it can be caused by the distance of about 14 km between the two measurement locations. The tidal wave can transform over this distance. Besides that the configuration of the IJmuiden measure station is not exactly known. It can be the case that wave set up plays a more important role at this place than at the fieldwork location during high water.

7.2.2 Groundwater pressure variations compared to tide at sea

The purple and green lines in Figure 33 show the groundwater pressures near the low and high waterline during a specific time interval. The pressures measured by the groundwater divers are constantly higher than de pressure above the ground at the low waterline. In the first place this can be explained by means of the vertical difference between the pressure sensors of the divers. Table 4 shows the vertical spacing compared to the top of beach pole RSP 43250, from Figure 22, with an inaccuracy of approximately 5 cm.

Diver number	3	7	13
Vertical distance compared to beach pole	-2,80 m	-2,22 m	-2.17 m

Table 4: Vertical spacing of divers 3, 7 and 13

It will be obvious that diver 3 measures the highest pressure because this diver is placed at the lowest level. Diver 7 is placed a little bit lower than diver 13, but this diver measures almost constantly a disproportionately higher pressure than diver 13. Only during high tide the difference is moderate. During low tide the groundwater level near the high waterline is more than one meter higher than the water level of the sea near the low waterline (certainly when taking into account that the water level is beneath the sensor of diver 13 when it measures the barometer pressure). The difference between low and high tide is about 45 cm around the high waterline, while at sea it is about 2.0 m (see Figure 32).

The tidal difference of the groundwater level near the low waterline is 1.13 m, compared to 2.0 m at sea. This difference is mainly seen during ebb tide, because the draining of the ground is slower than the decrease of the sea water level. During high tide, the time lag of the groundwater level near the high waterline compared to the low waterline is disappeared. Filling of the beach is a fast process while waves transport large volumes of water onto the beach. When the sea water level is at its maximum, the pressure it also at its maximum at every location.

7.3 Pressure measurements on wave scale

7.3.1 Wave pressure variations at different locations

Besides slow tidal variations of the groundwater, quick variations, caused by wind waves, are observed with the divers. At different locations pressure variations caused by wind waves are visible. Diver 13 measured the real wave heights near the low waterline, when the diver was completely submerged. Some divers measured the pressure variation in the bottom near the low waterline, at a depth of 0.7 – 1.4 m and in a PEM. Other divers measured the pressure variations in the bottom near the high waterline. The divers only measured wind waves when the measurement frequency was high enough: 0.5, 1 or 2 Hz. Also a frequency of 0.1 Hz gives information about wind waves. Although the individual waves are not recognizable anymore the scatter is correlated to the wave height.

It is remarkable that only waves are measured in the bottom when they are washing above the measurement location. Before the sea has reached this location a slowly varying pressure is present, while fast pressure variations appear when the sea (with wind waves) had inundated the area above the diver. Apparently, high frequency pressure variations are not transported over large distances (> 10 m) in horizontal direction.

7.3.2 Different wave lengths

When waves on the tidal scale (approximately 12.5 hours) are filtered out, shorter waves are visible as the scatter on the right side of Figure 35. Different wave periods could be present in this “scatter”. Wind waves can have periods between 4 and 12 seconds, while interaction between waves can lead to wave groups. The period of wave groups is about seven times the period of the individual waves.

Figure 34 shows the water pressure fluctuations just above the ground near the waterline. The tide and wind waves of 40-60 cm height are filters out (see Appendix E). The remaining variation of apparently 5-15 cm has a frequency of 20 in 15 minutes, which means a period of 45 seconds. This variation can be caused by wave groups.

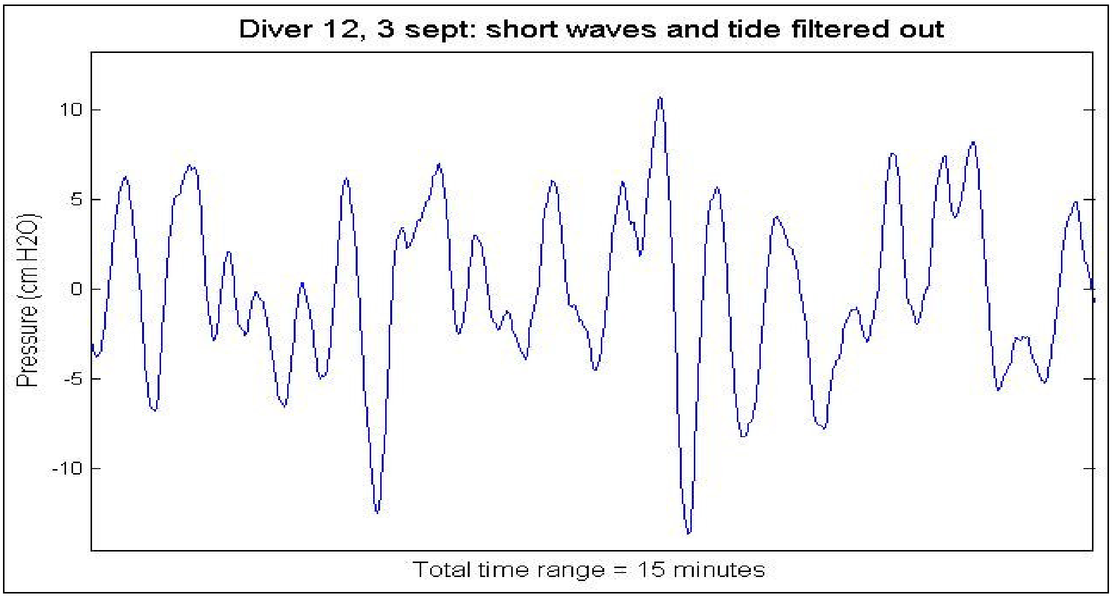

Figure 34: 15 minutes of groundwater pressure variations without wind waves and tide

7.3.3 Fourier analysis

In all data series tidal variations are visible and in most of the series also short pressure variations, caused by passing wind waves, can be noticed. In order to study the short waves the long variations have to be filtered out. In Appendix E the way to do this is explained. Figure 35 shows the plot of an original data series on the left side and a plot of the data series without long time variation on the right side.

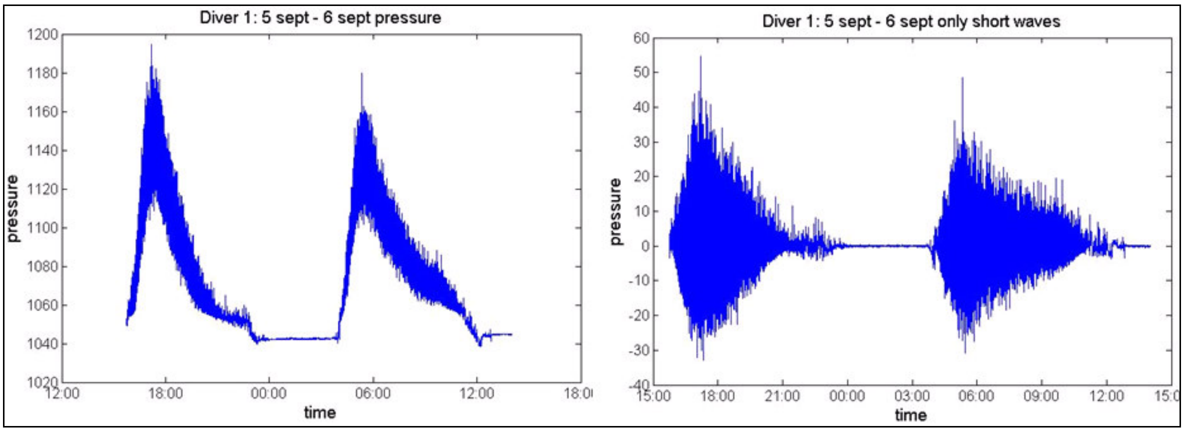

Figure 35: Original groundwater pressure (left), tidal variation filtered out (right)

With Matlab a Fourier analysis can be made of a data series which shows short period pressure fluctuations (see Appendix E). In fact, these data series show a wave spectrum which can be constructed of sine functions with all kinds of periods and amplitudes. The result of the analysis is a distribution of the wave energy in the wave spectrum over different frequencies. The integral of this distribution between two particular frequencies shows the total wave energy between those frequencies.

Figure 40 shows an example of the Fourier analysis of pressure variation in the bottom, near the low waterline. It becomes clear that the low frequencies are better transported through the ground than the high frequencies. The frequency domain of the wind waves (0.1 – 0.2 Hz) contains less energy than the lower frequencies (0.01 – 0.1 Hz).

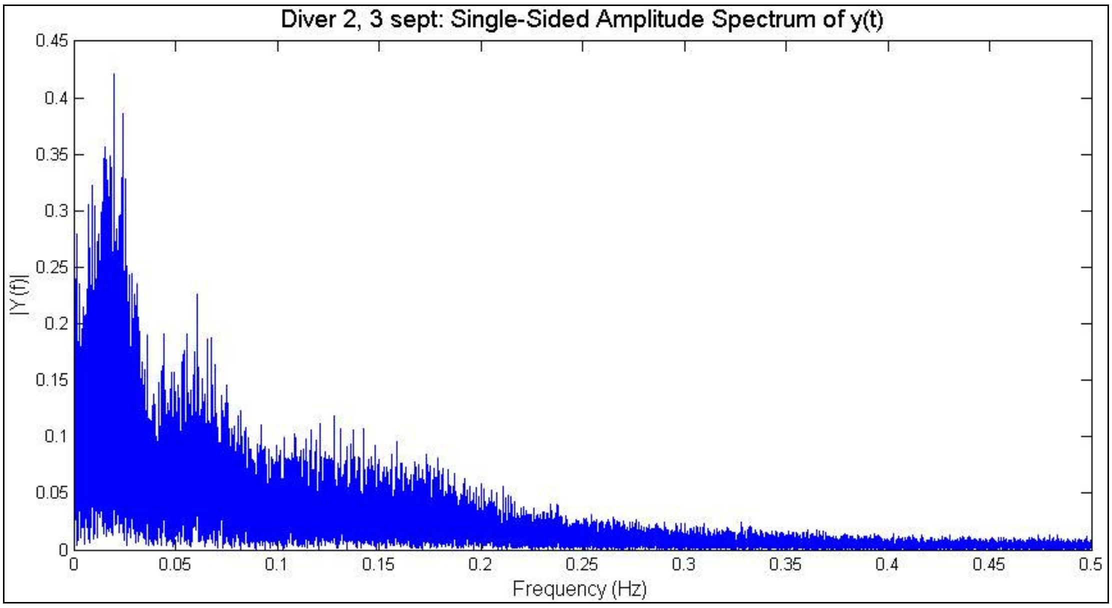

Figure 36: Fourier analysis of pressure varations in the bottom near the low waterline.

7.3.4 Horizontal variation of pressures caused by wind waves

Because wind waves move with a limited speed through the swash zone is may be expected that the pressure variations measured in the bottom at nearby locations are dependent on these wave movements. Figure 37 shows the pressure measurements of 4 divers, which are located in the ground near the low waterline, at exactly the same time. Figure 22 shows the exact location of the divers.

It is expected that diver 5 (green line) has a small time lag compared to diver 2, which is placed 1.0 m more land inward than diver 5 (red line). The waves should move in a land inward direction. However, Figure 37 shows the opposite, which makes believe that the time setting of both divers is not completely similar. Although the diver clocks were set similar regularly a small deviation could arise. Apparently the clock settings of the divers are not accurate enough to register differences of tenths of seconds.

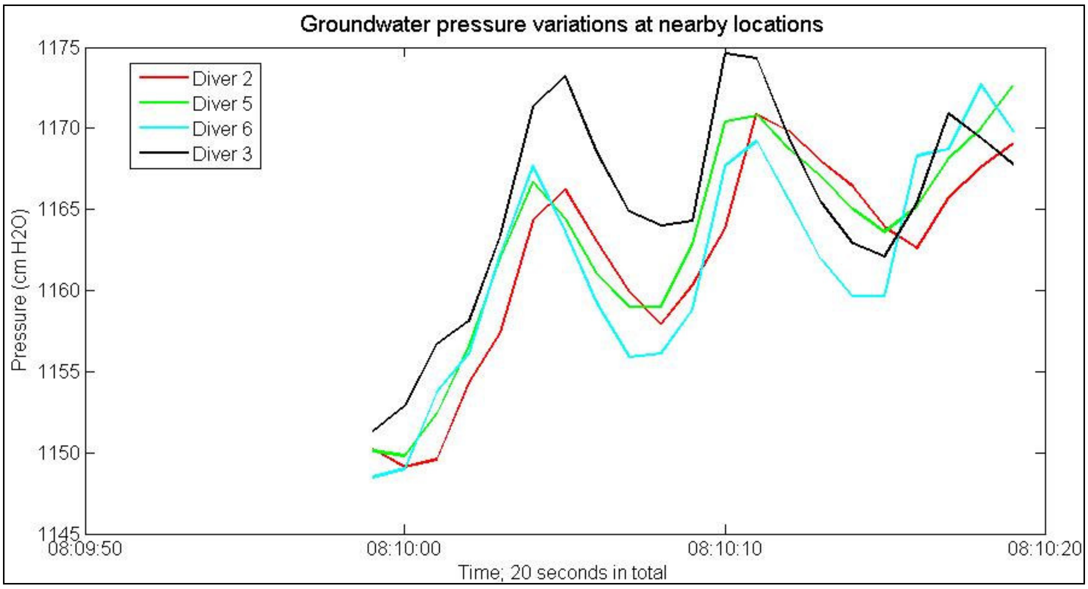

Figure 37: 20 seconds of pressure measurements of 4 different (nearby located) divers

7.4 *Conductivity measurements*

7.4.1 Purpose and reliability of the measurements

Most of the divers used during the fieldwork (the 9 CTD divers) were able to measure the conductivity of the groundwater. The conductivity of the groundwater gives information about the quantity of salt dissolved in the water. North Sea water with a temperature of 15°C has a conductivity of about 42 mS/cm, while fresh groundwater has a conductivity of << 1 mS/cm. With conductivity measurements, the location, transport and mixing of fresh groundwater and saline seawater can be studied. Besides the conductivity of groundwater, the diver detects air when it measures a conductivity of 0 mS/cm.

The conductivity measurements during the fieldwork have a limited reliability for two reasons. The first reason is the sensor of the divers itself, which should have an accuracy of +/- 1.0 %. Calibration before the measurements showed no problems, but calibration after the fieldwork showed errors up to 11% in the domain of beach groundwater salinity (see Appendix D.2, Table D3). The divers are supposed to have become inaccurate during the fieldwork, growing linearly in time. The second source of inaccuracy could be the nylon sock around the divers, protecting them from sand particles. This nylon sock possibly retains small air bubbles which can influence the conductivity measurements of the divers. When conductivity characteristics of the groundwater are used the reliability of these data always has to be taken into account.

7.4.2 Influence of tides on the conductivity of the groundwater

Especially near the low waterline the groundwater pressure and conductivity seam to behave similarly. Near the high waterline possibly a more complex relation between tidal forcing and groundwater salinity is visible. Figure 38 shows the pressure (blue line, above) and conductivity (red line, under) during 6 tidal cycles, measured near the low waterline at a depth of approximately 1.0 m. The conductivity varies between 28 and 32 mS/cm in the total period, while during one tidal cycle the difference can be just over 2 mS/cm. When the water level is increasing the salinity of the groundwater also increases, and during ebb tide the salinity decreases again.

The behaviour of the conductivity in Figure 38 can be explained by the exfiltration of fresh groundwater. The area around the low waterline is in general an exfiltration zone, while the high waterline is in general in infiltration zone. This is explained by the groundwater circulation in paragraph 3.2.4. The exfiltration occurs near the low waterline because at this location the mean groundwater level is relative low. During low water the groundwater experiences little resistance to flow out. A mix of fresh and saline water leads to a lowering of the conductivity then. During high water the outflow of groundwater is stopped temporary and even salt water infiltrates.

The behaviour of the conductivity of the groundwater near the high waterline, at a depth of about 1.4 m, can also be explained by the groundwater circulation. Although the measurements in this area are not unambiguous (see Appendix D.5). During high water the conductivity of the groundwater near the high waterline decreases, see Figure 39. The exfiltration zone might move from the low waterline in the direction of the high waterline, because the water level near the low waterline is not low compared to the high waterline anymore.

Besides the physical explanation of the phenomenon of Figure 38, also a failure of the conductivity measurements of the divers had to be taken into account. When the conductivity changes automatically synchronous with the pressure the variation shown in Figure 38 has no physical explanation. Nevertheless Figure 39 does not show the same behaviour.

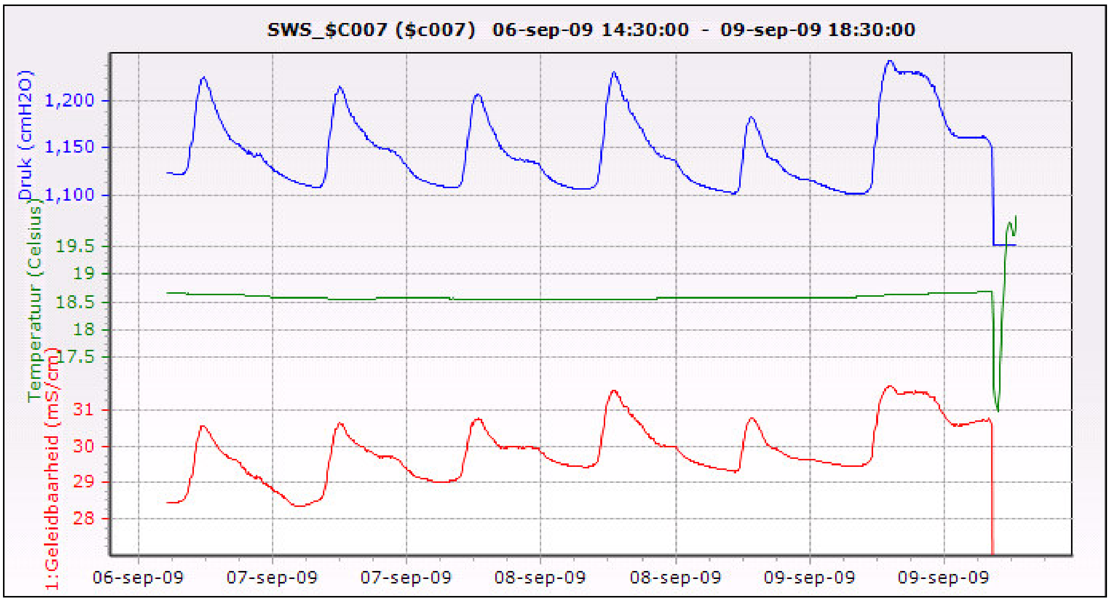

Figure 38: Pressure, temperature and conductivity of groundwater at the low waterline

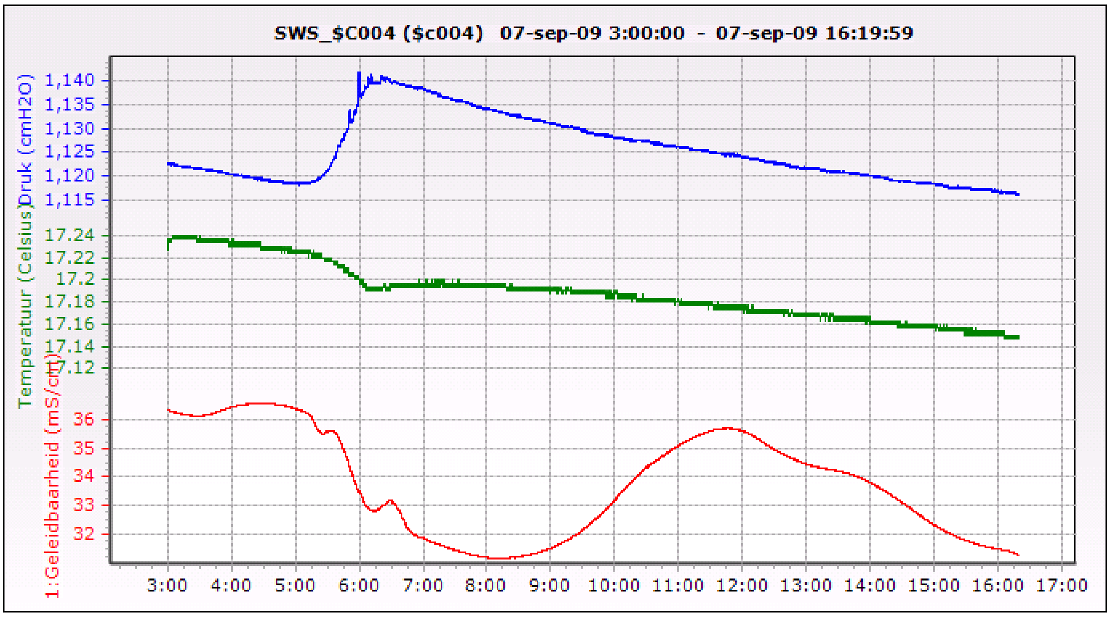

Figure 39: Pressure, temperature and conductivity of groundwater at the high waterline

7.5 Temperature measurements

All divers used during the fieldwork measure the temperature. The temperature variations of the groundwater are small and the temperature of the seawater plays an important role. The measurements started on the 30th of August and ended on the 10th of September. In this period the temperature of the (shallow) groundwater slowly, but not regularly, decreased. Besides this variation in the time, a difference exists between the groundwater temperature near the high waterline and near the low waterline, where it is relatively cold.

Measurements of June 2009 already showed clear temperature differences over depth (see Appendix D.4). The groundwater temperature near the high waterline decreased during the fieldwork from 18.4 ºC to 17.1 ºC. While near the low waterline the temperature decreased from approximately 18.6-19.8 ºC to 18.2-18.6 ºC (see the graphs of Appendix D.5).

The difference between the high and low waterline can be explained by the relative influence of the seawater and the groundwater. The groundwater at a depth of 10 m has an almost constant temperature of 10-14 ºC in the Netherlands. The sea water at the low waterline had temperatures between 17-21 ºC during the fieldwork period, dependent on the time and the weather circumstances (see measurements of diver 13, Appendix D.5). Because, compared to the high waterline, the low waterline is influenced by large amounts of seawater during most of the time, the seawater temperature has more influence on the shallow groundwater. This is also the reason of larger temperature variations at the low waterline than at the high waterline.

Figure 40 shows the temperature in the top (red line) and in the lower part (green line) of PEM f, near the low waterline. Also the conductivity measured in the top is plot by the blue line to see when the top of the PEM is filled with water. In general the water temperature in top of the PEM is lower than in the bottom. Only in the afternoon of the 9th of September the water in the PEM was considerably by the high. The air temperature and actual sea water temperature will have influenced the temperature in the top of PEM f, since it was above surface level after the storm of the 5th of September. The shallow groundwater is relatively warm, because it still has the temperature of the seawater some days – weeks earlier.

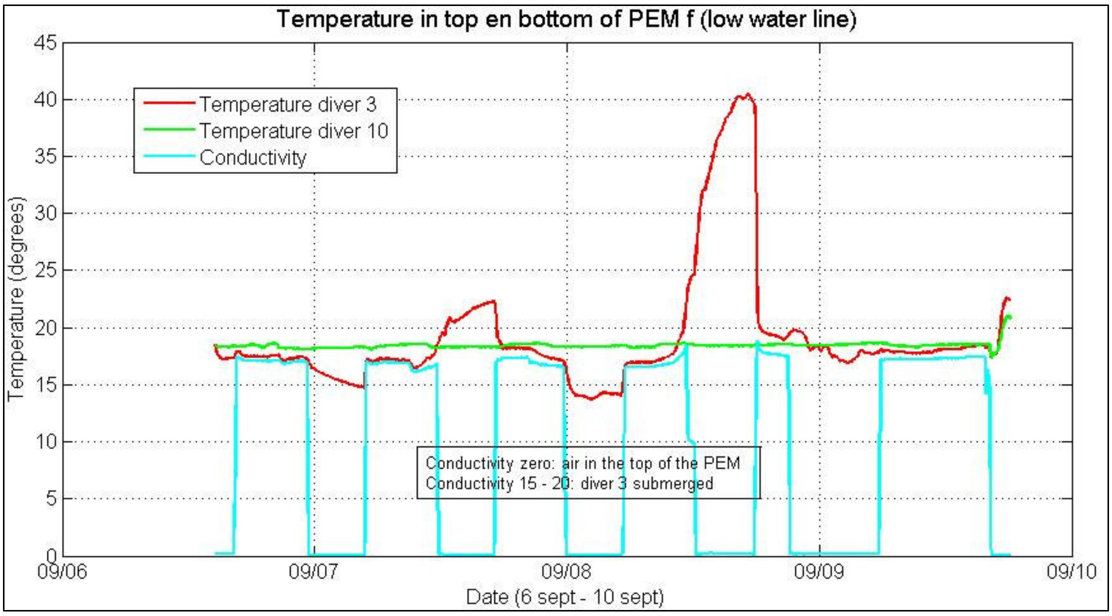

Figure 40: Temperature and conductivity in PEM f

7.6 Hypothesis: Lowering of the groundwater table

7.6.1 Testing the hypothesis with diver data

The first hypothesis of a working mechanism of Ecobeach, leading to an increase of the sediment volume at the beach, is described in paragraph 4.4.2. This hypothesis has a lowering of the groundwater as the initial event.

To find out if a PEM really influences the surrounding groundwater level the available data of diver measurements have to be used. The level difference caused by the PEM may be large enough to directly detect it with pressure measurements. The lowering could also be too small to stand out against natural variability though still influence important processes at the beach. To study this case, the cause of the lowering had to be observed: is groundwater flowing in downward direction through the PEMs? First the groundwater levels will be studied in and around a PEM and after that the temperature and conductivity of the groundwater in and around a PEM is examined.

7.6.2 Groundwater levels around a PEM near the low waterline

To see if the row of PEMs, and especially PEM f influences the groundwater level in the area around the PEMs some divers are places around PEM f. These divers have measured the groundwater levels before the PEMs were installed ("natural situation") and after placement of the PEMs. When the PEMs influence the groundwater level, it may be expected that the groundwater behaviour close to PEM f (0.5 m interspacing) will change compared to the groundwater level at a larger distance (5 m interspacing).

Only water level variations over a relative long timescale are taken into account. Short pressure variations of the order of seconds or minutes are filtered out. Figure 41 and Figure 43 show the pressures measurements of divers 2, 5 and 6 during several days before the PEMs were placed and after the PEMs were placed. The three lines are almost synchronic, which means that the depth of the divers is almost the same and so are the water level fluctuations on long time scale. To notice differences between the measured pressures, the pressure differences between the divers are plotted in Figure 42 and Figure 44. The pressure differences between the divers close to the PEM (2 and 5) and the diver at a larger distance (6) are plotted. The range of the pressure difference is about 7 cm.

In Appendix E Figure 42 and Figure 44 are plot together with the tidal variation (see Figures E7, E8, E9 and E10), to be able to interpret the pressure variations.

In Figure 42, before the PEMs are placed, the pressure differences between the divers close to the location of PEM f deviates from the pressure difference measured with diver 6. According to Figure 44, the same pressure difference exists after the PEMs are placed. It appears that the placement of the PEMs does not influence the variation of the pressure near the PEM at a timescale of hours.

In Figure 42 and Figure 44 some regular behaviour is visible in the pressure difference between the different divers, which is correlated with the tidal variation. Figure 45 shows the mean pressure difference between the divers close to PEM f and the remote diver at particular phases of the tide.

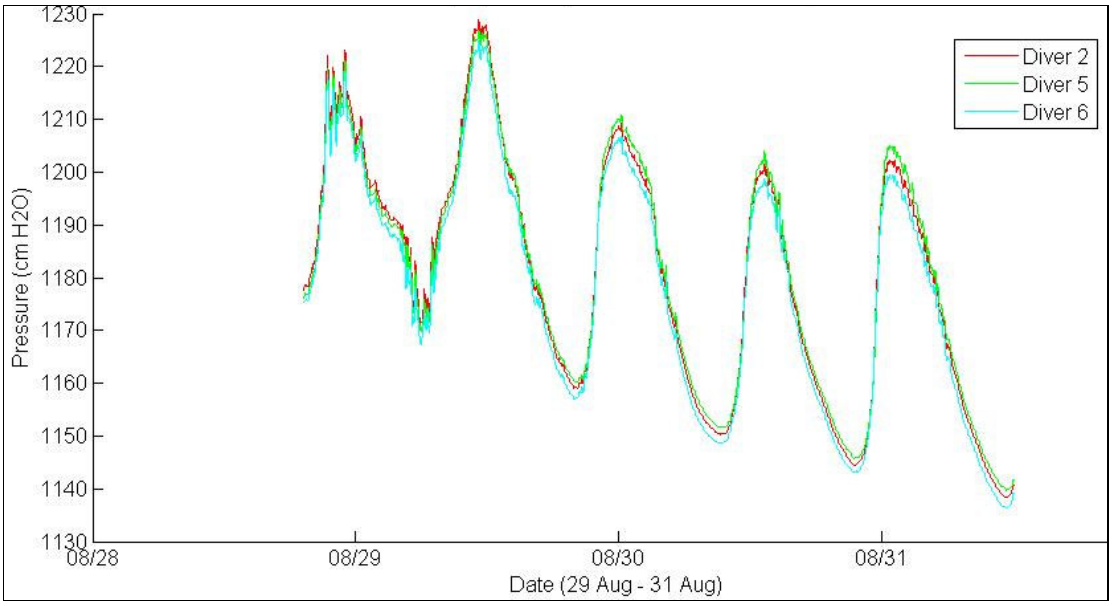

Figure 41: Pressures measured with Diver 2, 5 and 6 (low waterline) before PEMs were placed

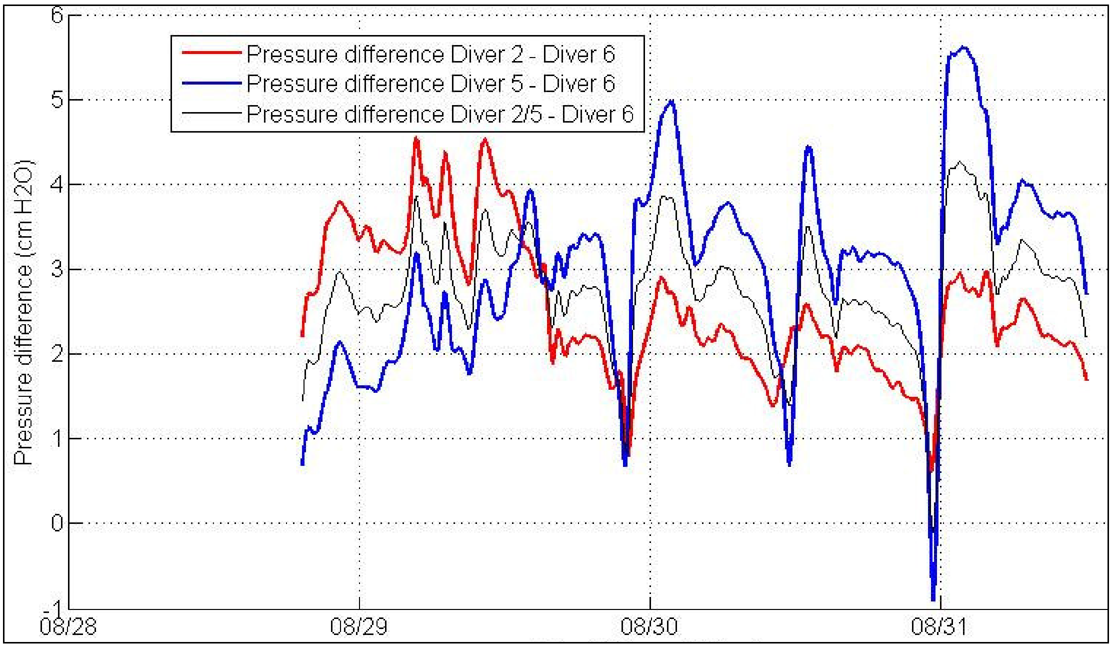

Figure 42: Pressure differences in the ground near PEM f, before the PEM was placed

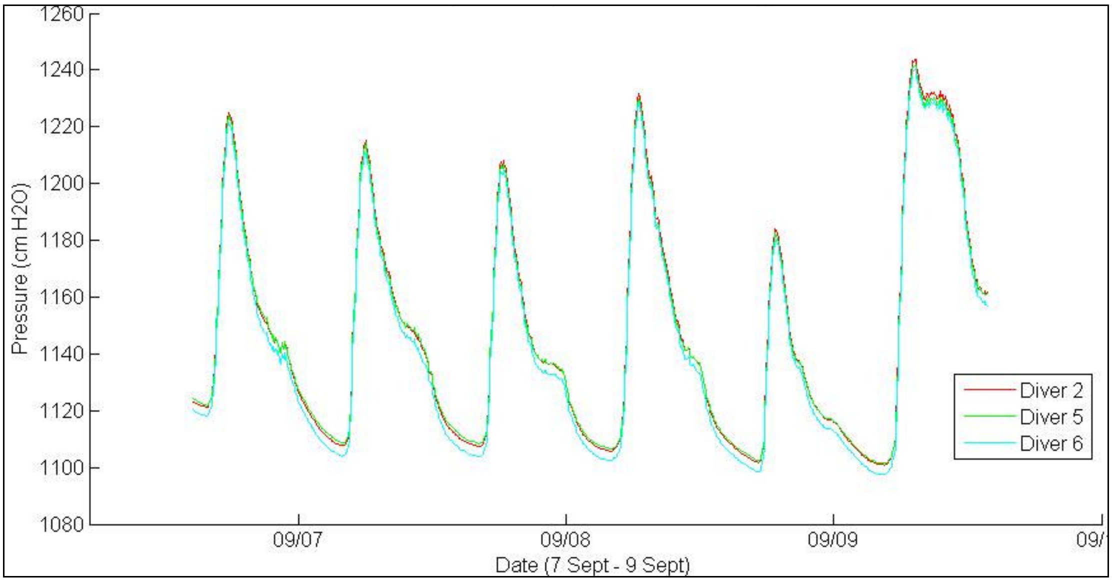

Figure 43: Pressures measured with Diver 2, 5 and 6 (low waterline) after PEMs were placed

Before and after the row of PEMs was placed, the pressure differences do not show exactly the same course. Figure 45 illustrates some characteristic values. Without PEMs the difference between divers 6 and 5 is relative small (1 cm) during rising tide and relative large (5 cm) when the water level is maximal. During ebb tide the difference is in between (3 cm). After the PEMs are placed, with PEM f close to diver 5, the difference is during ebb tide relative large, while during the rest of the tidal cycle it is relatively small. Diver 2, located close the diver 5 and PEM f, shows the same differences compared to diver 6 (only a little bit smaller) before the PEMs where placed. In the second measurement period the level difference is almost constant during the tidal cycle.

The changes in long-term groundwater behaviour after placing the PEMs are not uniform comparing the diver measurements close to PEM f and at a larger distance. The differences and changes are also very small. This means that these measurements do not clearly indicate a change of the groundwater level caused by Ecobeach.

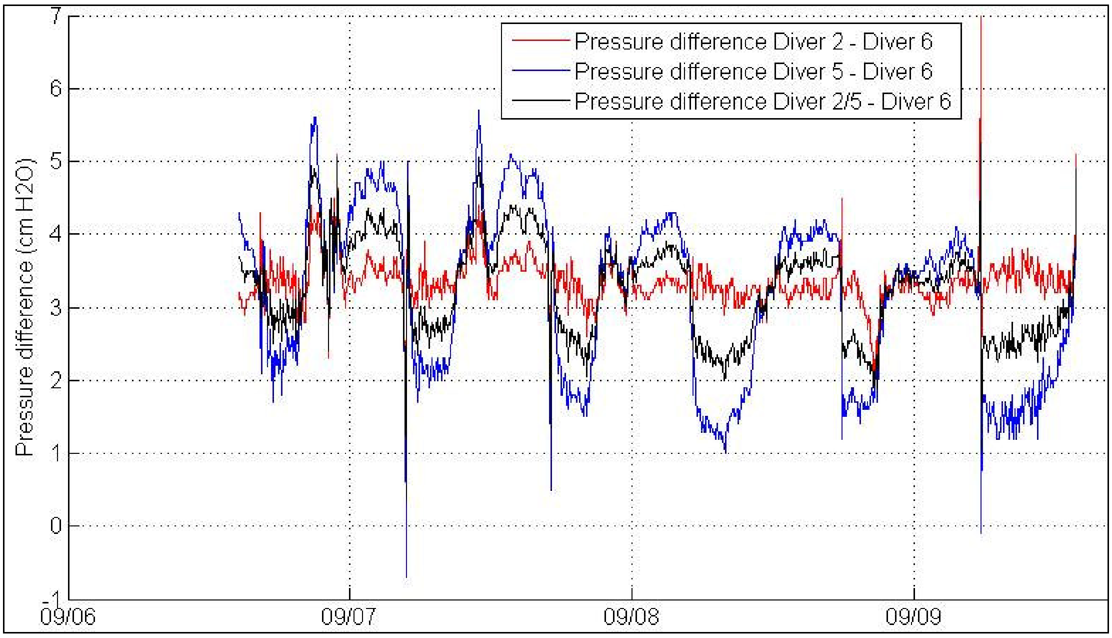

Figure 44: Pressure differences in the ground near PEM f, after the PEM was placed

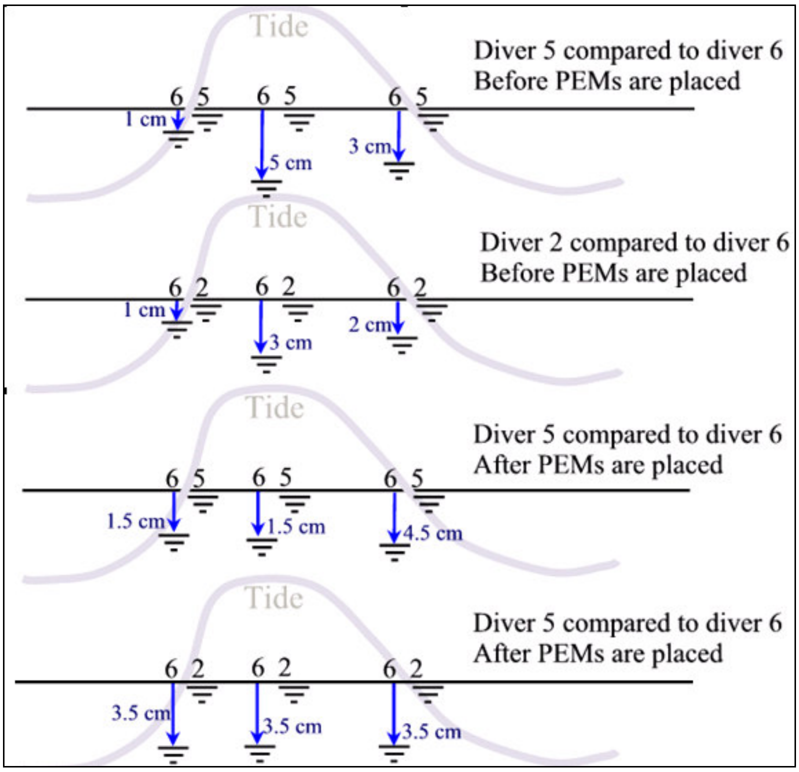

Figure 45: Pressure differences during different phases of the tide

7.6.3 Groundwater levels inside and outside a PEM

After the PEMs were placed also diver measurement have been done in PEM f. The pressures in the ground and in the PEM measured from 7 – 9 September are plot in Figure 46. The pressure differences between diver 11, which is located in PEM f, and the divers in the bottom around this tube, are shown in Figure 47. The pressure differences are between 10 and 17 cm, because diver 11 is placed at a larger depth than the surrounding divers. The maximum variation in the groundwater level difference is 2 cm, which is less than the variation in the difference between diver 5 and 6 (Figure 42), before the PEMs were placed. This indicates that 2 cm can be natural variation between different locations.

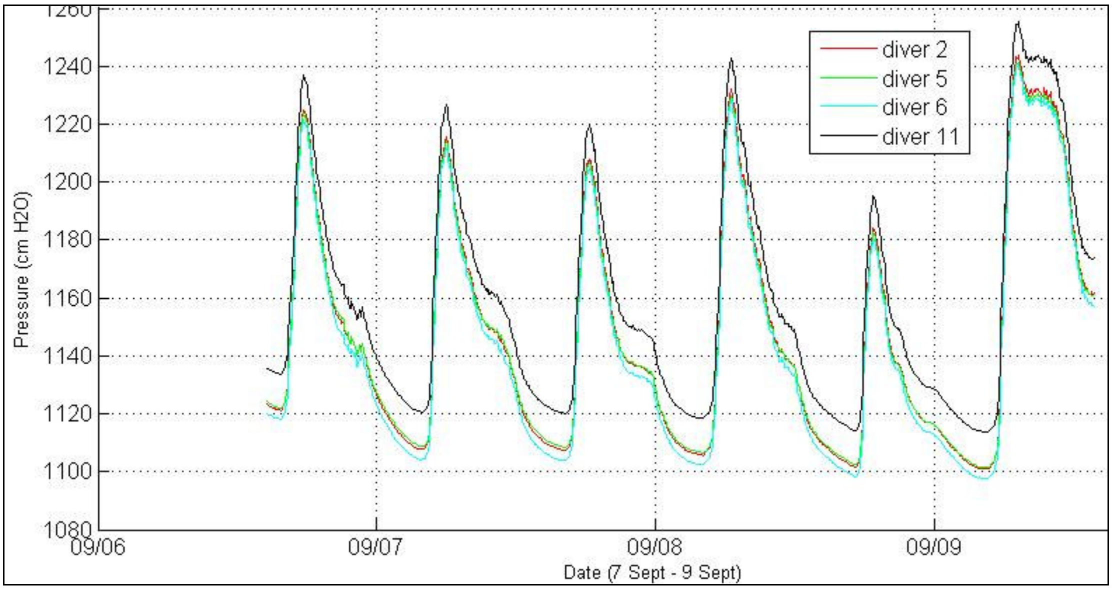

Figure 46: Pressures measured inside and outside PEM f

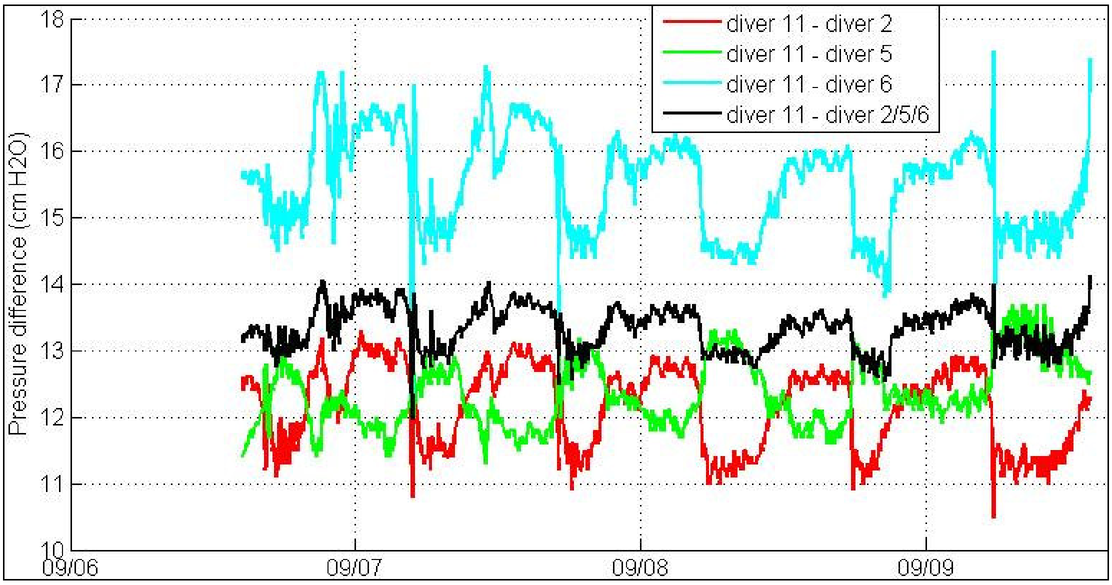

Figure 47: Pressure differences between diver in PEM f and divers in the surrounding area

Near the high waterline the long time (tidal scale) groundwater level difference inside and outside PEM b is compared. Figure 48 shows the water level variation between 8 – 10 September. The tide is not clearly visible, because during high water the water level was still beneath the location of PEM b. Figure 49 shows the pressure differences between diver 10, in the tube, and divers 4 and 7, located at 0.5 and 5.0 m distance from PEM b.

The pressure differences are quite constant, which means that the groundwater behaviour is almost the same in the area of the divers. Only when the groundwater level is rising fast, during flood tide, the water level at 5.0 from PEM b is 1.0 – 1.5 cm higher than close to and in the PEM. This may be drainage of the PEM, but compared to the “scatter” of Figure 42 it is a very small lowering of the groundwater level.

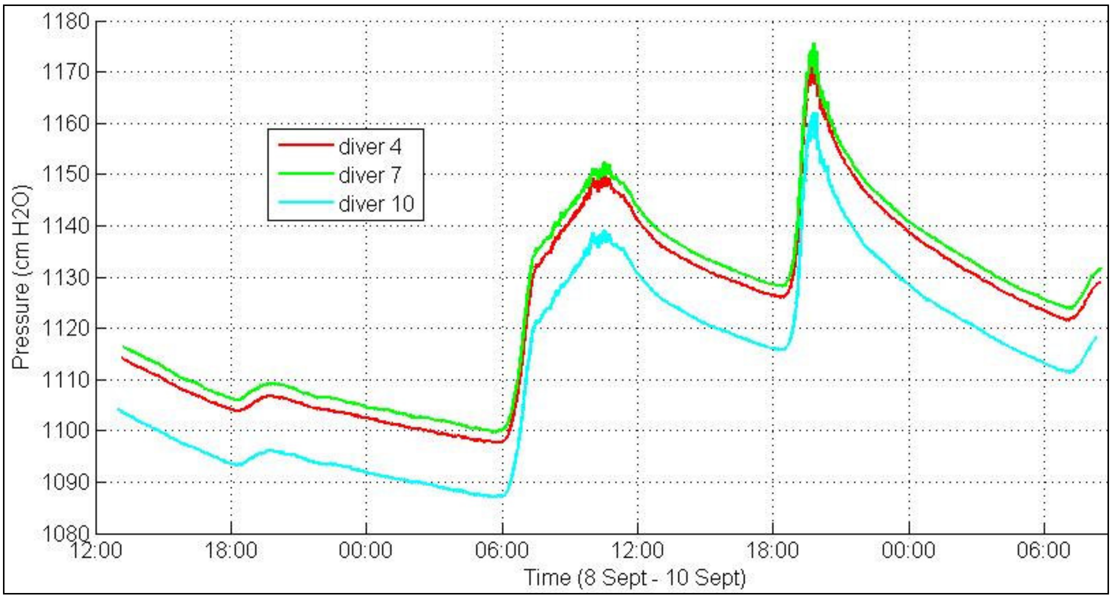

Figure 48: Pressures measured with Diver 4, 7 and 10 (high waterline) inside and near PEM b

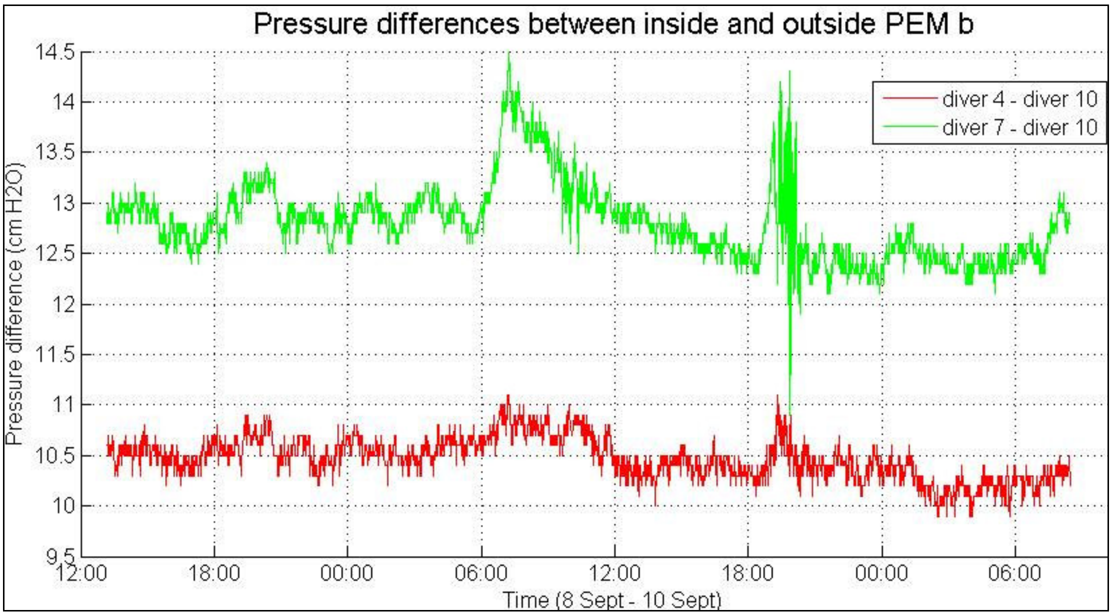

Figure 49: Pressure differences between diver in PEM b and divers in the surrounding area

7.6.3 Transport of water through a PEM

As proved with diver measurements in June 2009 (see Appendix D.4) the groundwater temperature varies with the depth. This is why vertical transport of water through a PEM can be indicated by temperature variations, but only in a qualitative way. Only the direction of the possible vertical transport can be found. In Figure 50 and Figure 51 the temperature variations of the groundwater in and around PEM f (low waterline) and PEM b (high waterline) are plot. The black line in both figures is the temperature variation in the PEMs, while the other lines indicate the surrounding groundwater temperature.

From both figures it becomes clear that the temperature variations in the PEMs are larger than in the ground. This indicates a vertical transport of water through the PEMs. Comparing the temperature variation of diver 11 in Figure 50 with the tidal variation no clear relationship is visible, which could indicate a structural behaviour of vertical transport through a PEM in combination with external forcing.

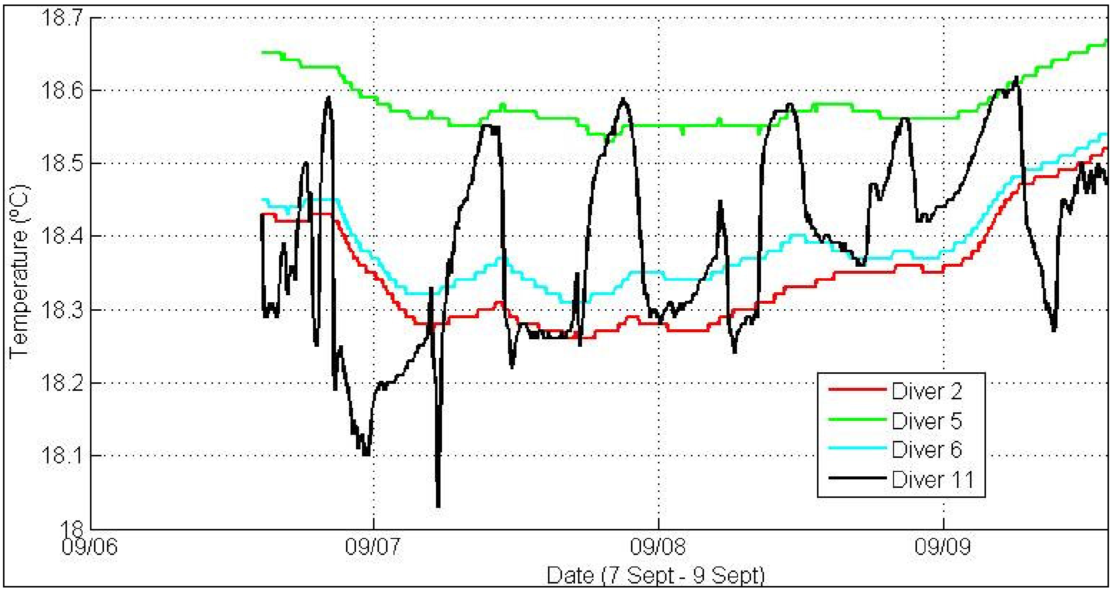

Figure 50: Groundwater temperature variations in PEM b and in the surrounding area

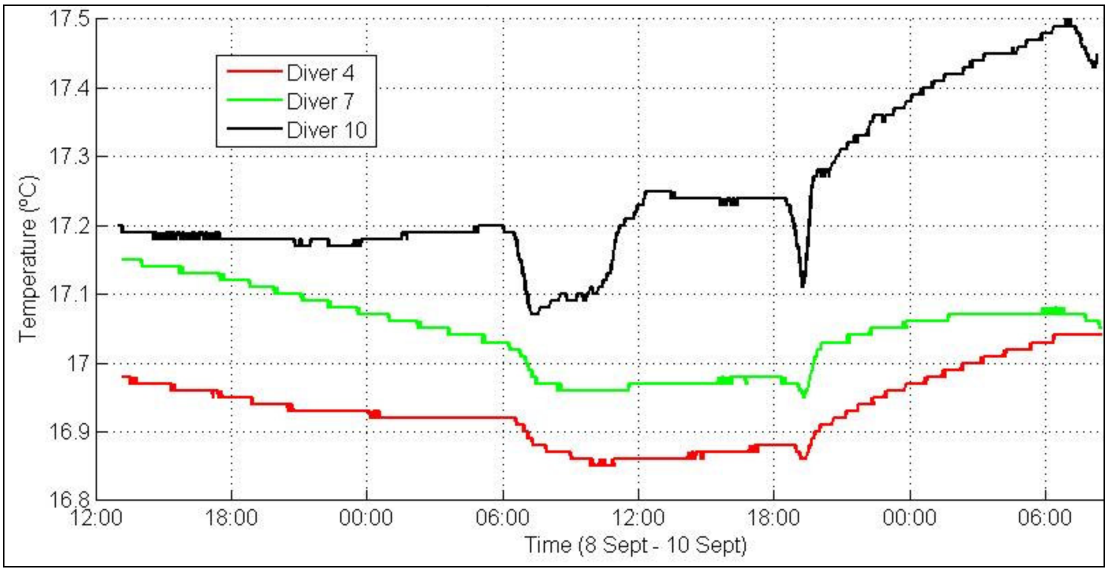

Figure 51: Groundwater temperature variations in PEM b and in the surrounding area

7.6.4 Conclusions

No lowering of the groundwater level is observed in the vicinity of a PEM near the low waterline and a PEM near the high waterline. The difference of the groundwater pressure at different locations, with an interspacing of 0.5 – 5.0 m, is within a range of several cm very random and the possible influence of a PEM is hidden in this randomness. The divers are not accurate enough to detect a difference of several millimetres, but natural variability seems to be larger than the diver inaccuracy.

Nevertheless in a PEM clearly more transport of water occurs compared to the surrounding bottom. The temperature fluctuations, which indicate vertical transport of groundwater, are much larger in a PEM than in de ground. This transport through the PEM can not be linked to an external force to explain it.

7.7 Hypothesis: Promoting/decreasing (local) exfiltration

7.7.1 Testing the hypothesis with diver data

Paragraph 4.4.3 describes the hypothesis of a PEM, influencing the exfiltration near the low waterline. By concentrating the outflow of groundwater in the PEMs, the outflow in the surrounding area is decreased. Moreover the circulation of groundwater from the high waterline to the low waterline could be promoted in general.

The groundwater flow through a PEM could be noticed thanks to the fact that the groundwater has different conductivities at different locations and depth, see paragraph 7.4. Near the low waterline, mixed fresh/saline groundwater is flowing out. Therefore, during low water the conductivity is relatively low. When the PEMs promote the exfiltration, the salinity in (the direct vicinity of) the PEM should be lower than at a horizontal distance of several meters from the PEM, in long coastal direction.

7.7.2 Conductivity

In Figure 52, some conductivity measurements in the ground near the low waterline are plot. Above, the measurements after placing a row of PEMs are visible while at the bottom of this figure, the measurement before placing of the PEMs are shown. Graphs with the same colour belong to measurements from the same diver at exactly the same location. The dark blue line belongs to diver 3, which stopped functioning at the 6^{th} of September.

It may be concluded from Figure 52 that the accuracy of the conductivity data is very low, because divers at locations where the same conductivity is expected show differences of 20 – 200 %. Moreover, the conductivity measured by one individual diver generally increases in time (see Figure 53). This can be caused by the sock which protects the divers against sediment particles. Air might be enclosed in this sock, escaping slowly during the measurement period. Taking this into account, the values measured with diver 1 can not be clarified, because this diver (measuring in PEM f) was not protected by a sock. When the accuracy of the conductivity data is low, it is very difficult to find small differences between the measurements inside and outside PEM f, at different distances and before and after the PEM was placed.

If the divers measure between the fault margin of 10%, indicated by the producer (van Essen) after he had tested the instruments before and after the fieldwork (see table D2 of Appendix D.3), the upper part of Figure 52 can show an interesting phenomenon. The groundwater in PEM f had a relative low conductivity, while at a distance of 5 m from the PEM (diver 6) the conductivity is relative high. The groundwater conductivity in the vicinity of the PEM (0.5 m distance) has a value in between the extremes. This can be explained by canalizing the fresh water outflow in the area around the low waterline through a PEM, while reducing the exfiltration in the surrounding area.

7.7.3 Conclusions

The accuracy of the conductivity data of the groundwater, collected in the area around the low waterline, is rather low. This makes it hard to say something about the influence of a PEM on the salinity of the groundwater, which could indicate if exfiltration near the low waterline is influenced by Ecobeach.

If the divers, which indicate a remarkable salinity distribution around PEM f, are as accurate as the manufacturer declares, canalizing of exfiltrating fresh groundwater can be the case. The PEM forms a shortcut for the groundwater flowing out to the surface. More accurate measurement equipment should be used to put a matter beyond doubt.

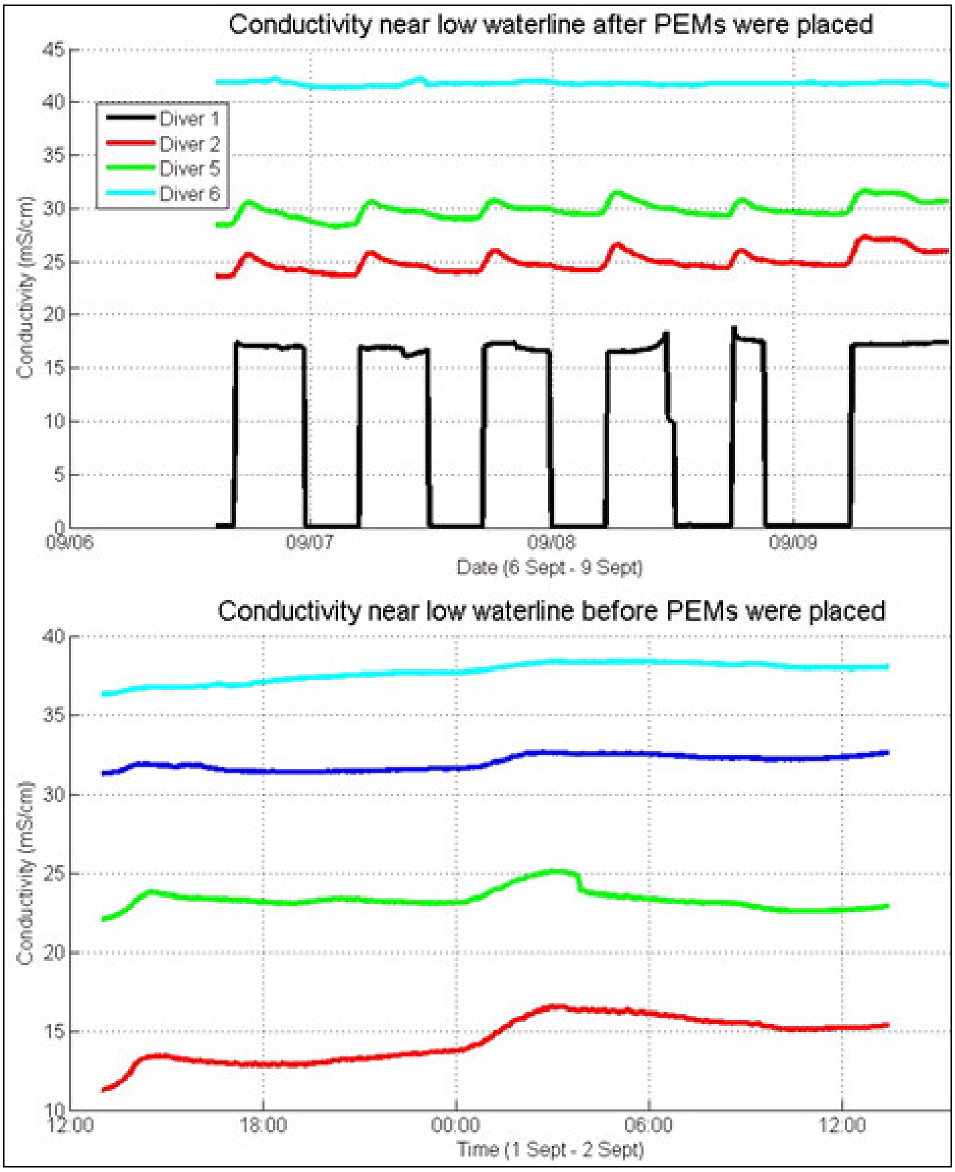

Figure 52: Conductivity measured before and after PEM f was placed

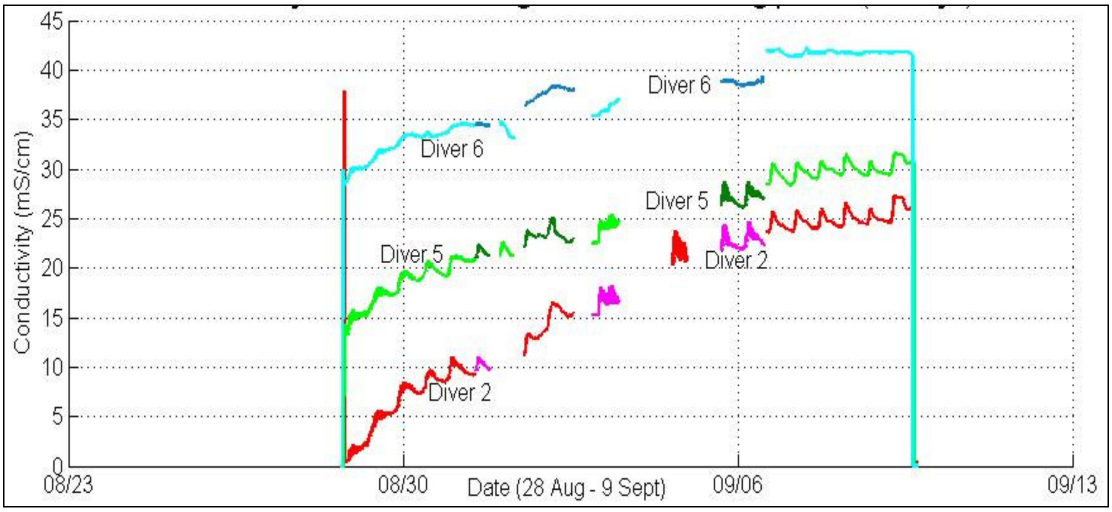

Figure 53: Conductivity near PEM f during the total measuring period (12 days)

7.8 Hypothesis: Increasing pressure variations in the bottom

7.8.1 Testing the hypothesis with diver data

An important hypothesis of Ecobeach is described in paragraph 4.4.4. The vertical pipes of the drainage system could conduct pressure variation into the ground, drilling the particles into a more stable packing.

Divers have measured the high frequency pressure variations (with a sample frequency of 0.5, 1 or 2 Hz) very close (0.5 m) to the location of PEMs b and f and at a larger distance (5 m) from these locations, before and after the PEMs have been placed. In PEM f, near the low waterline, also inside the PEM the high frequency pressure variations have been measured. The high frequency variations in the groundwater pressure are caused by passing wind waves, with frequencies of 0.08 – 0.25 Hz (periods of 4 - 12.5 s). Groups of wind waves can cause pressure variations with frequencies of 0.0125 – 0.05 Hz (periods of 20 – 80 s).

With a Fourier analysis, the amount of energy per wave frequency in the data series of the groundwater pressure measurements can be found. Appendix E shows the Matlab code of this analyses and describes the meaning of the output. After a Fourier analysis, different waves from different data series are easily comparable with each other.

7.8.2 Pressure variations of wind waves

The pressure variations in the ground, caused by waves, have frequencies and a specific amount of energy. A Fourier analysis gives the distribution of the wave energy over the frequency domain. Figure 36 is an example of such a distribution. By integration, the area under the energy distribution between specific frequencies can be calculated.

Near the low waterline divers have measured the pressure variations in the ground extensively. In Table 5 the amount of energy between the frequency borders of short waves and between the frequency borders of middle long waves is displayed. The upper part of the table contains values measured before the PEMs have been installed at the beach, while the measurements of 5-6 September are done after the PEMs have been installed. Between brackets, a larger frequency domain of the short waves is displayed. The frequencies of 0.25 – 0.4 Hz have not been measured at 5-6 September, because the sampling frequency was too low (2 s) at these days.

Comparing the data collected at different times with each other is meaningless, because on the 5th and 6th of September, the waves were much higher than on the 2nd and 3rd. Moreover the length of the data series is different and the beach profile (depth of the divers) has been changed between the 3rd and 5th of September. To find out if the PEMs influence the amount of wave energy of specific wave frequencies in the ground, the energy measured by the divers close to PEM f and in PEM f will be compared with the energy at locations at a larger distance. By comparing the energy at a specific location with the mean energy of all locations it can be observed if the energy of the groundwater pressure fluctuations is relative high or low.

It is interesting to compare the energy of the short waves measure with divers 2 and 5 (0.5 m from PEM f) with the mean short wave energy of all divers, which is pretended to be 100%. More high frequency engergy might be conducted into the ground by a PEM. Moreover, the amount of short wave energy could be changed relative to the amount of long wave energy. Table 6 contains results of an analysis of the numbers shown in Table 5.

Date	Diver (serie)	Inter-val	Energy short waves 0.08 – 0.25 Hz (0.08 – 0.4 Hz)	Energy long waves 0.0125 – 0.05 Hz	Short waves compared to mean	Long waves compared to mean
2-3 sept	2 (42)	1 s	0.2374(0.2937)	0.1809	101.71 %	100.28 %
2-3 sept	3 (28)	1 s	0.2337(0.2922)	0.1811	100.13 %	100.39 %
2-3 sept	5 (36)	1 s	0.2150(0.2634)	0.1791	92.12 %	99.28 %
2-3 sept	6 (21)	1 s	0.2492(0.3128)	0.1799	106.77 %	99.72 %
2-3 sept	9 (54)	1 s	0.2319(0.2855)	0.1811	99.36 %	100.39 %
2-3 sept	13(72)	1 s	0.7891(1.1935)	0.2209		
2-3 sept	2 to 9		0.2334(0.2895)	0.1804	100 %	100%
5-6 sept	1	2 s	0.8840	0.2630	98.46 %	98.50 %
5-6 sept	2	2 s	0.8947	0.2689	99.65 %	100.71 %
5-6 sept	3	2 s	0.9850	0.2720	109.71 %	101.87 %
5-6 sept	5	2 s	0.8347	0.2602	92.97 %	97.45 %
5-6 sept	6	2 s	0.8991	0.2675	100.14 %	100.19 %
5-6 sept	11	2 s	0.8891	0.2704	99.03 %	101.27 %
5-6 sept	13	2 s	2.2445	0.3812		
5-6 sept	1 to 11		0.8978	0.2670	100%	100 %

Table 5: Distribution of wave energy near the low waterline between short waves and long waves

Diver number (distance to PEM f)	2/3 Sept; short wave energy relative to mean	2/3 Sept; short wave energy relative to long wave energy	5/6 Sept; short wave energy relative to mean	5/6 Sept; short wave energy relative to long wave energy
2 / 5 (0.50 m)	96.92 %	125.67 %	96.31 %	326.86 %
3 / 6 (10 m / 5 m)	103.45 %	133.77 %	104.93 %	349.23 %
1 (top PEM f)	XXX	XXX	98.46 %	336.12 %
11 (bottom PEM f)	XXX	XXX	99.03 %	328.81 %

Table 6: Comparison of wave energy in PEM f, close to PEM f and at al larger distance from PEM f

Before the PEMs are placed, the energy of the high frequency pressure variations close to the future PEM f is a few percents lower than the mean high frequency energy, while at a larger distance from the future PEM f, the energy is a few percents higher than the mean value. This distribution stays nearly the same after installation of the PEMs. Near PEM f (before the PEM was placed), the high frequency energy is 125.67 % of the low frequency energy. This is 6.1 % less than at a larger distance. After the PEMs have been placed, the short wave energy compared to the long wave energy near PEM f is 6.4 % less than at a larger distance. According to these facts (shown in Table 6) no effect of the PEMs on the energy of the groundwater pressure variations is noticed.

7.8.3 Shock caused by air in top of a PEM

Figure 54 shows the pressure measured in the top of PEM b (red line) compared with the air pressure above the ground (green line). At this location, in the top of a PEM near the high waterline, no complete tidal cycle is visible. During the highest water level, a water column of almost 20 cm is measured. During the rest of the time a constant (air) pressure of about 1 cm under atmospheric pressure is observed in the top of the PEM. When the groundwater is rising, no heavy high frequency pressure fluctuations are visible. This means there is no evidence for pressure variations which can drill the sediment into a stronger packing.

A remarkable phenomenon is the under pressure in the top of PEM f after the groundwater level has been decreased under the position of the pressure sensor of diver 3. Apparently, the upper part of the PEM, which is not perforated, is sucked vacuum by the decreasing groundwater. The under pressure is about 9 cm water column at its maximum and the duration of the under pressure is about 1:15 h. Apparently the small air filter in the top of the PEM can not be reached by air, which has to be transported through the capillary zone, above the phreatic surface. The under pressure in the top of the PEMs can create a downward force on the sediment particles above the PEM. In this way the stability of the sediment can be increased while the groundwater level is dropping from the top of the PEM to a few decimetres under the top.

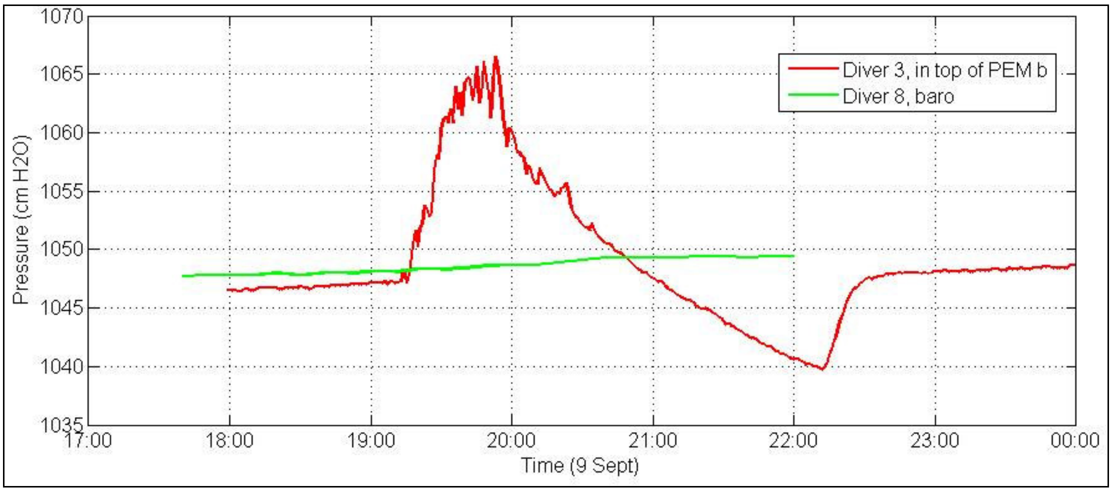

Figure 54: Under pressure in PEM b when the groundwater level falls under the top of the PEM

7.8.4 Conclusions

No indication is found for an effect of the PEMs on the high frequency pressure variation in the groundwater. The relative amount of high frequency energy compared to low frequency energy (which is little subjected to influencing) did not increase or decrease after PEMs have been placed. The distribution of high frequency wave energy over the divers at different distances of PEM f also stayed unchanged after placing the PEMs.

An other interesting effect is discovered during the analysis of pressure. An under pressure can be created in the top of a PEM, while the water level is dropping and after it is under the top of the PEM. This “vacuum” can have a stabilizing force on the sediment above the PEM.

7.9 Hypothesis: Decreasing pressure variations in the bottom

7.9.1 Testing hypothesis with diver data

Paragraph 4.4.5 describes the hypothesis of PEMs reducing pressure variations in the bottom. This reduction of the pressure variations could be a result of an air bell in top of a PEM. This volume of air acts as a shock absorber for pressure variations which move through the bottom near a PEM.

To know if this phenomenon occurs, first it had to be tested if a volume of air stays in the top of a PEM when the PEM is submerged. A CTD diver in top of PEM f measures no conductivity as long as the conductivity sensor is filled with air. With this observation it is possible to know if the top of the PEM contains air or saline water (fresh water has a very low conductivity). If it can be observed that air stays in top of PEM f, high frequency pressure variations measured in and in the direct vicinity op this PEM can be analyses at the time the air bell exists.

7.9.2 Air in top of a PEM

PEM f has been placed near the low waterline at a depth of about 30 cm, with different diver in it and in the surrounding bottom. Unfortunately a severe storm at the 5th of September lowered the beach profile near the low waterline with almost 50 cm. After that storm PEM f was not totally in the ground anymore, but the top was visible above the surface. The possible enclosing of air in top of a PEM could only be measured in PEM b, the PEM near the high waterline, with also divers in it.

Between the 8th and 10th of September diver 3 measured the pressure and conductivity in the top of PEM b. During these days the top of the PEM was submerged only one time. This event is the only possibility to check if air could escape directly through the small filter in the top or if it was not able to flow out through the capillary zone. The sensor of diver 3 was located 15 cm under the top of the PEM. If air is enclosed in the upper 15 cm of the PEM, the pressure has to increase before the groundwater has reached the sensor, which is indicated by non-zero conductivity.

Figure 55 shows both the pressure and the conductivity in the top of PEM b at the moment diver 3 was submerged. Before 19:15 h and after 22:10 h the conductivity sensor is above the water level in the PEM. The pressure starts to rise above atmospheric pressure when the sensor of the diver is submerged. It is possible that air is enclosed in the top of the diver after the water level has been raised above the conductivity sensor. According to Figure 54, an under pressure exists in the top of PEM b which is neutralized when it has reached a maximum of 9 cm water column below atmospheric pressure. When the groundwater level is lowered 9 cm under the top of the PEM, it seems to be possible for air to flow into the air filter in top of the PEM again. Before this moment, capillary forces between sand particles block this air flow.

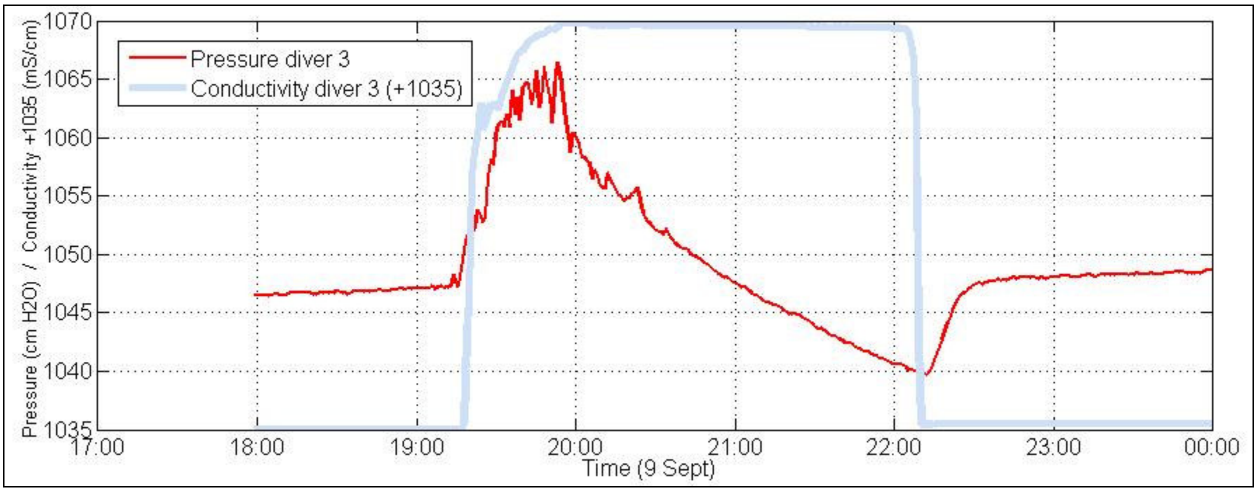

Figure 55: Pressure variation and conductivity in the top of PEM b

7.9.3 Conclusions

A “vacuum” is observed in the top of PEM b, during decreasing groundwater level. After the groundwater level is 9 cm under the top of the PEM, air can flow into or escape from the PEM trough a small air filter in the top. When the water table is rising, no more than 9 cm air can be enclosed in the top of the PEM, because the capillary zone which can block an air flow, seems to extends at its maximum 9 cm above the phreatic level. Because the water level was just around the surface level at 19:45 h, high frequency wave pressures have not been measured. Unfortunately, PEM f, near the low waterline, was connected to the atmosphere after a lot of erosion. This made it impossible to compare the pressure variations close to a PEM, which was possibly filled with some air, with the pressure variations at a larger distance from this PEM.

7.10 Hypothesis: Guiding captured air to the surface

Not a special monitoring technique for this phenomenon has been developed, because this fifth hypothesis (described in paragraph 4.4.6) has been invented after the preparation of the fieldwork. With the available data it is not possible to test this hypothesis. When air is flowing out of the PEM, an under pressure might exist in the PEM, because flowing air decreases the pressure. Nevertheless, this is not visible in the data, because air flowing out through the small filter in top op the PEM will not cause large velocities in the tube, which has a much larger flow area than the filter. To find out if air flows in or out of the PEM measurements should be done, with a very accurate device, in the air filter in the top.

7.11 Concluding remarks

7.11.1 Measurement technique and data

The pressure and temperature measurements with divers are very accurate. The maximum difference between two succeeding pressure measurements is about 0.6 cm, while the pressure is expected to be constant. The conductivity measurements seem to be inaccurate. While the manufacturer of the divers claimed accuracy within 1%, calibration of the divers after the fieldwork determined a margin of more than 10% for several divers. Before the fieldwork the calibration resulted in inaccuracies around 1%. Moreover, the inaccuracy of the conductivity generally seemed to increase during the period the divers had been in the ground and the conductivity could be pressure dependent.

In total 13 divers were available for the fieldwork, 2 of them could not be used in the end anymore. This made is possible to measure around 2 PEMs, one near the low waterline and one near the high waterline. Unfortunately not enough divers were available to measure at different depths, monitoring flows of water with different temperatures and salinities.

7.11.2 Probability of the hypotheses

The diver measurements can not prove some hypotheses with certainty. Some hypotheses are unlikely according to the results, but for others it is difficult to say something about the probability, making use of the diver data. A possible lowering of the groundwater level due to the draining capacity of the PEMs is not measurable at a distance of 0.5 m from a PEM. Apparently, a possible groundwater table change by the PEMs is obviously smaller than the measuring accuracy of the divers (1 cm) and the natural variability (order of 1-2 cm). A transporting function of the PEM may be plausible, because the temperature of the water in the PEM fluctuates much more than in the surrounding groundwater.

The conductivity measurements are not reliable enough to prove a canalisation of outflow of groundwater through a PEM near the low waterline. Nevertheless, a supposition arises while studying these data. High frequency pressure variations are not conducted into the ground by a PEM. Multiple measurements of the high frequency pressure variations in the groundwater at different distances from a PEM invalidate this presumption.

Air can be preserved in the top of a PEM when the groundwater level rises. Measurements show that at its maximum 9 cm of the length of the tube can stay filled with air when the groundwater level rises above the top of the PEM. The obstruction of an inflow or outflow route for air trough the top of a PEM by capillary forces can cause an under pressure when the water level is decreasing. The last hypothesis of a PEM as an escape route for air which is locked up under a lens of water can not be examined with the actual measurement data.

7.11.3 Recommendations for future research

To measure vertical currents in the ground and in the PEMs, it will be important to install a lot of temperature and conductivity sensors at different depths. Compared to the fieldwork described in this report, at least twice as much measurement equipment around a PEM near the low waterline is required, while this amount should also be installed in the vicinity of a PEM near the high waterline. The conductivity measurements of the CTD divers were very inaccurate. For the purpose of conductivity measurements better equipment is required.

During a measurement period of 2 weeks, the morphology of the beach can change a lot, causes by a storm. Before measurement equipment and PEMs are place the weather forecast has to be studied to make an estimation of the erosion and sedimentation at different locations. Anticipating on the weather conditions, the equipment or PEMs have to be placed at a larger or smaller depth than according to plan, to prevent the material is sticking out of the bottom or is located too deep after a couple of days.

8. Conclusions

The start of the study to pressure equalizing modules (PEMs) in the beach was very open. Very little knowledge existed about the innovative system with PEMs, called Ecobeach, which was tested at the Dutch coast near Egmond aan Zee. Before the test very little scientific research was done. The main question for this study was: does Ecobeach work?

During a scientific workshop about the PEM system with scientists from different disciplines, it became clear that a possible working mechanism could be found in a lot of directions. After many discussions with scientists and some orientating research at the beach, like groundwater conductivity measurements and sediment analysis, the main goals of the MSc Thesis became clear. The groundwater behaviour in the vicinity of a PEM and the influence of a PEM on it should be an important issue. Besides that the sediment composition inside and outside the Ecobeach test area should be investigated.

An analysis of the Ecobeach test area makes clear natural variability, on yearly scale caused by weather circumstances and on longer timescale caused by bar migration and possibly sand waves, makes it difficult to prove the working of Ecobeach by a statistical analysis of the coast. Under the saline beach groundwater fresh water flows out from the dunes. The transition from saline to fresh groundwater is situated at a depth of about 7 – 9 m. PEMs are not long enough to transport fresh water to the surface in the Dutch situation. Some measurements of the groundwater show at 1.0 m depth pressure variations as large as half the wave height and relative fresh groundwater near the low waterline, suggesting exfiltration of groundwater. Sediment in the swash zone is coarser than near the high waterline, while at an arbitrary location in the southern Ecobeach test area the sediment in the swash zone is coarser than at an arbitrary location in the reference area.

According to the literature study, a lot of sediment transport occurs between the low and high waterline, where PEMs are installed. The transport processes are very complicated. Among others, the quantity of transported material depends on infiltration and exfiltration of groundwater. At coarse beaches, the sediment transport is increased by infiltration, while at fine beached transport is increased by exfiltration. The critical changeover point of the grain size appears to lie around 0.5 mm. At beaches, a circulation flow of groundwater exists in the swash zone. Infiltration generally occurs near the high waterline, while the low waterline is an exfiltration zone.

5 hypotheses are defined as possible working mechanisms of the Ecobeach system increasing the volume of sand at the beach. The hypotheses are based on events in the groundwater behaviour which could be caused by PEMs. The different hypotheses form a complex scheme of interacting events. In the scheme also results of the events are mentioned. Those results can be visible at the beach, for instance a steeper beach face, a wider beach or a coarser intertidal beach.

Some of the initial effects, possibly leading to a wider beach, are investigated during a fieldwork with groundwater measurements around PEMs. A lowering of the groundwater level in the vicinity of a PEM, indicating a draining effect of the PEM, has not been found. The lowering could be too small to observe within the natural variability or the measurement accuracy. Notable temperature fluctuations of the water in a PEM indicate vertical transport of water through the tube. Conductivity measurements could indicate a promotion of groundwater exfiltration through a PEM near the low waterline, but unfortunately the conductivity measurements of the "divers" were much too inaccurate to say something with certainty.

It becomes clear from the high frequency pressure variation measurements in the groundwater that a PEM does not function as a pressure conductor, leading pressure variations into the ground. This makes the hypothesis of drilling sediment particles into a more stable structure unlikely. An under pressure is measured in a PEM during decreasing groundwater level. This indicates air can be enclosed in the top of a PEM. The maximum quantity of air in the top of a PEM near the high waterline is estimated to be 9 cm of the tube. If this is enough to moderate pressure fluctuations in the ground, could not be investigated. Other effects of an under pressure, like stabilizing the overlying sediment, are imaginable. With the measuring methods used during the fieldwork it can not be made clear if PEMs guide captured air to the surface.

Some understandability is created about the influence of a PEM on the groundwater behaviour, but a lot of questions still exist. Moreover, new knowledge of the behaviour of beach groundwater is obtained by the diver measurements.

One of the indicators of the workings mechanisms of the PEM system, which are defined in the report, is coarser sediment in the intertidal zone. A sediment analysis along the southern Ecobeach test area and the bordering beaches is executed, leading to an interesting result. The sediment in the intertidal zone of the test area is, with a D50 of over 400 MU, clearly coarser than the bordering areas, which have a D50 of around 350 MU. This could be in indication of a visible effect of the PEM system.

9 Recommendations

The study to the Ecobeach drainage system is still not completed and the results shown in this report are a reason to proceed with the research. At this moment, the continuity of the study is already guaranteed.

The measurements in the field are very important to find out the possible working mechanism of the PEM system. Supplementary groundwater measurements can be executed. The measurement equipment has to be more accurate according to the conductivity measurements to study small changes in the global groundwater flow. Moreover, more sensors have to be placed at different depths, because of the 3-dimensionallity of the environment on which the PEMs can have an influence.

One of the results presented in this report, is an under pressure developing in a PEM during decreasing water level. The consequence of this for the processes in the swash zone is still not completely clear. This can be examined in the future.

The 5th hypothesis mentioned in this report (guiding captured air to the surface) is developed after the fieldwork was executed. For this reason no specific measurements were done to study this hypothesis. It is worth while to search for evidence of this theory by measuring the air transport through the small filter in the top of a PEM.

The results of the sediment analysis along the coast are promising. A larger analysis is already implemented and the first results (still conceptual during the finishing of this report) confirm the picture sketched in Chapter 6. The connexion between the Ecobeach system and the relative coarse sediment is still not found. To get more certainty about the correlation between PEMs and coarser sediment the same analysis should be done in Ecobeach test areas at other locations, like Denmark and South Africa.

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Appendix A Ecobeach system (United States Patent 6547486)

A.1 Patent information

Name: Method for Coastal Protection
Inventor: Poul Jakobsen
Assignee: SIC Skagen Innovationscenter
Patent no.: US 6,547,486 B1
Date of Patent: 15 April 2003

A.2 Abstract

In a method for coastal protection, where the coastal area has an underlying freshwater basin and below this a salt water tongue which extends obliquely down into the coastal area, the pressure is equalized in the groundwater basin at least along an area at the shore line completely or partly to the atmosphere through pressure equalization modules, preferably in the form of pipes with a filter at the bottom, which extend down into the groundwater basin. This causes sedimentation of material and thereby an increase in the width of the shore. The resulting sand drift may be utilized for additional building-up of the coastal area by further establishing fascines.

A.3 Claims

What is claimed is:
1. A method for protecting a coastal area which includes a beach area that meets salt water at a shoreline, and where a freshwater basin underlies the coastal area and a salt water tongue extends below the freshwater basin at an oblique angle, the method comprising extending atleast one pipe downwardly in the beach area near the shoreline so as to reach the freshwater basin and communicate the freshwater basin with the atmosphere such that at least a partial equalization of a pressure in the freshwater basin with a pressure of the atmosphere is achieved in said beach area by means of said communication.
2. A method according to claim 1, wherein said at least one pipe includes a filter in a part thereof that extends into the freshwater basin.
3. A method according to claim 1, wherein a plurality of pipes are extended downwardly through the beach to the fresh water basin at a distance from the shoreline.
4. A method according to claim 3, wherein, said coastal area also defines a swash zone adjacent said shoreline, and including placing a plurality of additional said pipes in said swash zone to communicate with said freshwater basin.
5. A method according to claim 1 wherein fascines are provided on the coastal area.
6. A method according to claim 1, wherein said at least one pipe includes an anchoring element.
7. A method according to claim 6, wherein said at least one pipe has a pipe stub which protrudes upwardly from the coastal area and a downwardly bent extension attached to the stub which includes an aperture facing downwardly and which defines an upper free end of the pipe.

A.4 Description

A.4.1 Background of the invention

1. Field of the Invention
The present invention relates to a method for coastal protection where the coastal area has an underlying freshwater basin and below this a salt water tongue which extends obliquely down into the coastal profile.

2. The Prior Art

For coastal protection, it is generally known to build breakwaters of huge stones or concrete blocks which extend from the beach to a distance into the water. Breakwaters are effective, but the costs of construction and maintenance are relatively great. Another coastal protection method is coastal feeding where large amounts of sand are transported to the stretch of coast which is to be protected. This method also involves great costs of construction and maintenance, since large amounts of sand have to be transported. These two methods are still the most widely used coastal protection methods.

In connection with the establishment of intakes for the pumping of sea water for use in salt water aquarias, it was discovered in the early 1980s that sedimentation took place around the intake, which became clogged because of the deposits on top of the intake. This was the incentive for experimenting with a new method for coastal protection, as described in DK 152 301 B. The idea of the method is to pump water from drains established along the shore line, resulting in sedimentation at the drains. However, this method never found extensive use, as it requires a great pumping capacity and consequently high costs of construction and high pump operating costs.

U.S. Pat. No. 5,294,213 discloses a similar system likewise based on drainage pipes established in parallel with the coastal both on the beach and in the water. The operation of the system, which is likewise based on pumping of water, is adapted to the weather, i.e., whether ordinary water level, low water, high water or storm conditions. The system includes a water reservoir into which the water may be pumped through the drainage pipes, and water may be pumped through these into the sea, e.g., to remove sand banks formed by a storm.

A corresponding method is known from U.S. Pat. No. 4,898,495 to keep an inlet, which debouches into the sea, open. This method is likewise based on pumps. The system comprises various diffuser arrangements to remove deposits from the mouth of the inlet by fluidizing these and transporting the material further downstream of the inlet mouth by generating a flow. Sedimentation is carried out downstream of the inlet mouth by pumping water from drains to the diffuser arrangements. An object of the present invention is to provide a method for coastal protection which is not vitiated by the drawbacks of the known coastal protections.

A.4.2 Summary of the invention

This is achieved according to the invention by a method which is characterized in that the pressure of the groundwater basin at least along an area at the shore line is equalized completely or partly through pressure equalization modules, preferably in the form of pipes with a filter at the bottom, which extend down into the groundwater basin. It has surprisingly been found by the invention that positioning of pressure equalization modules in the beach results in sedimentation of material at the area where the modules are placed.

A possible explanation as to why coastal accretion takes place is that the very fine sand which is fed to the profile partly by the sea and partly by the wind and which is packed with silt and other clay particles, reduces the hydraulic conductivity. Deeper layers in the coastal profile, which have exclusively been built by the waves of the sea, are primarily coarse in the form of gravel and pebbles which have a greater hydraulic conductivity. The difference in hydraulic conductivity will be seen clearly when digging into a coastal profile, it being possible to dig a hole in the profile, and the groundwater will then rise up into the profile once the water table is reached. The reason is the very different hydraulic conductivity and that the freshwater is under pressure from the hinterland. Thus, the coastal profile may be compared to a downwardly open tank where the tank is opened at the top with the pressure equalization modules which extend through the compact layers of the profile so that the water runs more easily and thereby more quickly out of the profile in the period from flood to ebb. This means that a pressure equalized profile is better emptied of freshwater and salt water in the fall period of the tide.

When the tide then rises from ebb to flood, a greater fluctuation occurs in the foreshore, as the salt water in the swash zone is drained in the swash zone so that materials settle in the foreshore during this period of time. Conversely, coastal erosion takes place if the freshwater is under pressure in the foreshore, as the salt water will then run back into the sea on top of the freshwater and thereby erode the foreshore. In reality, the pressure equalization modules start a process which spreads from the pressure equalization modules, as the silt and clay particles are flushed out of the foreshore when the fluctuation is increased because of the draining action of the modules.

Further, a clear connection has been found between the amount of sediment transport on the coast and the rate of the coastal accretion. It has been found that the pressure equalization modules create a natural equilibrium profile with a system of about 1:20, so that the waves run up on the beach and leave material, as water in motion can carry large amounts of material which settle when the velocity of the water decreases. The profile must therefore have a given width with respect to the tide and a maximum water level in the area. Coastal profiles with pressure equalization modules naturally become very wide, which results in a very great sand drift on the foreshore. This great sand drift is utilized by establishing longitudinal fascines high up in the beach and transverse fascines with an increasing height toward the foot of the dune, the fascines forming the upper part of the beach profile. The invention will be described more fully below with reference to the accompanying drawings.

A.4.3 Brief description of the drawings

FIG. 1 shows a cross-section through a coastal profile
FIG. 2 shows a pressure equalization module intended to be positioned on the beach
FIG. 3 shows a pressure equalization module intended to be positioned in the swash zone
FIG. 4 shows a stretch of coast seen from above with pressure equalization modules and fascines
FIG. 5 shows a coastal profile in the stretch of coast in FIG. 4

A.4.4 Detailed description of the preferred embodiments

As shown in FIG. 1, a freshwater basin is present below a coastal profile 1, and this freshwater basin is defined at the bottom in a downwardly inclined plane by a tongue of salt water 3 which has a greater density than freshwater. The reason for coastal erosion is thus that when the freshwater below the beach profile is under pressure, the salt water seeping down into the profile runs back into the sea on top of the freshwater 2, as shown in FIG. 1. When the pressure of the freshwater decreases, the salt water seeps down through the material in the coastal profile and is mixed with the freshwater and thus does not erode the coastal profile, but, instead, material settles on the beach.

As shown in FIG. 2, the pressure equalization modules may consist of a rigid filter pipe 6 which is connected to a pipe 7 having a sleeve 7a. The filter and the pipe may thus be pressed, flushed or dug into the freshwater basin 2. Preferably, the pipe 7 has a length such that it protrudes slightly above the surface of the coastal profile 1 when the filter is in position in the freshwater basin. The pipes with filters, as shown in FIG. 2, are arranged in a row in a line which is perpendicular or approximately perpendicular to the shore line. The pipe 7 is open at the top so as to create good hydraulic contact down to the freshwater basin.

When the pressure in the freshwater basin has been equalized by means of the pressure equalization modules 12, the sedimentation of material on the stretch of coast may be accelerated according to the invention by establishing further pressure equalization modules 13 in the swash zone 4. An expedient arrangement of a module to be positioned in this zone is shown in FIG. 3 and comprises a rigid pipe 7' connected with a horizontal filter pipe 6'. In both cases, the modules are provided with an anchoring element 8 intended to be dug into the sand to prevent unauthorized removal of the modules. The anchoring element is in the form of two angled plate elements secured to the rigid pipe. Furthermore, the pipe end, which protrudes from the sand, is provided with a curved termination 9 to prevent unauthorized filling of the pipe with sand, stone, etc. Optionally, the pressure equalization modules may be connected with dug pipes which are run to the foot of the dune where free communication with the atmosphere is created, thereby avoiding protruding pipe stubs. The use of such pressure equalization modules on a stretch of coast has resulted in a land reclamation of a width of 4-6 metres and an increase in the coastal profile of 60-70 cm in 40 days.

Coastal profiles with pressure equalization modules naturally become very wide, as mentioned, which results in a great sand drift on the foreshore. As will appear from FIGS. 4 and 5, this great sand drift is utilized by establishing longitudinal fascines 10 high up in the beach and transverse fascines 11 of an increasing height toward the foot of the dune. The upper part of the beach profile may be given the desired shape by adapting the length, orientation and height of the fascines. The fascines may, e.g., be formed by brushwood of pine and spruce or the like dug into the coastal profile or stacked between buried piles, which makes it easy to give the fascines the desired shape.

The invention is unique by low costs of construction and operation, the cost of operation involving merely ordinary inspection and maintenance of the systems. New research in the field has documented that the groundwater pressure on a coastal profile is very decisive for its appearance. It has been demonstrated that coastal profiles having a high freshwater pressure become narrow and concave (also called winter profile), while coastal profiles without noticeable freshwater pressure become wide and convex (also called summer profile). Narrow, concave coastal profiles having a high freshwater pressure are seen in Denmark typically at Vejby Strand on the north coast of Zealand and south of Lønstrup at Mårup Kirke. Narrow, concave coastal profiles are greatly exposed to erosion, while wide, convex coastal profiles have beach accretion. With the invention, as described, it is possible to convert a narrow, concave coastal profile into a wide, convex coastal profile and thereby to protect the coast.

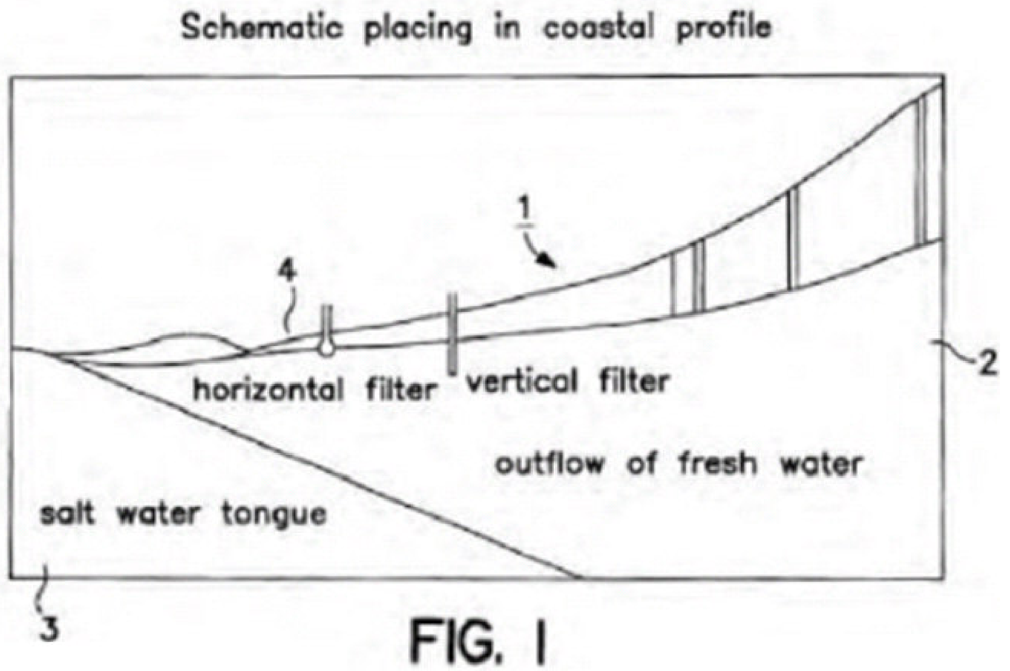

FIG. 1

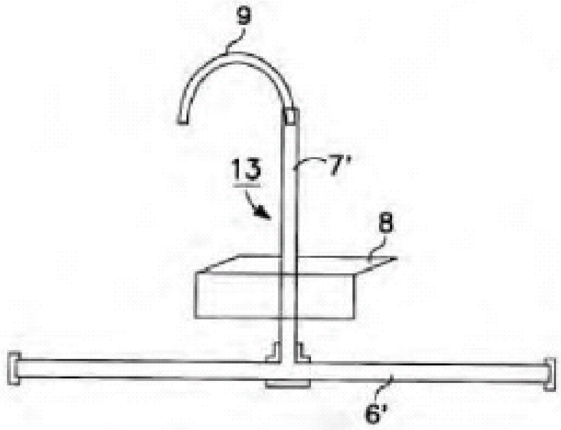

FIG. 3

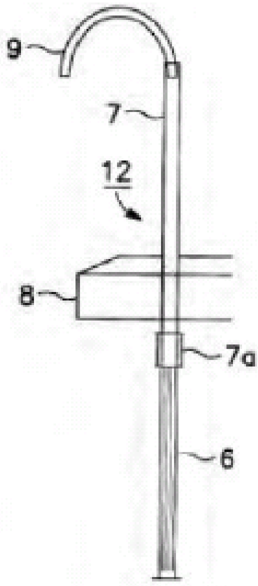

FIG. 2

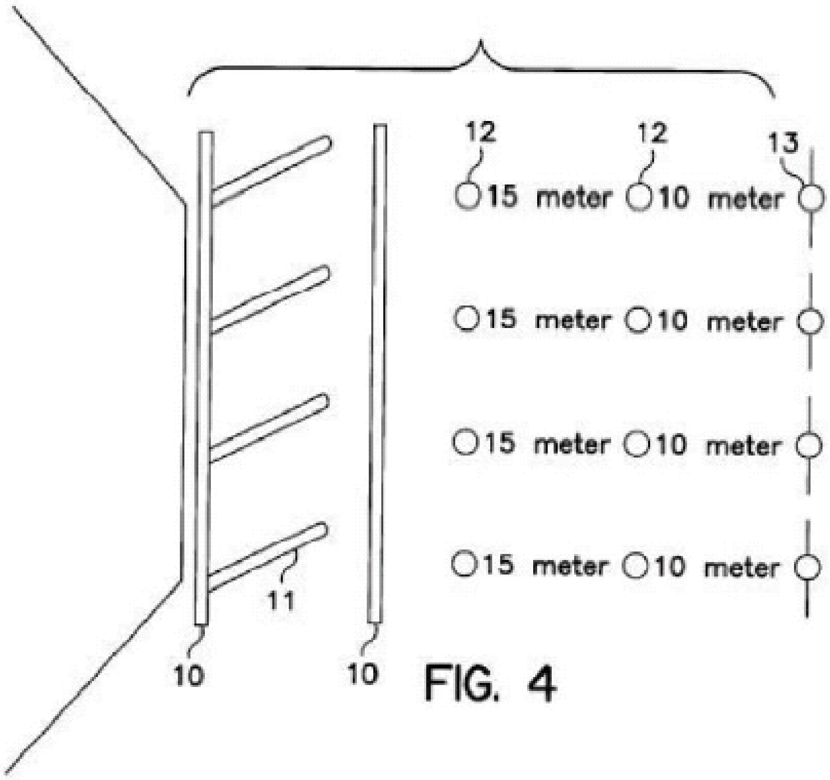

FIG. 4

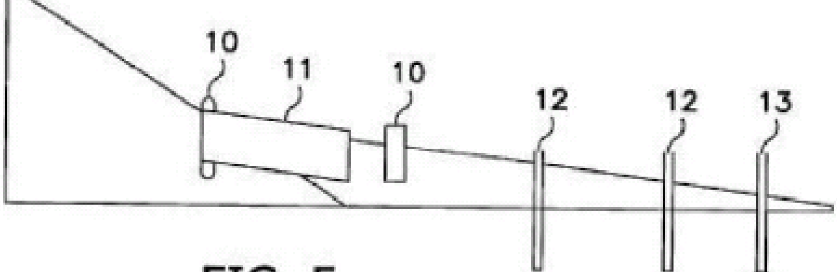

FIG. 5

Appendix B Analysis of the Dutch test site

B.1 Introduction

Two test areas of 3 km length are situated along the coast of Noord-Holland. The location of the test areas can be expressed in “JARKUS-raaien” (RSP), in which the position along the Dutch coast is being indicated. The northern test area is situated between RSP 3600 and RSP 3900 and the southern test area between RSP 4000 and RSP 4300.The northern test area is located in a region which has been heavily nourished during the past decade, while the southern area is located in a fairly undisturbed region.

An essential starting position investigating the Ecobeach system is a description of the area in which Ecobeach is functioning. In this appendix, the conditions at the test site are being outlined. The scientific program of Ecobeach mainly focuses on the southern, undisturbed, test area, whereas there will be a focus on the Deltares analysis of coastal development as well. This appendix will mainly give a description of the southern test area.

B.2 General

The Southern Ecobeach test area has a length of 3 km and is located just on the south of the Dutch coastal village Egmond aan Zee. Egmond aan Zee is located in the northwest of the Netherlands (see Figure B1), along the central part of the Dutch coast, the so-called *Holland Coast*. The beach is facing the North Sea and shoreward a dune area exists which is approximately 1.5 – 2 km wide. In Figure 2 both the northern and southern Ecobeach test area are indicated by red lines.

At the village of Egmond aan Zee the coastal defence is pretty weak. The beach of Egmond is a popular attraction for tourists. The southern test area, however, is not so crowded, because it adjoins a wide dune area, which is a natural reserve. Cameras (Argus webcams) have been installed in the middle of the southern Ecobeach test area to watch the beach continuously. Figure B1 shows a view of the test area with an Argus camera which is directed to the south.

Figure B1: View of the southern Ecobeach test area with an Argus webcam

B.3 Conditions of the ground

Coastal system

In the Google Earth aerial view of Figure B2 the coastal system at the 3 km long southern Ecobeach test area is shown. From the left up to the right, the figure shows the North Sea in which the outer breaker bar is slightly visible, the beach, the dunes, and the agricultural landscape with the village of Egmond Binnen which is protected by the dunes against the sea.

Figure B2: Aerial view of the coastal system, containing the southern Ecobeach test area [8]

Beach, foreshore and bars

Figure B3 shows the foreshore of the beach of Egmond aan Zee. The coast is to be oriented in a north-south direction. Thus waves coming from a western direction approach the beach perpendicular. Due to the shape of the North Sea the largest waves approach the Dutch coast form a north western direction. The foreshore exists of two breaker bars, which reduce the height of the incoming waves, so they loose energy, caused by friction and breaking. The inner breaker bar appears above the water during very low sea water level, while the outer breaker bar is always submerged.

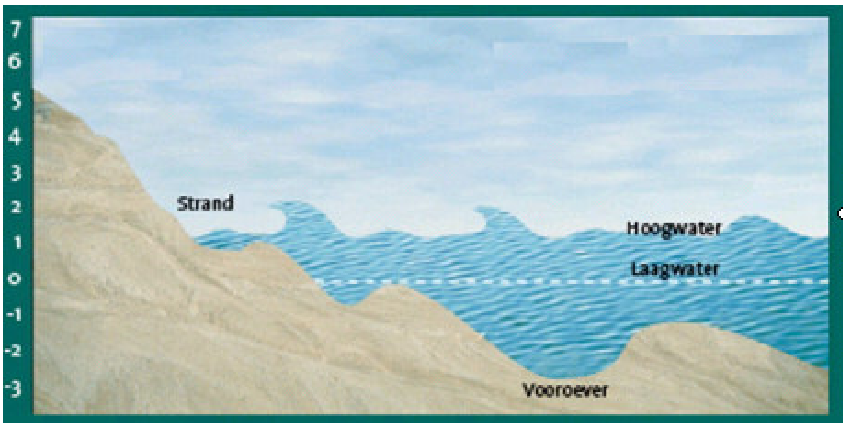

Figure B3: Foreshore of the beach near Egmond aan Zee [1]

The beach width (distance between the dune foot at NAP +3 m, and NAP +0 m, see Figure 3) varies from approximately 60 m to 120 m, which depends on the beach angle. During storm surge, waves can reach spots well over NAP +3 m and the beach can be totally submerged.

The slope of the beach is not the same all over between the dune foot and the waterline and varies strongly in time. In Figure B4, the profile of the beach and foreshore is given at an arbitrary location near Egmond [JARKUS measurements, RWS]. The different colours show the profiles at different moments between 1968 and 1980 at exactly the same location. Besides the beach slope the location of the bars is not stable. The bars seem to move offshore, which agrees with [3].

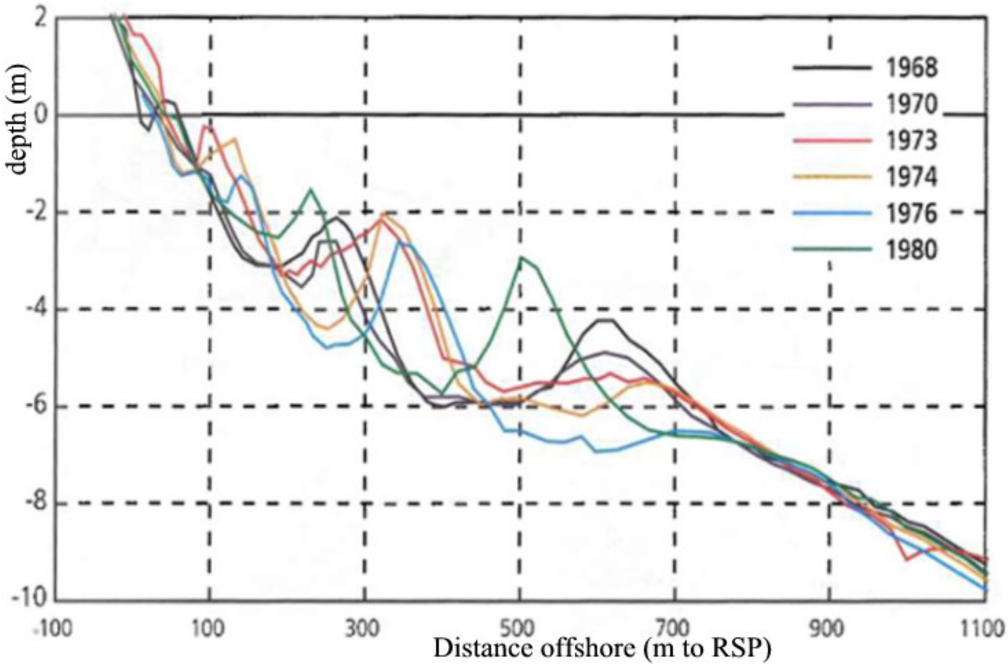

Figure B4: Profile development of beach and foreshore at a location near Egmond [7]

The distance from the outer breaker bar to the beach, varies along the coast (see Figure B2) and in the time (see Figure B4). The position of this breaker bar can have an effect on the wave climate at the beach behind this bar and the development of this beach.

Dunes

The dune area on the shore side of the southern Ecobeach test area has a width of minimal 1.5 km, at the widest point about 2.5 km. The first row of dunes, which forms a protection against the sea, has a height of 15 – 20 m. The height of the dune area behind this seaside row (see Figure B5) varies from 4 m in the valleys to 30 m at the highest tops. The groundwater level of the dune area lies several meters (up to 4 m) above mean sea level [9].

Figure B5: The dune area bordering the southern Ecobeach test area

Bottom material
The foreshore, beach and dunes at the southern Ecobeach test area mainly consist out of sand. Some (thin) layers of peat might be present in the upper 20 m of the bottom [9]. After stormy circumstances, peat can be found on the beach, which indicates the presence of shallow peat layers. At the beach the uniform sand body contains irregular layers of shelves.

Information has been gathered about the grain sizes at the beach surface in the southern Ecobeach test area, around RSP 4200. Close to the dune foot the D50 is 250 – 290 MU, while at the lower part of the beach, the D50 is 330 – 380 MU (see Appendix F.2, Figure F1, sediment sizes at Egmond beaches). Overall, from the deep water to the intertidal beach, the sediment gets coarser [Van Rijn, 2002] and from the intertidal beach to the dunes the sediment gets finer again (Appendix F.2).

B.4 Hydrology

Tides, waves and rainfall
At the southern Ecobeach test area, the coast experiences a micro-tidal semidiurnal tide, with a neap tide range of 1.4 m and a spring tide range of 2.1 m. The asymmetric tidal wave, travelling along the coast from south to north, makes the flood period (3 – 5.5 hours), shorter than the ebb period (6.5 – 9.5 hours). Due to the asymmetry, the flood current, directed to the north, can reach larger velocities than the ebb current, which appears in a southern direction.

In general, the wave climate at the Ecobeach test area, which is to be situated along the North Sea, is calm. In the storm season, during a northwester storm, the offshore significant wave height $H_{S,0}$ can exceed 4.0 m (see Table ***B*** B1). The outer breaker bar, which is to be situated at a depth of 4-6 m beneath storm surge level, reduces the wave height to 2-3 m before approaching the inner breaker bar, which indicates the beginning of the beach. Table ***B*** B1 shows statistical information about the offshore wave climate near Egmond aan Zee [4].

Wave classes	Offshore wave height $H_{S,0}$ (m)	Spring and summer % of occurrence	Autumn and winter % of occurence
Winter (D-J-F)	0-1	60%	25%
Spring (M-A-M)	1-2	30%	40%
Summer (J-J-A)	2-3	10%	20%
Autumn (S-O-N)	3-4	0	10%
Year	>4	0	5%

Table B1: Offshore wave climate near Egmond aan Zee [4]

The average net rainfall (rainfall minus evaporation) at Egmond aan Zee is on average positive during the year [10]. The average net rainfall of the last 30 years is given in Table B2. The data have been split into the different seasons.

	Rainfall	Evaporation	Net rainfall
Winter (D-J-F)	175.0 mm	30.5 mm	+144.5 mm
Spring (M-A-M)	130.6 mm	183.0 mm	-52.4 mm
Summer (J-J-A)	168.7 mm	280.0 mm	-111.3 mm
Autumn (S-O-N)	268.6 mm	89.2 mm	+179.4 mm
Year	742.9 mm	582.7 mm	160.2 mm

Table B2: Climate Egmond aan Zee: net rainfall

Groundwater characteristics
The relatively high groundwater level under the dune area makes fresh water flowing out under the beach by an overpressure. Layers of clay and peat in the bottom, which cannot be traced exactly, possibly influence this flow. The upper layer of the beach consists of saline water, filled on a daily basis by tides and waves.

The transition layer between the fresh and saline water is to be located at a depth of 7 – 10 m. Near this layer, mixing occurs. Figure B6 shows a cross shore groundwater profile in the Ecobeach test area, measured by CVES (see Appendix C.3). The blue and green colours indicate saline water, while red and purple show the deeper located fresh water.

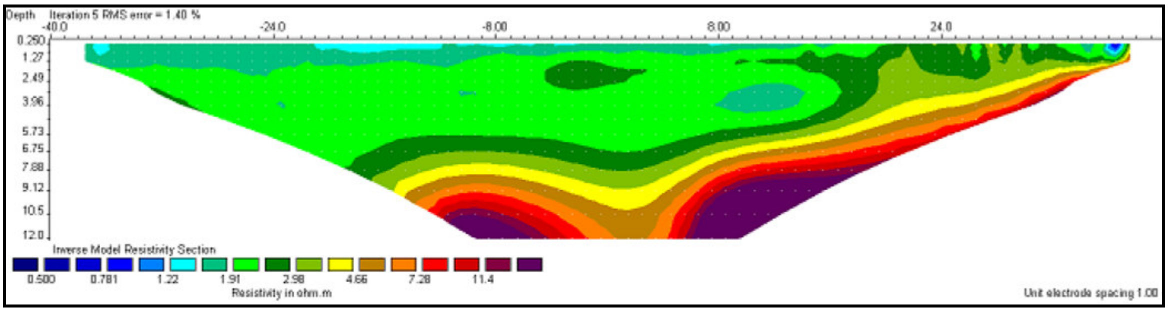

Figure B6: Cross shore groundwater salinity profile, RSP 4200, Februari 2009

The tidal variation of the sea water level is asymmetric, as stated before. The tidal variation propagates through the ground under the beach. During this propagation in the direction of the dunes the amplitude decreases due to the limited permeability of the sand body. Apart from that, the asymmetry increases and the average groundwater level increases, because the beach getting filled with water (infiltration of waves) is a much faster process than getting emptied (due to a difference in water level, Darcy).

Influence by wind waves
Wind waves transport volumes of water onto the beach and cause pressure differences inside the ground. The pressure differences caused by wind waves are being measured with divers (pressure transducers) at the Egmond beach. Although the period of the waves is only 3 – 5 s, the waves can be noticed very well at a depth of 1.0 m. Pressure differences of 0.50 – 0.60 m water column at the surface are reduced to 0.20 – 0.30 m water column at 1.10 m depth (see Figure B7 and Appendix D.4).

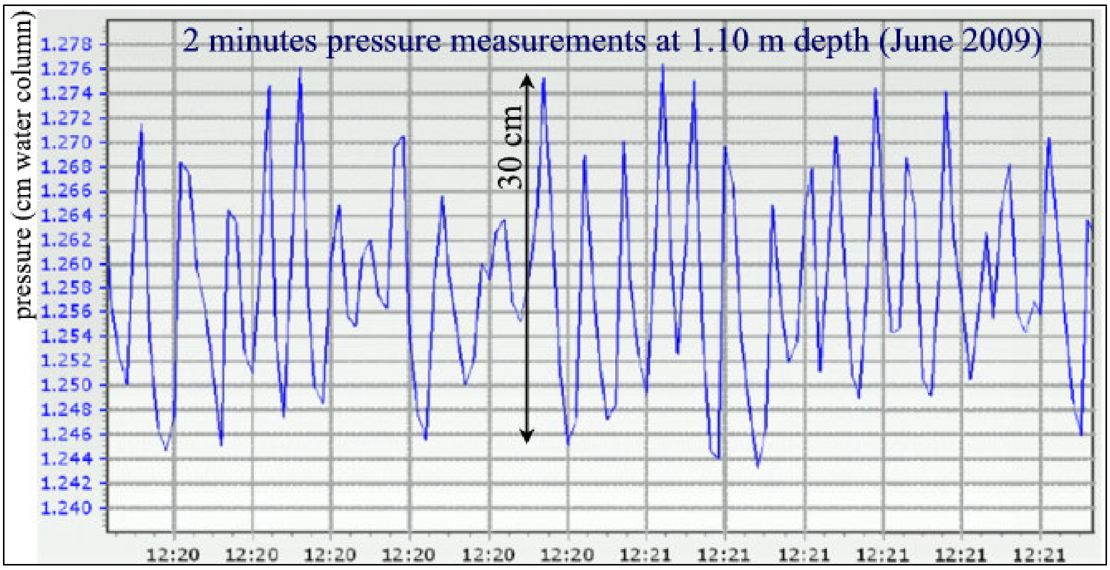

Figure B7: Groundwater pressure variations due to short waves

Each wind wave transports a volume of water onto the beach, through the swash zone. In the (upper) swash zone this water is partly being infiltrated into the beach. This causes an average water level at this location, which is higher than near the low waterline and a "circulation" groundwater flow from the higher beach (where water is being infiltrated) to the lower beach (where water is being exfiltrated). See paragraph 3.2.4.

B.5 Variability of the coastline

Different phenomena and timescales
At different timescales, the coastline is changed due to different phenomena. Important timescales are: a couple of hours (one storm event), a year (seasonal changes) and a couple of decennia, in which long term behaviour trends can be shown.

During storms large amounts of sand can be transported from the dune foot to the beach and from the beach to the foreshore (see Table B3). This is only a redistribution of the material and after the storm season an inverse redistribution will start. Under quiet conditions, waves will transport more material during uprush than during backwash and sand from the foreshore is being transported to the upper beach and wind will transport the material to the dune foot [4]. Apart from this yearly cycle, a variation of the coastline exists within a longer timescale. Within a period of 16.4 years, the beach volume near Egmond fluctuates around a very slowly increasing trend [3]. This fluctuation is caused by the offshore migration of sand banks and it might have something to do with the sand waves, about which is still much unknown, and which were able to move along the coast.

At the timescale of centuries, we can see clear trends in the coastline development of the Dutch central coast [4]. Between 1600 and now, the coastline near Egmond retreated landward about 0.75 m/year. Southward of Egmond the shoreline retreat is less pronounced, while northward of Egmond the retreat shows values of 1 to 2 m/year. During the last 140 years, the coastline at Egmond was almost stable, but over the period 1963-1986, the sediment budged showed a deficit in net volume of about 150.000 m³/year between the foredunes and 3500 m offshore (Hoekstra, 1990). The changes in shoreline position along the central Dutch coast over the last 140 years can be shown within three regions:
1. Hoek van Holland – Den Haag: retreat of 0.35 m/year.
2. Den Haag – Egmond: accretion of 0.20 m/year.
3. Egmond – Den Helder: retreat of 0.95 m/year.

Alongshore sediment transport
Most studies show an agreement of the direction of the net sediment transport along the coast of Egmond aan Zee. The net transport direction is from south to north. In different studies, the net quantity varies between -30.000 m³ and 200.000 m³ per year [6]. This large range indicates a lot of insecurity. The general transport direction along the Dutch west coast is from south to north, but this is being disturbed by large breakwaters at IJmuiden, 18 km south of Egmond aan Zee. Just on the north of these breakwaters, the net sediment transport leads in southern direction, with a changing point south of Egmond aan Zee. The very location of this point is not exactly known, but it is likely that this location should be situated in or just on the south of the southern Ecobeach test area. Knoester (1990) estimates the location of the changing point at RSP 4000.

Sand waves are big volumes of sand which influence the coastline position while moving along the coast. Sand waves at the Egmond coast are a questionable phenomenon. Their existence is proven in some studies and denied in others [11]. They should be a result of offshore movement of the breaker bars (see Figure B3) and/or the difference within alongshore sediment transport quantities along the coast. The beach dynamics possibly depend on sand waves, but they move relatively slow (<100 m / year) compared to the length of the Ecobeach test area.

Estimated sediment transport volumes

The volume of sediment which is transported at the beach and foreshore of Egmond strongly depends on the wave conditions, see Table B3 [4]. The longshore transport is far more important than the cross-shore transport. This indicates that large scale changes of the beach profile (probably "sand waves") occur for a significant part by means of longshore sediment transport.

During a major storm, 20 times as much sand can be transported in longshore direction than during calm weather. In cross-shore direction, the transport capacity during storms can be 50 times as much compared to calm conditions. During storms the transport is in offshore direction while during a quiet wave climate the transport direction can be onshore.

Wave conditions	Longshore current (mean value in m/s over surf zone width)	Longshore transport		Cross-shore transport	
		kg/s/m	m^3/day integrated over surf zone	kg/s/m passing over crest of inner bar	m^3/m per day passing over crest of inner bar
Low waves $H_{S,off}$<1.5 m	0.3	0.05	1500	+0.01 to -0.02 (onshore)	+0.5 to -1 (onshore)
Minor storm $H_{S,off}$=1.5-3 m	0.6	0.15	4500	-0.1 (offshore)	-5 (offshore)
Major storm $H_{S,off}$>3 m	1.2	1	30000	-0.5 (offshore)	-25 (offshore)

Table B3: Estimates of longshore and cross-shore transport at Egmond beach [4]

Nourishments

In the period 1999 – 2009 several nourishments of the beach and the foreshore have been executed to counterbalance the natural coastal retreat. In this period, no nourishments have been done in the southern Ecobeach test area, but in 2003 and 2004, nourishments have been executed just north of this area. Table B4 shows the nourishment locations since 1999.

<table>
<tr><th>Year</th><th>Nourishment location</th><td rowspan="6">Northern Ecobeach test area: RSP 3600 – 3900
Southern Ecobeach test area: RSP 4000 – 4300</td></tr>
<tr><td>1999</td><td>RSP 3600 – 3950</td></tr>
<tr><td>2000</td><td>RSP 3700 – 3850</td></tr>
<tr><td>2003</td><td>RSP 3600 – 4000</td></tr>
<tr><td>2004</td><td>RSP 3500 – 4000</td></tr>
<tr><td>2005</td><td>< RSP 3500, 3700 – 3950</td></tr>
</table>

Table B4: Nourishments near Ecobeach over the last 10 years

Appendix C Groundwater salinity analysis

C.1 Introduction

The groundwater situation in the Ecobeach test area and in a lesser degree the reference area is examined by different experiments which map the groundwater salinity up to a depth of about 12 tot 60 m (dependent on the execution of the experiment). EM-34 measurements have been done which sketch the electromagnetic conductivity of the ground. These measurements were done in an area at the southern Ecobeach test beach (around RSP 4200) and in an area 2 km to the south, at the reference beach (around RSP 4400). After comparison of the EM-34 measurements in the two areas the measurements in the area around RSP 4200 were continued with more accurate ones. VES and CVES measurements investigated the electric conductivity of the ground.

The EM-34 measurement show a big difference between RSP 4200 (Ecobeach) and RSP 4400 (reference area), but the difference is not clear at a small depth. Only between 7.5 and 40 m depth the salinity near RSP 4400 is clearly higher than near RSP 4200. It could be caused by natural differences in dune height or composition of the ground layers.

The VES measurements also show a depth of about 7-10 m of the transition layer between salt and saline water. This makes clear that the Ecobeach PEMs, with a length of 2 m, and a maximum depth of 3 m, do not reach into the totally fresh water.

The CVES measurements give a detailed description of the groundwater salinity under the beach. In the upper 2 m of the profile a small difference is recognizable between the location of a row of PEMs a location between 2 rows of PEMs. In Figure C17 the salinity in the upper layer is a little larger than in Figure C16 and Figure C18, which could be the effect of the PEMs.

In the southern Ecobeach test area (RSP 42000) an interesting study is done to the large scale groundwater behaviour under the dunes beach and foreshore [9] by Pieter Pauw.

C.2 EM-34 Measurements

C.2.1 Description of the method

EM-34 is a particular electromagnetic investigation of the ground. With electromagnetic investigation one measures the electric conductivity of the ground by electromagnetic induction. Electromagnetic investigation gives a general interpretation of the composition of different ground layers in a fast and cheap way. Also discrepancies in electric conductivity, caused by pollution or variation in salinity of the groundwater, can be detected.

The basic principle behind the application of EM-34 is simple (see also Figure C1). A transmitter loop at one side of the instrument sends an alternating current with a determined frequency into the ground. This alternating current generates a primary magnetic field in the underground. This primary magnetic field induces little currents in the underground, which generate a secondary magnetic field. This secondary magnetic field is recorded by the receiver loop together with the primary magnetic field. At the EM-34 display the electric conductive capacity of the underground can be read out in milliSiemens per meter [mS/m]. The electric conductivity of the ground that can be read out is the so-called apparent conductivity: it presents a mean value of the electric conductivity of the different layers which form the bottom. The EM-34 can reach several tens of meters deep, dependent on the intercoil spacing.

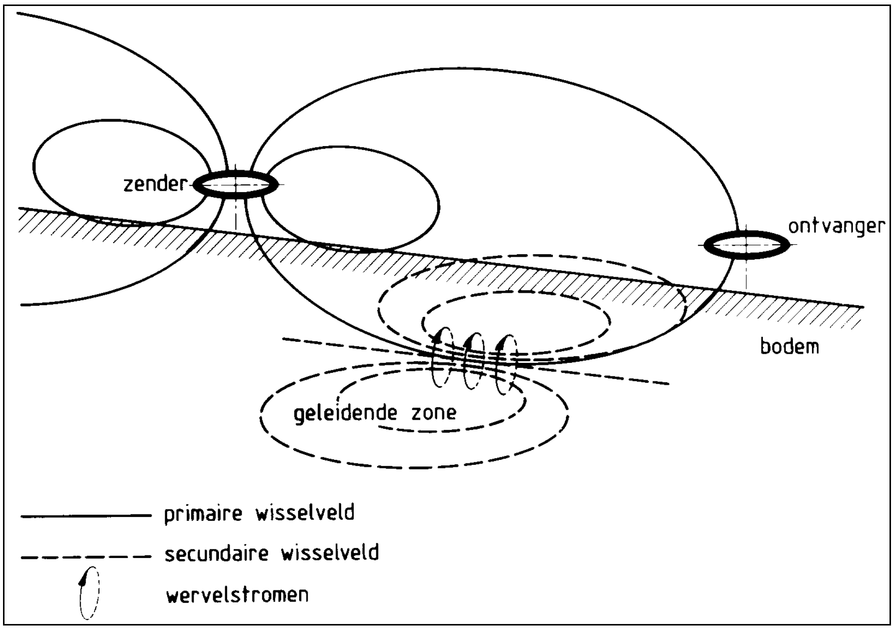

Figure C1: Basis principle behind EM-34

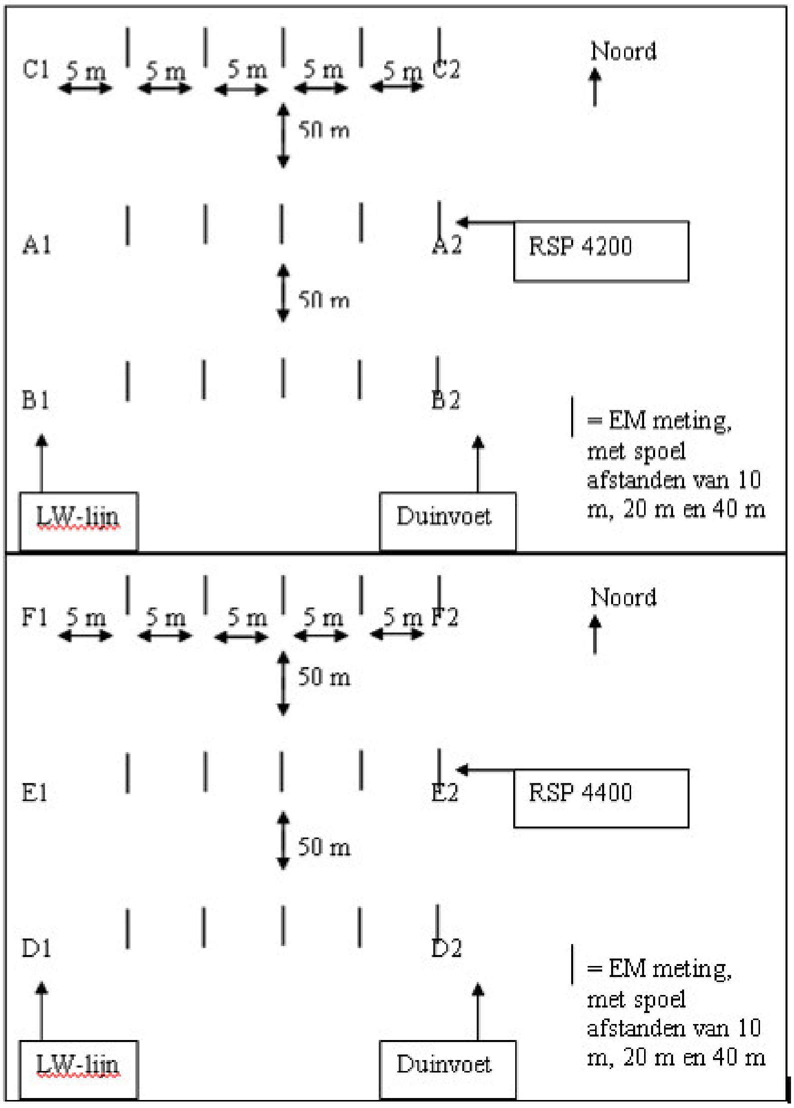

Figure C2: Locations of EM-34 measurements

At the beach, where the composition of the bottom is quite homogeneous, mainly information will be collected about the variation of the salinity of the groundwater and the location of the transition between the saline seawater and the fresh water lens under the dunes. Three measurements have been done at every location: one with an intercoil spacing of 10 m which investigates the conductivity of the upper 7.5 m of the bottom, one with an intercoil spacing of 20 m which investigates the conductivity of the upper 15 m of the bottom and one with an intercoil spacing of 40 m which investigates the conductivity of the upper 30 m of the bottom. Combination of this information produces a fairly detailed picture of the situation.

On the beach around Egmond aan Zee 256 EM-34 measurements have been done to map out the local groundwater characteristics around RSP 4200 and RSP 4400. At each of those areas three rows of measurements were done from the dunefoot to the waterline, with an inter spacing of 50 m (see Figure C2). The rows had a length of 60 or 65 m and the inter spacing between the measurement locations in the rows was 5 m. At each location 3 measurements were done: with intercoil spacing of 10, 20 and 40 m.

The EM-34 measurements were done on 25th (RSP 42000) and 26th (RSP 44000) of November 2008. Both days a south-western breeze was blowing of about 3 Beaufort and the measurements were done in the morning, during low water. The days before the 25th were calm and cold, but the 21st of November a western storm had occurred, which made the water level rise to the foot of the dunes, inundating the whole beach.

C.2.2 Results of the EM-34

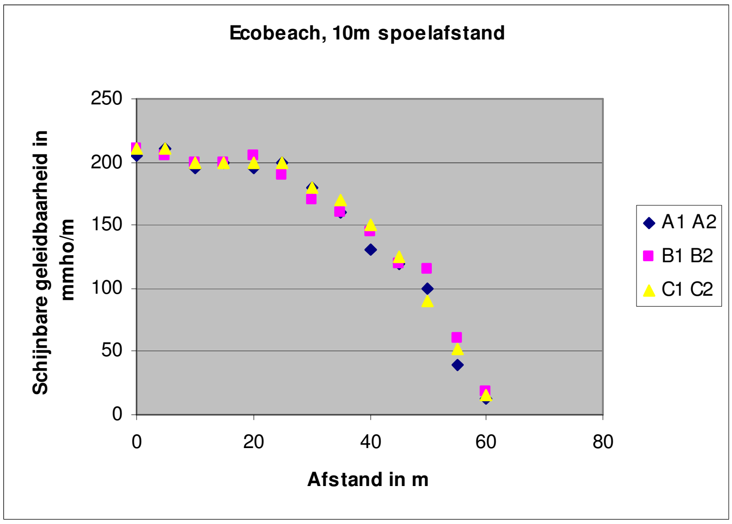

Figure C3– Figure C8 show the apparent conductivities at different depths inside (Figure C3– Figure C5) and outside (Figure C6 – Figure C8) Ecobeach. Every figure contains the data of 3 rows of measurements in the same area and with the same intercoil distance. Figure C9 shows the mean values of the measurements in the Southern Ecobeach test area (RSP 42000) and

Figure C10 shows the mean values of the measurements in the reference area (RSP 44000). Every time 3 measurements with the same distance to the dunefoot are averaged. Every graph contains the mean values of the apparent conductivities with an intercoil distance of 10 m, with an intercoil distance of 20 m and with an intercoil distance of 40 m.

To compare the apparent conductivities of RSP 42000 (Ecobeach) with those of RSP 44000 (reference area) the graphs of the same intercoil distance of these two different areas are plot together. Figure C11 – Figure C13 show these plots.

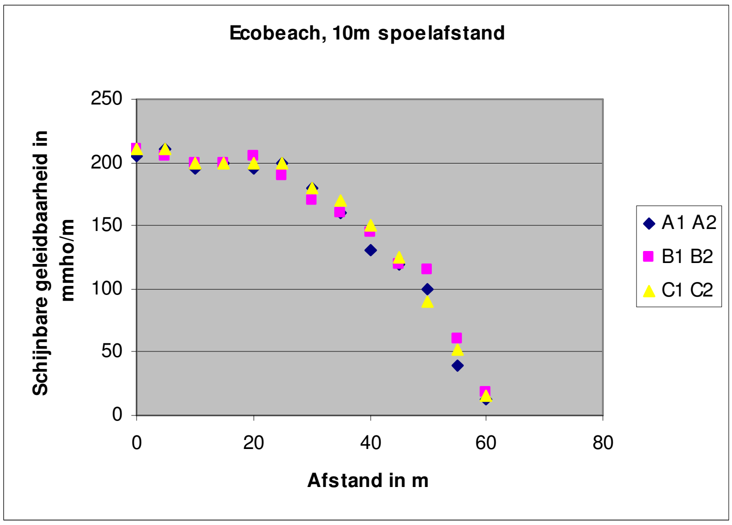

Figure C3: Apparent conductivities RSP 42000, with 10 m intercoil distance

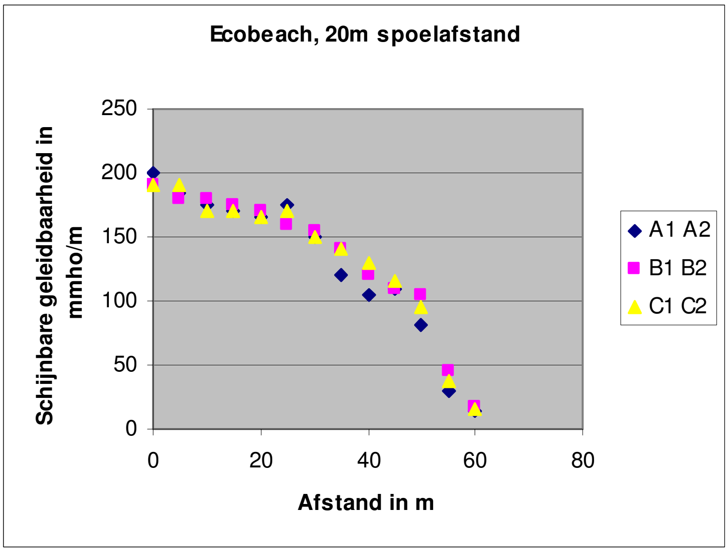

Figure C4: Apparent conductivities RSP 42000, with 20 m intercoil distance

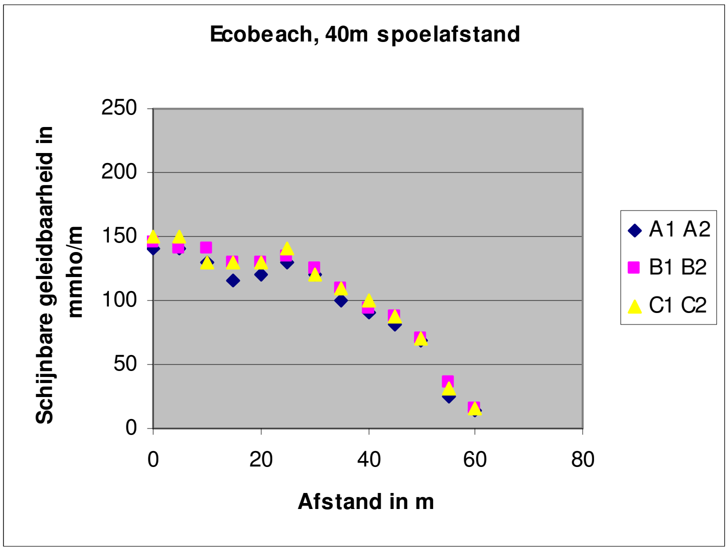

Figure C5: Apparent conductivities RSP 42000, with 40 m intercoil distance

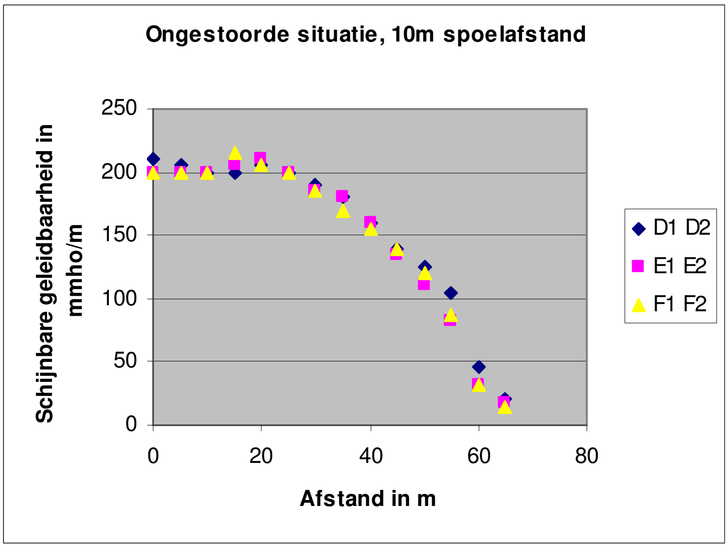

Figure C6: Apparent conductivities RSP 44000, with 10 m intercoil distance

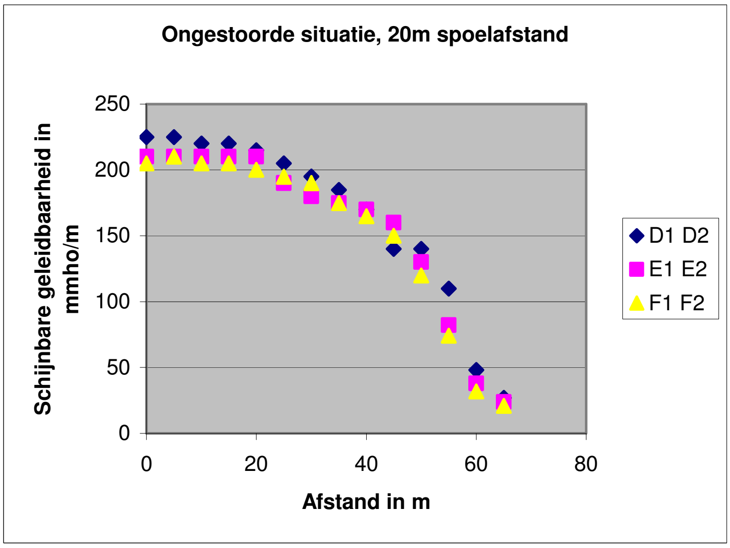

Figure C7: Apparent conductivities RSP 44000, with 20 m intercoil distance

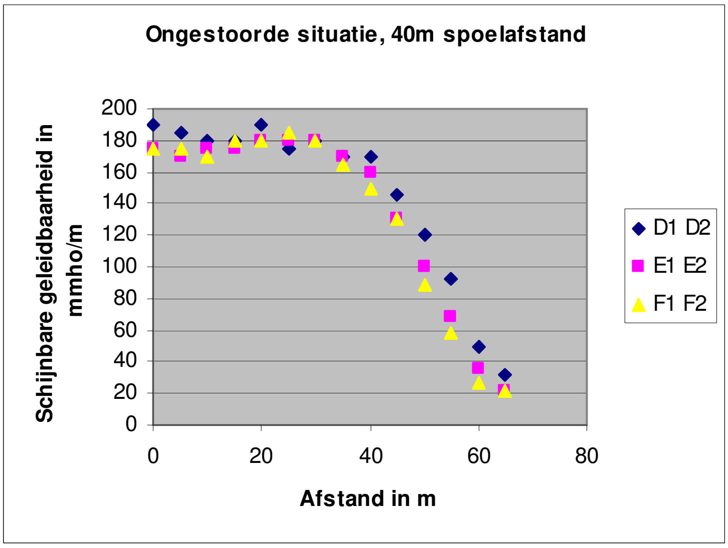

Figure C8: Apparent conductivities RSP 44000, with 40 m intercoil distance

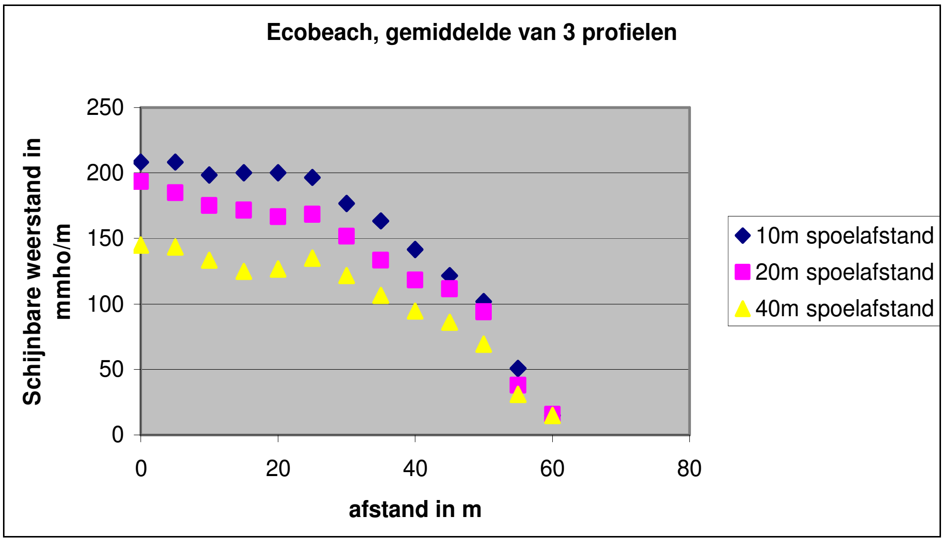

Figure C9: Mean apparent conductivities RSP 42000

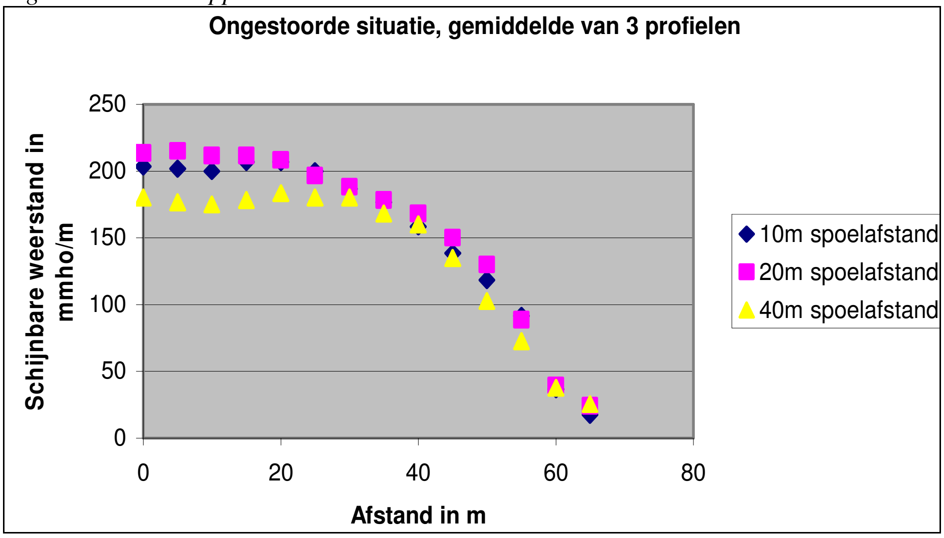

Figure C10: Mean apparent conductivities RSP 44000

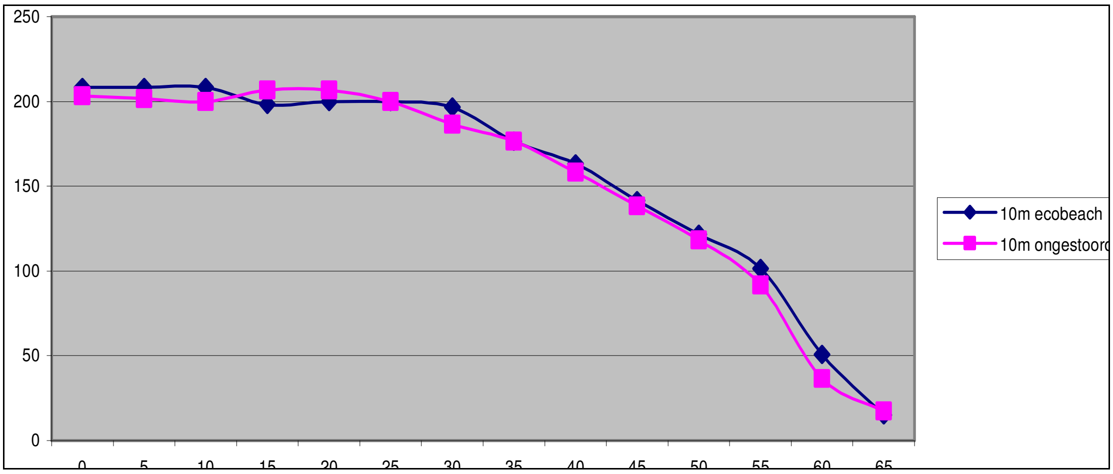

Figure C11: Comparison apparent conductivities, with 10 m intercoil distance

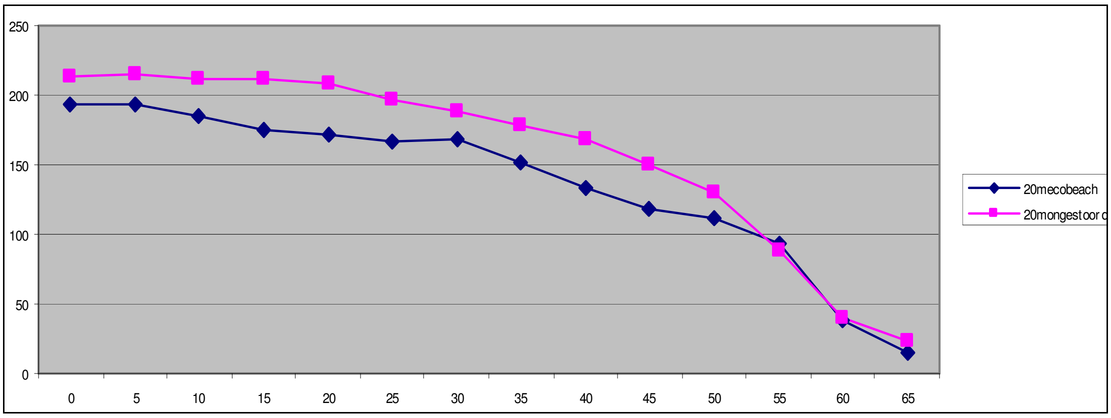

Figure C12: Comparison apparent conductivities, with 20 m intercoil distance

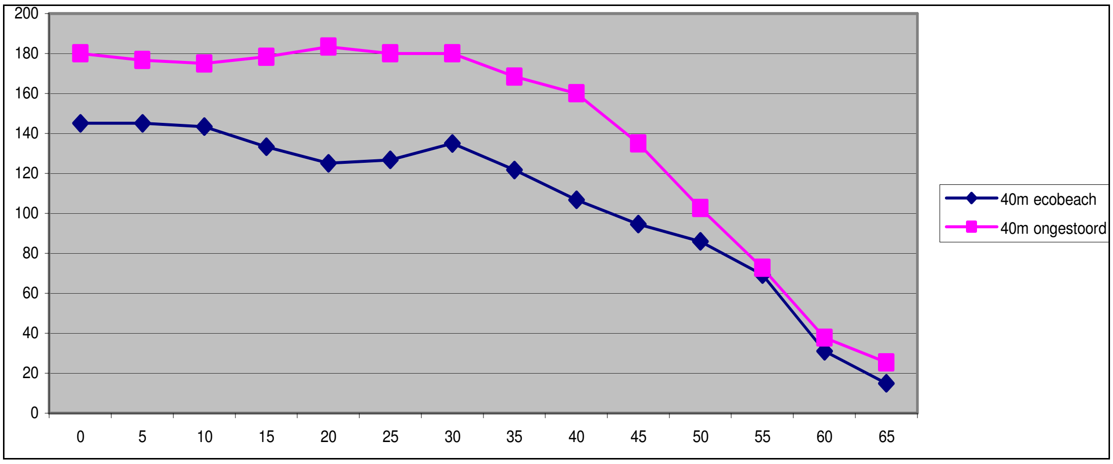

Figure C13: Comparison apparent conductivities, with 40 m intercoil distance

C.3 VES and CVES measurements

C.3.1 Description of the method

Vertical Electrical Sounding, called VES ("Verticale Elektrische Sondering") is a method to gather information about the lithology of the underground and the salinity of the groundwater. This is achieved by geo-electrical measurements, carried out along a horizontal line at the surface. Under the middle point of this line data can be collected up to a depth of 200 m, but the deeper the measurement reaches the less details can be observed. After interpretation of the data, the VES measurements have different applications. The most important application is determining the location of the transition layer between fresh and saline groundwater.

A VES measurement records differences in the specific electrical resistance of the underground. Two current electrodes drive a current into the ground and two potential electrodes, situated between the potential electrodes, measure the potential difference. This potential difference gives together with the amperage and a constant value, using Ohm's law, the apparent conductivity of the underground. The measured apparent conductivities are the mean values of the upper layers of the underground. A VES measurement has a fixed midpoint, while the outer electrodes (the current electrodes) are placed further to the outside. The larger the distance between the current electrodes, the deeper we look into the ground.

During the experiment at the Egmond beach the "Schlumberger-arrangement" was used, which means that the distance between the middle electrodes (the potential electrodes) is small compared to the distance between the potential and current electrodes, see Figure C14.

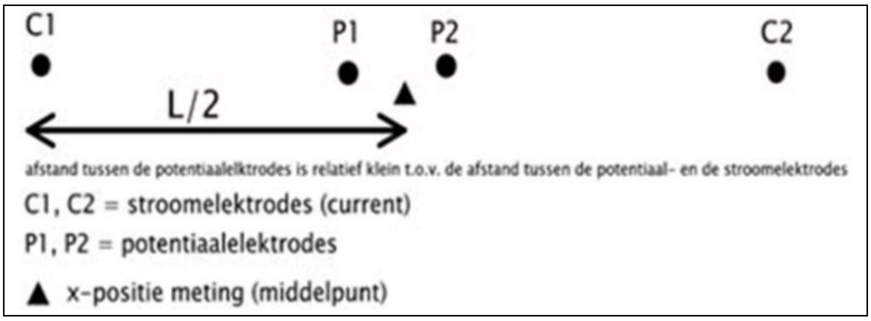

Figure C14: Schumberger arrangement of the electrodes which was used for the VES

CVES is a continuous VES. This means that a large number of electodes are placed into the ground along a transect (or a grid, if one wants 3D measurements in stead of 2D). In stead of replacing the electrodes after each measurement, there are done a lot of measurements, each with an other combination of 4 electrodes. The data can be transformed into an earth model that describes the resistivity of the subsoil. For the experiments the Schulmberger array was used.

4 VES and 3 CVES measurements were conducted. First the VES measurements were done around RSP 4200 and RSP 4400, in addition to the EM-34 measurements. Later, after interpretation of the EM-34 en VES results, the CVES measurements were only done around RSP 4200. Every VES was directed along shore. 2 times the VES was done as close as possible to the low waterline, with RSP 4200 and 4400 as midpoint of the row of electrodes. 2 times the VES was done at the position of the high waterline, also with RSP 4200 and 4400 as midpoint of the electrodes. The length of the measurements at RSP 4400 was 300 m and at RSP 4200 400 m (at the low waterline) and 100 m (at the high waterline, because the current was not able to travel larger distances with the dry upper layer of the beach).

VES 1: RSP 4200, 25 m west (seaward) of the beach pile, 15-12-2008 10:00-12:45
VES 2: RSP 4200, 17 m east (landward) of the beach pile, 15-12-2008 13:00-15:45
VES 3: RSP 4400, 25 m west (seaward) of the beach pile, 16-12-2008 10:00-12:45
VES 4: RSP 4400, 17 m east (landward) of the beach pile, 16-12-2008 13:00-15:45

Every CVES was directed cross shore, between the low waterline and the high waterline (length of 80 m). The locations were exactly RSP 4200 (above a row of Ecobeach PEMs), RSP 3995 (just between 2 rows of Ecobeach PEMs) and RSP 3990 (above a row of Ecobeach PEMs). This means the distance between the measurement rows was 50 m. Figure C15 shows the VES and CVES measurement locations.

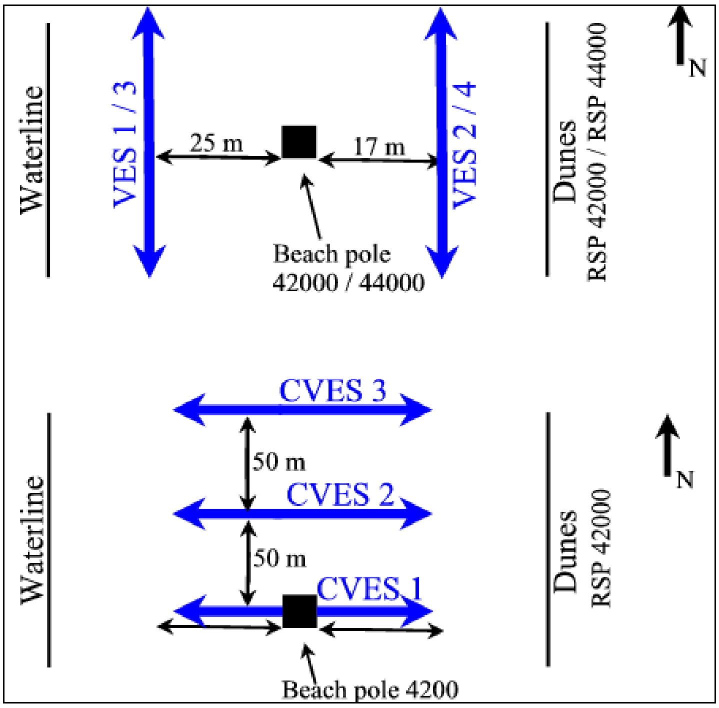

Figure C15: Locations of VES and CVES measurements

The VES measurements were done the 15th (RSP 4200) and 16th (RSP 4400) of December 2008. Those days were quiet and cold, with an eastern wind. Thanks to this wind the beach was wide. De days before the measurements also were quiet. The last south-western breeze that could lead to a high seawater level occurred a week before de VES. The CVES measurements were done the 27th and 28th of January 2009. Those days were also quiet, with an eastern breeze, which was the same as the two days before. 3-5 days before the measurements it had rained a lot.

C.3.2 Results of the VES and CVES

The VES measurements resulted in an interpretation of the conductivity of the groundwater at different depths. Between 6-9 m depth and 80 m depth the conductivity is high. Because the measurement at RSP 44000 near the high waterline could not be completed over the total length of 400 m of the VES the lower transitions of the saline groundwater was not measured here. It can be noticed that transitions between sweet and saline water are located at:
RSP 42000 seaside: 10 m / 70 m
RSP 42000 landside: 7 m / 75 m
RSP 44000 seaside: 11 m / 80 m
RSP 44000 landside: 9 m / lower transition not measured

Figure C16 – Figure C18 show the interpretation of the CVES measurements. The conductivity of the ground (= salinity of the groundwater) is expressed in colours: purple is low conductivity (fresh) and blue is high conductivity (saline). Figure C16 – Figure C18 show the upper 12 meters of the beach profile. The transition between saline (sea) water and fresh (dune) water is found at a depth of 7-8 m. The curves at the bottom of the graphs are not realistic. These are a fault of the model, due to little information about the boundaries of the picture.

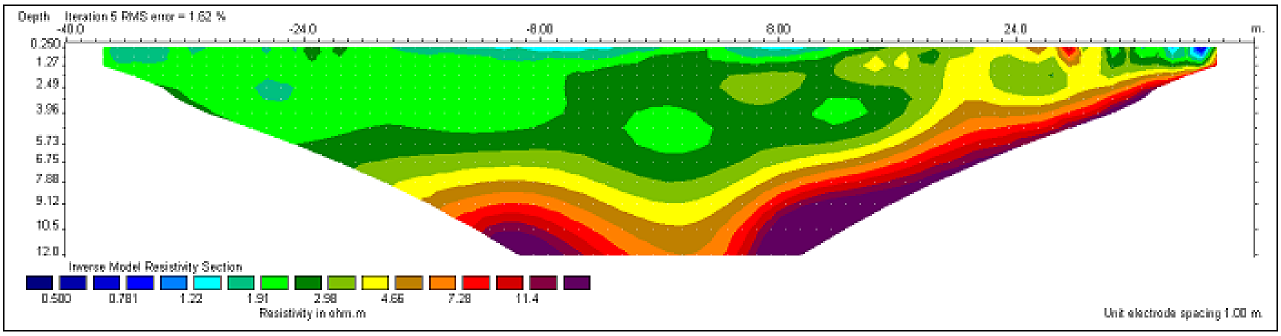

Figure C16: Profile at RSP 42000 (location of a row of PEMs)

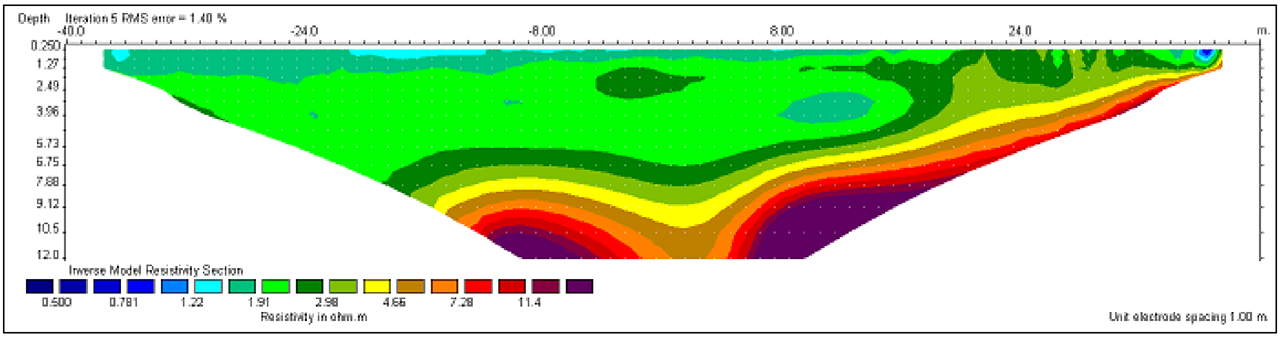

Figure C17: Profile at RSP 41950 (between two rows of PEMs)

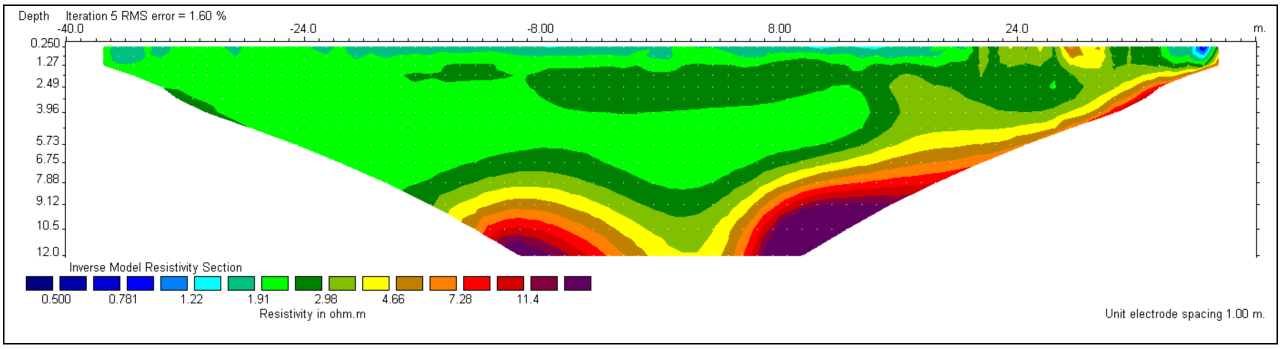

Figure C18: Profile at RSP 41900 (location of a row of PEMs)

Appendix D Diver measurements

D.1 Divers used during the fieldwork

For the investigation of the groundwater 13 divers were available, 8 CTD-divers and 5 Cera-divers. The CTDs were new and not for sale already. Van Essen lent them out in change for measurement results and experience of measurements in an unknown area (the beach). The Cera-divers were new ones, bought by BAM. Besides the divers, 8 cables were bought for programming and reading the instruments without taking them out of the ground. Every diver has a unique code and besides that they are numbered from 1 – 13 for this field investigation. Table D1 shows the number, code and type of all divers used during the fieldwork.

Number	Diver code	Diver type
1	SWS_$c011	CTD
2	SWS_$c010	CTD
3	SWS_$c005	CTD
4	SWS_$c004	CTD
5	SWS_$c007	CTD

6	SWS_$c001	CTD
7	SWS_$c008	CTD
8	SWS_$c014	CTD
9	SWS_b9888	Cera
10	SWS_b5793	Cera
11	SWS_c5014	Cera
12	SWS_c7403	Cera
13	SWS_a9074	Cera

Table D1: Divers used during the fieldwork

D.2 Characteristics of the divers

The 8 CTD divers can measure (water) pressure, temperature and conductivity (which indicates the salinity of the water). The 5 Cera divers only can measure pressure and temperature. All divers used during the fieldwork had a ceramic housing, because steel is probably not resistant against the saline beach groundwater. Figure D1 shows one of the CTD divers. The accuracy of the different data measured with the divers, according to manufacturer, is described in Table D2.

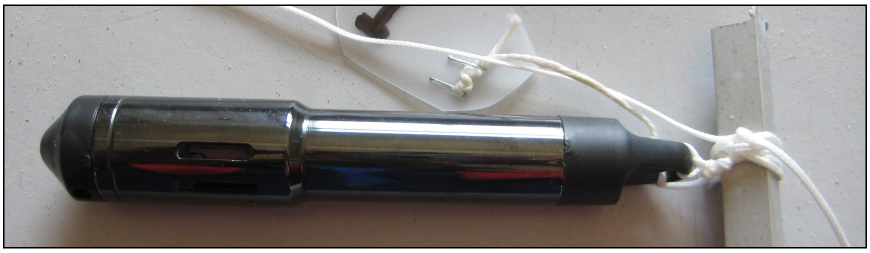

Figure D1: CTD diver (number 1) just before placement in de top of PEM f

The CTD divers are calibrated before and after the measurements. The accuracy of the conductivity measurements was not as good as given by the manufacturer. Before the fieldwork the conductivity measurements were accurate. The deviation after the fieldwork is shown in Table D3. The conductivity measurements of the new (prototype) divers seem to become inaccurate during the use in the saline beach groundwater. Only diver 8, which was used as baro diver does not show a significant deviation. Probably the deviation arose gradually during the measurement period. Half time the experiment half of the percentage in Table D3 has to be subtracted from the measured value.

	Cera	CTD
Dimensions	Ø 22 mm X 90 mm	Ø 22 mm X 183 mm
Memory	48.000 measurements	48.000 measurements
Sample interval	0.5 s – 99 h	0.5 s – 99 h
Weight	55 grams	150 grams
Temperature accuracy	± 0.1 ºC	± 0.1 ºC
Temperature resolution	0.01 ºC	0.01 ºC
Pressure accuracy	± 0.5 cm H2O	± 1.0 cm H2O
Pressure resolution	0.2 cm H2O	0.2 cm H2O
Conductivity accuracy	-	± 1% of reading
Conductivity resolution	-	± 0.1% of reading

Table D2: Specifications of the divers according to the manufacturer

Diver	0.158 mS/cm	0.996 mS/cm	6.08 mS/cm	14.24 mS/cm	41.7 mS/cm	78.4 mS/cm
8	-0.018	-0.6%	0.2%	0.5%	2.0%	1.6%
5	0.002	8.4%	7.9%	8.0%	10.5%	14.0%
6	0.002	6.4%	6.6%	6.5%	6.4%	7.9%
3	0.002	8.4%	8.1%	7.9%	7.1%	8.0%

7	0.002	8.4%	7.9%	8.4%	10.3%	18.4%
4	0.002	7.4%	6.1%	5.2%	2.8%	-0.1%
1	0.012	10.4%	9.2%	9.5%	11.4%	13.2%
2	-0.008	6.4%	6.9%	6.8%	6.9%	9.7%

Table D3: deviation of the conductivity measurements after the fieldwork

D.3 Installation of divers

D.3.1 Protection against grains

It is common to use divers in combination with a piezometer which is placed in de ground, and protects the diver against the surrounding. Measurements with and without a piezometer pipe were done at the beach of Egmond to compare both situations (see Appendix D.4). It became clear that the diver which was placed without piezometer pipe, directly surrounded by the bottom material, registered pressure variations causes by wind waves the best. Figure D3 shows the protection of a diver which is placed directly into the sand body.

D.3.2 Installation of divers in a PEM

To measure the groundwater behaviour in a PEM divers have been placed in the tube as shown in Figure D2. A small steel beam is placed under the top of the PEM. From this beam different divers can hang at different levels. The cap is not turned as far as possible to close the PEM, but some space is left above the beam to make the air filter in the middle of the cap still function.

Figure D2: Diver placed in a PEM

Figure D3: Protection of a diver against sand particles

D.3.3 Drilling of a hole and removing the divers

A pulse drill is used to place measurement equipment and PEMs in the ground. Figure D4 shows the use of a pulse drill, which is quite heavy work. The pulse is "eating" material of the ground, while a surrounding tube is drilled down by the body weight of the researcher. When the hole is deep enough a diver or PEM is put in the tube (with a maximum length of 3 m) and the tube is removed while the diver or PEM remains in the ground. This way of placing the equipment does not disturb the ground very much. Only the risk exists of cutting through relative impermeable layers. The pulse drill is also used to remove divers and PEMs. To reduce the force to pull this equipment out of the bottom, material was removed next to it by pulsing.

Figure D4: Operation of a pulse drill

D.4 Test measurements June 2009

D.4.1 Introduction

In June 2009 some measurements have been done with the divers which are going to be used during the fieldwork in August/September. During one day the divers have measured in the bottom of the beach of Castricum aan Zee, in the reference area, south of the southern Ecobeach test area. An objective is to get used to the groundwater measuring device. The main goal is the compare diver measurements in a piezometer pipe, which is the normal configuration of a diver in de ground, with diver measurement of a diver which is directly surrounded by the bottom material. The best of these two methods should be used during the fieldwork. Besides these objectives it is interesting to observe the behaviour of the groundwater at different locations and depths at the beach, because very little is known about this behaviour as a consequence of wave forcing.

D.4.2 Realisation of the experiment

Figure D5 shows the measurement area. Diver 1 and 2 are placed close to the low waterline at about the same depth. Diver 1 is place in the traditional way, in a piezometer pipe, while diver 2 is placed direct in the bottom, protected by a small sock. Diver 3 and 4 are placed in the middle of the swash zone at different depths, both direct in the bottom, without piezometer pipe.

The divers are placed early in de morning, during low water, and removed in the afternoon. In between those times, during high water, they measure with a frequency of 1 measurement per second. This short interval makes it possible to register pressure variations cause by wind waves. The way of placing and removing divers is already discussed in the previous paragraph. During the measurements (at the 18^{th} of June) the tidal difference is with 174 cm quite large for this location and. The wave height is estimated to be 50 cm.

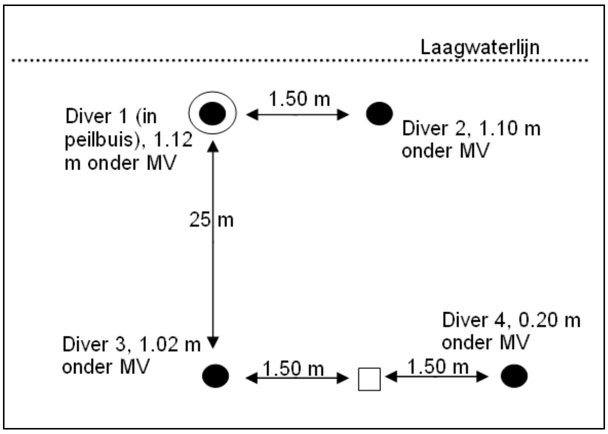

Figure D5: Arrangement of the measurement area

D.4.3 Conclusions of the experiment

Pressure propagation in the ground:

The passing wind wave with a period of 3-6 s are very well visible at a depth of more than 1.0 m (see Figure). The demping of pressure waves in the sand body is limited.

Difference diver in piezometer pipe / direct in the ground:

Pressure variations in the ground which are by passing wind waves are registered clearly by the divers. A significant difference is visible between de divers 1 and 2. Diver 1, placed in a piezometer, measures smaller pressure variations than diver 2, placed direct in the ground. Figure D6 shows one minute of measurements of divers 1 and 2. The mean pressure variation in the observations of diver 2 is 64% larger than in the observations of diver 1.

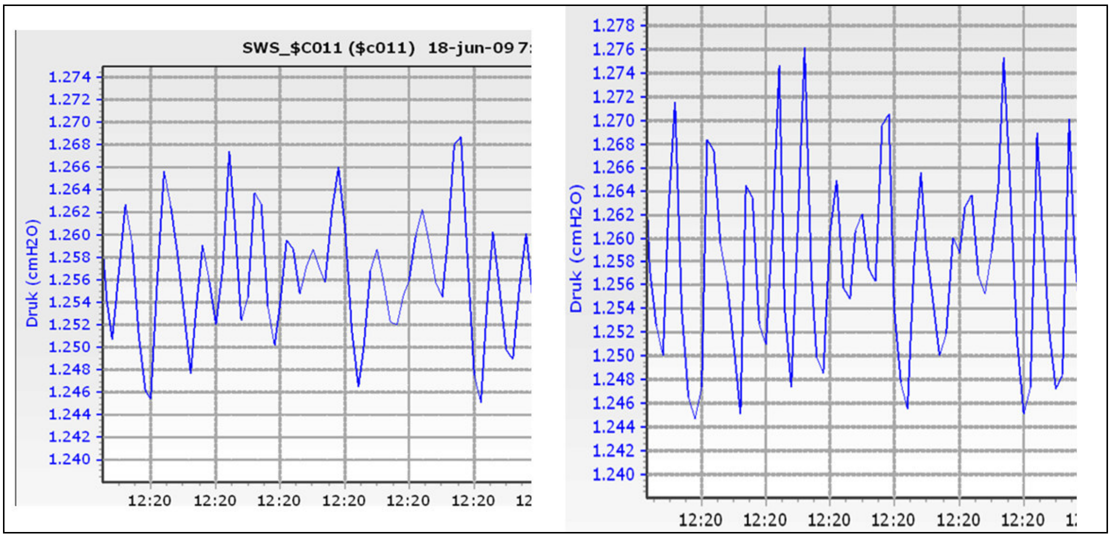

Figure D6: Difference in the observations of diver 1 (left) en 2 (right)

Difference between divers at a different depth:

The measured pressure differences between divers 3 and 4 are not the same. Diver 3, at a depth of 1.02 m measures smaller pressure differences the diver 4, at a depth of 0.20 m. The maximum difference occurring during 30 minutes measurements of diver 4 is 67% larger than the maximum difference occurring during 30 minutes measurement of diver 3. When only 30 seconds of measurements are compared, the maximum difference of diver 4 is 108% larger than of diver 3. This means that long time pressure variations (order of minutes: wave groups) easy travel through the bottom, while short time pressure variations (order of seconds: individual wind waves) are more decreased by friction.

Temperature measurements:

Diver 1, which is place in a piezometer pipe, measures temperature variations, while divers 2, 3 and 4, which are places in a sock in de ground, measure a constant temperature. This indicates that the temperature of the groundwater is relatively constant at a specific depth. The temperature variations in the tube can be interpreted as water from different depths transported in vertical direction. This is a very interesting observation, because temperature measurements may be an indication of vertical transport of groundwater through a tube.

Water levels:

During rising tide the water level did not rise with the same speed at all measurement locations. Close to the low waterline the water level rises more gradually than at a higher part of the beach, because waves suddenly fill the ground with water. The fastest drop down of the pressure during falling tide occurs near the low waterline. See Table D4.

Location	Fastest pressure increase	Fastest pressure decrease
1	20 cm / h	17 cm / h
2	20 cm / h	17 cm / h
3	120 cm / h	14 cm / h
4	240 cm / h	14 cm / h

Table D4: Maximum speed of groundwater level changes

Conductivity:

The salinity of the beach groundwater measured during the test was not realistic. After some time an analysis was done together with the manufacturer of the divers. The (double) sock to protect the diver against sand particle maybe enclosed some air which influenced the conductivity measurements. During the fieldwork of August/September the protection of the divers had to be done with as little nylon as possible.

D.5 Measurements August/September 2009

During the field work, described in Chapter 5, a lot of measurements are done with 13 divers. The analysis of these measurements is described in Chapter 7. Table shows which divers have measured and what the purpose and the period of these measurements was. A summary of all data series collected during the fieldwork is shown in Table D6.

The global picture of the different data series is sketched by some examples in the figures D7 – D18 at the end of this appendix. This overview is a background for the pictures of pressure, conductivity and temperature measurements in Chapter 7 and Appendix E. Figures D7 – D9 are measurements of the groundwater near the high waterline, D10 – D 15 are measurement of the groundwater near the low waterline, D16 is a shallow groundwater measurement (20 cm depth), D 17 is the output of the baro diver and D 18 is a measurement above the ground near the low waterline.

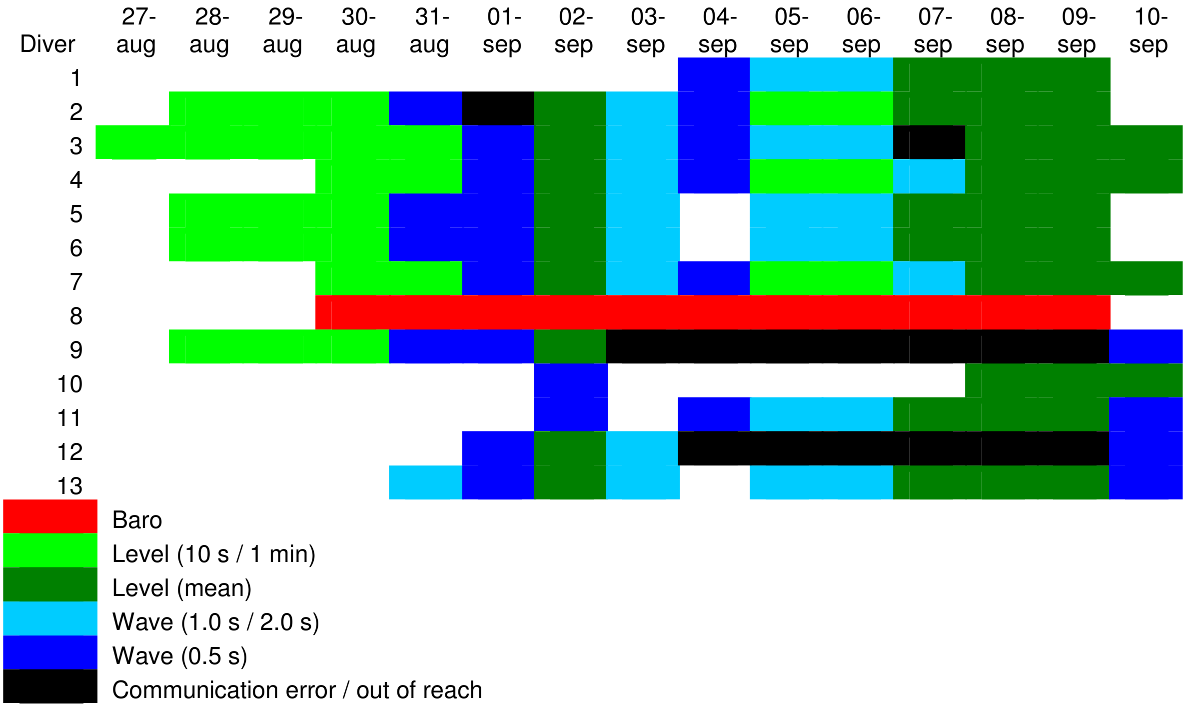

Table D5: Measurement scheme of the divers

Diver	code	Measurement period	Sample period
6	SWS_$C001	28-aug-2009 16:30:00 - 30-aug-2009 12:50:30	vast 10 s
6	SWS_$C001	31-aug-2009 12:55:00 - 31-aug-2009 19:34:59	vast 0.5 s
6	SWS_$C001	01-sept-2009 01:00:00 - 01-sept-2009 07:39:59	vast 0.5 s
6	SWS_$C001	01-sept-2009 13:00:00 - 02-sept-2009 13:36:00	gem 4 s - 3 min
6	SWS_$C001	02-sept-2009 23:00:00 - 03-sept-2009 12:19:59	vast 1 s
6	SWS_$C001	05-sept-2009 15:45:00 - 06-sept-2009 12:36:30	vast 2 s
6	SWS_$C001	06-sept-2009 14:30:00 - 09-sept-2009 18:05:00	gem 2 s - 5 min
4	SWS_$C004	30-aug-2009 17:00:00 - 31-aug-2009 18:20:50	vast 10 s
4	SWS_$C004	01-sept-2009 01:00:00 - 01-sept-2009 07:39:59	vast 0.5 s
4	SWS_$C004	01-sept-2009 14:15:00 - 02-sept-2009 15:48:00	gem 4 s - 3 min
4	SWS_$C004	02-sept-2009 23:00:00 - 03-sept-2009 12:19:59	vast 1 s
4	SWS_$C004	04-sept-2009 15:30:00 - 04-sept-2009 22:09:59	vast 0.5 s
4	SWS_$C004	05-sept-2009 14:00:00 - 06-sept-2009 20:49:10	vast 10 s
4	SWS_$C004	07-sept-2009 03:00:00 - 07-sept-2009 16:19:59	vast 1 s
4	SWS_$C004	08-sept-2009 13:10:00 - 10-sept-2009 09:25:00	gem 2 s - 1 min
3	SWS_$C005	27-aug-2009 15:00:00 - 28-aug-2009 14:55:00	vast 1 min

3	SWS_$C005	28-aug-2009 16:30:00 - 31-aug-2009 19:00:20	vast 10 s
3	SWS_$C005	01-sept-2009 01:00:00 - 01-sept-2009 07:39:59	vast 0.5 s
3	SWS_$C005	01-sept-2009 13:00:00 - 02-sept-2009 14:00:00	gem 4 s - 3 min
3	SWS_$C005	02-sept-2009 23:00:00 - 03-sept-2009 12:19:59	vast 1 s
3	SWS_$C005	04-sept-2009 15:30:00 - 04-sept-2009 22:09:59	vast 0.5 s
3	SWS_$C005	05-sept-2009 16:00:00 - 06-sept-2009 18:39:58	vast 2 s
3	SWS_$C005	08-sept-2009 13:00:00 - 10-sept-2009 08:52:00	gem 2 s - 1 min
5	SWS_$C007	28-aug-2009 16:30:00 - 31-aug-2009 12:15:20	vast 10 s
5	SWS_$C007	31-aug-2009 12:45:00 - 31-aug-2009 19:24:59	vast 0.5 s
5	SWS_$C007	01-sept-2009 01:00:00 - 01-sept-2009 07:39:59	vast 0.5 s
5	SWS_$C007	01-sept-2009 13:00:00 - 02-sept-2009 13:45:00	gem 4 s - 3 min
5	SWS_$C007	02-sept-2009 23:00:00 - 03-sept-2009 12:19:59	vast 1 s
5	SWS_$C007	05-sept-2009 15:45:00 - 06-sept-2009 12:53:22	vast 2 s
5	SWS_$C007	06-sept-2009 14:30:00 - 09-sept-2009 18:30:00	gem 2 s - 5 min
7	SWS_$C008	30-aug-2009 17:00:00 - 31-aug-2009 18:14:30	vast 10 s
7	SWS_$C008	01-sept-2009 01:00:00 - 01-sept-2009 07:39:59	vast 0.5 s
7	SWS_$C008	01-sept-2009 14:15:00 - 02-sept-2009 15:45:00	gem 4 s - 3 min
7	SWS_$C008	02-sept-2009 23:00:00 - 03-sept-2009 12:19:59	vast 1 s
7	SWS_$C008	04-sept-2009 15:30:00 - 04-sept-2009 22:09:59	vast 0.5 s
7	SWS_$C008	05-sept-2009 14:00:00 - 06-sept-2009 20:54:00	vast 10 s
7	SWS_$C008	07-sept-2009 03:00:00 - 07-sept-2009 16:19:59	vast 1 s
7	SWS_$C008	08-sept-2009 13:10:00 - 10-sept-2009 09:09:00	gem 2 s - 1 min
2	SWS_$C010	28-aug-2009 16:30:00 - 31-aug-2009 12:03:40	vast 10 s
2	SWS_$C010	31-aug-2009 12:45:00 - 31-aug-2009 19:24:59	vast 0.5 s
2	SWS_$C010	01-sept-2009 13:00:00 - 02-sept-2009 14:51:00	gem 4 s - 3 min
2	SWS_$C010	02-sept-2009 23:00:00 - 03-sept-2009 12:19:59	vast 1 s
2	SWS_$C010	04-sept-2009 15:30:00 - 04-sept-2009 22:09:59	vast 0.5 s
2	SWS_$C010	05-sept-2009 15:45:00 - 06-sept-2009 13:19:18	vast 10 s
2	SWS_$C010	06-sept-2009 14:30:00 - 09-sept-2009 18:25:00	gem 2 s - 5 min
1	SWS_$C011	04-sept-2009 15:30:00 - 04-sept-2009 22:09:59	vast 0.5 s
1	SWS_$C011	05-sept-2009 15:45:00 - 06-sept-2009 14:00:56	vast 2 s
1	SWS_$C011	06-sept-2009 14:30:00 - 09-sept-2009 18:15:00	gem 2 s - 5 min
8	SWS_$C014	31-aug-2009 16:50:00 - 09-sept-2009 22:00:00	vast 10 min
13	SWS_a9074	31-aug-2009 11:30:00 - 31-aug-2009 17:58:42	vast 1 s
13	SWS_a9074	01-sept-2009 01:00:00 - 01-sept-2009 07:39:59	vast 0.5 s
13	SWS_a9074	01-sept-2009 13:00:00 - 02-sept-2009 21:36:00	gem 4 s - 3 min
13	SWS_a9074	02-sept-2009 23:00:00 - 03-sept-2009 12:19:59	vast 1 s
13	SWS_a9074	05-sept-2009 15:00:00 - 06-sept-2009 13:44:54	vast 2 s
13	SWS_a9074	06-sept-2009 14:30:00 - 09-sept-2009 18:05:00	gem 2 s - 5 min
13	SWS_a9074	10-sept-2009 02:00:00 - 10-sept-2009 08:39:59	vast 0.5 s
10	SWS_b5793	02-sept-2009 14:00:00 - 02-sept-2009 20:39:59	vast 0.5 s
10	SWS_b5793	08-sept-2009 13:00:00 - 10-sept-2009 08:49:00	gem 2 s - 1 min
9	SWS_b9888	28-aug-2009 16:30:00 - 31-aug-2009 12:25:30	vast 10 s
9	SWS_b9888	31-aug-2009 12:45:00 - 31-aug-2009 19:24:59	vast 0.5 s
9	SWS_b9888	01-sept-2009 01:00:00 - 01-sept-2009 07:39:59	vast 0.5 s
9	SWS_b9888	01-sept-2009 12:00:00 - 02-sept-2009 13:39:00	gem 4 s - 3 min
9	SWS_b9888	10-sept-2009 02:00:00 - 10-sept-2009 08:39:59	vast 0.5 s
11	SWS_c5014	02-sept-2009 14:00:00 - 02-sept-2009 20:39:59	vast 0.5 s
11	SWS_c5014	04-sept-2009 15:30:00 - 04-sept-2009 22:09:59	vast 0.5 s
11	SWS_c5014	05-sept-2009 15:45:00 - 06-sept-2009 14:13:30	vast 2 s
11	SWS_c5014	06-sept-2009 14:30:00 - 09-sept-2009 18:15:00	gem 2 s - 5 min
11	SWS_c5014	10-sept-2009 02:00:00 - 10-sept-2009 08:39:59	vast 0.5 s
12	SWS_c7403	10-sept-2009 02:00:00 - 10-sept-2009 08:39:59	vast 0.5 s

Table D6: Summary of all data series collected during the fieldwork

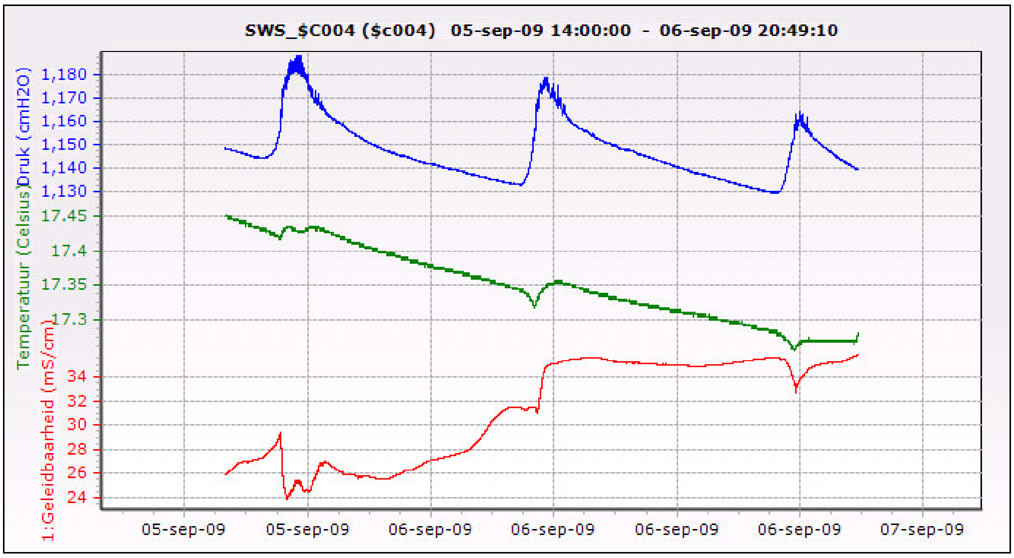

Figure D7: Diver 4, 5 sept 14:00 – 6 sept 20:49, measurement interval 10 s

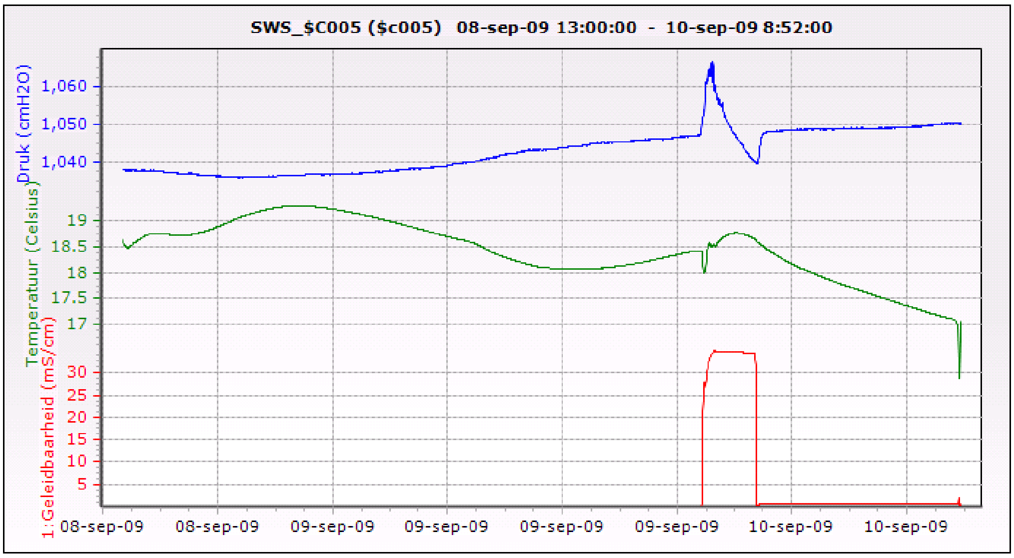

Figure D8: Diver 3, 8 sept 13:00 – 10 sept 8:52, measurement interval 2 s → mean 1 min

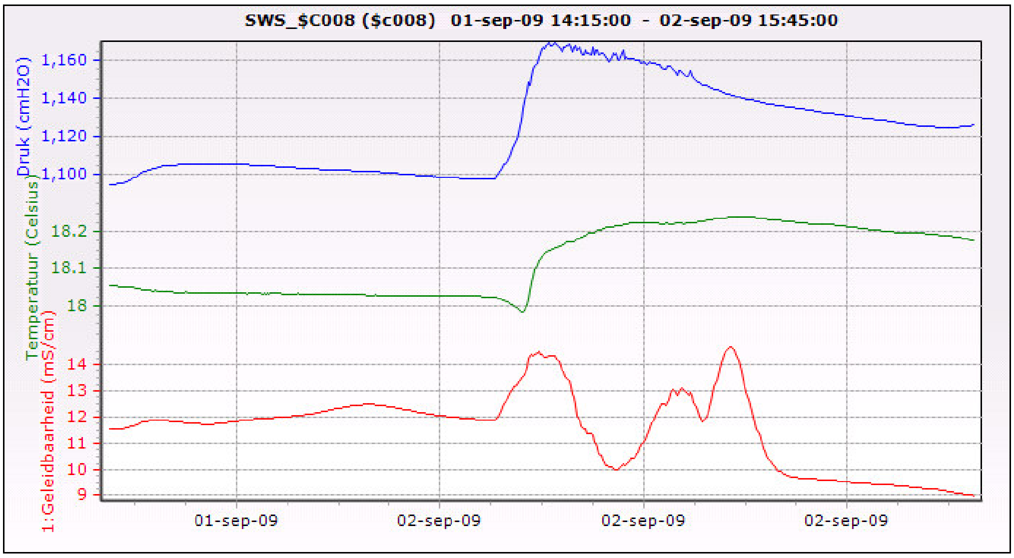

Figure D9: Diver 7, 1 sept 14:15 – 2 sept 15:45, measurement interval 4 s → mean 3 min

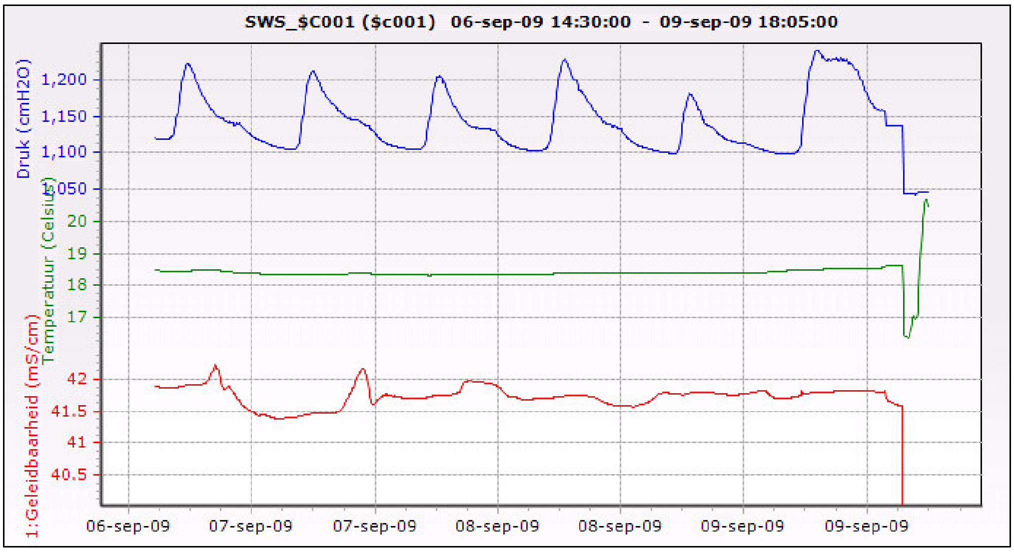

Figure D10: Diver 6, 6 sept 14:30 – 9 sept 18:05, measurement interval 2 s → mean 5 min

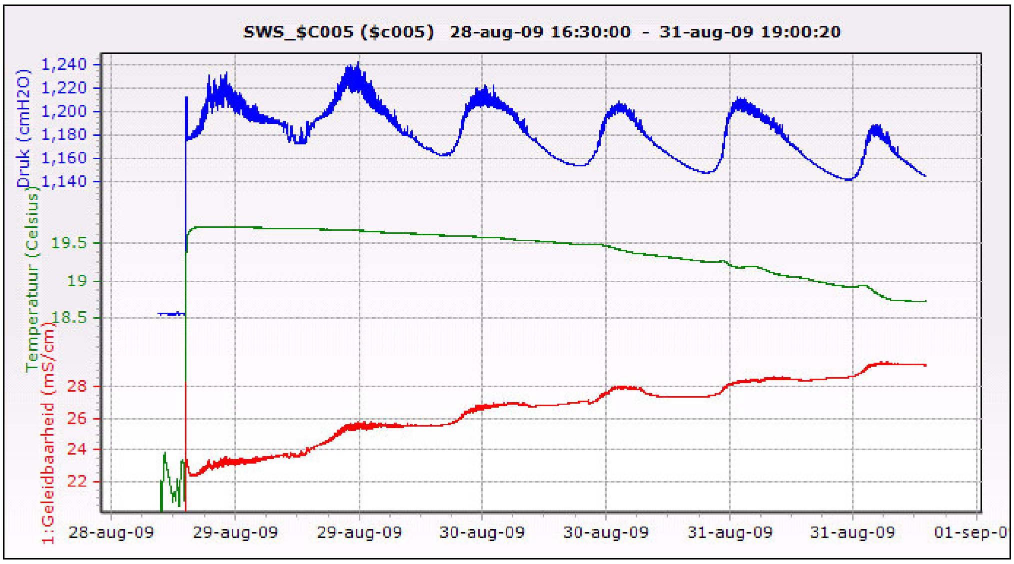

Figure D11: Diver 3, 28 aug 16:30 – 31 aug 19:00, measurement interval 10 s

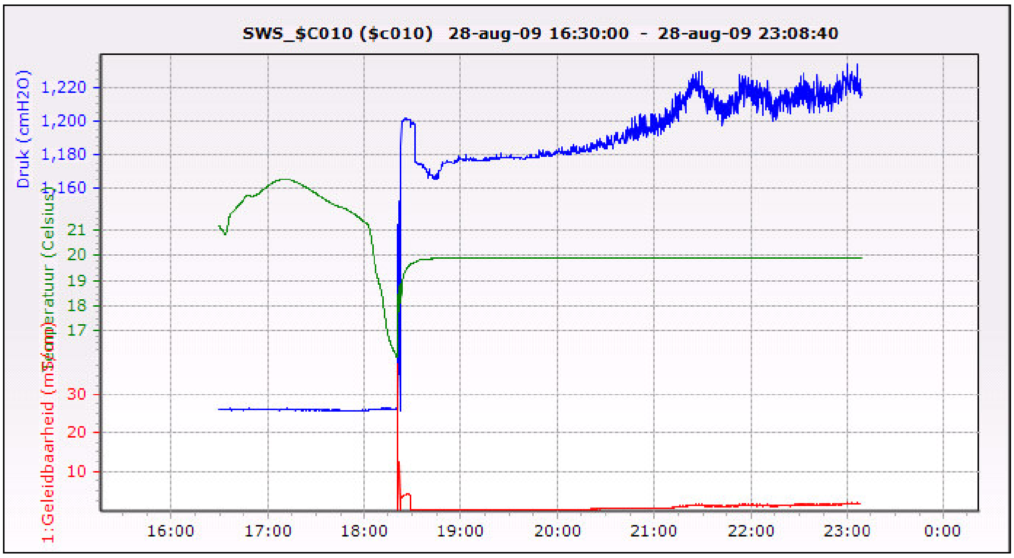

Figure D12: Diver 2, 28 aug 16:30 – 28 aug 23:09, measurement interval 0.5 s

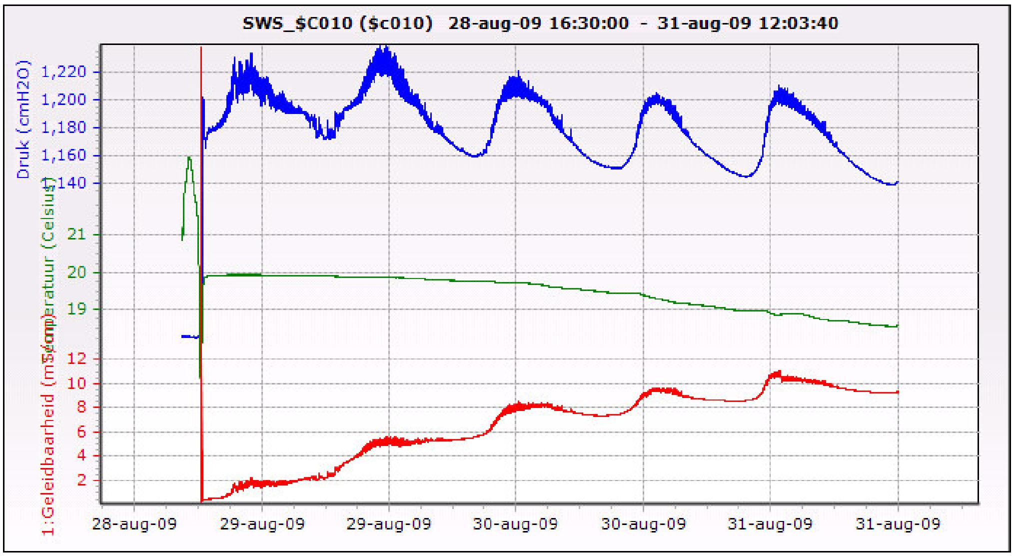

Figure D13: Diver 2, 28 aug 16:30 – 31 aug 12:04, measurement interval 10 s

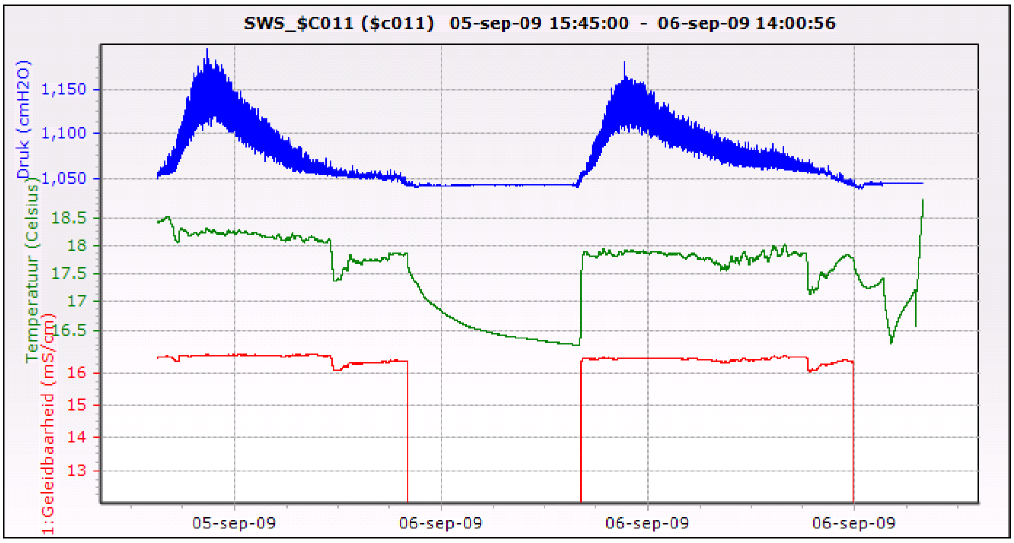

Figure D14: Diver 1, 5 sept 15:45 – 6 sept 14:01, measurement interval 2 s

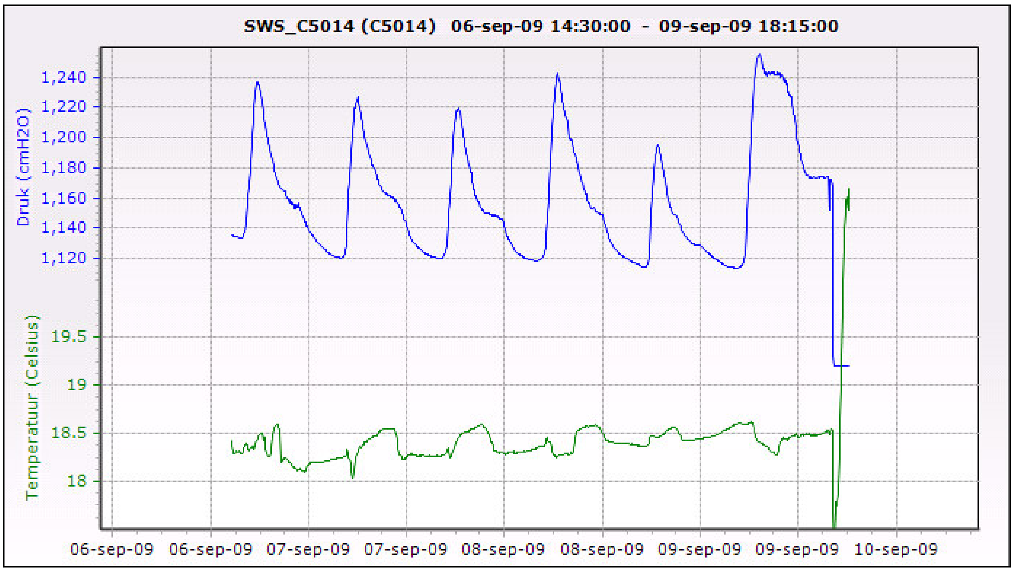

Figure D15: Diver 11, 6 sept 14:30 – 9 sept 18:15, measurement interval 2 s → mean 5 min

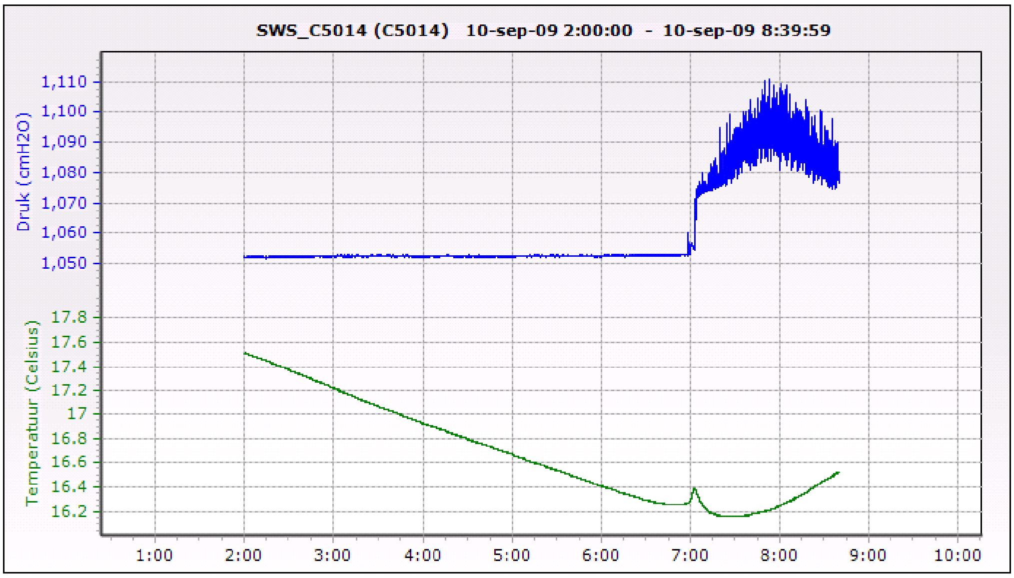

Figure D16: Diver 11, 10 sept 2:00 – 10 sept 8:40, measurement interval 0.5 s

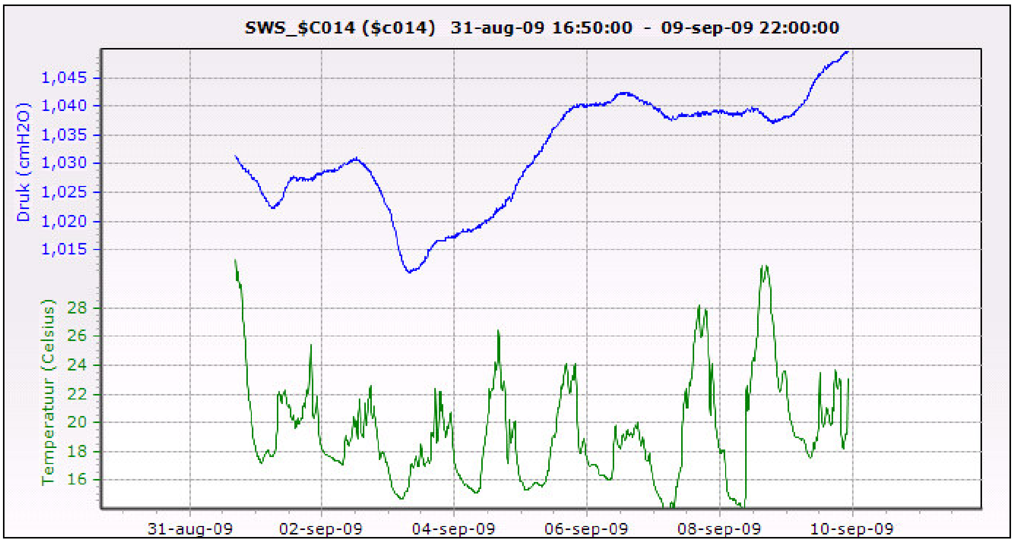

Figure D17: Diver 8, 31 aug 16:50 – 9 sept 22:00, measurement interval 10 min

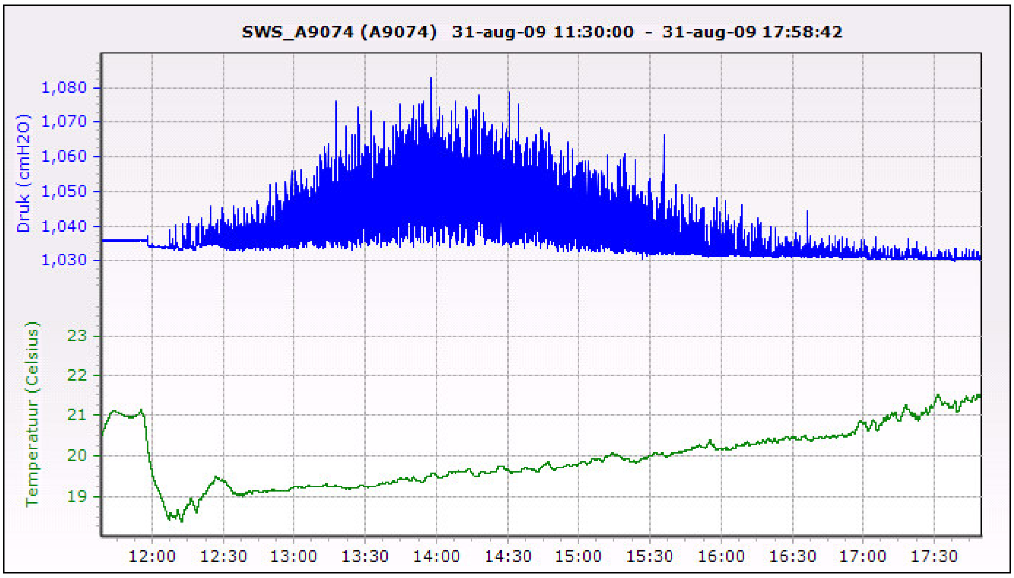

Figure D18: Diver 13, 31 aug 11:30 – 31 aug 17:59, measurement interval 1 s

D.6 Diver measurements in the Danish test area

In 2005 a field test was carried out on the west coast of Jutland in Danmark, where an Ecobeach test area is situated. During a period of 2 weeks groundwater pressures were measures along a row of Ecobeach PEMs between the high and low waterline. The test showed that on a dry beach the water level inside the PEMs was up to 15 cm lower than in the neighbouring wells, indicating effective downward draining of the beach. PEMs in the swash zone that were submerged due to high tide, showed a higher level than the neighbouring wells. This indicated that the outflow of water is increased by the PEMs. More information about this test is available in [5].

Appendix E Matlab calculations and graphs

Introduction

For the analysis of groundwater data, generated by diver measurements, Matlab, which is a high-performance language for technical computing, is used. With Matlab it is easy to make calculations with large matrices and vector, like the columns with diver data. These columns can contain 48000 elements. Once the data can be imported in Matlab it is easy to make computations with them. For instance subtraction of different vectors to calculate the difference between measurements at different locations or Fourier analyses to make a distribution of energy in a wave spectrum into different frequencies. Besides that the graphical tools of Matlab are very advanced. Data can be easily expressed in graphs, which makes them easier to interpret.

This appendix contains all Matlab plots used for the analysis of the diver measurements. Not all plots are shown in Chapter 7, to keep the text clear. In the text of Chapter 7 is referred to these graphs in this appendix. Sometimes the Matlab code to generate a graphs is shown to make clear which functions are used for the analysis.

The measurement data was regularly downloaded from the divers during the fieldwork. These data series were saved in “Diver Office”, a program to order the series and make plots of them. The format of the saved series caused some troubles by uploading them in Matlab. A program was written to read every type of data series no matter the columns where divided by commas or spaces or the numbers contained points or commas. All data series are ordered in a matrix called “M” of which the first row contains 73 cells each of which is an individual diver measurement. Those measurements exist of 3 or 4 columns: time, pressure, temperature and conductivity. For calling specific data in Matlab this arrangement is used.

Plots end important code

Plots used for the analysis of Chapter 7, which are not shown in that chapter, are put in this appendix. Besides that plots of which the Matlab code is presented here are sometimes plot in the appendix as well as in Chapter 7. Always a plot will be shows, after which a short description about the graph is given. Sometimes this description is followed by the Matlab code used for the realisation of the graph.

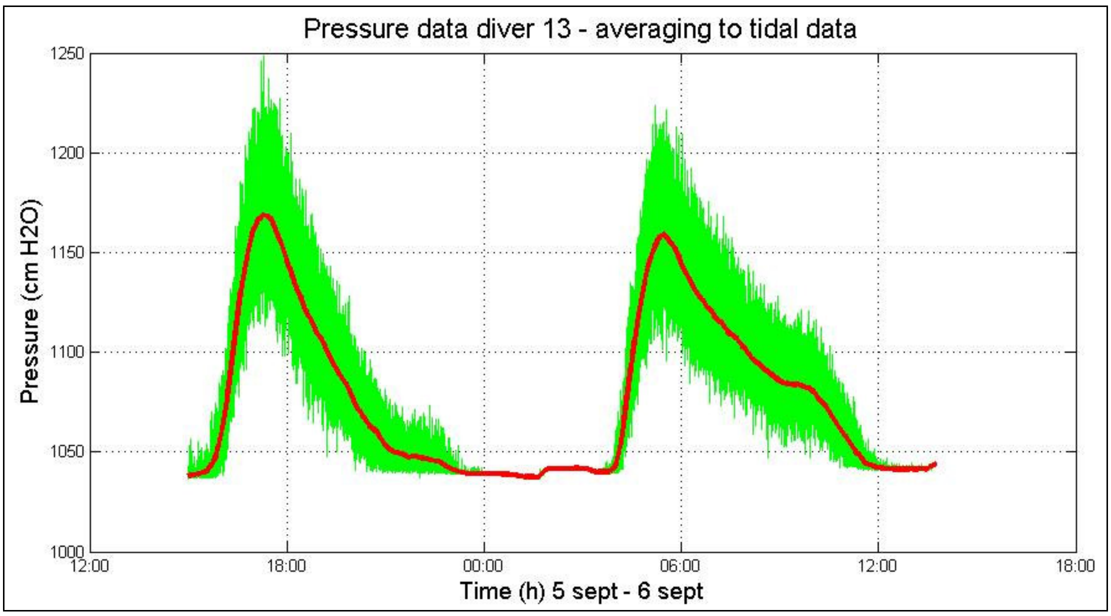

Figure E1: High frequency pressure variation (green) and tidal variation (red)

When a high measurement frequency is applied the water pressure data contain all high frequency pressure variations, caused by wind waves (blue line in Figure E1). If only the low frequency (for instance tidal) variation is interesting the high frequency pressure variations can be filtered out, resulting in the red line in Figure E1. In the Matlab code below the function filtfilt is used to calculate a "moving average" of the data series:

```
i = 73 % Number of data series
a = 1
b = [ones(1,300)/300] % Moving average of 300 data points
hold on
plot(M(1,i).data(:,1),M(1,i).data(:,2)); datetick
plot(M(1,i).data(:,1),filtfilt(b,a,M(1,i).data(:,2))); datetick
```

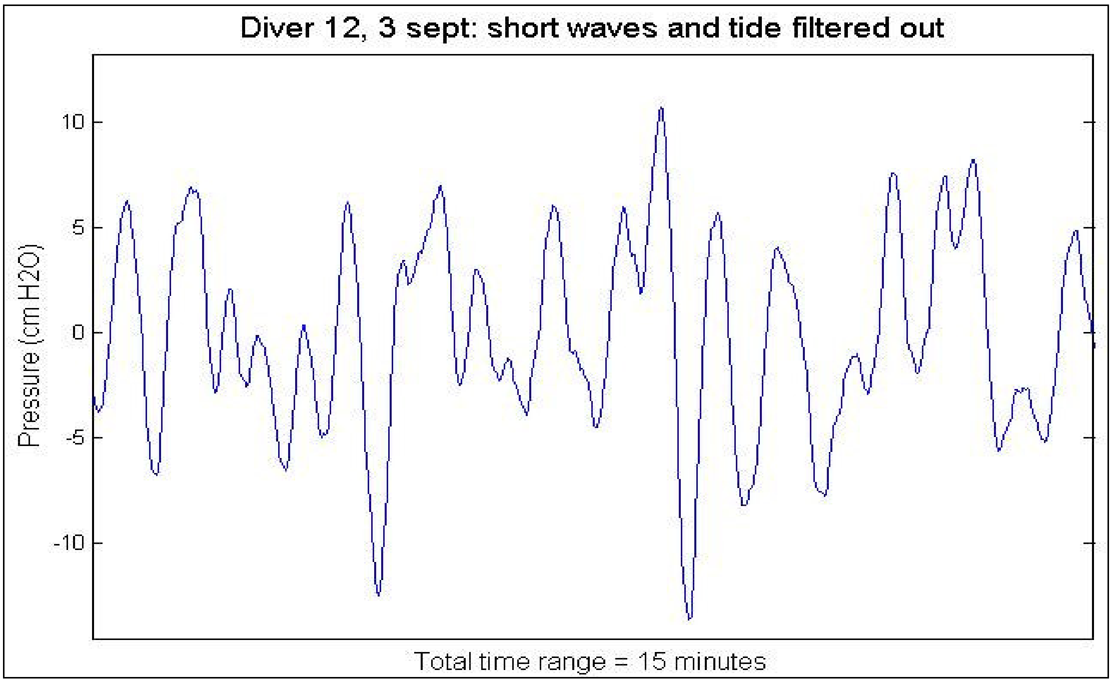

Figure E2: "Middle frequency" variation of the groundwater near the low waterline

It is also possible to remove the tidal variation and the wind waves from a data series. After this procedure only the "middle long" wave remain. Figure E2 shows these waves with a period of the order of 1 minute and amplitudes of 5 – 10 cm. The following code was used to create this graph:

```
i = 72
a = 1
b = [ones(1,600)/600]
c = [ones(1,25)/25]
plot(filtfilt(c,a,M(1,i).data(:,2))-filtfilt(b,a,M(1,i).data(:,2))); datetick
```

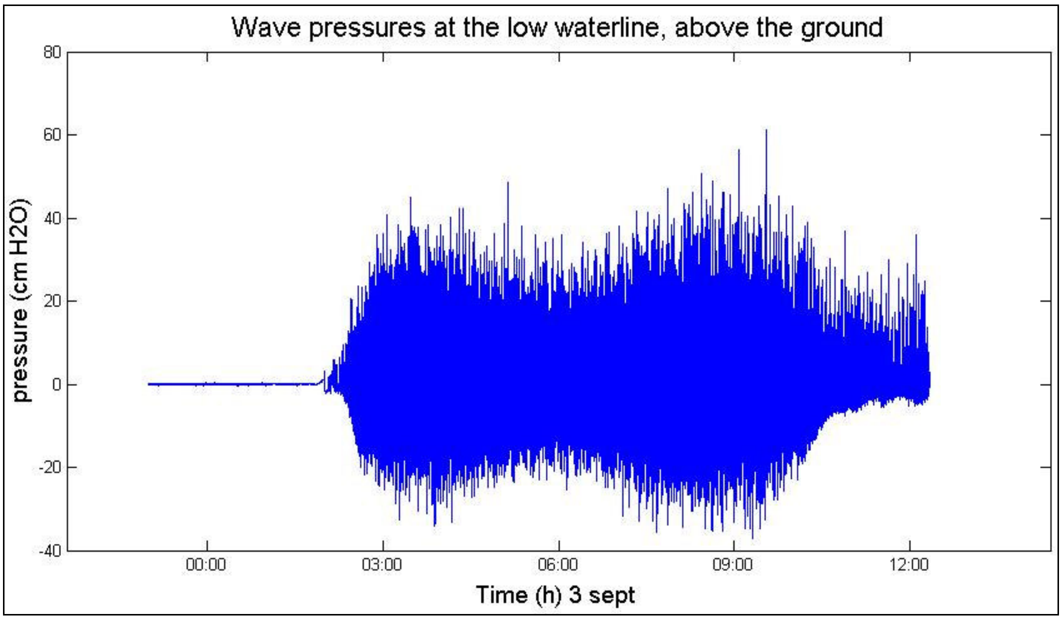

Figure E3: High and middle frequency pressure variation, without tidal variation

When the low frequency pressure variation is subtracted from the total pressure measurement only the high frequencies remain. The result is a graph of the short waves only as shown in Figure E3.

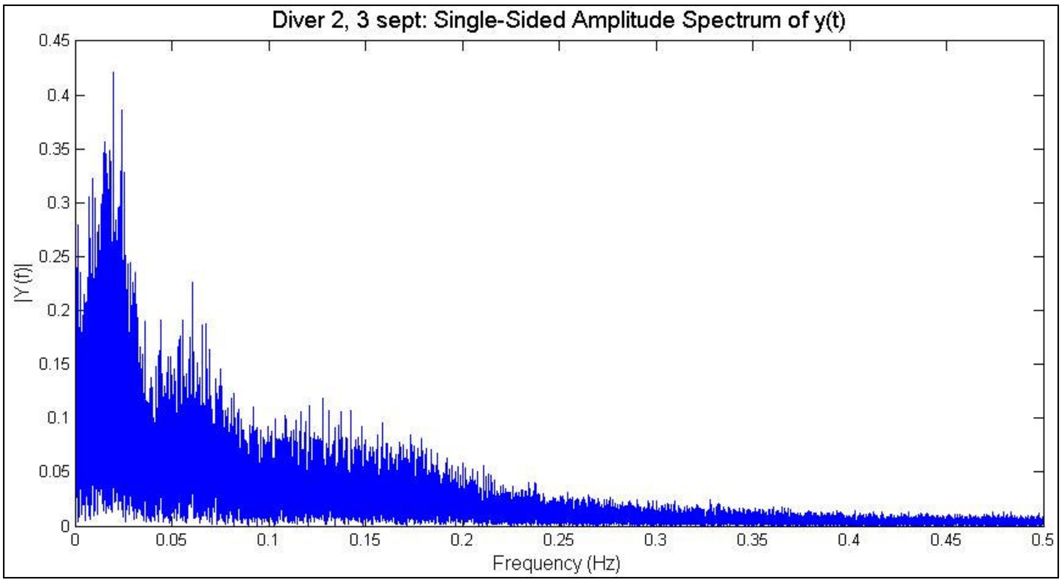

Figure E4: Amplitude spectrum of high and middle frequency pressures, like Figure E3

After tidal variation is filtered out of the measurement data, like in Figure E3, it is possible find the quantity of wave energy in the spectrum divided over the appearing frequencies. To achieve this, a Fourier analysis can be applied according to the following Matlab code (see Figure E4):

```
Interval = 1; L = 48000  % Length data series
Fs = 1/Interval
y = M(1,i).data(:,2)-filtfilt(b,a,M(1,i).data(:,2))
L = LengteMeetreeks
NFFT = 2^nextpow2(L); % Next power of 2 from length of y
Y = fft(y,NFFT)/L;
f = Fs/2*linspace(0,1,NFFT/2+1);
plot(f,2*abs(Y(1:NFFT/2+1)))
```

To calculate the area under the amplitude spectrum of Figure E4, the midpoint rule is used. The high frequency wave energy ("KORT") and the low frequency wave energy ("LANG") are calculated using the midpoint rule and multiplied by 100 to get the numbers of Table 5 in Chapter 7. The following code was made for this calculation:

```
opp1 = 0; opp2 = 0; input = 2*abs(Y(1:NFFT/2+1))
L1 = round((0.08/0.5)*length(input)) %0.08 Hz
L2 = round((0.25/0.5)*length(input)) %0.25 Hz
L3 = round((0.0125/0.5)*length(input)) %0.0125 Hz
L4 = round((0.05/0.5)*length(input)) %0.05 Hz
for h = L1:L2
    w = input(h)*(0.5/65536)
    opp1 = opp1 + w
end
for h = L3:L4
    w = input(h)*(0.5/65536)
    opp2 = opp2 + w
end
OppervlakteKORT  = 100 * opp1; OppervlakteLANG  = 100 * opp2
```

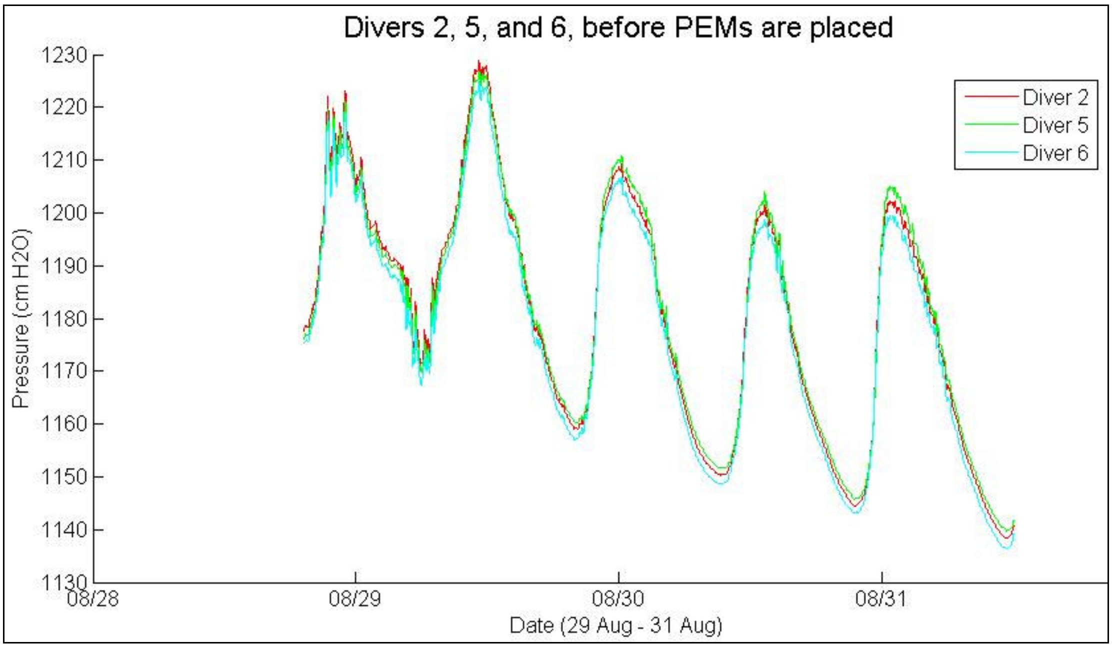

Figure E5: Pressures measured with Diver 2, 5 and 6 (low waterline) before PEMs were placed

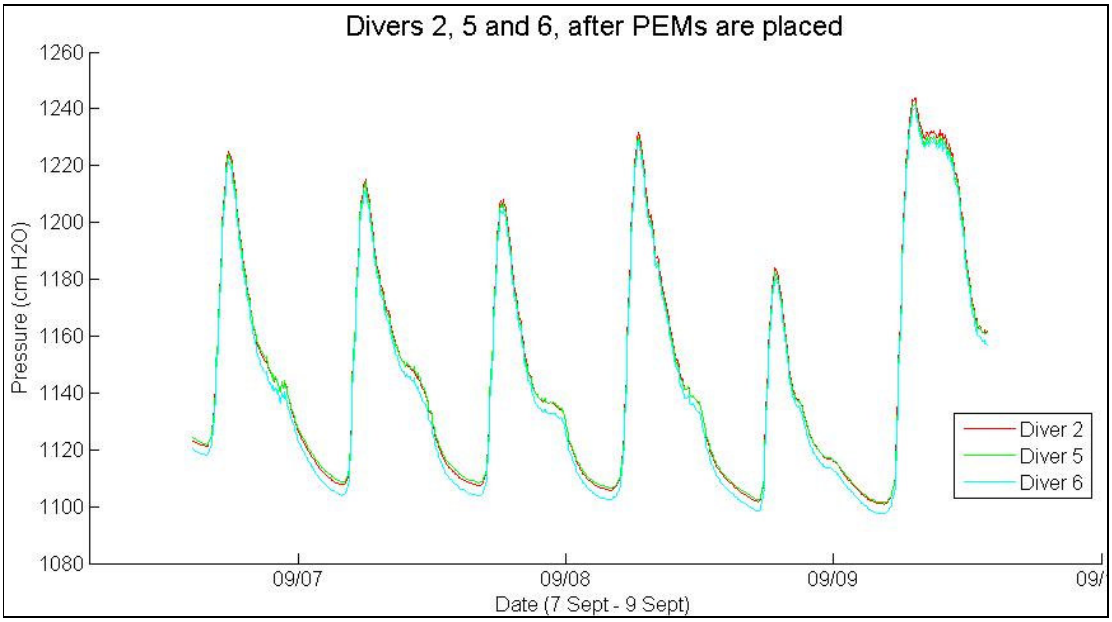

Figure E6: Pressures measured with Diver 2, 5 and 6 (low waterline) after PEMs were placed

In Figures E5 and E6 the pressure measurements of different diver near the low waterline are plot. Before (E5) as well as after (E6) the PEMs were placed the low frequency pressure variation of the groundwater seems to be nearly identical at different locations compared to PEM f.

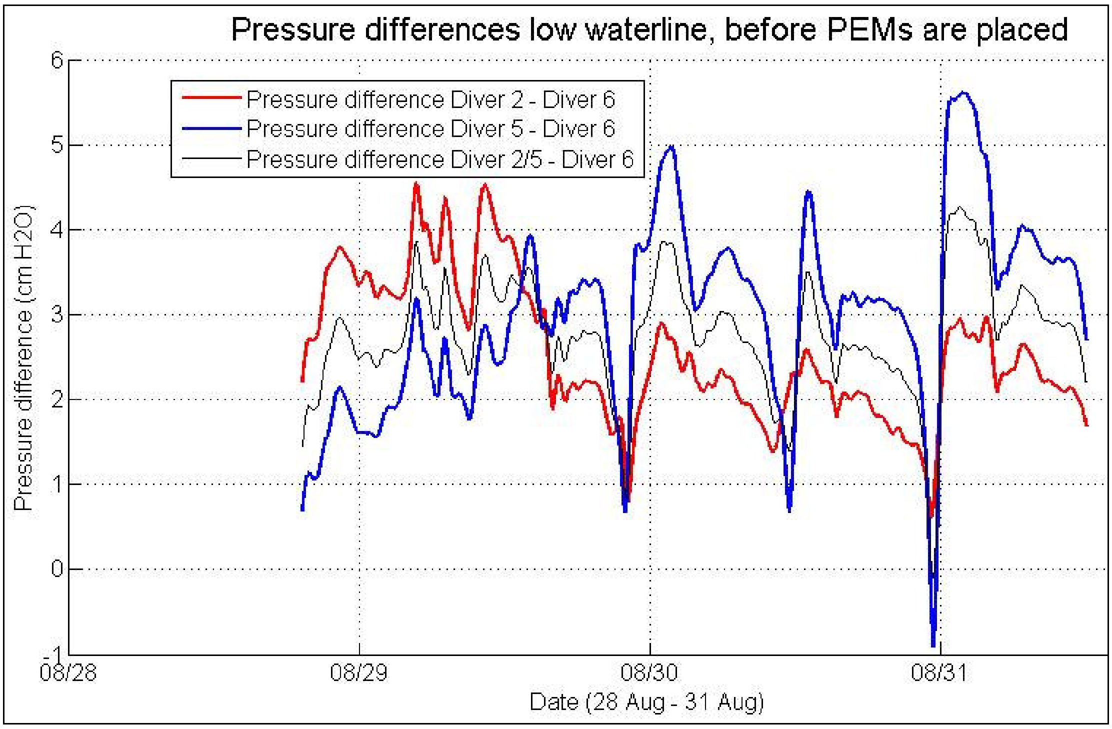

Figure E7: Pressure differences in the ground near PEM f, before the PEM was placed

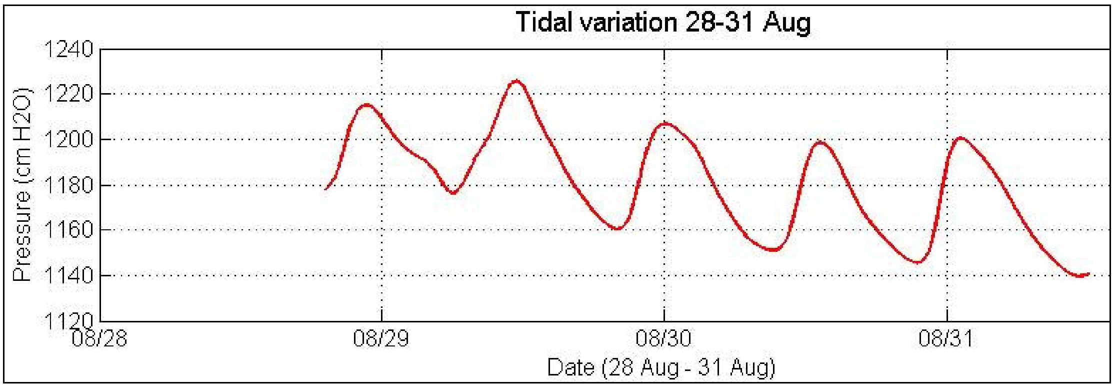

Figure E8: Tidal variation during pressure differences of Figure E7

Figure E7 shows the pressure differences between divers around the future location of PEM f, while under this graph, Figure E8 represents the tidal variation at sea. This makes it possible to compare the pressure differences with the tidal phase. The same purpose Figures E9 and E10 are plot together. It is possible to compare the pressure difference of the groundwater at different locations around PEM f with the tidal phase after the PEMs are placed. The mean pressure difference at the different locations described in Figures E7 and E9 are caused by the small difference of the depth at which the different divers are placed. Only the variation in pressure difference is interesting for the analysis in Chapter 7.

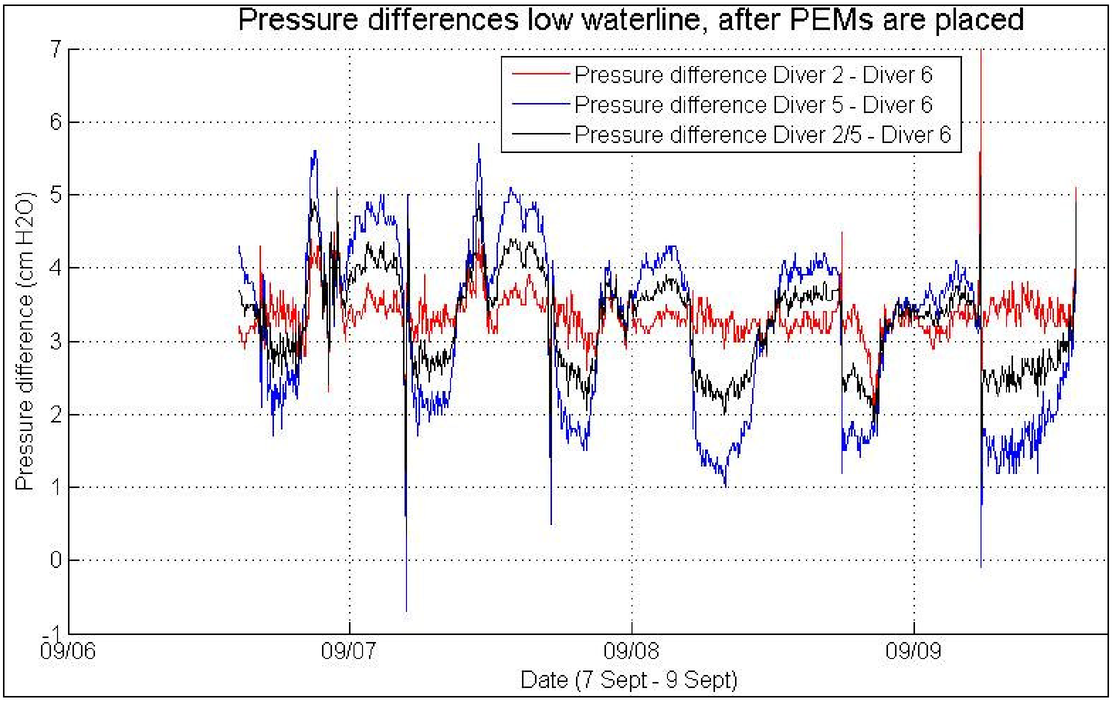

Figure E9: Pressure differences in the ground near PEM f, after the PEM was placed

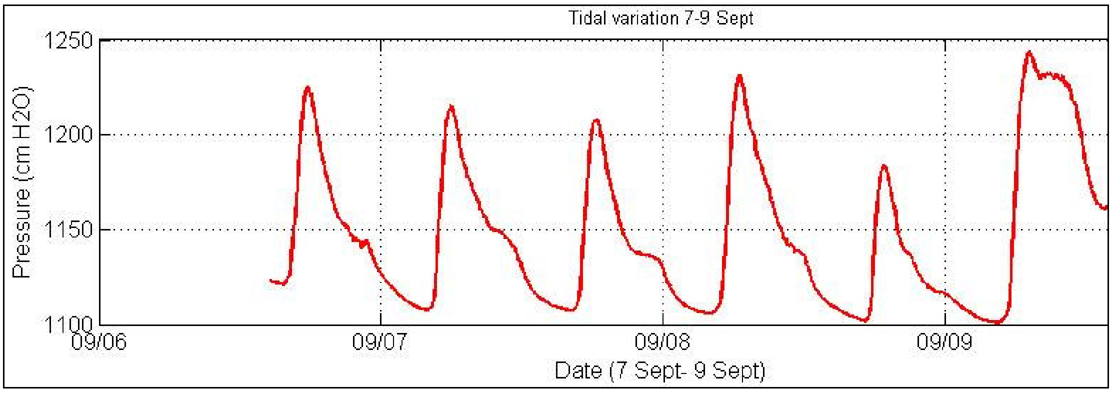

Figure E10: Tidal variation during pressure differences of figure E7

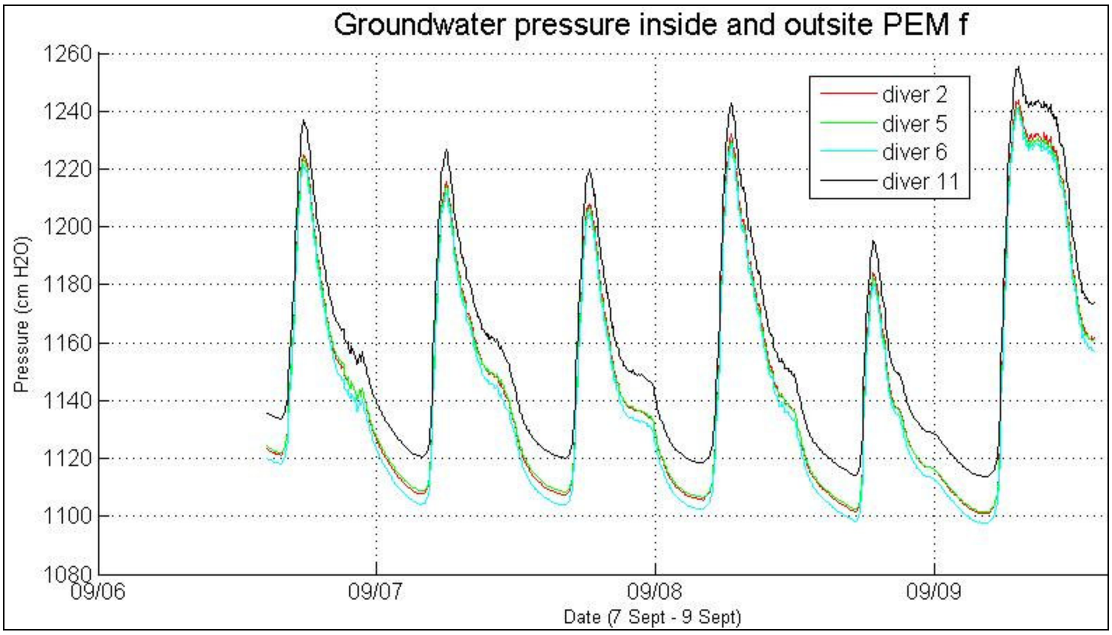

Figure E11: Pressures measured inside and outside PEM f

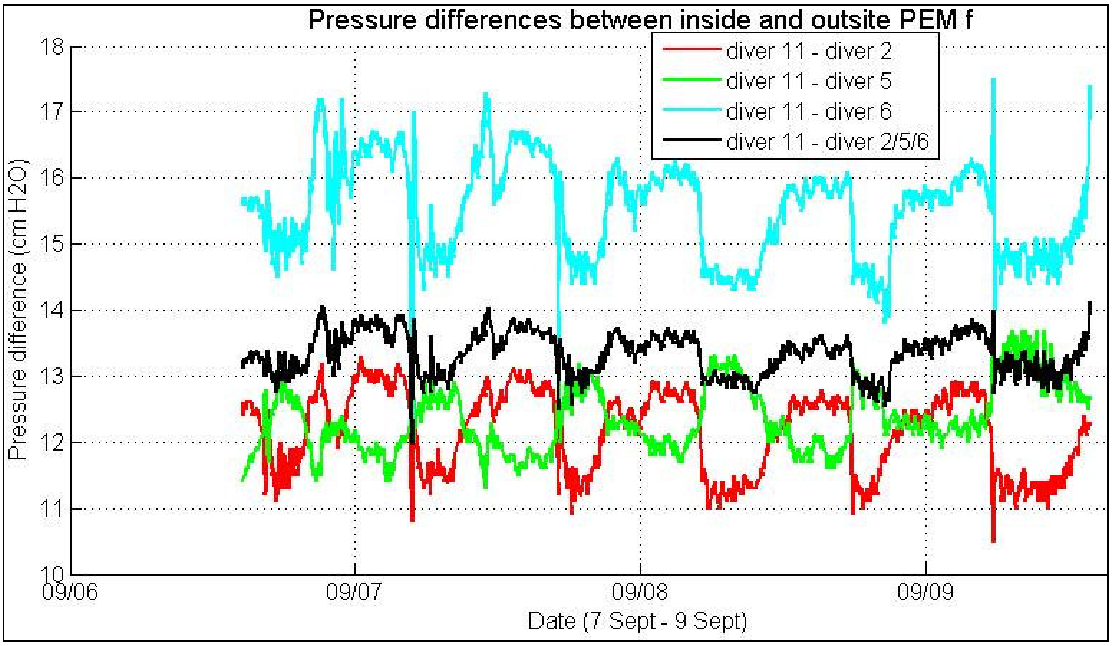

Figure E12: Pressure differences between the groundwater near PEM f and inside the PEM

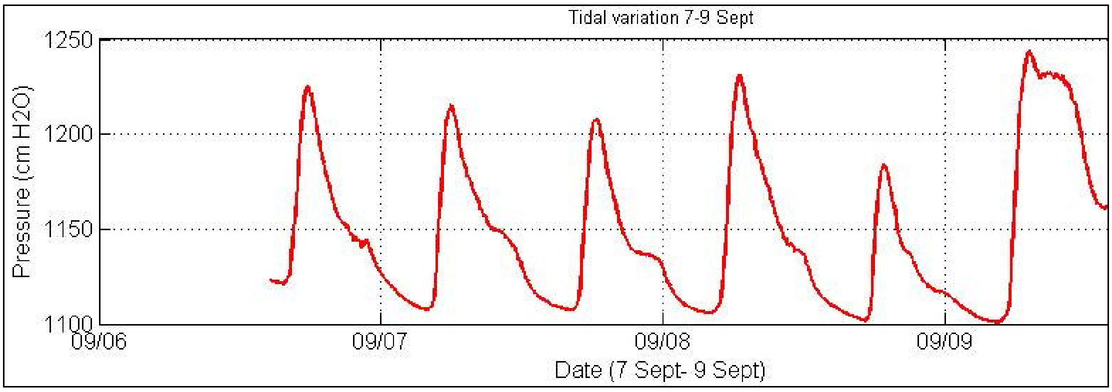

Figure E13: Tidal variation during pressure differences of Figure E12

Figure E11 shows the groundwater pressures measure in the groundwater near PEM f and inside this PEM. Figure E12 shows the pressure differences between divers around PEM f and inside this PEM, while under this graph, Figure E13 represents the tidal variation at sea. This makes it possible to compare the pressure differences with the tidal phase. It is possible to compare the pressure difference of the groundwater at different locations around PEM f with the tidal phase. The mean pressure difference at the different locations described in Figure E12 is caused by the difference of the depth at which the different divers are placed. Only the variation in pressure difference is interesting for the analysis in Chapter 7.

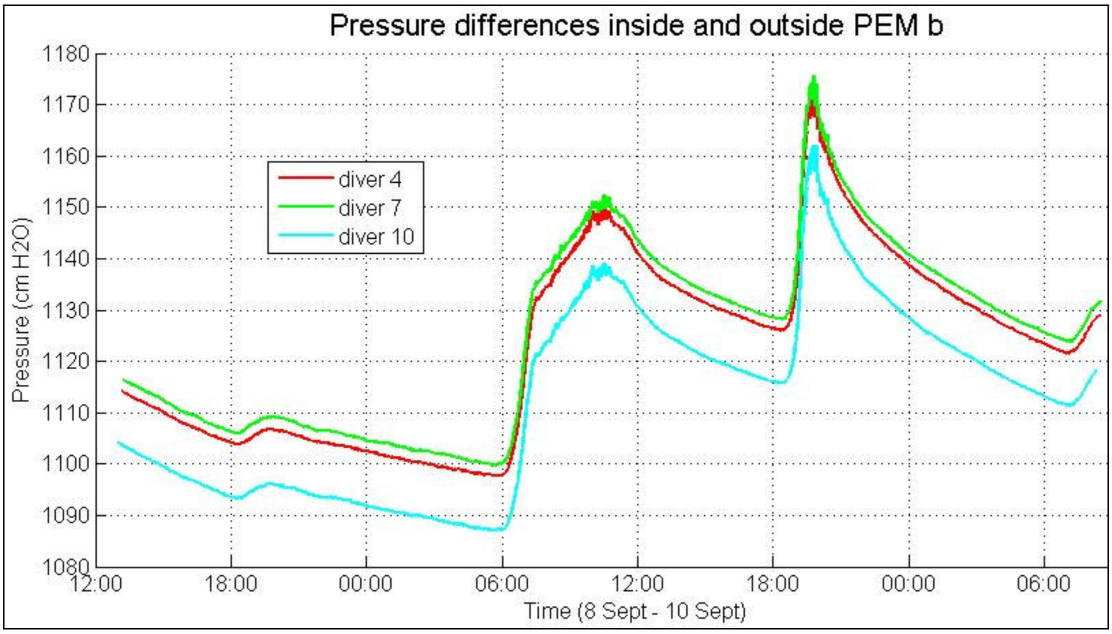

Figure E14: Pressures measured with Diver 4, 7 and 10 (high waterline) inside and near PEM b

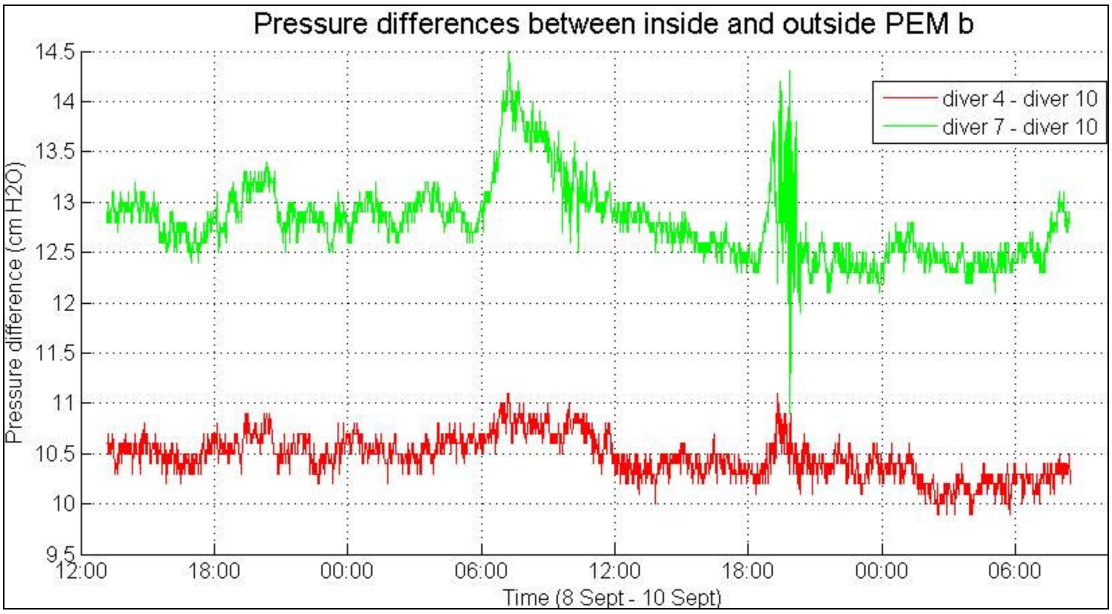

Figure E15: Pressure differences between the groundwater near PEM b and inside the PEM

Figure E14 shows the groundwater pressures measure in the groundwater near PEM b and inside this PEM. Figure E12 shows the pressure differences between divers near PEM b and inside this PEM. It is possible to compare the pressure difference of the groundwater at different locations around PEM f with the tidal phase. The mean pressure difference at the different locations described in Figure E15 is caused by the difference of the depth at which the different divers are placed. Only the variation in pressure difference is interesting for the analysis in Chapter 7.

Appendix F Sediment analysis

F.1 Introduction

During the scientific program of the Dutch Ecobeach test project the sediment characteristics at the beach of Egmond plays an important role. Sediment size is one of the visible parameters in the scheme of Figure 12, Chapter 4, to indicate some process is going on at the beach. First in November 2008 at 5 locations (southern test area and reference area) sediment samples were taken. The result of this analysis was the reason to execute a broader analysis in September 2009, which is described in Chapter 6. This resulted in a very interesting picture. Just before this report was completed the next sediment analysis was done, which confirmed the results of the first and second analysis.

F.2 Sediment analysis November 2008

In November 2008 sediment samples are taken from the upper layer of the beach at 5 locations in and around the Ecobeach test area over a length of 10 km. The most important locations are RSP 4200 (Ecobeach) and RSP 4400 (reference area). In each of these areas 15 samples are taken. Those samples were situated in three rows of five, from the foot of the dunes to the waterline, with equal distances between the samples (see Figure F1). The distance between the rows was 50 m. At RSP 4200 the northern and southern row were situated between two rows of Ecobeach PEMs, while the middle row was situated just above a row of PEMs.

In the other areas (RSP 3425, RSP 3700 and RSP 4500) 4 or 5 samples were taken: only one row between the foot of the dunes and the waterline (see Figure F1). The samples in these areas can give a better overall picture of sediment sizes along the coast around Egmond, which makes the interpretation of the samples from RSP 4200 and RSP 4400 easier. RSP 3700 finds itself in the northern Ecobeach test area, which is however influenced by artificial sand supply in the last years.

At each sample location some sediment from the upper 10 cm of the beach was taken by a little spade. These samples were sealed in plastic bags so in the laboratory the upper 10 cm of the beach was investigated. To compare the upper layer of the beach with deeper layers also samples were taken (some days later) in the area of RSP 4200 at a depth of 30 cm (see Figure F1). This can make clear if a daily fluctuation of sediment sizes in the upper layer of the beach has to be taken into account.

The samples at RSP 4200, RSP 4400 and RSP 4500 were all taken in the same circumstances, at one day, 12-11-2008 between 12:00 – 15:00 h. The day after the samples at RSP 3425 and RSP 3700 were taken around 17:00 h. The circumstances during both days were quiet, with a breeze from a south western direction. This implies, not a lot of sediment transport by wind and wave had occurred between the sampling found place. The days before the sampling an average to strong wind from a south western direction had blown and at the 10th of November it had rained seriously

Cross-shore variability:

In general, the D50 of the sediment on the beach decreases from the waterline to the dunefoot. This is considered in all areas where sediment is analysed. In particular in the southern Ecobeach test area (RSP 4200) the difference between the intertidal beach and the area around the high waterline is considerable. The mean D50 of the 18 samples at the higher part of the beach (all samples with the numbers 1, 2, 6, 7, 11 and 12) is 272 MU, while the mean D50 of the 18 samples at the lower part of the beach (all samples with the numbers 4, 5, 9, 10, 14, 15 and 3 at RSP 4500) is 306 MU. This significant difference also follows from other research projects.

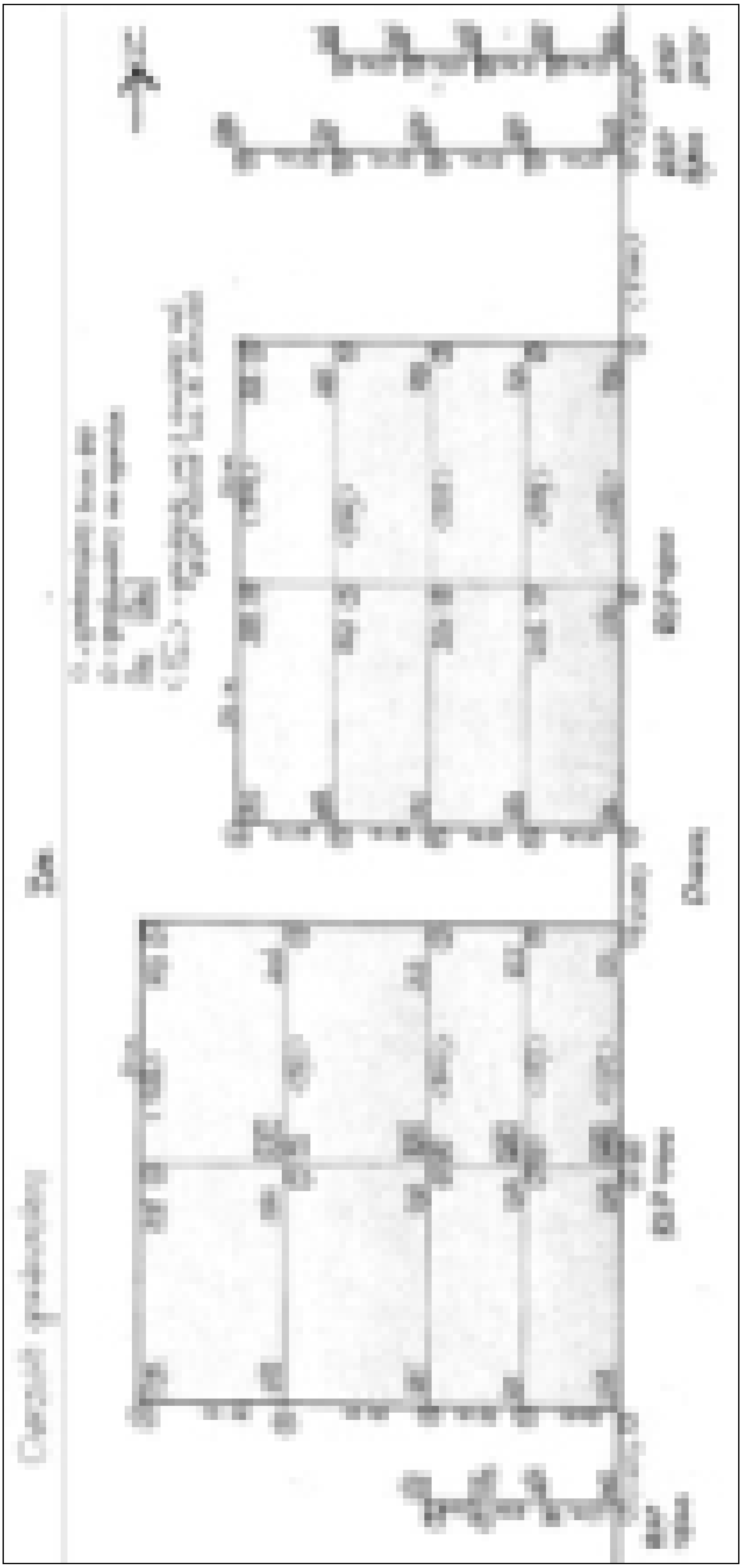

Figure F1: D50 at all sample locations of November 2008

The distribution over the beach cross section described above can be explained by the transport mechanism. The waves loose energy in the swash zone and in the end they will transport less large particles than at the transition between the surf and swash zone. Besides that the wind will generally transport the smallest particles to the foot of the dunes.

Longshore variability:
Particularly in the intertidal part of the beach a significant difference of D50 between RSP 4200 and the other areas is visible. At the highest part of the beach this difference is not visible. Looking at the 3 sea side samples of each row of 5 samples, a big difference exists between RSP 4400 (and all other areas) and RSP 4200. RSP 4200 (Ecobeach) and RSP 4400 (reference area) are close to each other and both not so much influenced by artificial sediment supply in the last ten years. Because most samples are taken in those two areas it is interesting to compare them. Samples 3, 4, 5, 8, 9, 10, 13, 14 and 15 of both areas are averaged and form a graph, with the classes of small particles melted together. See Figure F2. It is obvious that the particle sizes in the Ecobeach area are large compared to those in the reference area.

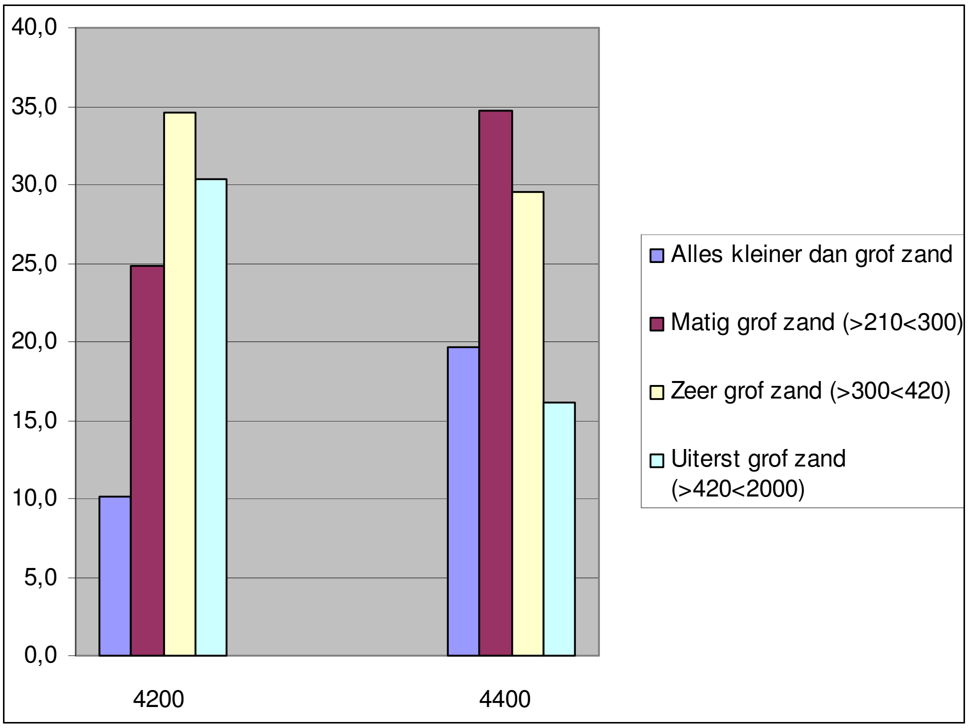

Figure F2: Comparison of sediment size distribution between RSP 4200 and RSP 4400

F.3 Analysis data September 2009

In Chapter 6 the results are presented of a sediment analyses along the Egmond coast as well as at the location of the fieldwork. In Table F1 the size distribution of the18 samples at the fieldwork location and the 30 samples along the coast are visible. The code of the samples in Table F1 consists of a number of 6 digits, which is given by the laboratory of VU University, followed by a description of the sample location.

The first part of the sample location description of the first 18 rows in the table described the cross shore location, compared beach pole 43250, in metres (seaward direction is positive). The second part describes the depth of the samples in metres. The sample location of the 30 lower samples in Table F1 indicates the along coastal position, expressed in RSP.

Code		Uiterst fijn < 100 mu	Fijn zand 100 - < 163	Matig fijn zand 163 -< 230	Matig grof zand 230 - < 325	Zeer grof zand 325 - < 460	Uiterst grof zand 460 - < 2000
142156	-15m 0.0	1.34	3.07	14.99	40.46	29.06	11.05
142157	-15m 0.5	1.07	2.37	10.81	33.58	33.22	18.95
142158	-15m 1.25	0.87	1.75	7.54	23.48	28.04	38.32
142159	-15m 2.0	1.13	2.6	8.99	22.8	25.54	38.94
142160	strandp 0.0	1.07	2.28	10.49	35.45	34.85	15.85
142161	strandp 0.5	1.13	2.78	8.68	25.4	32.74	29.26
142162	strandp 1.25	0.91	1.46	6.51	23.67	32.91	34.54
142163	strandp 2.0	0.54	0.99	3.67	11.97	20.18	62.6
142164	+15m 0.0	1.23	3.33	10.69	28.26	31.47	25
142165	+15m 0.5	0.57	1.89	5.6	15.36	25.73	50.84
142166	+15m 1.25	0.74	1.74	6.82	21.07	27.96	41.64
142167	+15m 2.0	1.08	2.9	10.53	26.04	25.87	33.55
142168	+35m 0.0	1.08	2.55	9.16	26.44	31.19	29.54
142169	+35m 0.5	0.91	1.44	5.75	18.18	24.79	48.95
142170	+35m 1.25	0.7	1.16	4.86	16.62	25.92	50.71
142171	+35m 2.0	0.75	1.64	6.86	20.45	26.26	44.05
142172	-15m 1.4	0.65	1.06	4.06	13.98	23.71	56.53
142173	strandp 1.6	0.7	1.21	4.8	15.65	22.54	55.1
142174	38000	1.31	2.68	11.15	36.14	33.27	15.45
142175	38250	1.28	2.52	11.31	37.4	33.04	14.48
142176	38500	0.41	0.92	6.22	26.5	36.77	29.15
142177	38750	0.59	1.65	9.1	33.17	35.45	20
142178	39000	0.77	1.99	10.65	35.8	33.63	17.17
142179	39250	0.42	0.58	4.91	22.81	36.07	35.2
142180	39500	1.07	1.9	8.79	31.9	35.42	20.91
142181	39750	0.79	1.25	5.09	19.81	33.1	39.94
142182	40000	0.95	1.37	5.93	23.39	34.86	33.51
142183	40250	0.83	1.3	5.61	21.75	34.52	36
142184	40500	1.09	1.95	9.66	31.55	32.17	23.59
142185	40750	0.76	1.16	5.17	20.15	31.98	40.77
142186	41000	0.64	0.9	3.63	14.29	28.46	52.04
142187	41250	0.88	1.47	6.61	24.02	33.38	33.65
142188	41500	0.66	0.98	3.73	13.71	26.48	54.46
142189	41750	0.75	1.17	4.71	17.72	31.55	44.06
142190	42000	0.52	0.74	2.47	9.4	23.19	63.67
142191	42250	0.61	0.82	3.29	14.53	33.81	46.91
142192	42500	0.61	0.82	3.11	13.26	31.55	50.66
142193	42750	0.85	1.04	4.64	18.45	32.48	42.55
142194	43000	1.04	1.53	7.41	27.71	35.87	26.44
142195	43250	0.77	1.12	4.46	17.36	33.53	42.76
142196	43500	0.98	1.52	6.89	24.02	31.77	34.83
142197	43750	1.16	2.3	10.27	31.18	32.37	22.73
142198	44000	1.27	2.72	12.7	37.05	31.53	14.75
142199	44250	0.74	1.21	4.82	17.69	30.37	45.16
142200	44500	1.33	2.59	11.53	31.38	29.53	23.67
142201	44750	1.09	1.88	8.96	30.3	32.27	25.46
142202	45000	1.08	1.76	7.74	26.36	33.16	29.9
142203	37750	1.12	1.64	8.04	32.79	37.82	18.58

Table F1: distribution of the particles of all samples over different size classes

F.4 Analysis November 2009

In November 2009 a sediment analysis is executed along the coast near Egmond aan Zee by Hugo Ekkelenkamp. The result of the analysis of September 2009 (described in Chapter 6) and November 2008 (Appendix F.2) is confirmed by the results of this analysis. Figure F3 [31] shows the distributions of the D50 along the Egmond coast. In the middle of the figure the southern Ecobeach test area is demarcated. In the southern Ecobeach test area the sediment seems to be coarser then at the bordering beaches.

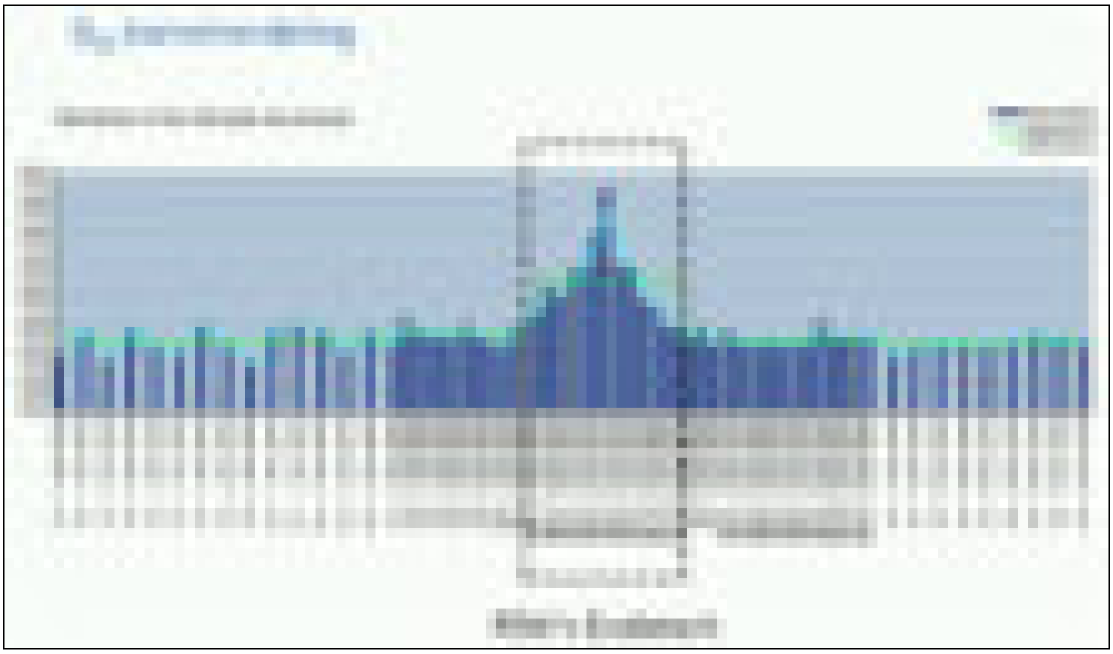

Figure F3: D50 of the sediment along the coast near Egmond aan Zee, November 2009 [31]

F.5 Laser analysis procedure

The particle sizes of the samples are examined by laser diffraction. At first the samples have to be prepared for the laser analysis. All organic material can be removed by a reaction with hydrogen peroxide (waterstofperoxide) and the calcium can be removed by hydrochloric acid (zoutzuur) to achieve that the samples only existed of quartz particles. In November 2008 by hydrochloric was used, but in September 2009 it was not, because shelves were supposed to be also interesting to measure.

From the prepared samples about 1 cm³ is used for the laser analysis, which is an automatic procedure. The outcome of the analysis is an accurate particle size curve for every sample, like a sieve curve. Only mater

By way of the laser diffraction the grains of each sample are distributed in 56 different diameter classes. The volume percentage of the sample in every class is given. The correlation between the diameter unity [mm] and [φ] is given by the following formula:

$$\varphi = -\log_2 d_{(mm)}$$

Appendix G Overview of beach dewatering projects

G.1 Introduction

Beach dewatering is seen as a way to reduce erosion and promote accretion. In the last 20 years different beach dewatering systems have bean installed in Europe and the United States, but the idea of beach dewatering originated from the forties already. BAGNOLD (1940) proposed that erosion and accretion are correlated with beach face permeability, while GRANT (1946, 1948) was the first to suggest that the elevation of the groundwater influences erosion and/or accretion [26].

In the seventies the first laboratory studies (Machemehl et al., 1975) and small field investigations (Chapell et al., 1979) were done. With pumped wells or drains connected with pumps the beach groundwater was artificially lowered.In 1985 the first full-scale test was executed at the beach of Thorsminde in Denmark, which was followed by other commercial installations in Danmark, USA, UK and France.

Figure G1 shows the common procedure of the installation of a beach dewatering system. A drain with a length of several hundreds of meters is put in a trench parallel to the coastline, dug in the intertidal area. Gravity transports the water in de drain to a low laying storage from where it is pumped out by mechanical pumps. In the next paragraph three of the most important beach dewatering projects are described and an overview is given of all large projects between the beginning of the eighties and 2000.

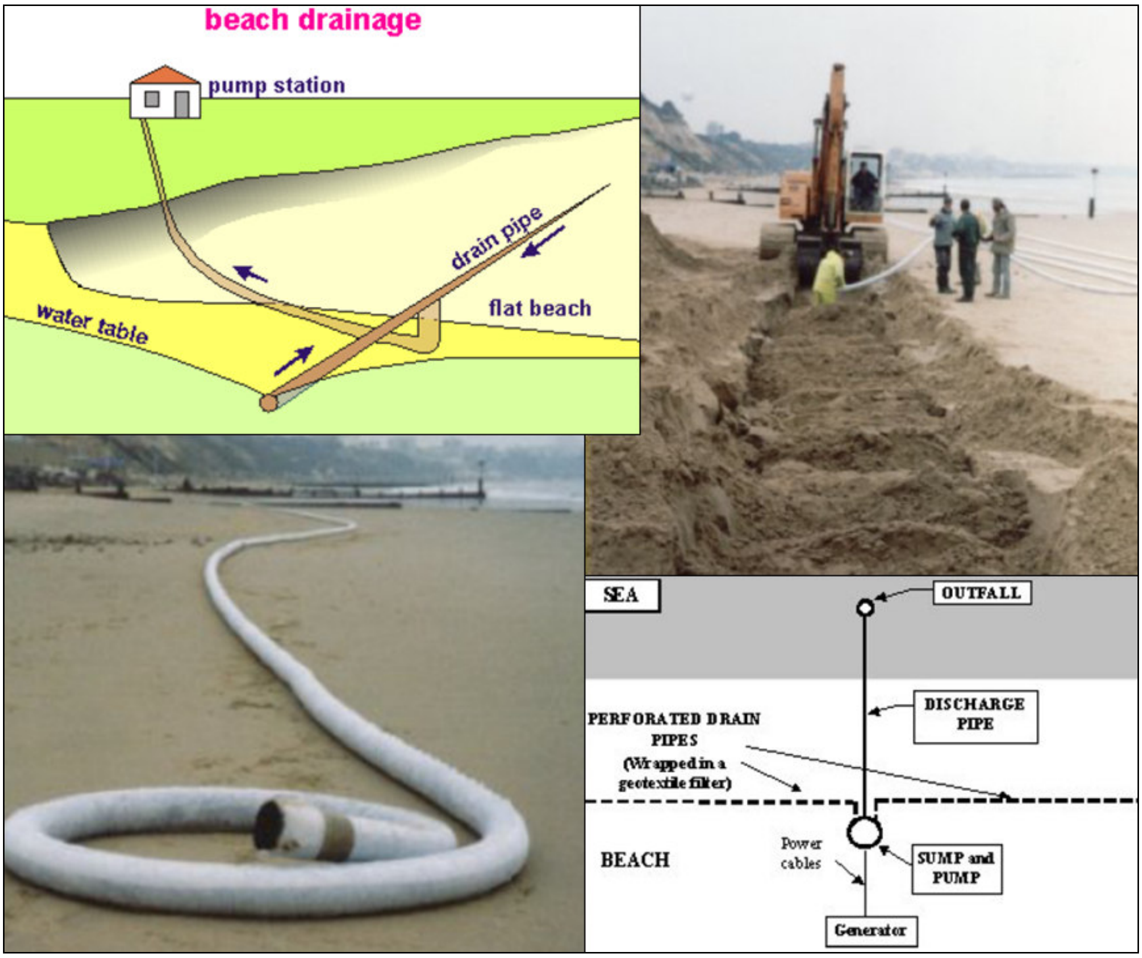

Figure G1: Installation of a beach dewatering system [27]

G.2 Examples of full-scale tests

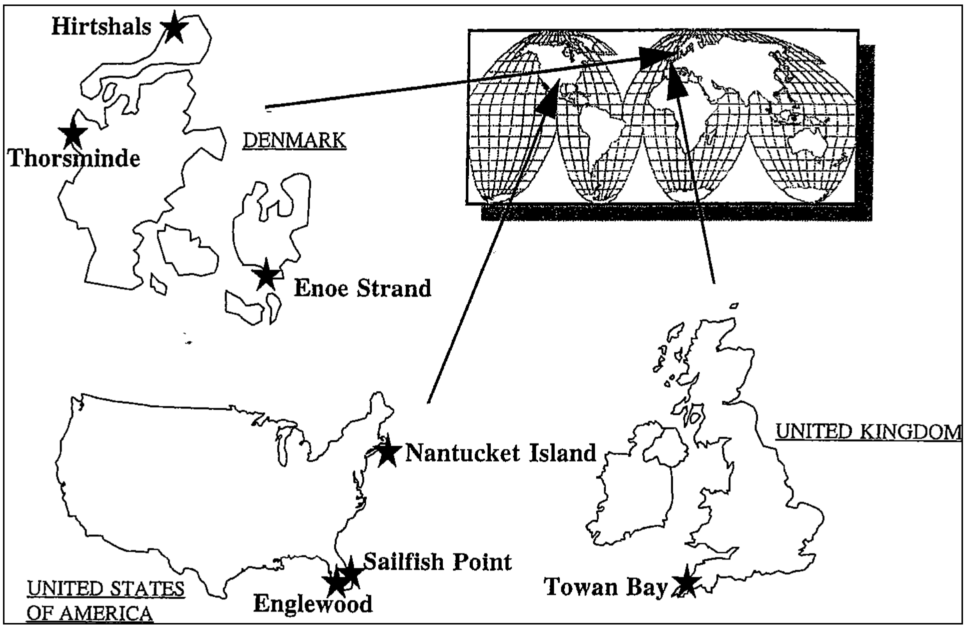

Figure G2: Locations of commercial dewatering systems up to mid-1995 [26]

Thorsminde, Danmark (1985-1991)

In the early eighties the Danish Geotechnical Institute received a positive signal about beach drainage Hirtshals (see Figure G2). The Danish North Sea Research Centre pumped beach groundwater for heat pumps and aquaria, but in six months the capacity of the system reduced by 40%. This seemed to be caused by accretion of the beach. The resistance between the beach surface and the 200-300 mm perforated PVC pipe (at 2.5 m below mean sea level) had increased a lot [26].

In 1985 a test was started at the beach of Thorsminde, on the west coast of Denmark (see Figure G3). This beach consists of mixed gravel and medium grained sand with local some organic mud, underlain at an elevation of -3.5 to -5 m by silt and clay. Under the beach, which retreated on average 4 m per year and fluctuated seasonally by about 15 m, a 500 m long and 200 mm diameter drain was installed. Concrete pipes connected the drain with a pump which was located 60 m inland.

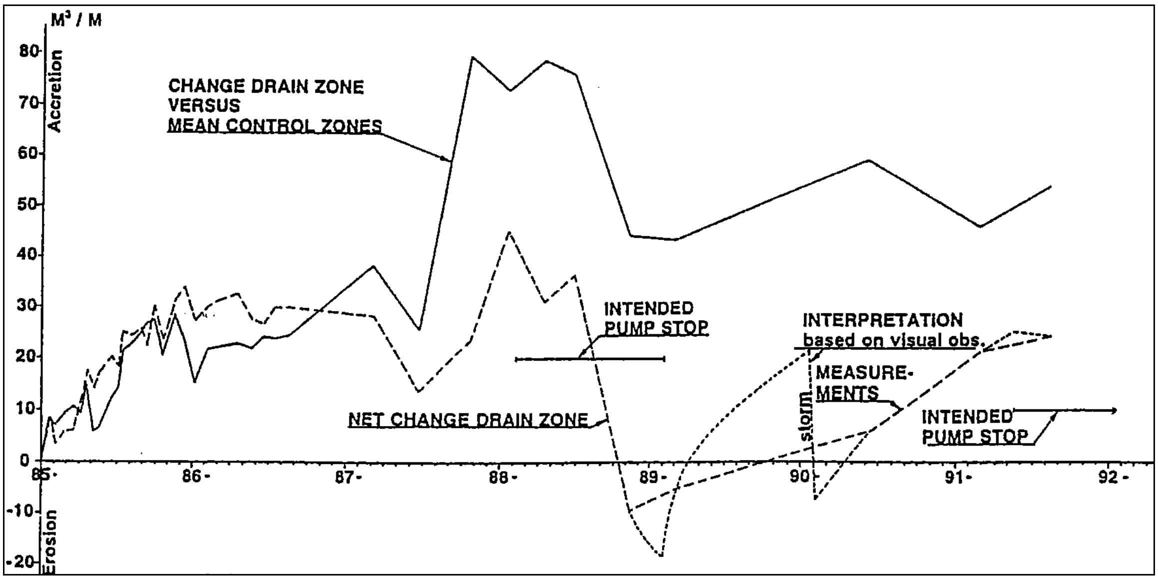

Figure G3: Beach volume changes at Thorsminde beach [28]

Figure G3 shows the beach volume of the test site compared to the initial volume (dotted line) and compared to the volume change of the adjacent control sites (solid line). The graph shows an accretion of about 30 m³/m in the first year, staying constant during the following 1.5 year. Two large erosion events are visible: the first during a pump stop and the second during a 1 in 100 year storm. In the end of the test the accretion of the test area compared to the adjacent control sites is 50 m³/m.

Sailfish Point, Florida, USA (1988-1993)
In 1988 a 180 m long beach dewatering system was installed at Sailfish point (see Figure G2), where the beach is composed of fine-grained well-sorted sand and 100 – 150 m offshore a rock reef provides natural shoreline protection. In the period 1972 – 1986 the shoreline retreated 2 m per year, but just before the installation of the beach drains the beach accreted for a period of two years. With the 0.3 – 0.5 m diameter PVC pipe after 8 months a water table lowering of 1.0 m was achieved.

After 20 month of operation DEAN (1990) reported a positive effect of the dewatering system on the beach [26]:
1. The dewatering system appeared to have resulted in local moderate accretion in contrast to a general erosional trend to the north and a relatively small accretionary trend to the south.
2. The system appeared to result in a considerably more stable shoreline relative to both control segments north and south.

From 1991 until the end of the test in 1993 the pumping were only allowed for 6 month annually (the most important part of the year for the beach dewatering system pumping was forbidden) to prevent disturbing the turtle nesting season. In the end after the test, no publication shows a clearly positive effect of the system on erosion-accretion of the beach [26].

Les Sable d'Olonne (1999 - present)
In April 1999 a beach drainage system was installed to protect the beach of Les Sable d'Olonne against erosion. This is a 1500 m long beach along the French Atlantic coast, situated in a protected bay. The sediment at the beach is fine sand (150 MU < D50 < 250 MU) with clay layers present at one metre below the shore face. The tidal range is about 5.6 m, with tidal currents of 0.2 – 0.4 m/s. The cross-shore and longshore sediment transport is around 1000 m³/year [27].

After 3 years a positive result of the 300 m long drain (under the mean water line) was measured and the system was extended. In March 2002 a second drain of 300 m length was placed under the mean water line and a 700 m drain under the high water line, behind both 300 m drains [Couton]. In 2002 the erosion of the beach was stabilized above the drains or sedimentation was increased. Nevertheless it was too early to conclude the system increases the beach width.

G.3 Overview of beach drainage projects

Table G1 gives an overview of beach dewatering installations until 2001. In common a positive effect of the dewatering on the amount of sediment at the beach can be noticed in the table.

Nr	Project (year installed)	Period of operation	System length, depth	Tidal range	D50 mm	Initial/final beachslope	Draw-down
1	Hirtshals W, Denmark (1981)	Since 9/81	200 m, -2.5 m	1.5 m	0.26	1:20/1:20	
2	Hirtshals E, Denmark (1983)	2/3 of 1983	200 m, -2.0 m	1.0 m	0.2	1:25/1:20	
3	Thorsminde, Denmark (1985)	1/85 – 4/91	500 m, -2.5 m	1.5 m	0.35	1:25/1:20	
4	Sailfish Point Stuart, Fl. USA (1988)	7/88 – 8/96	177 m, -2.4 m	0.8 m	0.3	1:25/1:25	0.8 m
5	Enoe Strand, Denmark (1994)	Since 7/94	600 m, -1.8 m	0.5-1.0	0.25	1:15	1.0 m
6	Towan Bay, UK (1994)	Since 9/94	180 m,	7 m	0.2	1:45	
7	Codfish Park, Natucket I, MA, USA ('94)	Since 1/95	357 m, -2.1 m	1.0-1.5	1.5	1:45	0.3 m
8	Lighthouse S, Natucket I, MA, USA ('94)	Since 1/95	309 m, -2.1 m	1.0-1.5	0.8	1:6	0.3-1.3
9	Lighthouse N, Natucket I, MA, USA ('94)	Since 1/95	405 m, -2.1 m	1.0-1.5	0.4	1:6	0.9-1.8
10	Chigasaki-Naka Beach, Japan (1996)	5/96 – 7/97	180 m, -2.3 m	1.6 m	0.5	1:10	
11	Riumar, Ebro Delta, Spain (1996)	Since 10/96	300 m, -2.3 m	0.2-0.4	0.2	1:20	1.0 m
12	Hornbaek W, Danmark (1996)	Since 12/96	450 m, -0.8 m	0.2-0.4	0.3	1:10	0.5 m
13	Hornbaek E, Danmark (1996)	Since 12/96	530 m, -1.5 m	0.2-0.4	0.3	1:20	1.0 m
14	Ystad, Sweden (1998)	Since 3/98	200 m, -1.5 m	1.0 m	0.3	1:15	1.0 m
15	Branksome Chine, Dorset, UK (1998)	3 months	100 m, -1.5 m	2.0 m	0.25	1:18	
16	Hitotsumatsu Beach, Japan (1998)	Since 6/98	800 m, -2.4 m	2.0 m	0.25	1:20	
17	Les Sables d'Olonne, France (1999)	Since 4/99	300 m, -1.2 m	3.4 m	0.25	1:70	
18	Riumar II, Ebro Delta, Spain (1999)	Since 12/99	300 m, -2.0 m	0.2-0.4	0.25	1:20	
19	Markgrafenheide, Germany (2000)	Since 8/00	300 m, -1.4 m	0.3 m	0.7	1:30	
20	Lido di Ostia, Italy (12-2000)		400 m, -1.4 m	0.3 m	0.25	1:40	

Nr	Pump capacity	Initial(/final) flow rate	comments
1	400 m^3/h	2.0/1.0	25.000 m^3 sand harvested each year to renourish other beaches
2	100 m^3/h	0.4/0.15	Width maintained. Erosion rate: 7 m/year
3	700 m^3/h	1.7/1.1	Experimental system, width increased by 25 m
4	340 m^3/h	1.5/0.60	Width increased by 20-25 m during operation, protected by offshore reef
5	300 m^3/h	0.4/0.1	Width increased by 3 m August 1996. Maintained. Semi-protected coast
6	200 m^3/h	1.27/1.0	General Accretionary tred. Exposed seawall footing safeguarded. Semi-protected coast
7	700 m^3/h	1.7 m^3/h/m	Erosion during storm events in treated areas reduced compared to untreated areas, open Atlantic coast
8	1400 m^3/h	1.1 m^3/h/m	
9	1400 m^3/h	3.2 m^3/h/m	
10	500 m^3/h	2.8 m^3/h/m	Typhone: temporary shut down. Shore-line stabilized and beach level increased
11	290 m^3/h	0.5 m^3/h/m	Width maintained after severe storm event in Oct. 97
12	170 m^3/h	0.1 m^3/h/m	Width increased by 0 – 5 m, May 1997
13	325 m^3/h	0.3 m^3/h/m	
14	240 m^3/h	0.8 m^3/h/m	Accretionary trend on the lea side of the 90 metres long groyne
15	65 m^3/h	0.4 m^3/h/m	Experimental system. Increased beach level
16	2 X 300		Accretionary trend. Beach level increased.
17	250 m^3/h		Accretionary trend and substantial foreshore dry up in the drain zone
18	400 m^3/h		No measurements at present
19	300 m^3/h	0.9 m^3/h/m	Width increased by 8 – 10 m in October 2000
20	3 X 140		Pumps not running yet

Table G1: Overview of beach drainage projects until 2001 [26]

G.4 Ecobeach compared to other beach dewatering projects

Ecobeach is called a beach drainage system (see paragraph 2.1.2), but the Ecobeach system is not comparable with the beach dewatering systems described in Table G1. All projects from Table G1 consist of one or more horizontal drains under the beach, with an active drainage by a pumping station resulting in a lowering of the groundwater level from some decimetres to more than a meter.

In contrast with this, Ecobeach consists of vertical drains which are not connected with a pump and no lowering of the groundwater level of several decimetres to a meter can be expected. Although the knowledge of the many beach dewatering tests in history is important to analyse Ecobeach. A different view at this system is required to find all possible working mechanisms.

Appendix H Report scientific workshop Ecobeach

H.1 Workshop Ecobeach –10 september 2008

Het ochtendprogramma, de workshop, vond plaats in Zoetermeer, waarna een aantal van de aanwezigen nog een bezoek aan de proeflocatie in Egmond aan Zee brachten.

Er waren ’s ochtends 18 mensen:

Koos Groen	Hydrologie	VU Amsterdam
Meindert Van	Grondmechanica	Deltares
Erik Vastenburg	Grondmechanica	
Wim Uijttewaal	Vloeistofmechanica	TU Delft
Marcel Stive	Waterbouwkunde	TU Delft
Dave Callaghan	Ecologie	NIOO-CEME
Dano Roelvink	Internationaal	IHE
Frank van der Meulen	Internationaal	IHE
Anna Cohen		Deltares
Sander van Rooi	Coastal management	Deltares
Leon Wijnker		Rijkswaterstaat
Evelien van Eijsbergen	Coastal management	Rijkswaterstaat
Bas Reedijk	Waterbouwkunde	BAM
Jelle-Jan Pieterse	Stagiair TU Delft	BAM
Ed van Veneveld	Geotechniek	BAM
Ad van ’t Zelfde		BAM
Bram Bakker	Geotechniek	BAM
Sietsche Eppinga		BAM
Andy Egon	Stagiair TU Delft	BAM

Ad van ’t Zelfde (innovatiemanager BAM Infraconsult) heet alle aanwezigen welkom namens Rijkswaterstaat, WINN, BAM en Deltares.

H.2 Het programma begint met een korte introductie

Ecobeach is een proefproject op het strand in Egmond aan Zee. Het strand wordt gedraineerd met 2 meter lange verticale pijpjes met een diameter van ongeveer 6 cm. Het is een concept dat in Denemarken bedacht is door Skagen Innovation Center. In Egmond zijn in twee proefvakken van elke 3 km lang deze drains geïnstalleerd. Om de 100 m is een rij drains geplaatst met een onderlinge afstand van 10 m, vanaf de gemiddelde hoogwaterlijn tot ongeveer NAP -2 m. Ook is er een referentievak. De volumes zand in deze vakken worden gemeten door Deltares. De proef is in november 2006 begonnen en binnenkort wordt het tweede meetrapport verwacht, waarin recente meetgegevens zijn verwerkt.

Luchtfoto’s van een eerder project in Denemarken laten het effect van de drains overtuigend zien, dat het stand is flink aangegroeid. Toch heeft de uitvinder Poul Jacobson veel critici onder de Deense wetenschappers, die de werking van Ecobeach in twijfel trekken. De metingen van Poul Jacoboson worden niet betwist, echter het ontbreken van een aanvaarde verklaring van de werking van het systeem leidt niet tot acceptatie van het systeem. Verschillende projecten in hele wereld laten een toename van de hoeveelheid zand op het strand zien en een verandering van een concaaf naar een convex profiel (van een smal hoog gedeelte en een breed laag gedeelte, naar een breed hoog gedeelte dat steil afloopt bij de waterlijn).

Het project is een nieuwe samenwerkingsvorm tussen Rijkswaterstaat en de BAM, die wordt toegelicht door Leon Wijnker van Rijkswaterstaat. Voor Ecobeach is er een partnerschap tussen RWS en BAM, in plaats van de gebruikelijke opdrachtgever-opdrachtnemer relatie.

Rijkswaterstaat hoopt dat Ecobeach een mogelijke aanvulling kan worden op strandsuppleties voor de kustverdediging.

De drains worden ook wel PEM's (pressure equalization modules) genoemd. De onderste meter is geperforeerd met horizontale gleufjes met een breedte van ongeveer 0.2 mm, terwijl de bovenste meter gesloten is. De dop bevat een filtertje, waardoor lucht kan stromen dat bij eventuele drukverschillen de pijpjes wil verlaten of binnengaan. Het geperforeerde deel van de pijpjes moet zich altijd onder het strandoppervlak bevinden. De korrels vormen hier een geometrisch filter, die de ze afsluiten voor zandkorrels. Als de pijpjes met het geperforeerde deel boven het zand uitsteken, worden ze in no-time gevuld met zand. Het is echter de bedoeling dat de pijpjes zich geheel onder het zand bevinden, om te voorkomen dat strandgangers hun voeten kunnen stoten. Zodra de drains gesignaleerd worden, spuit men ze dieper de grond in.

H.3 Doel van de workshop

Het doel van de workshop is inzicht verkrijgen in de werking van de innovatie. Ad van 't Zelfde benadrukt de uitdagingen die aan deze vraag verbonden zijn

- Voor de wetenschap is de volgorde omgekeerd: eerst toepassen dan testen in plaats van eerst testen en dan toepassen.
- Nieuwe rol voor alle betrokken partijen (BAM, Rijkswaterstaat en Wetenschap)
- Uitdaging ligt op de randgebieden van de wetenschappelijke disciplines
- Wetenschappen beschikken over verschillende methodes
- Vraag die moet worden beantwoord (mechanisme plausibel of een designmanual)

Voor de sessie van vandaag komen twee belangrijke vragen naar voren:

1. wat zijn kansrijke werkingsmechanismen van de proef
2. hoe kunnen we de voorgenomen proef verrijken

Op deze sessie komt een vervolg. Aan de orde zullen/kunnen komen

- terugkoppeling proef
- resultaten van afstudeerders
- presentatie Jacobson

H.4 Resultaten brainstormsessie

Na de introductie zijn de aanwezigen in 4 groepen ruim een uur gaan brainstormen over de mogelijke werkingsmechanismen van de PEM's. De resultaten werden vervolgens gepresenteerd aan alle aanwezigen en zijn hieronder samengevat.

Groep 1:

- Verticale stromingscomponent

Het stromingspatroon in de bovenste laag van het strand wordt beïnvloed door de drainage. De voornamelijk horizontale stroming krijgt een grotere of kleinere horizontale component. Deze verticale component oefent een kracht uit op de bovenste korrels, die hierdoor moeilijker of juist makkelijke meegenomen worden door de horizontale stroming.

- Onderdruk in drains

Er bevindt zich water en lucht in de pijpjes. Als de waterspiegel verandert, kan er een onderdruk ontstaan. Deze onderdruk trekt aan de korrels, waardoor deze minder gemakkelijk weggespoeld worden.

- Betere pakking

Als de drainage een dichtere pakking van het zandpakket tot gevolg heeft, zullen er grotere capillaire spanningen in het pakket ontstaan als het wil vervormen (bijvoorbeeld als golven het willen wegspoelen). Hierdoor zal het zand stabieler blijven liggen.

- Veranderingen in de gradatie van de korrels of veranderingen in korrelgrootte rond de drains.
- Inzuiging golfoploop

Door breking van de gelaagdheid kan er mogelijk meer water infiltreren bij golfoploop. Hierdoor zal er bij golfoploop meer zand het strand op getransporteerd worden dan terug naar de vooroever.

- Biologische verkitting

Veranderingen in de omgeving zorgen voor veranderingen in de organismen die in het zand leven. Mogelijk is er een toename van organismen die er voor zorgen dat zandkorrels aan elkaar gaan kleven.

Groep 2:

- Vermindering van de erosie
- Bevordering van aanzanding

Drukverlaging in poriën heeft tot gevolg een vermindering van erosie door golven, omdat hierdoor de verticale component omlaag van de kracht op de bovenste korrels groter wordt. Ook kan er meer aanzanding optreden als er een lagere druk heerst in het bovenste deel van het zandpakket. Dit hoeven maar zeer kleine veranderingen te zijn om een merkbaar effect te veroorzaken, omdat er met duizenden golven per dag enorme hoeveelheden zand getransporteerd worden.

Door minder erosie / meer aanzanding kan het droge gedeelte van het strand groter worden, waardoor er meer zandtransport door de wind plaats kan vinden. Hierdoor wordt er meer zand naar hoger gelegend delen van het strand aangevoerd.

- Gunstige leefomgeving voor lijmproducerende organismen.

De zoetwaterbel in de duinen stroom af naar de zee. Deze stroming gaat onder het hoge deel van het strand heen en de uitstroom van zoet water is rond de laagwaterlijn, of nog verder zeewaarts gelokaliseerd. De uitstroom van zoetwater kan mogelijk geconcentreerd plaats gaan vinden rond de drains. Behalve dat hierdoor de rest van het strand droger zou kunnen worden, verandert de omgeving van de drains qua zoutgehalte en kunnen er andere organismen gaan leven, die mogelijk een verkittende werking hebben op de zandkorrels.

Groep 3

- Richelvorming

In het geval dat de buisjes boven de grond uitkomen, kunnen deze zand opvangen.

- Korrelspanningen

Vooral bij de overgang van hoog naar laag water kan het freatisch vlak (sneller) omlaag getrokken worden door de drains. Hierdoor worden de korrelspanningen groter, waardoor de terugtrekkende golven (vooral de kleine golven) minder zand eroderen.

- Zoet-zout

In Denemarken zijn flinke variaties in korrelgrootte in het zandpakket van het strand. Dit kan gelaagdheid tot gevolg hebben (Nederland meer homogeen?).

Een afsluitende laag kan ook ontstaan op de scheiding tussen zoet water uit de duinen en zout water uit de zee. Deze scheiding bevindt zich als een horizontaal vlak onder het strand oppervlak en het kan dat op deze scheiding vlokken gevormd worden die een afsluitende laag vormen. De pijpjes vormen dan shortcuts door deze afsluitende laag.

Groep 4

- Grondwaterpeil in het inter-getijdengebied

Infiltratie van water bevordert aanzanding, terwijl ex-filtratie (kwel → lagere korrelspanningen) erosie bevordert. Bij een lager grondwaterpeil zal er iets meer infiltratie plaatsvinden van golven in de swash zone (waar het meeste zandtransport plaatsvindt) en hebben de teruggaande golven iets minder kracht. Het evenwicht kan de andere kant opgaan bij een FRACTIE verschil in grondwaterpeil.

- Herverdeling grondwaterdrukken

Drukverschillen worden door de drains 2 m omlaag doorgegeven. Drukgolven worden omlaag getransporteerd en daardoor in de bovenste laag afgevlakt. Er vindt afvlakking van de grondwaterstand plaats.

- Verschuiven zoet-zout systeem

Onder het interessante gebied (swash zone) vindt een zoetwater stroming plaats richting te zee. Een chemische reactie tussen zout en zoet water zou stabiliserend kunnen werken.In zoet water bezinkt zand veel sneller dan in zout water (proefje: twee spaflessen met zout en zoet water vullen + zand, schudden en laten bezinken, het verschil is zo groot dat het niet alleen door het dichtheidsverschil kan komen, maar er moet een chemische reactie optreden). Door zoet water te laten ontsnappen rond de laagwaterlijn in plaats van verder de zee in, zou er hier een snellere bezinking van sediment kunnen optreden. Wat kunnen reacties tussen zoet en zoet water tot gevolg hebben: vastere pakking? minder wegstroom of opwaaiing? Zoet water bevat ijzer in tegenstelling tot zout water. Dit zou neer kunnen slaan op de zandkorrels, die daardoor een iets grotere dichtheid krijgen. Korrels met een iets grotere dichtheid dan kwarts zullen mogelijk beter blijven liggen, waardoor er minder erosie plaatsvindt. Het zuurstofgehalte in de grond hangt af van de grondwatersamenstelling (zoet water bevat weinig zuurstof). Organismen die in het strand leven (bijvoorbeeld “gravertjes”) zijn afhankelijk van zuurstof in de grond.

- Zandaanvoer

Voor herverdeling van het zand is geen aanvoer nodig, maar als de hoeveelheid zand op het strand daadwerkelijk toeneemt, is het niet genoeg om naar processen van dwarstransport te kijken. Om kilometers strand te laten groeien moet er een flinke hoeveelheid zand uit het langstransport worden opgepikt. Het zou kunnen dat er eerst een herverdeling in het strandprofiel plaatsvindt en dat deze herverdeling effect heeft op het langstransport.

H.5 Conclusies

Na de presentaties van de vier groepen vat Ad de bevindingen uit de brainstormsessie samen in de volgende conclusies:

1. Kleine verschillen kunnen op de lange duur grote effecten veroorzaken
2. Draineren via het Ecobeach systeem kan leiden tot veranderingen in het geohydrologische gedrag
3. Welke effecten treden op bij de menging van zout en zoet water?
4. Grote vraag blijft hoe een op zich voorstelbaar (lokaal) effect van het ecobeach systeem kan leiden tot een grootschaliger effect van zandaangroei door het langstransport

H.6 Proeven

In Denemarken is een meetproef gedaan op het strand, waar naar de invloed van de drains op de grondwaterspiegel werd gekeken. Deze test was zeker niet uitgebreid en op korte termijn willen we in een Nederlands proefvak een betere proef gaan houden. Met alle aanwezigen hebben we erover gesproken hoe we de Deense test kunnen verrijken, wat we er aan kunnen toevoegen en welke parameters extra onderzocht kunnen worden. De punten die hierbij ter spraken kwamen zijn hieronder genoemd.

Eerst een korte omschrijving van de Deense proef: gedurende ongeveer 2 weken werden de grondwaterstanden in het proefvak gemeten met divers. De divers werden direct in de drains geplaatst, in peilbuizen op 5 m afstand van de drains (precies tussen 2 drains in) en op een gedeelte van het stand waar geen drains waren geplaatst. Elke 2 min deze de divers een meting en zo werd het verloop van de grondwaterstand in kaart gebracht. De drains leken een klein effect op de getijdendynamiek in het zandpakket te hebben. De vraag is hoe deze proef nu verder verrijkt kan worden (binnen budget e.d.).

Voor de proef zijn de volgende opmerkingen gemaakt:

- Om de seconde gaan meten in plaats van om de 2 min, zodat er behalve over het effect van getijden ook gegevens worden verkregen over het effect van golven op het grondwater in de omgeving van de pijpjes.
- Vergelijk het grondwatergedrag op een raai waar drains zitten met het grondwatergedrag op een raai op 50 m afstand van de drains (tussen 2 rijen in).
- Divers direct in het zand plaatsen in plaats van in peilbuizen, omdat peilbuizen invloed kunnen hebben op het zandpakket.
- Nadat de proef is opgezet, deze opzet goed doornemen er erover discussiëren.
- Stroming in de drains meten.
- Met divers de temperatuur, druk en het zoutgehalte van het grondwater meten.
- Grondonderzoek uitvoeren; dichtheid en doorlatendheid bepalen.
- Infiltratieproeven doen om de doorlatendheid op verschillende dieptes te bepalen.
- Meten met glasfiberkabel
- Binnen en buiten de projectvakken zeefkrommes maken en kijken naar de verschillen. Wat is hierop de invloed van windtransport en van golftransport.
- Het drainerend effect van de pijpjes in een laboratorium onderzoeken.
- Veel data verzamelen om ideeën te krijgen voor een doelgericht onderzoek.
- Variëren in de afstand tussen en de diameter van de drains.
- In het veld gegevens verzamelen, die in het lab geïsoleerd kunnen worden onderzocht.
- Bathymetrie meten met behulp van een Jetski (TU Delft). Hiermee kun je heel dicht bij de kustlijn komen. In combinatie met metingen op het strand kun je dan goed de sedimentbalans opmaken.
- Vaker metingen doen van het volledige strand (niet alleen raaien meten met een tussenafstand van 100 m).

H.7 Afsluiting door Ad

Deze sessie was zeker een succes en het is de bedoeling om deze te vervolgen in latere sessies. We moeten dan proeven gedaan hebben, die we kunnen bespreken. Het zou leuk zijn om Poul Jacobson, de uitvinder van het systeem, te bevragen om de kennis die tussen zijn oren zit los te peuteren. Doelstelling is om binnen een half jaar ongeveer, nadat er proeven zijn gedaan, weer samen te komen voor een vervolggesprek.

Na de lunch ging een aantal van de aanwezigen nog een kijkje nemen op de proefvakken op het strand bij Egmond aan Zee