Moisture-including modeling of annual aeolian sand supply to coastal dunes

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Contents

Abstract

The erosion of the coastal dunes has been understood and simulated quite well over the past years. But there is a lack in understanding dune recovery. Many variable factors influence the aeolian transport on a beach, such as the surface moisture, the fetch length, ice and snow. Therefore in many studies the researchers often prefer to ignore these factors to make it simple but these studies produce strongly over-predicted results. Thus, the variable factors that influence the aeolian transport have to be considered, especially the surface moisture.

In order to test a more realistic moisture-including model in predicting long-term (annual) aeolian sand supply to the coastal dunes, field data are needed. In this study, the data-set comprises annual profiles of a 5 km stretch of coast (RSP 40-45) between Castricum and Egmond aan zee with 250 m spacing. The data are available from 1964 until 2013.The purpose of the data analyses is to determine volume increase in foredune, so the years with erosion should be removed. After analyzing the field data, the model will be applied to make aeolian predictions, after which a data-model comparison can be performed.The model may be run in various scenarios: no moisture (old situation), just tide (no storm surges) and full tide (include storm surges),systematically explore moisture effects on annual aeolian input to the foredune. Boundary conditions for the model are wind speed and direction, as well as offshore water levels. These are available for the same time period from nearby measuring stations.

The results show that there is an increasing trend of the mean of the alongshore dune volume and in a certain year the dune volume change varies alongshore. This is because the beach width. The beach width has influence on dune erosion but has little influence on sediment supply. Since the beach-dune system is complex and variable, as a consequence, the model cannot predict accurately. Besides the surface moisture, there is another important factor, wind characteristic (wind speed and wind direction). The wind in Egmond is so oblique, when the oblique winds close to the foredune and become parallel to the dune, it brings no sediment to the dune. This is called "flow deflection". Due to this, the wind characteristic could cause similar effect to the surface moisture. In the future, the model predictions still need to be improved. For the surface moisture and ground water level model, the accuracy and calibration of data should be paid attention. Different situations have different parameter settings, it is important to make the model close to the realistic. Moreover, it suggests that maybe it is better to use the beach width of the wind direction instead of onshore beach width because of the flow deflection.

Key words: aeolian transport, costal dunes, surface moisture, beach width, aeolian transport modeling

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1. Introduction

Sand dunes are found in most climates of the world, from humid areas to arid areas. More than 99% of all sand dunes are located in deserts and less than 1% are located in humid climates and along some of the world's coastlines (Klijn, 1990).Nonetheless, the dunes located along low-lying and densely populated countries are quite important, as they function as natural barriers, protecting the coasts from storms and flooding. This means of protection has the advantage of being formed by natural processes, so it is more sustainable and resilient than hard engineering protection, such as dams and dikes. But the dune systems are dynamic and the safety level is variable in time.

Due to this, near shore research has traditionally focused on understanding and predicting beach and dune erosion. In previous studies, the erosion of the coastal dunes has been understood quite well. But there is a lack in understanding dune recovery. Nowadays, there is a growing interest in how aeolian (wind-induced) transport leads to the beach and dune recovery after a storm. But this is a complicated process, as many variable factors influence aeolian transport on a beach, such as surface moisture, the fetch length, ice and snow. Therefore in many early studies the researchers chose to neglect these factors and derived models that are based on wind alone. Such model predictions over-predict measured dune recovery. Thus, the variable factors that could influence the aeolian transport have been paid more and more attention, especially for the surface moisture. Although many researchers have made efforts to make a model of the dune recovery, it still needs to be improved hugely.

The overarching aim of this research is to thus test a more realistic moisture-including model in predicting long-term (annual) aeolian sand supply to coastal dunes. This aim is split in the following research questions:

1. What is the volume change in the foredune? Does this change vary alongshore in a given year? Does this change vary from year to year in a given transect?
2. What factors contribute to this variability?(e.g., beach width and wind characteristics)
3. How well can the model predict the measured volume change? How do beach width and moisture content affect annual predictions relative to a wind only model?

The coastal dunes near Egmond aan Zee, the Netherlands have been used as the case study.

The thesis is organized as follows. Chapter 2 introduces the field site, the available data and the moisture-including aeolian model. Chapter 3 presents the main results, which are then discussion in Chapter 4. The conclusions are provided in Chapter 5.

2. Methodology

2.1 Study area

The study area is Egmond aan zee which located along the central Dutch Holland coas, (Figure1.1, Keijsers et al., 2013). It is a wave-dominated and quite flat (about 1: 30) intertidal beach along with a foredune which is mainly covered by European marram grass (Ammophila arenaria), around 25 m high. The medium grain size (D50) of the sediments is about 0.25mm.The area is roughly north–south oriented and is primarily exposed to sea waves generated on the North Sea. Egmond aan Zee is characterized by a lower mesotidal regime, with a mean tidal range varying from around 1.2 m (neap tide) and 2.1 m (spring tide). Tidal currents are asymmetric with a stronger component towards the North. Wave height is characterized by a high seasonality with a mean wave height of about 1 m during the summer months and ranging between 1.5 – 1.7 m in the winter periods. More frequent waves come from the South West. The annual average Hs (significant wave height) and Tp (peak period) between 1999 and 2011 are Hs = 1.3 m and Tp = 5.9 s according to a recordings of a near-by directional wave buoy. During storms, the Hs could even increase to more than 7 m and Tp to around 12 s. These data are mainly based on the wave station IJmuiden Buitenhaven which is located about 15 km south of Egmond.

The coastal profile of Egmond aan Zee is described by a three-bar system: two breaker bars in the surf zone and a swash bar. The outer bar is more obvious, being characterized by a crest at -3 m below MSL (Mean Sea Level). This bar is located at 500 m offshore. A through with a depth equal to -5 m below MSL separates the outer bar from the inner bar. The inner bar crest is located 200 m offshore and its crest is located at 1 m below MSL. Between the inner bar and the swash bar is a through, with a water depth equal to 2 m below MSL. (Giardino A et al., 2010)

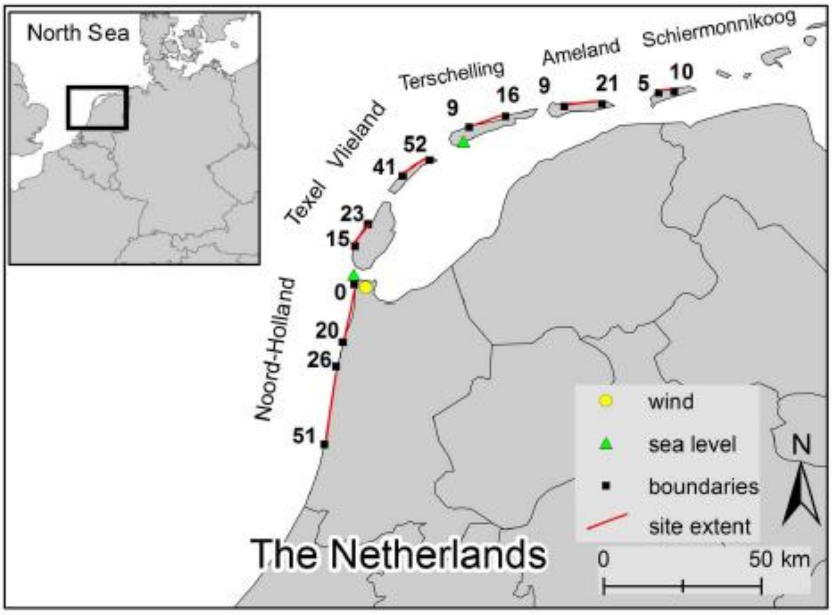

Figure 1.1 Study area. Positions and numbers of beach poles on the section boundaries are indicated. Inset shows the location of the study area within Northwestern Europe (Keijsers et al., 2013). In this study, 45-50 has been used.

Here, the wind characteristics are based on the dataset from Royal Netherlands Meteorological Institute (KNMI) and the wind speed (in m) and wind direction (in degree) were measured at 10m and they are the mean value during the 10-minute period preceding the time of observation. It shows that the wind speed in Egmond aan Zee is mainly about 5-10 m/s and the annual wind direction is generally SW (Figure1.2), the wind is blowing from South-West to North-East.

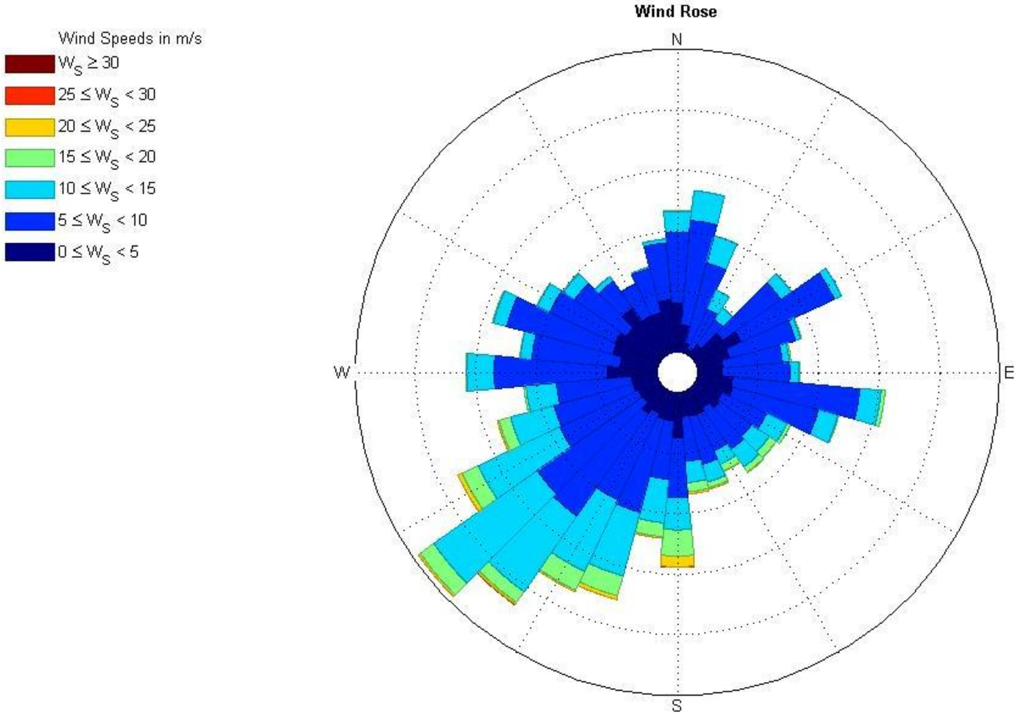

Figure1.2 Wind rose of Egmond aan Zee in year 1977, based on the dataset from Royal Netherlands Meteorological Institute (KNMI) and the wind speed (in m) and wind direction (in degree) were measured at 10m and they are the mean value during the 10-minute period preceding the time of observation.

2.2 Data and method of calculating dune volume change

We analyzed a 50-year cross-shore dataset, from 1964 to 2013, but there's no data available in 2002. There are 1029 data files and have been divided into 21 groups (different transects along shore). These cross-shore data were obtained from the JARKUS dataset. This dataset contains annual elevation measurements of coastal profiles (transects) extending from the foredune to approximately 1000 m seaward. Measurements are taken with respect to a series of permanent beach poles along the coast. The alongshore distance between the profiles is 200–250 m (Bochev et al., 2011). In this study, the data-set comprises annual profiles of a 5 km stretch of coast (RSP 40-45) between Castricum and Egmond aan zee with 250 m spacing.

The method of calculating is similar to Keijsers et al., 2013(Figure 2).Based on the dataset, two parameters were calculated, beach width (W in m) and dune volume change (ΔV in m^3/m). Here the beach width is defined as the distance between the dune-foot (X_{DF}) and the shoreline (X_{SL}) and dune volume change is the volume of sediment per meter longshore above the dune-foot level, seaward of a fixed landward boundary (X_{LB}), here the dune foot level is taken as +3 m NAP(Normaal Amsterdams Peil). (Ruessink and Jeuken, 2002). Here, the landward boundary is defined as a position behind the crest of the dune and the shoreline level is taken as 0m NAP. Moreover, the maximum water level (in m) of each year is based on the dataset from wave stations in IJmuiden Buitenhaven and the water level was measured every hourly, here we only choose the maximum value of the year.

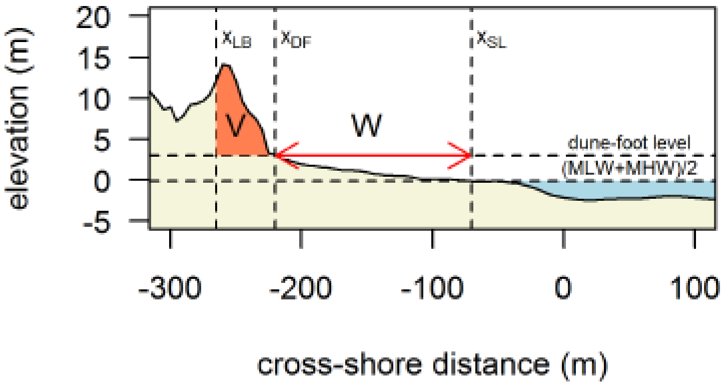

Figure 2 Definition of dune volume and beach width. Position of landward boundary (X_{LB}), dune-foot position (X_{DF}) and shoreline position (X_{SL}) for the black profile. Dune volume (V) and beach width(W) were calculated on the basis of these positions.(Keijsers,2013)

2.3 Data and method of testing aeolian transport to the dune by model

Aeolian transport is assumed to be relative to wind characteristics and sediment size. The potential transport means the potential aeolian transport into the dune based on wind speed and wind direction. The wind characteristics are based on the dataset from Royal Netherlands Meteorological Institute (KNMI) and the wind speed (in m) and wind direction (in degree) were measured at 10m and they are the mean value during the 10-minute period preceding the time of observation.

In addition, there are many other factors that can influence the aeolian transport on the beach. Usually, the magnitude transport is less than the potential transport as a result of the available fetch (F) is smaller than the critical fetch (F_c) and surface moisture. Figure 3(Irene Delgado-Fernandez, 2011) shows a schematic representation of a beach-dune system.

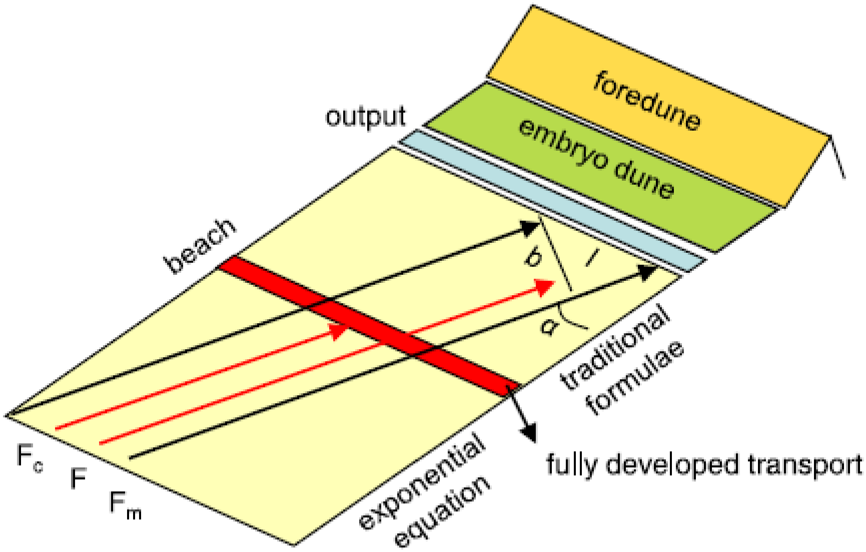

Figure 3 Framework for modelling aeolian sediment output from the beach to the dune based on the study by Bauer and Davidson-Arnott (2003).The red line on the beach surface indicates the area where transport is fully developed for an incoming wind speed. Fm is the maximum available fetch; Fc is the critical fetch and α is the angle of wind approach. Traditional formulae to predict sediment transport rates may be applied where F>Fc, whilst transport follows an exponential relation with distance where F<Fc. (Irene Delgado-Fernandez, 2011)

But here focus is on the surface moisture. And for the controlling factors of the surface moisture, the groundwater table is the most important. So, to connect the groundwater table with the surface moisture and to connect the surface moisture with the aeolian transport model are two important steps in the modeling.

2.3.1 Basic and main equations for aeolian transport

According to early researches (e.g. Bagnold, 1941; Hsu, 1974), the potential transport rate into the dunes per unit alongshore distance (q_n, kg $m^{-1} s^{-1}$) may be expressed as:

$$q_n = 1.16 * 10^{-5} * U^3 \cos \alpha \quad , \quad ①$$

where U is hourly wind speed in m s^{-1}, α is the wind direction. As it mentioned before, this ‘ideal’ (wind only) conditions do not exist. Beaches are narrow and aeolian transport needs ‘space’ (i.e., cross-shore distance) to grow. This is called the fetch effect.

Despite advances in the modeling of the fetch effect in agricultural areas (e.g., Stout, 1990; Gillete et al., 1996; Fryrear et al., 2000) there is no accepted equation describing the increase of sediment transport rate with fetch distance on beaches (Delgado-Fernandez, 2010). The equation used here is:

$$q_n(F) = q_n \sin\left(\frac{\pi}{2}\frac{F}{F_c}\right) \qquad ②$$

In this equation, numerical values for F_c are needed but there no current methods to calculate (Delgado-Fernandez, 2010). Figure 4 shows a high correlation between wind speed and the distance where transport attains a maximum (i.e., q_n as in Eq①) as reported in the numerical simulations by Spies and McEwan (2000) (curve A) and field results by Davidson-Arnott and Law (1990) (curve B).

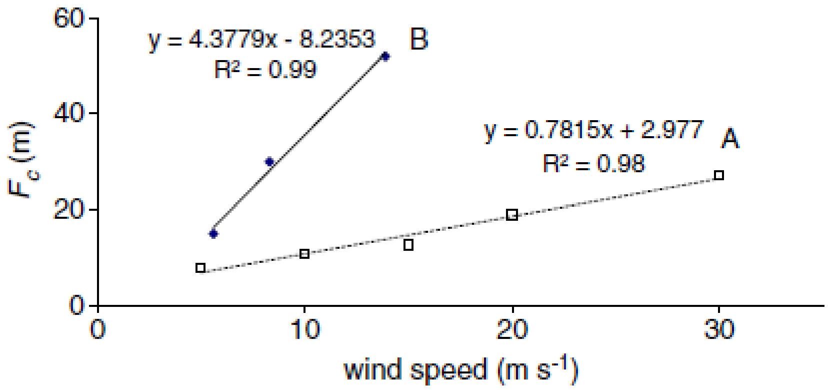

Figure 4. Correlation between wind speed and critical fetch (F_c) for the data presented by A0 Spies and McEwan (2000) and B) Davidson- Arnott and Law (1996). Note that wind speed (U) for curve A has been calculated from friction velocities (u*) reported By Spies and McEwan using the Law of the Wall (U=ln(z/z0)u*/k) and assuming a grain size of 0.25mm.(Irene Delgado-Fernandez, 2011)

Curve B has a steeper slope in agreement with other studies in natural areas showing critical fetch distances that are longer than those found by numerical simulations or laboratory analysis (e.g., Gillette et al., 1996; Fryrear et al., 2000; Davidson-Arnott et al., 2008). The expression associated with curve B is used here:

$$F_c = 4.38 * U - 8.23 \qquad ③$$

However, this equation above is only for “dry” conditions, so the calculations of “wet” conditions should be taken into consideration. There are several equations relating the threshold of sand movement with moisture content (e.g., Belly, 1964; Logie, 1982; Mckenna-Neuman and Nickling, 1989) or with sediment transport rates (e.g., Hotta et al., 1984; Sarre, 1987) but none for the relation between moisture,μ, and critical fetch distances (Delgado-Fernandez, 2010). Based on observations by Davidson-Arnott et al. (2008) it was assumed that homogenous moisture content increased the critical fetch calculated for dry sand (F_c) to a new larger value ($F_{c\mu}$) for a given wind speed with the increase being proportional to the value for moisture content. Based on this, a simple arbitrary scheme was utilized, with $F_{c\mu}$ resulting from an increase of F_c by 50% when $4\% \le \mu < 6\%$, and by 75% when $6\% \le \mu < 10\%$.

$$\begin{cases} F_{c\mu} = F_c & 2\% \leq \mu < 4\% \\ F_{c\mu} = F_c + 0.50F_c & 4\% \leq \mu < 6\% \\ F_{c\mu} = F_c + 0.75F_c & 6\% \leq \mu < 10\% \end{cases} \quad ④$$

Recall that there is no transport for μ>10%.Then the "wet" conditions could also be calculated as "dry" conditions taking $F_{c\mu}$ instead of F_c in Eq②. To summarize,

$$\begin{cases} q_n = 1.16 * 10^{-5} * U^3 \cos\alpha & F \geq F_{c\mu} \\ q_n(F) = q_n \sin\left(\frac{\pi}{2}\frac{F}{Fc\mu}\right) & F < F_{c\mu} \end{cases} \quad ⑤$$

Finally, the procedure calculates the total amount of transport for a particular PTP (Q_{PTP}):

$$Q_{PTP} = \sum_{q=1}^{q=n} q_n \quad ⑥$$

Here, the model of Delgado-Fernandez (2011) is used. A flow diagram of this model is given in Figure 5.The model contains two steps, filtering of the time series and calculation of transport for individual events. The filtering removes the transport to the dune cannot happen such as the wind speed is smaller than the threshold velocity for dry sediment. So the threshold conditions for potential transport periods (PTPs) have been provided.

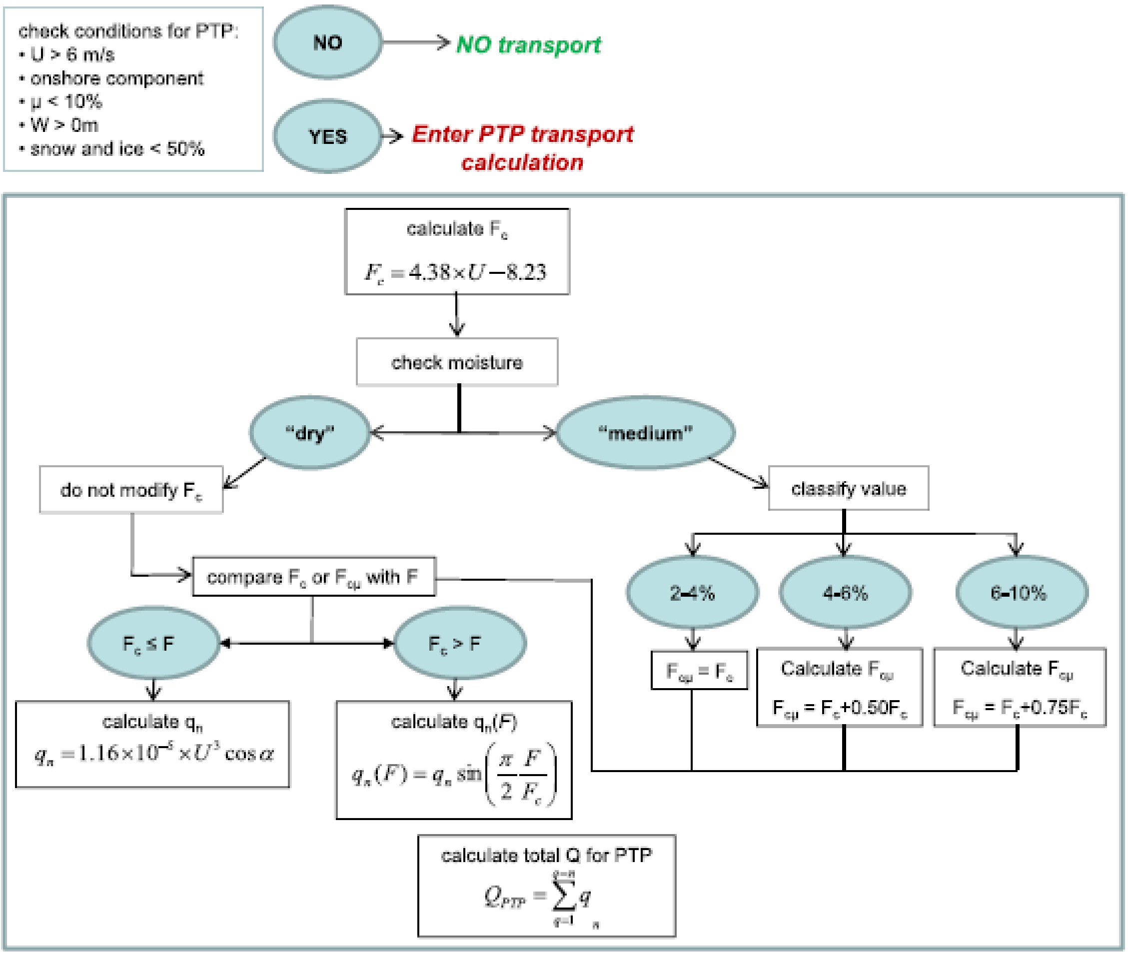

Figure 5 Modeling steps and analytical procedure applied to hourly records of wind speed (U) and direction (α), fetch distance (F), critical fetch distance (F$_c$) and moisture (μ) for potential transport periods (PTPs) isolated by the filtering.(Irene Delgado-Fernandez, 2011)

As can be seen in the top box in the left corner, there is no significant sediment transport to the dunes under any of the following conditions: wind speed (U) <6 m s^{-1}; offshore wind direction; "wet" surface (μ≥10%); Snow and ice cover>50%; and beach inundation by near shore process.

2.3.2 Surface moisture content

From the above, we can see that the surface moisture influences the aeolian transport through the fetch effect. As said, it is assumed that the moisture content at the sand surface is related to the ground water table. For this, the equation for the soil-water content-pressure head curve, θ (h), proposed by van Genuchten (1980) is applied,

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\beta h)^n]^m} \qquad ⑦$$

In this equation, θ is the volume soil-water content; θ$_s$ indicate the saturated values of the volume soil-water content and θ_r is the volume residual values of the soil-water content, h is the pressure head which is understood to be positive, β is related to the inverse of the air entry suction, β>0, n is a measure of the pore-size distribution, n>1. And where for the Mualem model,

$$m = 1 - 1/n \qquad ⑧$$

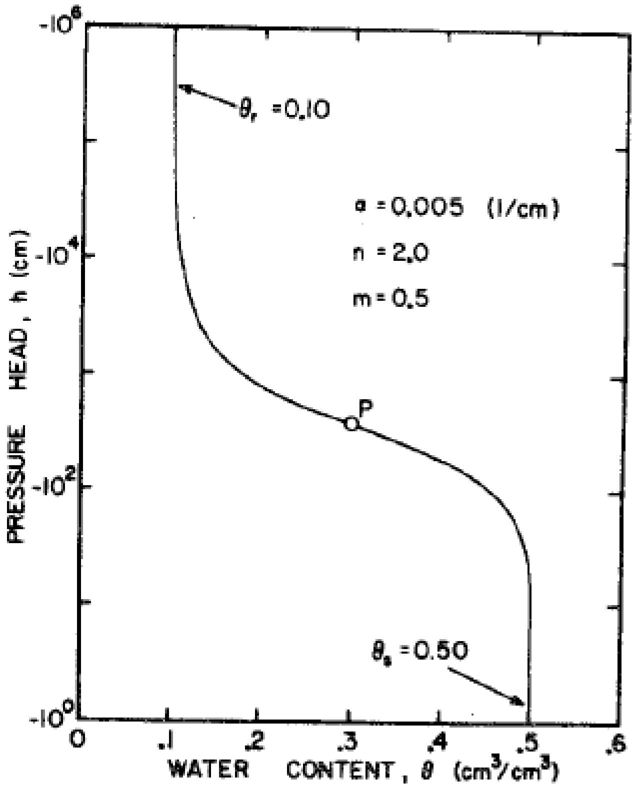

Figure 6 Typical plot of the soil-water retention curve based on Equation

$$\boldsymbol{\theta} = \left[\frac{\mathbf{1}}{\mathbf{1} + (\boldsymbol{\beta}\mathbf{h})^{\mathbf{n}}}\right]^{\mathbf{m}}$$

The point P on the curve is located halfway between θr (=0.10) and θs (=0.50). (M.TH. van Genuchten, 1980)

In Figure 6, we can see that a nearly symmetrical “S”-shaped curve is obtained, and the slope becomes zero when θ comes close to both its saturated and residual values. As the pressure head close to zero, the soil is close to saturation (here when h=-1, θ_s =0.50). As θ decreases, binding of the water becomes stronger. Point P is located halfway between the θ_r=0.10 and θ_s =0.50, one may recognize from the figure, the slope of the value at P is about 0.34, and then the S_p could be calculated, it is about 0.85. So m is about 0.5, n is around 2, β is about 0.005.

2.3.3 Water table fluctuations

Because of the tide, the ground water level in a beach fluctuates with time. Raubenheime and Guza (1999) researched tidal water table fluctuations in a sandy ocean beach and provided a basic equations for the groundwater model used here. The numerical model of water table fluctuation is based on the Boussineseq equation

$$\frac{\partial \eta(x,t)}{\partial t} = \frac{K}{n_e}\frac{\partial}{\partial x}\left\{[D(x) + \eta(x,t)]\frac{\partial \eta(x,t)}{\partial x}\right\} \qquad ⑨$$

This equation is for finite-amplitude (nonlinear) water table fluctuations and spatially variable aquifer thickness D(x). In the equation, t is the time, x is the cross-shore distance, η(x, t) represents deviations of the water table height at cross-shore position x and time t from the still height D. The total water depth h(x, t) = η(x, t) +D, K is the hydraulic conductivity, D(x) is the spatially variable aquifer thickness and n_e is the effective porosity.

For linear amplitude (small-amplitude) water table fluctuations and constant aquifer depth, the equation becomes

$$\frac{\partial \eta(x,t)}{\partial t} = \frac{KD}{n_e}\frac{\partial^2 \eta(x,t)}{\partial x^2} \qquad ⑩$$

These two equations were solved numerically using a centered finite different method in space and a fourth-order Runga-Kutta integration technique in time (Liu and Wen, 1997).And the seaward boundary condition for the solution is

$$\eta(x_s, t) = z_s \qquad ⑪$$

x_s is the horizontal shoreline location, z_s is the shoreline elevation. This solution assumes that the beach slope and aquifer depth have to be constant also the tides have to be monochromatic.

2.3.4 Boundary data of the model

For the application of the model, 2 years have been selected. The first is 1977, an all sedimentation year. The other one is 2009, with some erosion but on the whole a sedimentation-dominated year. Since we are interested in the volume of sediments have been transported to the foredune, so only sedimentation-dominated year has been selected. For both of the years, transect 8 (RSP 41.75) has been selected. In view of the fact that the profile of the transect 8 has a nice view of foredune and beach, also the slope of the beach is quite constant. Here we have extended the beach until an elevation of-5 m (Figure 7), but the beach boundary is taken as 3 m, it means that no computations will be carried out landward of 3m.

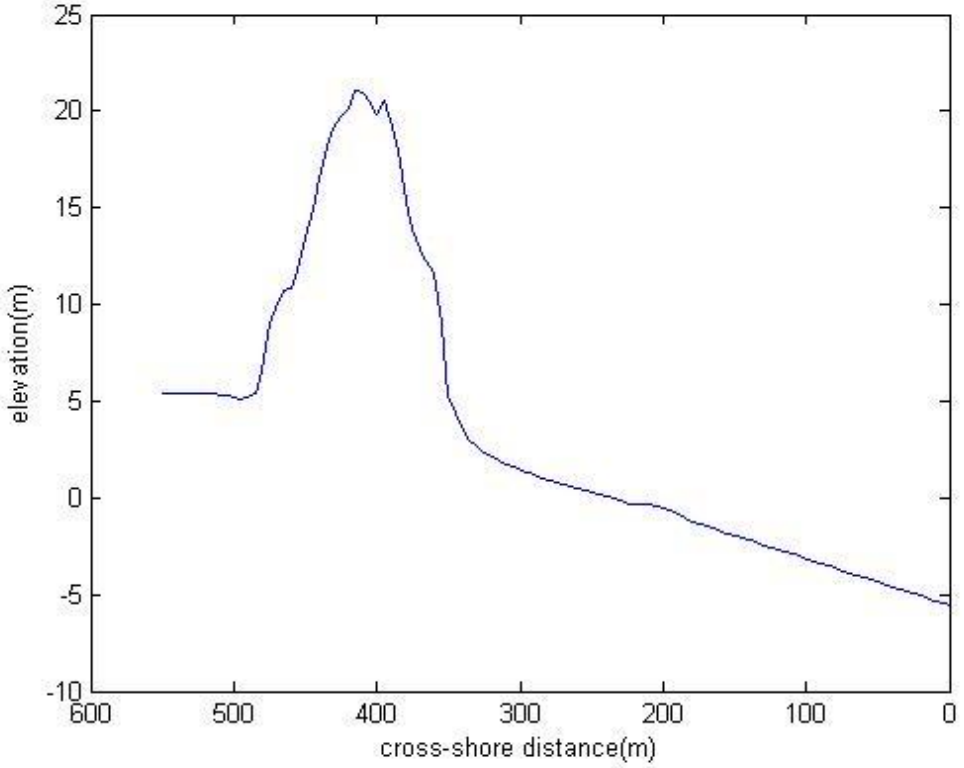

Figure 7 The profile of transect 8(RSP 41.75) in 1977. The boundary of the beach has been extended according to the slope of the beach.

As said before, the wind data is based on the dataset from Royal Netherlands Meteorological Institute (KNMI) and the wind speed (in m) and wind direction (in degree) were measured at 10m and they are the mean value during the 10-minute period preceding the time of observation. The water level data is based on the dataset from wave stations in IJmuiden Buitenhaven and the water level was measured every hourly. The time step of the model is 0.5 s, the grid size is 2 m and the output time is every 300 s. For ground water model parameters, D = 10m, K =0.002 cm/s, n_e = 0.215 and the ground water level with respect to NAP. For the capillary fringe model parameters, θ_r = 1, θ_s = 45, β = 3 and n = 2.7.

2.3.5 Parameter setting

The model contains a number of free parameters, which have to be turned to make meaningful prediction. At this point, K, D and n_e are in the water table fluctuation model, n and β in the moisture content model. The sensitivity of the model to these parameters was tested by running the model for one week, here 24-30 Nov, 1977 has been selected, because there is a very high water because of the storm surge in this week. The original data are D = 10 m, K = 0.002 cm/s, ne = 0.215, β = 3, n = 2.7. When the ground water level is high, the surface moisture content is also quite high; meanwhile the critical fetch will be smaller (Figure 8.1).It can been seen, when the distance is close to the foredune, the ground water level becomes lower also the surface moisture becomes smaller. It is noticed that around 75000 s, the ground water level reach a peak and even in very inland the ground water level is still in 2.5 m and it constants for around 24000 s. This means the water level becomes higher in that time maybe there is a storm or flood. Meanwhile, the surface moisture content on the beach also larger (around 17) and the time to become dry is quite long. Higher ground level cause higher surface moisture content and a small critical fetch.

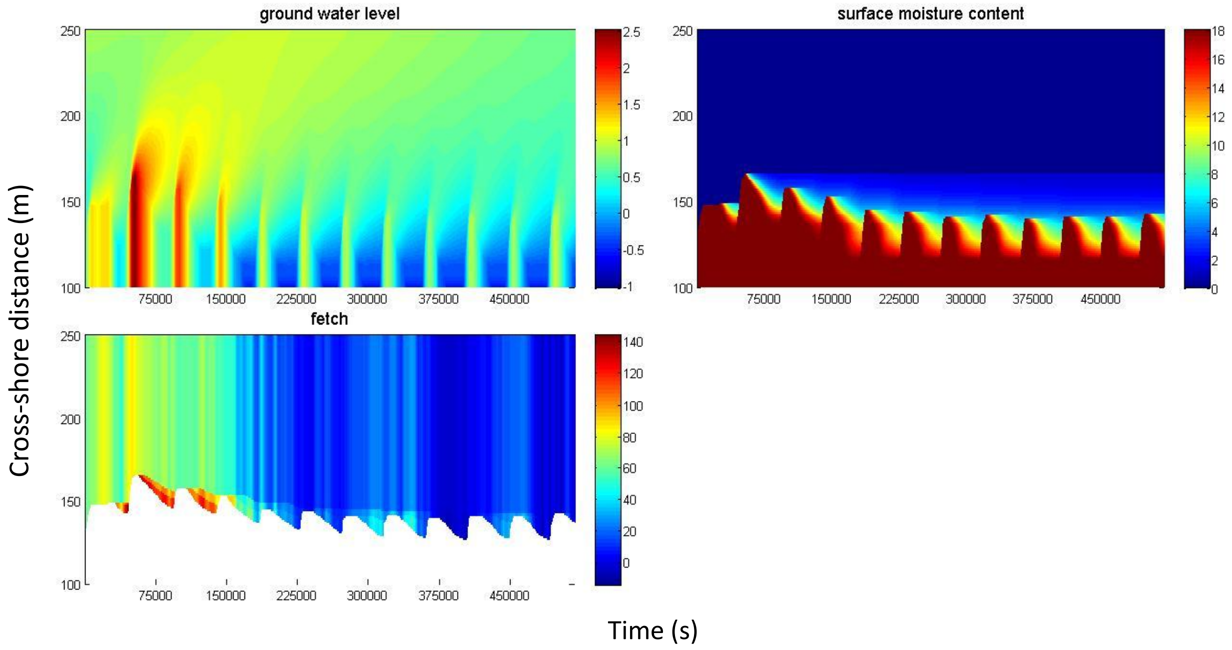

Figure 8.1 The ground water level, surface moisture content and critical fetch for Nov. 24 to Nov.30,1977, produced by original parameter settings (D = 10, K = 0.002,ne = 0.215, β = 3,n = 2.7).The x-axis is time(s) and y-axis is the cross-shore distance(m).

However, when compare to the realistic, the surface moisture dries to slow and also the ground water level must be higher than currently modeled, this is based on field work experience at Egmond (Donker J.J.A, personal communication). In order to be more realistic, the sensitivity analysis of the different parameters is needed. Here, based on the original settings, we adjusted the parameter to a smaller and larger value to see the change of ground water level and surface moisture.

In the equation⑦ (van.Genuchten, 1980), β and n become larger, theta (moisture content) will becomes smaller. In the equation⑨(B.Raubenheimer and R.T.Guza, 1999), K and D become larger, the ground water elevation will become higher. Since K describes the ease with which a fluid, usually water, can move through pore spaces or fractures. A larger K means that the water is easier to move through the soils and rocks. K has a relationship with D_{50}, when the sediment is fine; the water is hard to move through the soil so K will become small. Usually, the average hydraulic conductivity of the unconfined aquifer at cross-shore distance 60 and 91 m was 0.07 cm/s (Bouwer and Rice, 1976; Brown and Narasimhan, 1995). D is the aquifer thickness and the total water table height $h(x, t) = \eta(x, t) + D$, so the aquifer thickness increases the water table height will increase (Figure 8.2 and Figure 8.3). When n_e becomes larger the ground water elevation will become lower for it is denominator, and surface moisture content will become smaller and the beach will dry shorter (Figure8.4).

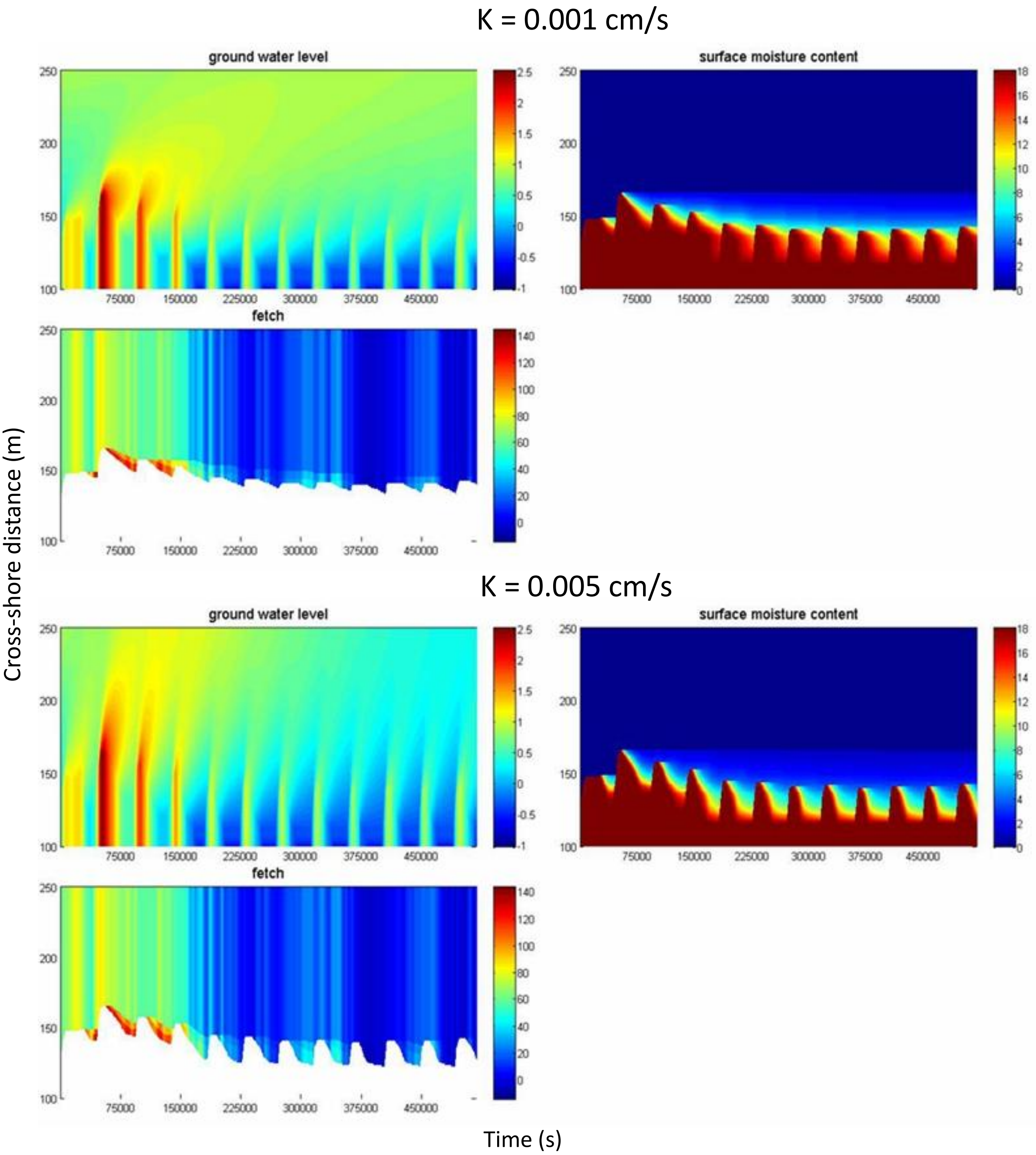

Figure 8.2 The ground water level, surface moisture content and critical fetch for Nov. 24 to Nov.30, 1977, changing K (hydraulic conductivity) to a smaller value (0.001 cm/s) and a larger value (0.005 cm/s).The x-axis is time(s) and y-axis is the cross-shore distance(m).

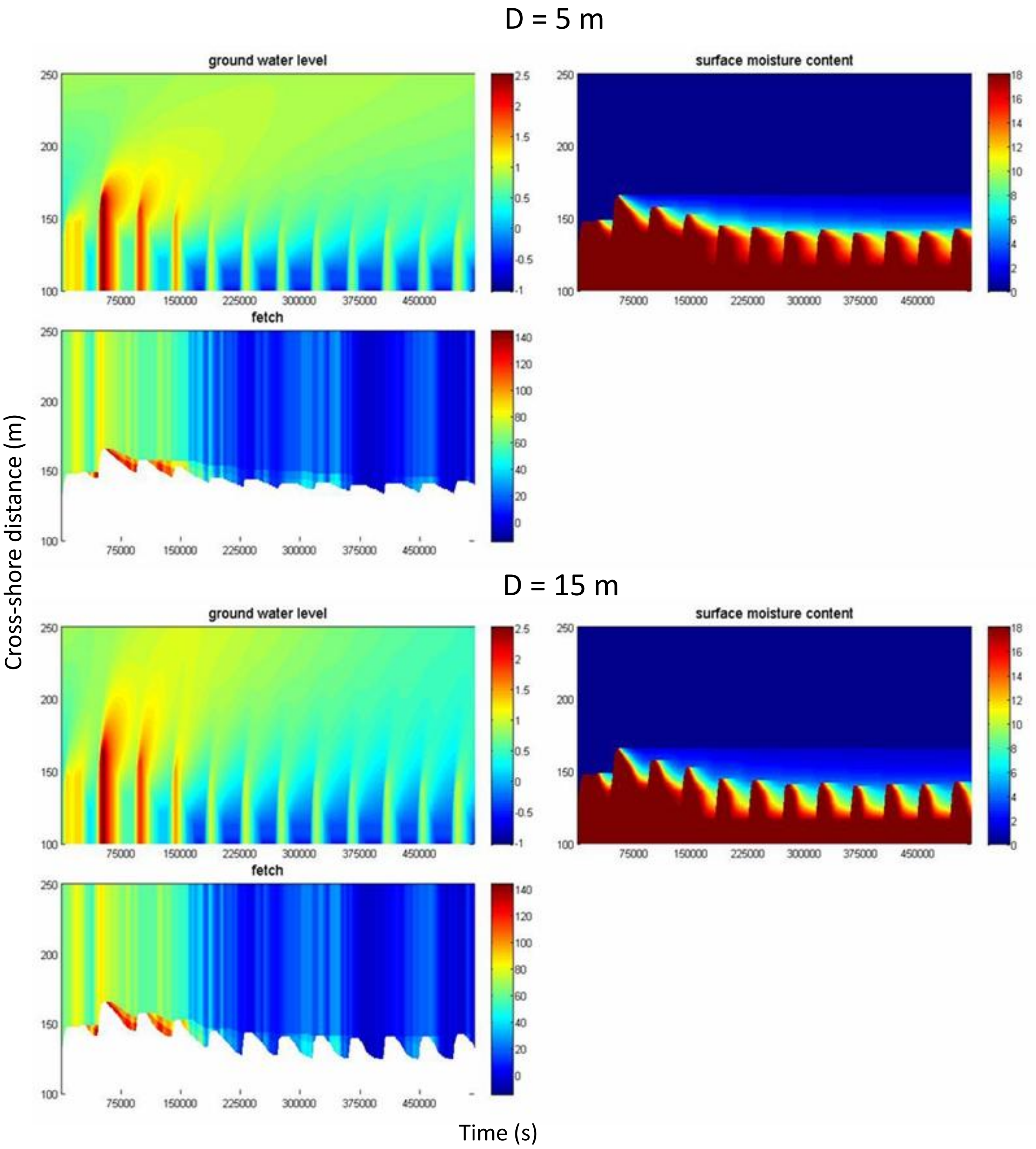

Figure 8.3 The ground water level, surface moisture content and critical fetch for Nov. 24 to Nov.30, 1977, changing D (constant aquifer thickness) to a smaller value (5m) and a larger value (15m). The x-axis is time (s) and y-axis is the cross-shore distance (m).

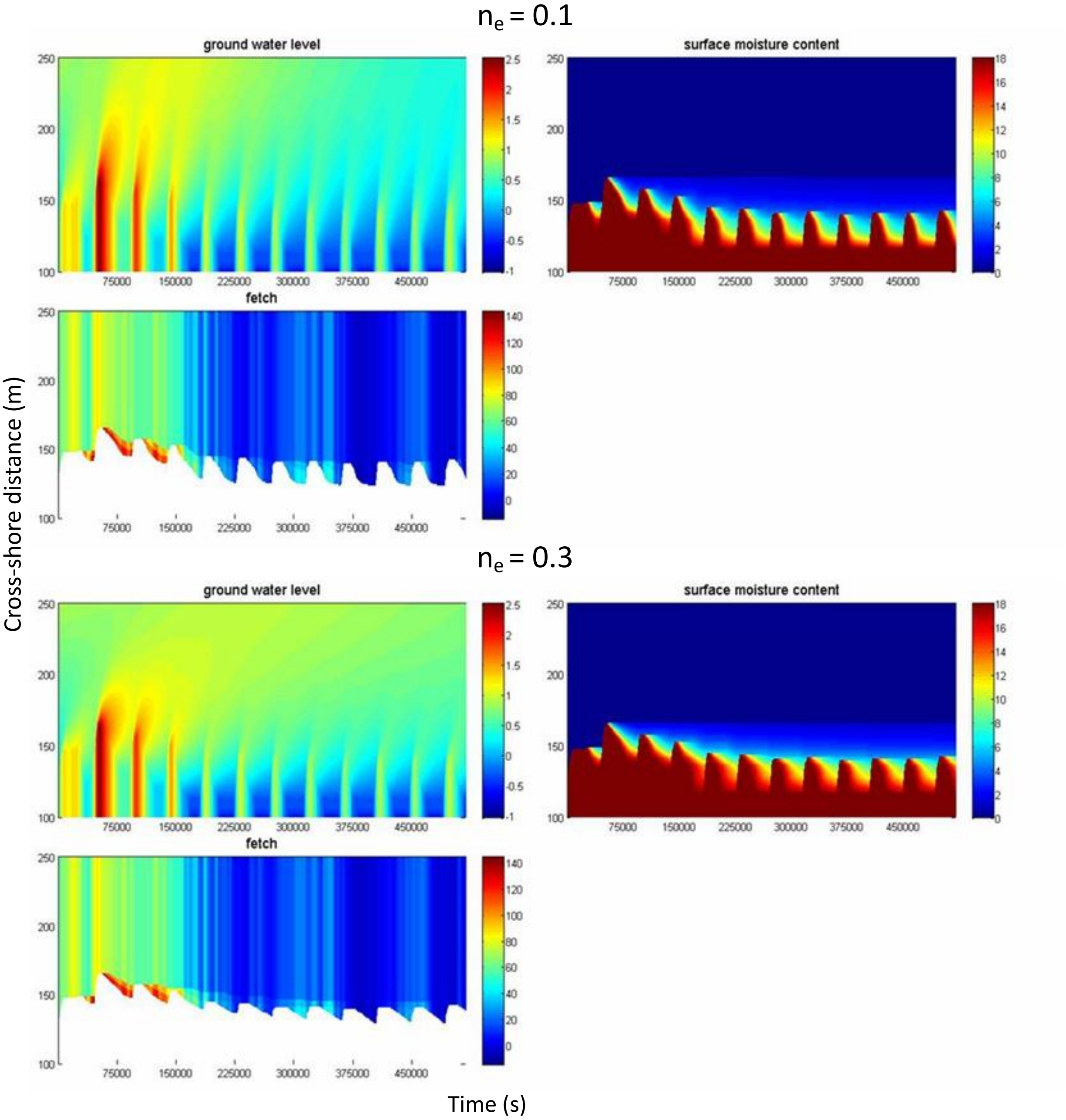

Figure 8.4 The ground water level, surface moisture content and critical fetch for Nov. 24 to Nov.30, 1977, changing n_e (effective porosity) to a smaller value (0.1) and a larger value (0.3). The x-axis is time (s) and y-axis is the cross-shore distance (m).

In order to see more clearly how the changing of parameter influencing the dry time, a sensitivity analysis of the 5 parameter versus the dry time has been done (Figure 8.5). Here, dry time (in h) is defined as the time the surface moisture takes to decrease from a certain large value (17) to a certain small value (5). From the above, D and K increase, the ground water level and surface moisture content will also increase. This will cause dry time increase. When D is between 0 m and 5 m, as D increases, the dry time increases considerably. However, when D is larger than 5 m, the dry time still increases but not that quickly. When K is between 0.001 cm/s and 0.004 cm/s, it influence the dry time notably, especially when it is smaller than 0.003 cm/s.

However, when K is larger than 0.004 cm/s, the dry time doesn’t change any more, which means that K has no influence on dry time any more. For n_e, it is opposite to K and D. When ne increases, the ground water level will decrease and this will make the surface moisture content decrease, finally, the beach will dry more rapidly. And it can be seen, when n_e is between 0.1 and 0.25, it influences the dry time significantly, but when it’s larger than 0.25 the dry time doesn’t change any more.Parameter β and n can influence surface moisture directly, since in the equation7 (van.Genuchten, 1980) when β and n become larger, theta (moisture content) will become smaller.This will cause the beach dry more rapidly. When β is between 2.5 and 4, the dry time drops significantly when β is larger than 4, the dry time decreases more gently. It is noticeable that for parameter n, when it’s smaller than 2.5 the dry time decreases drastically, however when n is larger than 3, it has slight influence on the dry time.

The five parameters all have influence on the dry time, however, the three parameters which control the ground water level, have small influence on the dry time. When compare with β and n, K, D and ne nearly have no influence on the dry time. It can be seen that β and n have significant influence on the dry time, when β and n increase, the dry time decreases obviously, however, for D, K and ne, the change is not that significant when weigh against β and n.

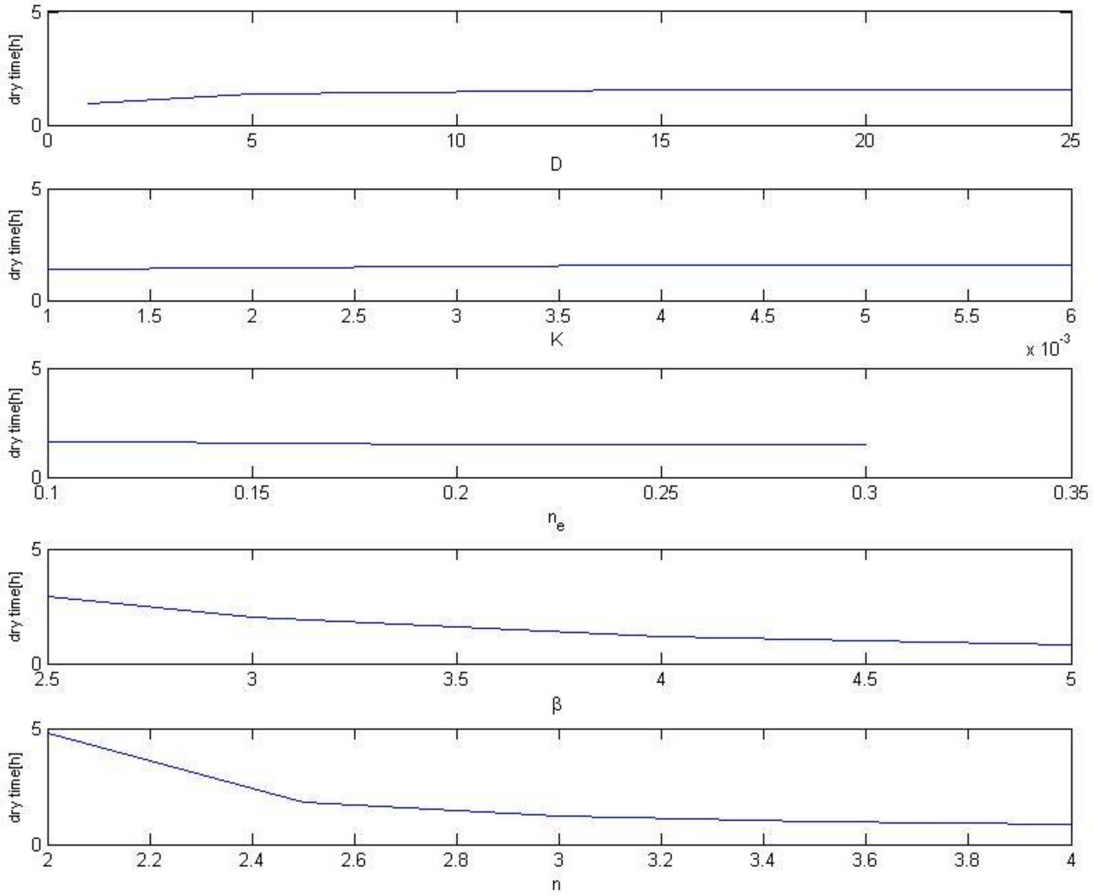

Figure 8.5 The five parameters verse the dry time (h). K, D and ne are parameters which influence the ground water level while β and n are parameters which influenced surface moisture.

As it mentioned above, when compared with realistic, the ground water level of original setting is lower and the surface moisture dries to slow. So it required a higher ground water level (a larger D or K or a smaller n_e) and less surface moisture (a larger β or n). So based on the original settings and according to the sensitive analysis of the 5 parameters (Figure 8.5), when the 5 parameters all have quite influence on the dry time (D is between 5 m to 8 m, K is between 0.001 cm/s and 0.004 cm/s, n_e is between 0.1 to 0.25, β is between 2.5 to 4 and n is smaller than 2.5). Finally, the parameters are decided as D = 7 m, K = 0.001 cm/s, n_e = 0.25, β = 3.5, n = 2.3, which they all have quite significant influence on the dry time (ground water level and surface moisture) and the values are in quite middle of the ranges.

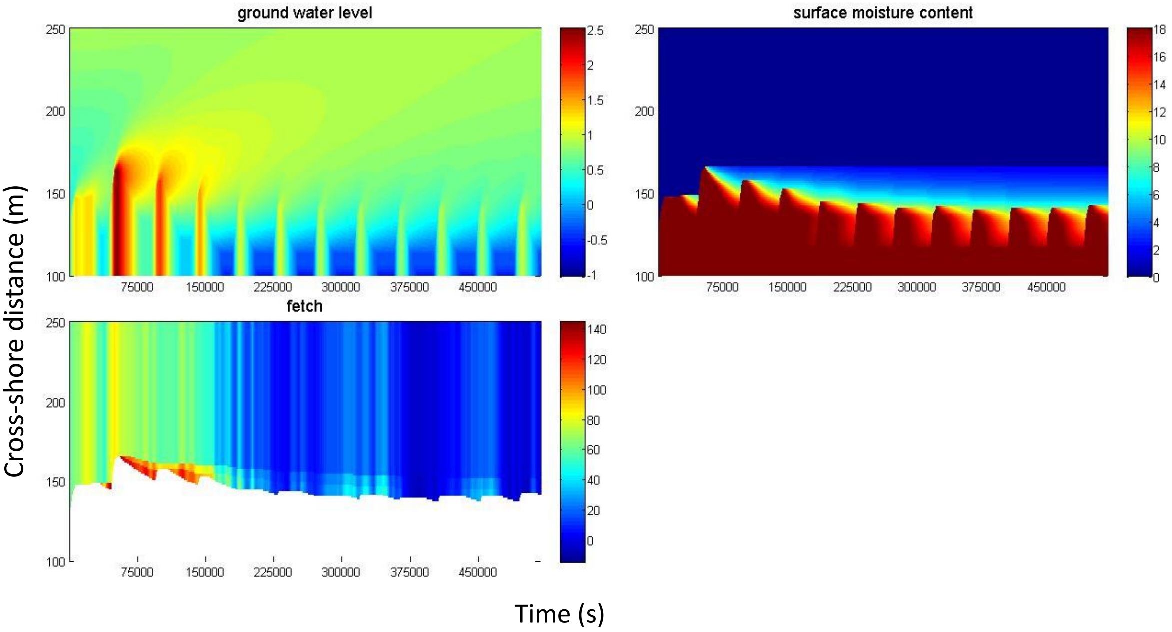

Figure 8.6 The ground water level, surface moisture content and critical fetch for Nov. 24 to Nov.30,1977, produced by new parameter settings (D = 7, K = 0.001,ne = 0.25, β = 3.5,n = 2.3). The x-axis is time (s) and y-axis is the cross-shore distance (m).

3. Results

3.1 Dune volume change, water level and beach width

Aeolian transport will increase the dune volume, but big storms in some years cause dune erosion. The main trend of the dune volume along the coast is increasing (Figure 9). For some specific year, such as 1976, 1983 and 2003, the dune volume decreased considerably (about 100 m^3/m), because of severe storms. But after the storm, the dune volume starts to increase again due to the aeolian transport.

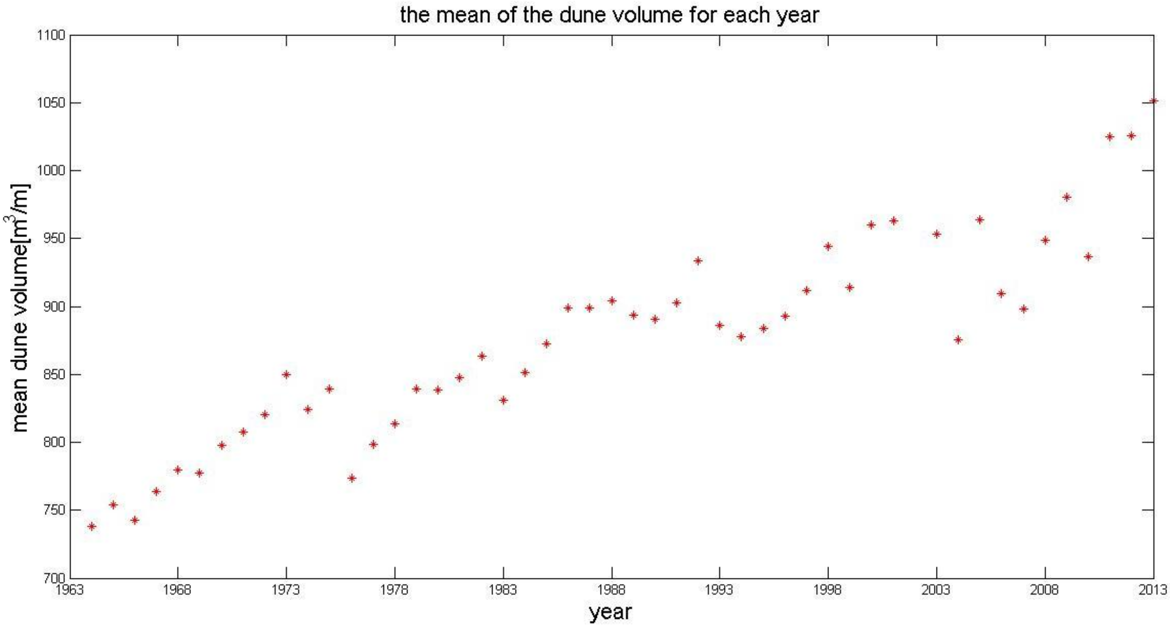

Figure 9 The mean of dune volume from 1964 to 2013.y-axis it the dune volume (m^3/m).In some year, such as 1976, 1983 and 2003, because of the storms, the dune volume decreases appreciably.

The dune volume in individual profiles also shows an increasing trend (Figure 10). Figure 10 is the dune volume from 1964 to 2013, different lines in the figure represent different transects along shore. It can be seen from the figure, in previous years (1964-1993), some transects have an increasing trend while some transects have a decreasing trend. However, form 1993 to 2013, all transects show a significant increasing trend (Figure 11.). It is interesting to know how the slopes change of the different transects. From Figure 10, it seems that all the slopes should be positive (about 10 m^3/m per year). However, it's not all positive (Figure 12).For some transects (5, 6, 13 and 19), the slopes are negative but not large (-2.8, -3.9 -4.3and -0.42 m^3/m per year). It can be seen an interesting cyclicity in dune volume change with alongshore wave length of ~2 km. This may influenced by the beach width and water level, so the relationship of dune volume, water level and beach width is required.

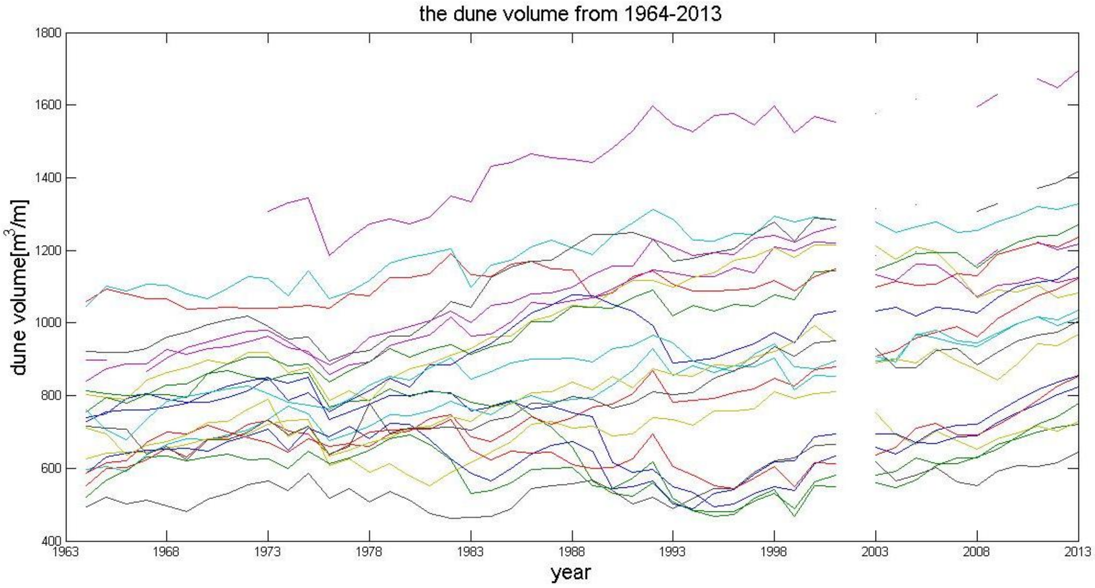

Figure 10 The dune volume from 1964 to 2013.The different color lines indicate different transects. In previous years some transects show a decreasing trend of the dune volume but after 1993, all transects show an increasing trend of the dune volume.

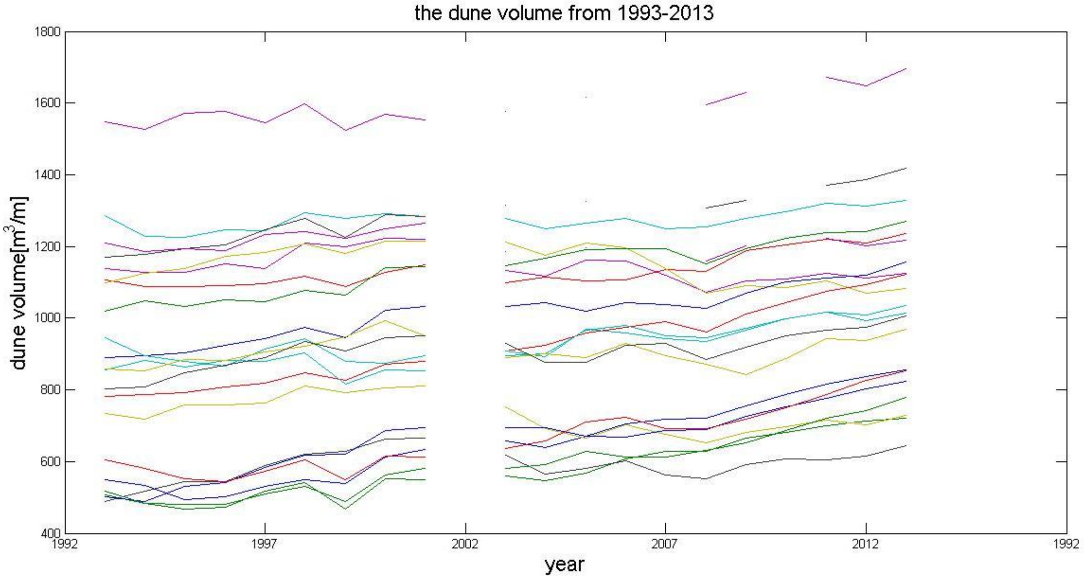

Figure 11 The dune volume from 1993 to 2013 for all transects. This period, the dune volume for all transects are increasing.

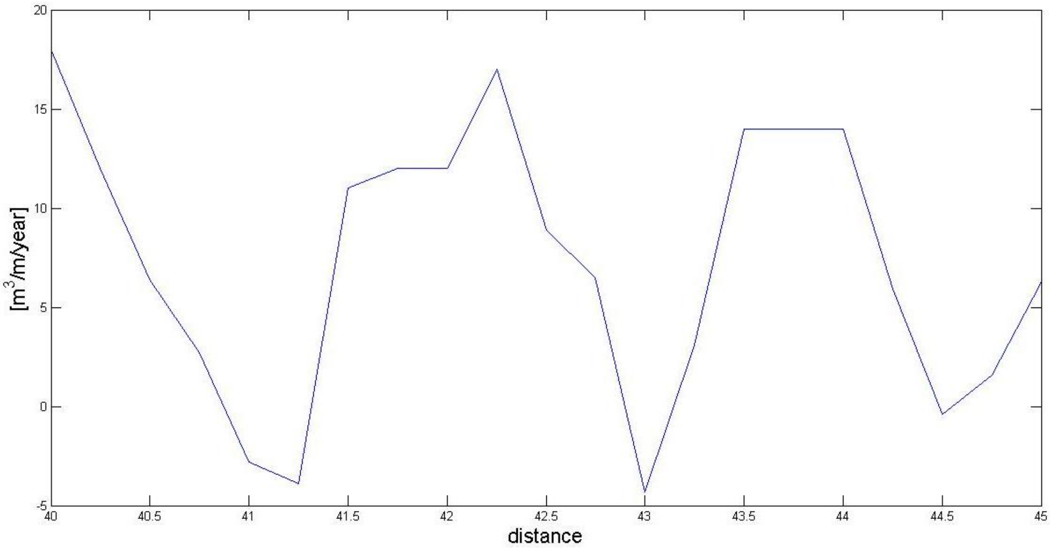

Figure 12 The slopes of the trend of dune volume for different transects. Although for all transects, the dune volume is an increasing trend, the slopes of the regression lines have some negative values.

The alongshore mean of the dune volume change (ΔV) is generally between -60 and 50 m^3/m, in most years (Figure 13). The mean of the dune volume change is positive, which means there is a growth of the dune. Years in which the mean of the dune volume change is negative (e.g. 1976), the maximum recorded water level is also quite high. From the Figure13 it can be seen, for water level, the first peak is in 1976, the second peak is not that significant, in 1984(2.93m), another one is in 2007(3.12m). However, the alongshore beach width seems quite the same (about 40-60 m), so more detailed analysis of the relationship between dune volume change and beach width has to be done on the profile scale.

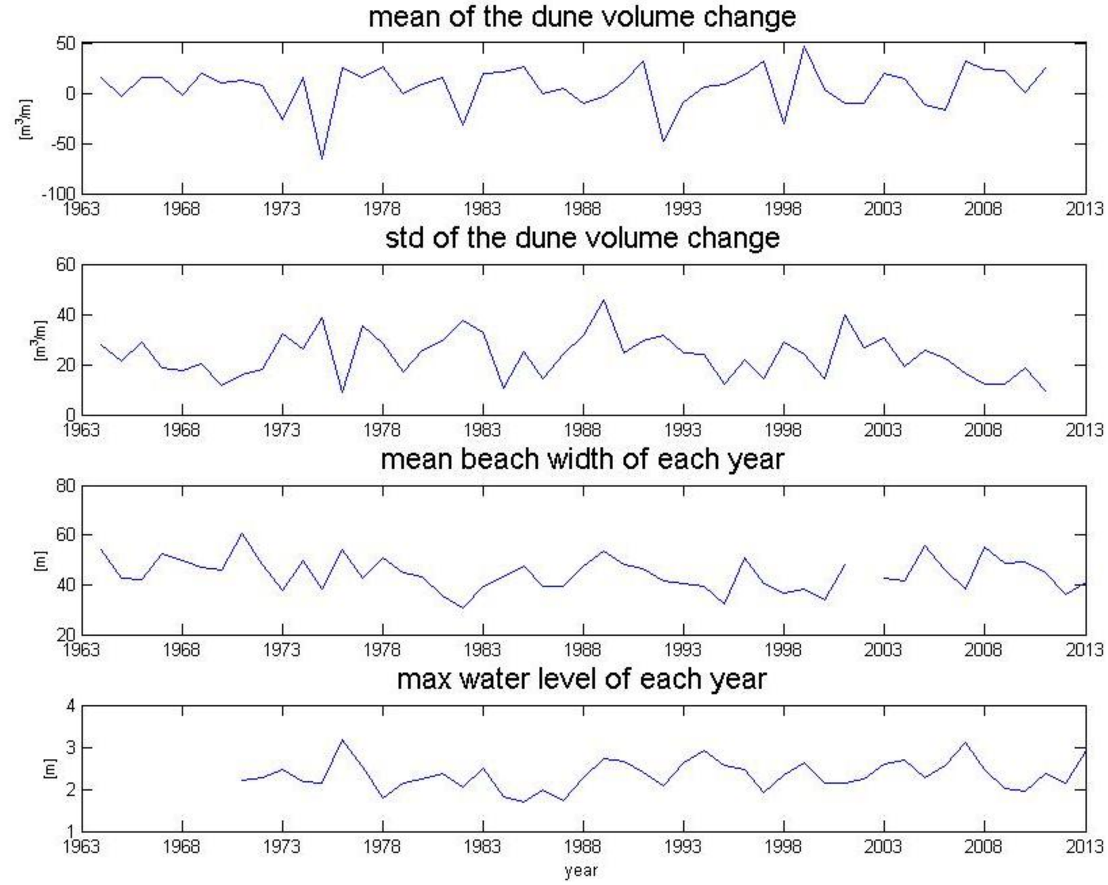

Figure 13 Mean of the dune volume change, std of the dune volume change mean beach width and max water level from 1977 to 2013.

From Figure 13, it can be seen that the alongshore averaged beach width is about 50 m. At this point, after analyzing all the dune volume data from 1964-2013, 6 years have been selected (Figure 14). The first row (1976 and 1993) contains the year with large erosion. The relationship between the dune volume change and beach width is positive (0.98 and 1.34), which means that dunes fronting wider beach experienced less erosion. The second row (1989 and 2001) are years with some (around 6 points are negative) erosion. There is still a positive slope but it becomes smaller (0.52 and 0.35). And for the last row (1977 and 1998), there is no erosion, as all data which positive. Now, it is nearly a horizontal line, the slopes are -0.15 and 0.005. This means that in accretion-dominated years, dune volume changes are similar for all beach widths. On the whole, in this situation, the dune volume change is constant alongshore in dune accretion years, and the relation between the dune volume change and beach width is significant in erosion-dominated years. Beach width thus influences dune erosion but not aeolian sand supply. This result is quite similar with earlier papers (Keijsers et al., 2014).

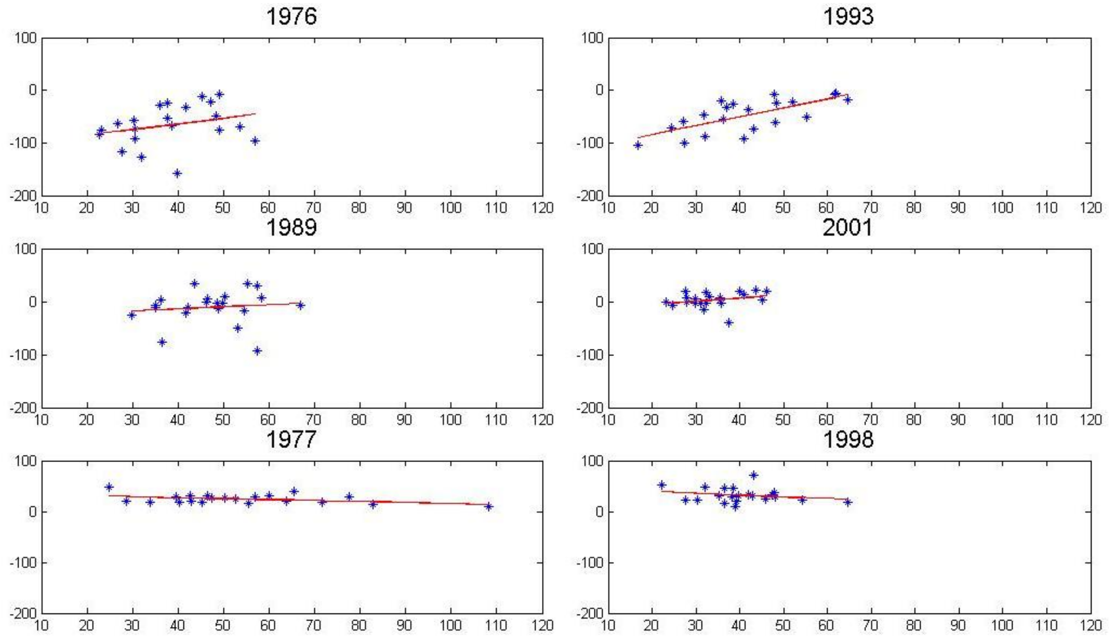

Figure 14 The dune volume change and beach width for 6 year. The first row (1976 and 1993) is the year with big erosion. The second row (1989 and 2001) is the year with some erosion. The last row (1977 and 1998), there are no erosion. And the red lines are the regression lines.

To study the dependence of dune volume change on beach width in all years, the data were separated into 4 groups:

- Group1: all ΔV are larger than 0 (ALL sedimentation) (4 years)
- Group2: all ΔV are smaller than 0(BIG erosion) (2 years)
- Group3: erosion-dominated (some erosion and some sedimentation, mean of the ΔV is negative) (14 years)
- Group4: sedimentation-dominated (some erosion and some sedimentation, mean of the ΔV is positive) (29 years)

For Group3 and Group4 there are many data points, but some of them the mean of the ΔV is not large (e.g. only 5 or -0.1 m^3/m). So here only the large ones (the mean of the ΔV is around 20-30 m^3/m, there are 6-7 years) have been plotted.

To explore whether the dependence seen in Figure 14 depend on the choice of the lower z boundary to determine beach width, the width was also computed in two additional ways. First, with z=1 m. The beach width is now that of the dry beach only. Second, with z=-0.5 m, so the beach now include more of the intertidal beach.

Table 1. The regression analysis of the different groups of the dune volume and beach width. ci_r : 95% confidence intervals for r (correlate coefficient). A line is statistically significant only when the 95% band for r is entirely positive, or entirely negative, that is, 0 is not part of the range

	z=-0.5		z=0		z=1	
	ci_r		ci_r		ci_r	
Group1	-0.33736	0.149649	-0.37157	0.045272	-0.38661	0.027727
Group2	0.243308	0.71708	0.276919	0.722107	0.228282	0.696292
Group3	-0.01881	0.391927	0.081912	0.429507	0.190589	0.504516
Group4	0.131029	0.457531	-0.01202	0.291156	-0.21751	0.089588

Table 1 is the regression coefficients of the different situations. For the shadow on the table, the ci_r are entirely positive. This means that the 95% confidence intervals do not include 0 and that the line is statistically significant. It can be seen that for the erosion groups (Group 2 and Group 3) the regression lines are statistically significant, independent of the choice of z. And for sedimentation groups (Group 1 and Group 4), the regression lines are usually not statistically significant. In the following, only results for z=0 m will be shown (Figure 15). From the figure, it can be seen that, for erosion groups (Group 2 and Group 3), there is a positive trend and the slope of the correlation between dune volume change and beach width is steep (1.13 and 0.36), means that when it is erosion-dominated, the relationship between dune volume change and beach width is significant. However, for sedimentation groups (Group 1 and Group 4), the slope of the correlation between dune volume change and beach width becomes smaller (-0.09 and 0.14), the influence of beach width is not that significant.

It’s also noticeable that, for Group 3(erosion-dominated), when it included intertidal beach (z=-0.5m), the beach width has no influence on the dune volume change, but when it’s only the dry beach, the beach width has significant influence on the dune volume change. And it’s opposite to Group 4(sedimentation-dominated), when it included intertidal beach, the beach width has a significant influence on the dune volume change, however, for dry beach; there’s no correlation between beach width and dune volume change. So for erosion-dominated, when the beach is dry, the beach width have influence on the dune volume change and have little or no influence when the beach is wet. On the contrary, for sedimentation-dominated, when the beach is wet, the beach width have influence on the dune volume change, and for dry beach, the dune volume change has no correlation with beach width.

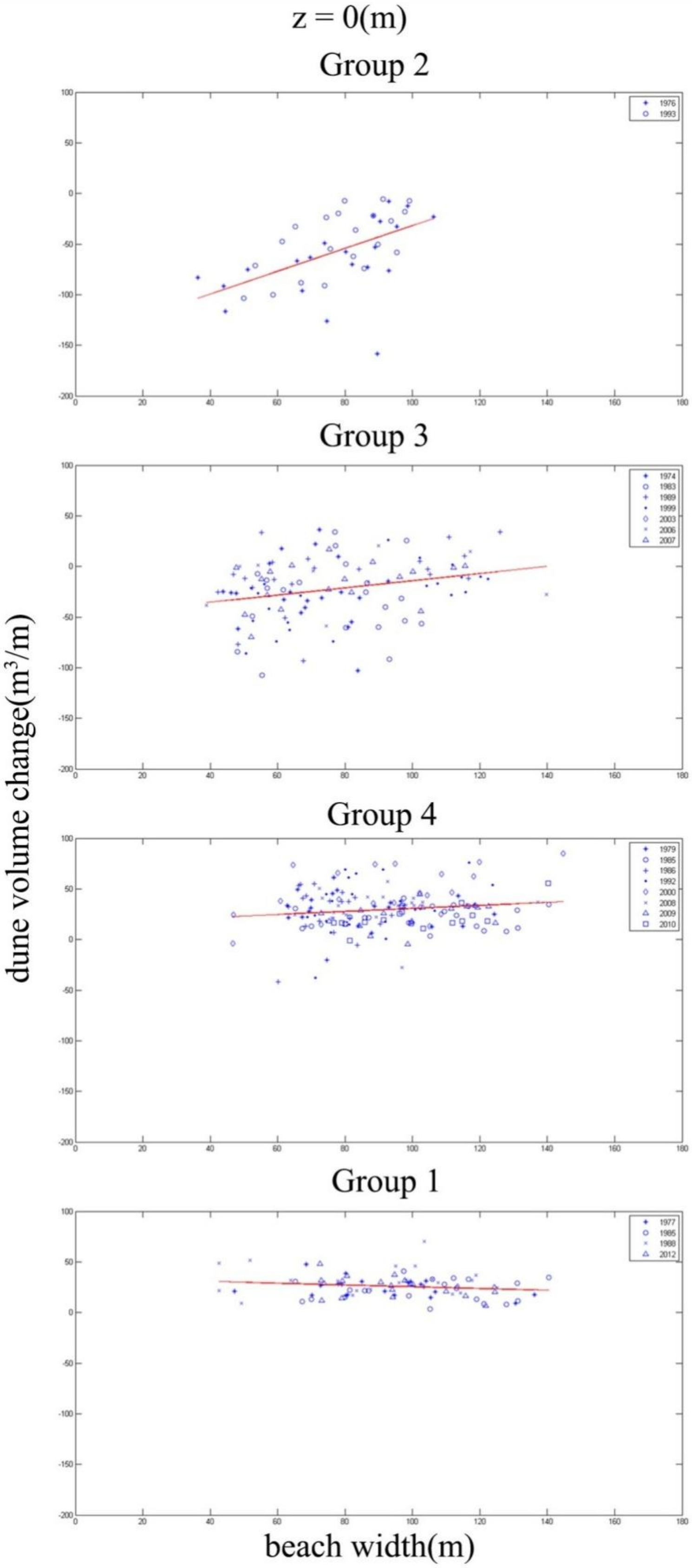

Figure 15 The regression of four groups and a certain beach width. (z=0m) The order of the subplot is groups for all erosion, erosion dominated, sedimentation dominated and all sedimentation.

3.2 Dune volume change predicted by Model

For the application of the model, 2 years have been selected. As said before, we are interested in how much sediment has been transported to the foredune by aeolian transport. So here only sedimentation-dominated years have been taken focus. There are two kinds of sedimentation-dominated year, one is all sedimentation and the other one is sedimentation-dominated but has some erosion. The first is 1977, an all sedimentation year. The other one is 2009, with some erosion but on the whole a sedimentation-dominated year.

For both of them, transect 8 (RSP 41.75) has been selected because of the good view of foredune and constant slope of the beach. And the condition for potential transport periods (PTPs) is not totally the same as it in Figure 5; here the threshold of wind speed is taken as 6 m/s. In the model, three 'q' have been calculated. qn is the potential transport disregarding moisture and fetch, q is the transport considering fetch, Q is the transport considering both moisture and fetch.

In the year 1977, nearly 70%-80% of time, F_c>F, the beach is quite narrow in 1977.Sine it has experienced a big storm in 1976.After running the model for 1977, qn=100.7035 m^3/m, q =89.2259 m^3/m and Q =73.6849 m^3/m, it can be seen that when only considering fetch effect, the predicted transport reduced by about 11 m^3/m, however, Q is the smallest one, when taken considering of the surface moisture, the predicted transport decreased by around 16 m^3/m compared with including fetch only. This means surface moisture has bigger influence on aeolian transport and it will reduce the aeolian transport. However, the dune volume change from the previous calculation in the same transect is 27.8208 m^3/m, the prediction of the transport is quite larger than the dune volume change, even when accounting for the limitations and moisture. Apparently, fetch and surface moisture reduce the aeolian transport input, but not a lot (11 and 16 m^3/m, each one taking about 10% of qn). This is asking for additional analyses why this is the case.

In Egmond, as said before, the wind speed is usually between 5- 10 m/s. So here a sensitivity analysis of wind speed has been done (Table 2). Although the coefficient in equation① ($1.16*10^{-5}$) is also calculated according to the wind speed, in earlier paper (Hsu, 1974), the equation is for general situations so there is no need to change it. From the table it can be seen that, when change the threshold velocity to > 7m/s, Q decreases to 60.2726 m^3/m and when set the threshold velocity to >9 m/s, Q reduces by about 7 m^3/m. Generally speaking, when increasing the threshold velocity by 1m/s, the predicted transport will reduce by 4 m^3/m to 10 m^3/m, also taking about 10% of qn. According to Figure 1.2, the wind speed in Egmond mostly is 7-8 m/s, so here, we change threshold velocity to >7 m/s.

Table2.The sensitivity analysis of the threshold velocity for PTPs (potential transport periods), 1977.

	Q (m^3/m)
>7m/s	60.2726
>8 m/s	56.9626
>9 m/s	53.021

The wind direction in Egmond is usually at SW or WSW (225° to 247.5°), it is quite oblique. This could also have influence on aeolian transport to the dune (Bauer et al., 2012). When the wind blows close to the front of the dune, it will become dune parallel and bring no sediment to the dune. So the threshold of wind direction has to be changed. Here we tested two ranges, one is 70° to 290° (cos70°), and the other one is 60° to 300° (cos60 °).Since these two range are not that oblique and also include most wind data. At this point, the condition of the PTPs has been changed to U>7 m/s and tested different ranges of wind direction (Table3). It can be seen that, when change the threshold of wind direction to larger than cos70° (wind direction is between 70° to 290°), Q decreases to 56.502 m^3/m. Generally, when reducing he wind angle by 10°, the predicted transport will reduce by 4 m^3/m to 10 m^3/m, also taking about 10% of qn.

Table 3 The sensitivity analysis of the condition for PTP for Q (m^3/m), 1977. Keeping the threshold of wind velocity as 7m/s and change the threshold of wind direction.

Threshold of wind angle	Q(m^3/m)
cos 70°	56.502
cos 60°	49.5119

Based on the tests above and new threshold values, the prediction of the year 2009 has also been done (Table 4). In this situation, the results are quite close. The predicted transport considering both fetch and surface moisture is 23.6398 m^3/m and the calculated dune volume change is 32.6928 m^3/m, there is only 9 m^3/m difference.

Table 4 The prediction of transport and dune volume change of 2009.Taking the threshold wind velocity as 7m/s, wind direction as 70 degrees.

Treshold of model and Q	Dune volume change by calculating
U>7m/s	
cos 70°	
23.6398 m^3/m	32.6928 m^3/m

4. Discussion

4.1 Dune volume change by calculating

Based on the dataset which contains annual elevation measurements of coastal profiles and the method of calculating the dune volume change in earlier papers, the dune volume change (ΔV in m^3/m) from 1964 to 2013 in Egmond aan Zee has been calculated in this study. The alongshore mean of the dune volume change is normally between -60 and 50 m^3/m. In addition, the study shows an increasing trend of the dune volume, means that in general, the volume of foredune will increase due to the aeolian transport. However, when there is a storm, the foredune will experience erosion (e.g. year 1976).Although during the storm there is a strong wind and theoretically it can transport larger volumes of sediment, it also causes a high water level, thus decreasing the fetch distance and increasing surface moisture. As a result, the actual aeolian transport is decreased.

In a given year, the dune volume change alongshore is different because of the beach width is variable alongshore. Beach width has influence on dune erosion but has little influence on sediment supply. In erosion-dominated years, the relationship between dune volume change and beach width is especially obvious, a larger width will experience less erosion. In accretion-dominated year, the dune volume change are similar along shore, it does not depend on the beach width.

This result is similar to the result of Keijsers et al. (2013).It also shows that in erosion-dominated year, there is a positive trend of the relationship between the ΔV and beach width. The positive trend indicates that wider beach experience less erosion than narrow beach. And for accretion-dominated year, the slope of the correlation between ΔV and beach width becomes led steep, indicating that the beach width has nearly no influence on the ΔV. In addition, in this paper, it also explores the relationship between ΔV and a large (>200m) beach width. It shows that where beach are wider, the slope of the correlation between the ΔV and beach width is close to 0.

4.2 Dune volume change by predicting

In this study, a model which included surface moisture and fetch effect has been built based on earlier papers (Irene Delgado-Fernandez, 2011; van Genuchten, 1980; Raubenheime and Guza, 1999). It is expected that the surface moisture could have influence on the aeolian transport and influence the dune volume change (Bauer and Davidson-Arnott, 2002; Bauer et al., 2008). However, the surface moisture has influence on the dune volume change but quite small; only reduce 10% of the transport. There is another important factor, wind characteristic (wind speed and wind direction). It can be seen from the above, even though the model considered the surface moisture, the predicted potential transport does not decrease much (only about 16 m^3/m) when compares with wind only model. However, when change the threshold of the wind characteristic (wind speed and wind direction), the predicted potential transport decreases dramatically, even 1m/s or 10 ° change can cause the same decrease with considering surface moisture. Because the wind in Egmond is so oblique, the regional winds are not a good predictor of local wind in front of a dune. Especially regional shore-oblique winds become dune parallel. When the oblique winds close to the foredune and become parallel to the dune, it brings no sediment to the dune.

The steep dune at Egmond causes regionally shore-oblique winds to become locally dune-parallel. This process is called "flow deflection", and happens especially in front of scarped ('steep') dune faces (Figure 16 Bauer et al., 2012). The situation in Egmond is quite similar to Figure 16B. As the regional approach angle becomes highly oblique (almost alongshore), the reduction in mean wind speed at the base of the dune becomes hardly noticeable since more flow momentum is carried across the dune profile. This has influence on increasing the transport potential along the beach while reducing the opportunity to transport sediment to the dune. Sediment transport potential on the dune slope may also decrease because an alongshore wind blows across a significantly greater vegetated fetch, thus inducing a larger difference in the transport response on the dune versus the beach. In the paper (Bauer et al., 2012), the dune crest is 9.75 m however in this study the dune crest is about 21 m, so it is excepted a bigger effect from the flow deflection.

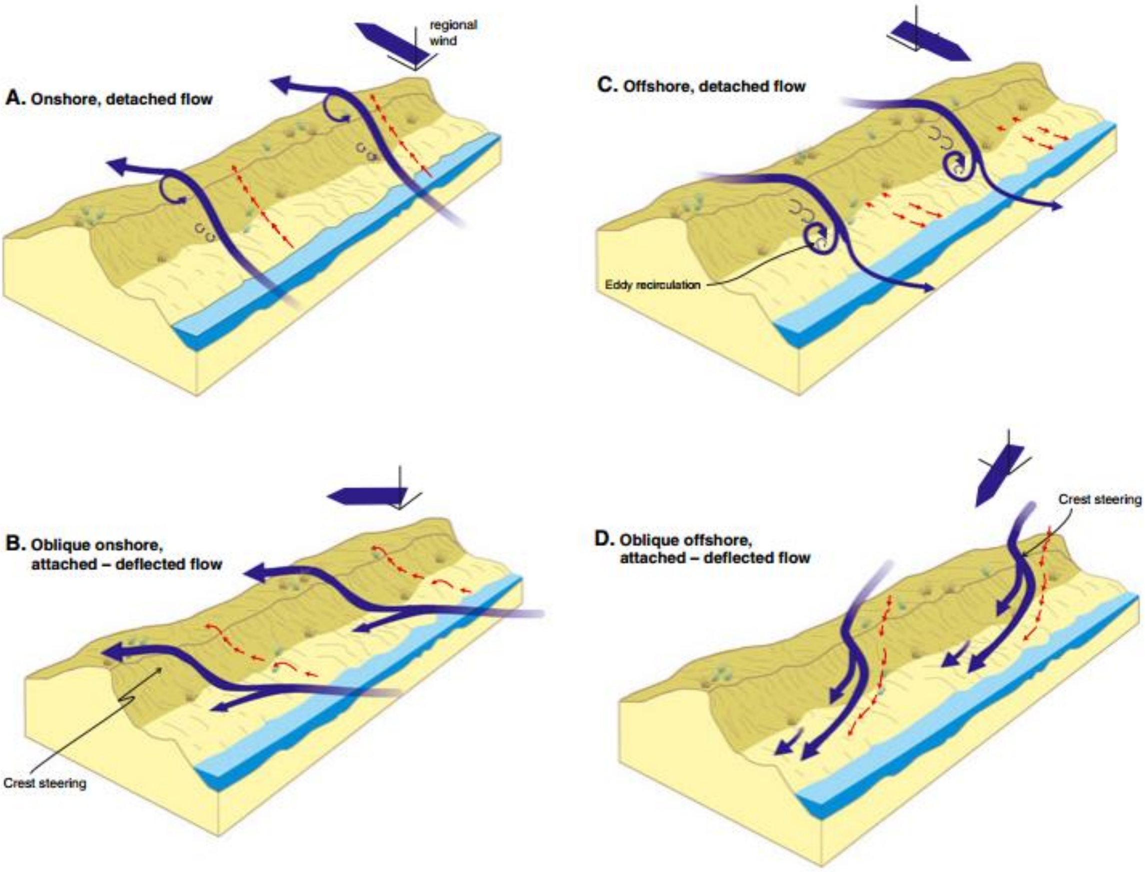

Figure 16 Conceptual model of flow–form interaction over large (> 8 m) foredunes for variable wind approach directions. Large solid arrows correspond to near-surface wind flows, modulated and steered by the local topography. Small arrows show likely sediment transport directions. (Bauer et al., 2012)

The direction of wind can really influence the aeolian transport to the foredune. It suggests that maybe it is better to use the beach width of the wind direction instead of onshore beach width. In Chapter 3, it shows less correlation between beach width and sedimentation, the lack of correspondence between beach width and volume growth may because we did not use beach width in the wind direction but cross-shore beach width.

Wind only model could have an over estimation (Irene Delgado-Fernandez, 2011; Keijsers et al., 2013), but when considering the surface moisture and fetch effect, the prediction will be more close to the calculated dune volume change. However, the reduction is not that much as expected. As a consequence, the model cannot predict the dune volume change accurately, since different transects have different profiles and also beach width can be various. And also for the ground water level and moisture model, it should be properly calibrated using measurements of groundwater levels and surface moisture contents. In above, when compare the model with realistic, we only based on the field experience without a proper calibration, so this would cause some inaccuracies. In addition, the prediction could be also influence by other factors, such as shells and foreign substance in sediments and the inaccuracies caused by measuring equipment. So trying to reduce the noise of data is necessary.

And there is one thing has to be mentioned, the dataset of annual elevation measurements of coastal profiles has been surveyed in April of each year, so the dune volume change in calculating, for example, 1976, is used data from April 1976 to April 1975(the big storm happened in January 3,1976),so here 1976 is an erosion year. But the dune volume change by model predicting is from December 1976 to January 1976, it would also cause some inaccuracies.

5. Conclusion

Using a data-set that comprises annual profiles of a 5 km stretch of coast (RSP 40-45) between Castricum and Egmond aan zee with 250 m spacing from 1964 until 2013, and using a model that included surface moisture and fetch effect to predict the dune volume change, the study shows that:

1. What is the volume change in the foredune? Does this change vary alongshore in a given year? Does this change vary from year to year in a given transect?

Generally, there is an increasing trend of the mean of the alongshore dune volume. However, the dune volume sometimes decreases, when there was a big storm. In a given year, the dune volume change is different alongshore. In dune accretion years, the dune volume change is constant along shore, and in erosion-dominated years, the relation between the dune volume change and beach width is significant.

2. What factors contribute to this variability? (e.g., beach width and wind characteristics)

Beach width has influence on dune erosion but has little influence on sediment supply. If it's erosion-dominated, beach width have influence on the dune volume change, a larger width will experience less erosion. In accretion-dominated year, the dune volume change are similar along shore, it does not depend on the beach width.

3. How well can the model predict the measured volume change? How do beach width and moisture content affect annual predictions relative to a wind only model?

Wind only model could have an over estimation, when considering the surface moisture and other factors (e.g. the threshold value of the wind characteristics), the potential transport will decrease by about 10%, the prediction will be more close to the dune volume change but not that much as expected. As a consequence, the model cannot predict accurately. There is another important factor, wind characteristic (wind speed and wind direction). This is because the wind in Egmond is so oblique; the regional winds are not a good predictor of local wind in front of a dune. Especially regional shore-oblique winds become dune parallel. When the oblique winds close to the foredune and become parallel to the dune, it brings no sediment to the dune. This process is called "flow deflection". So when change the threshold of wind characteristic, even 1m/s or 10 °, it will cause the similar effect (the potential transport will reduce by about 10%) to the surface moisture. For the next step to improve the predictions, the calibration and accuracy of data is of vital importance. Furthermore, because of the flow deflection, it is better to use the beach width of the wind direction instead of onshore beach width.

6. References

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Digital sources

Water level data
Available at: http://live.waterbase.nl/waterbase_wns.cfm?taal=nl

Weather (big storms) information
Available at: http://xmetman.com/wp/

Wind climate information
Available at: https://www.windfinder.com/