Sea breeze generated waves and coastal morphology

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Abstract

For the determination of the stability of coastlines, coastal erosion and the design of erosion protection studies, the "local" wave climate is the most important input parameter. For morphology, "local" means just outside the breaker line. On relatively calm days the local wave climate is strongly influenced by the effect of sea breeze. On the basis of the sea breeze model of HAURWITZ [1947] and HSU [1988] an operational method has been developed for the determination of sea breeze and the effect on coastal morphology. Examples are presented from Cartagena, Colombia, and from the Bulgarian Black Sea coastline.

Introduction

In many areas of the world the wave and swell climate is rather mild. In those areas sea breeze induced waves play an important role. Recently a team of the university of Western Australia (MASSELINK, G. AND PATTIARATCHI, C.B. [1998a], MASSELINK, G. AND PATTIARATCHI, C.B.[1998b], PATTIARATCHI, C.B., HEGGGE, B., GOULD, J., ELIOT, I. [1997]) has executed extensive observations on sea-breeze and sediment transport. In practical engineering it is in those conditions important to consider the effect of sea breeze. In order to do so, an straightforward computational approach is needed.

The sea breeze

With a lot of simplifications one may state that sea breeze is caused by the daily temperature difference between land and sea. During the day the land warms up more than the sea. Because of this air rises over land. The low pressure is compensated by an inflow from the sea, and so a circulation pattern of air starts. The maximum temperature difference occurs somewhat after mid day. And because of the time lag, the maximum wind velocity will occur somewhat later. According to HAURWITZ [1947] the velocity (in m/s) is approximately 1.2 times the temperature difference (in degrees centigrade). However, according to Simpson [1994] sea breeze may only occur if

$$\frac{u_g^2}{\Delta T} < SBI$$

in which u_g is the velocity of the geostrophic wind, Δt the temperature difference and SBI the Sea Breeze Index. There is no universal value for SBI, but it should be in the order of 5 or less. Some data presented in SIMPSON [1994] indicate that for Lake Erie is has to be 3 or less.

In order to quantify the magnitude of the sea breeze in more detail, one can follow the circulation equation, as presented by HSU [1988]. He assumes that the sea breeze is circulating within the mixed layer (planetary boundary layer). This layer has a height of 1 to 3 kilometres. The total circulation length is in the order of a couple of 100 kilometres. Assuming that the seaward extend and the landward extend are more or less identical, the total circulation is four times the seaward extend of the sea breeze (order 50 - 100 km). Using the equation of motion as a starting point, Hsu comes to the following equation

$$\frac{d\bar{v}}{dt} + k\bar{v} = A\cos\omega t$$

$$A = \Delta T \frac{R}{L} \ln\left(\frac{p_0}{p_1}\right)$$

in which:

v	Mean sea breeze velocity (m/s)
ΔT	Air temperature difference between land and sea (°C)
R	Gas constant for air (287 Nm/kg °K)
L	The total length of the circulation pattern (m)
k	Constant expressing the intensity of friction force
ω	earth frequency ($7.27 * 10^{-5}$ s^{-1})
p_0,p_1	pressure at surface, resp. at the top of the mixed layer

The standard solution of this differential equation is

$$v = c e^{-kt} + A(k^2 + \omega^2)^{-1/2} \cdot \cos(\psi - \omega t)$$

where

$$\cos\psi = k(k^2+\omega^2)^{-1/2} \qquad \sin\psi = \omega(k^2+\omega^2)^{-1/2}$$

Because this has to be a continuous varying function, one may argue that c = 0. The maximum velocity is reached when

$$\cos(\psi - \omega t) = 1$$

so

$$v_{max} = A(k^2+\omega^2)^{-1/2}$$

$$A = \frac{R}{L}\,\Delta T\,\ln\left(\frac{p_0}{p_1}\right)$$

The pressure p_0 and p_1 are approximately 1000 and 700 mbar. The velocity is not very sensitive to the exact value of p_0 and p_1. These values can be computed when the height of the mixed layer (h) is known.

Based on the above one can follow a straightforward method to compute the sea breeze velocity:

1. Determine with $U_g^2/\Delta T < 5$ if sea breeze may occur. If not, then this is not a sea breeze day.
2. Calculate the moment of maximum sea breeze, using $\cos\psi = k / (k^2+\omega^2)^{1/2}$.
3. Calculate maximum sea breeze velocity $v_{max} = A / (k^2+\omega^2)^{1/2}$.
4. Calculate v(t) using full equation $v = v_{max} \cos(\psi - \omega t)$.
5. Calculate the approach angle of the sea breeze $\varphi = \mathrm{atan}(-k/f)$, in which $f = 2\omega\sin\Phi$ (Φ is the latitude of the location, these equations can be derived from the balance of the Coriolis force, Friction force and the force due to the Pressure gradient).

The required parameter are:

u_g	velocity of the geostrophic wind
ΔT	temperature difference
E	extend of the sea breeze
Φ	latitude of the location
h	height of the planetary boundary layer (mixed layer)
k	friction number.

In practice, the determination of u_g, Φ and ΔT are very simple. The friction number k varies from $0.5*10^{-5}$ to $5*10^{-5}$. HAURWITZ [1947] suggests the value of $k = 2*10^{-5}$. The value of k can be estimated when observations are available. Both the direction of the sea breeze as well at the time when u_{max} depend on k. So, when observations are available, one can determine k.

The determination of h and E is more complicated. Both values vary in time and are different for each location. Meteorological observations may give an estimate for these values. In tropical areas h is in the order of 3 km, while on higher latitudes, especially in winter, h may reduce to 500 m. The extend E of the sea breeze sometimes can be determined from satellite pictures, using cloud patterns.

Calibration

For operational use of the Hsu/Haurwitz formula one needs to know the above mentioned input parameters. Usually temperature readings of the maximum and mean temperature can be obtained easily. Also hourly wind observations are not really a problem. By analysing dome data sets an estimate of k can be made. However, data regarding h and E are usually not available. For operational purposes it is most practical to estimate a realistic value of E and carry out a number of calibration calculations for the determination of h. As an example, using observed daily sea breeze velocities from Cartagena, Colombia, the height of the mixed layer has been computed using the Hsu/Haurwitz formula form the moment of maximum sea breeze. Data are used from the Rafael Nuñez airport of January 1998. The calculated average height is 2325 metres, with a standard deviation of 600 m. For the time being it is assumed that this mean and standard deviation is valid throughout the year. For a tropical non-monsoon country this assumption is realistic, but will be worked out in detail later.

Duration of the sea breeze and wave action

One may assume that the sea breeze only starts when the theoretical sea breeze velocity is at least 20% more than the geostrophic wind velocity. The sea breeze stops when the velocity drops below this value. When both moments are known, the theoretical sea breeze duration, t_t, can be calculated. During this time the sea breeze is not really constant. For practical reasons it is assumed that the sea breeze velocity is constant (and equal to the maximum sea breeze velocity) during approximately 80% of the time determined above.

Sea breeze velocities for Cartagena are in the order of 3 - 5 m/s. This results for a fetch length of approximately 50 km in a wave height of 0.4 to 0.5 m. According to the standard wave growth calculation method, it takes 3 hours to reach the fully developed stage. This means that the duration of the wave action is

$$t_w = 0.8 \cdot t_t - 3 \qquad [hrs]$$

In figure 1 an example calculation has been made for the sea breeze in Cartagena, given $k = 2*10^{-5}$, $\Delta T = 3.5$ °C and h=2200 m. Given a geostrophic wind speed of 1 m/s, the duration t_t = 10 hrs. This implies a duration of the wave action of 5 hrs.

The calculated approach angle of the sea breeze is 53°. Given the orientation of the coastline at Cartagena (the normal to the coast points towards NW, i.e. 315°). This implies that one would expect a sea breeze from 315 + 53 = 8°. Observations from the airport indicate that usually the wind between 13:00 hrs and 18:00 hrs comes from north.

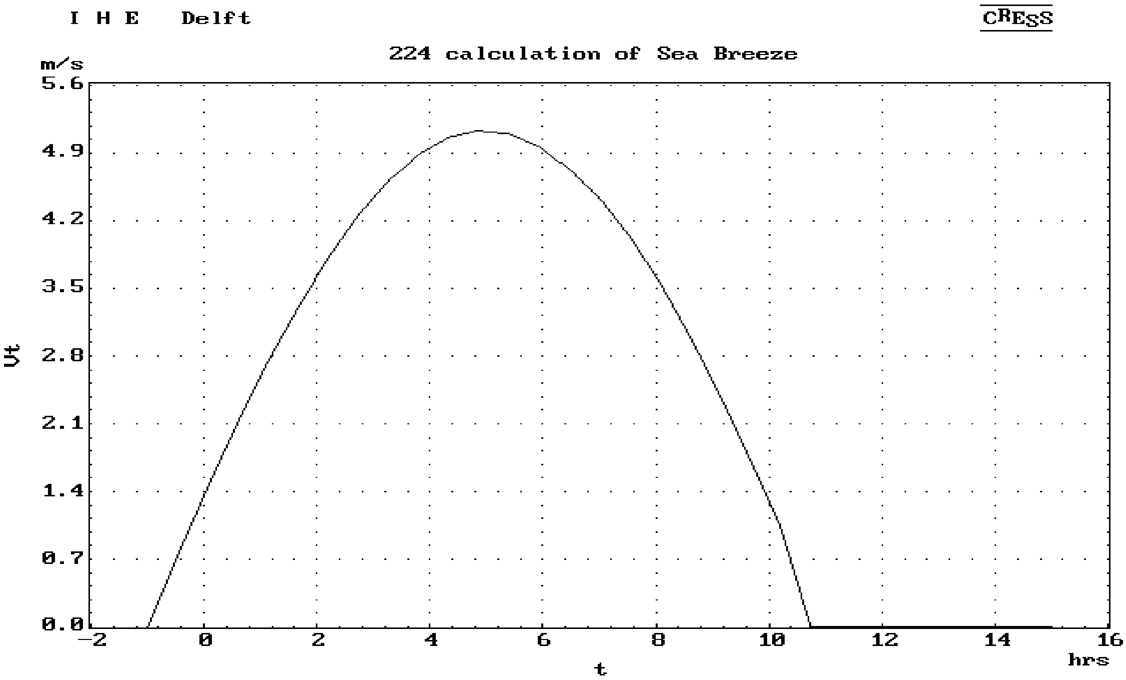

Figure 1: Example calculation of the sea breeze at Cartagena

Figure 2 shows observed wind velocities from Cartagena. It is clear that the changes of the velocities over the day are quite comparable to the computed case.

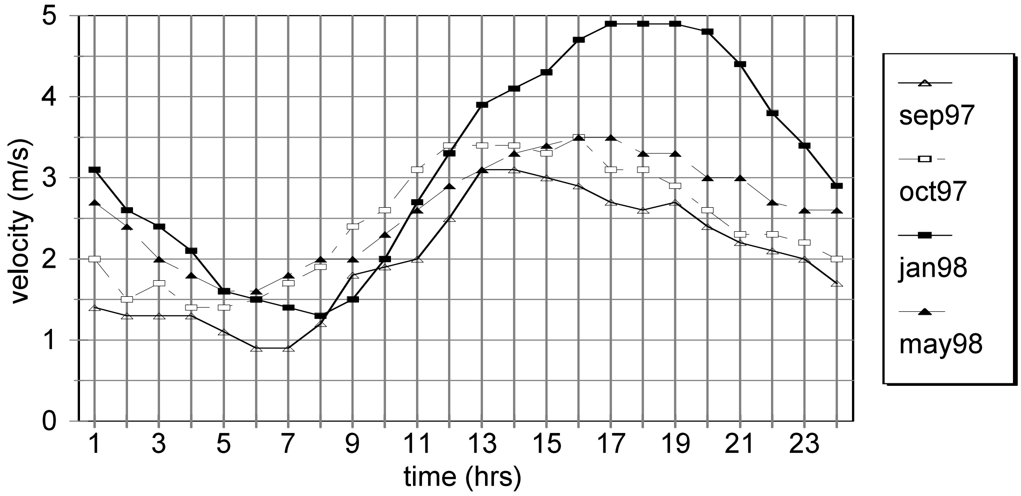

Figure 2: Observed wind velocity in Cartagena as function of the day time

Applying the wave growth formula of Bretschneider, a wind velocity 4.5 m/s and a fetch length of 50 km gives a wave height H_s = 0.4 m (period is 2.5 seconds). Other formula (Wilson, Krylov, etc.) give comparable values.

Sediment transport due to sea breeze

Applying the Queens sediment transport formula (see e.g. SCHONEES [1996]), and using a beach under water slope of 1:50, D_{50} = 200 μm and a porosity of 40%, this results in a sediment transport of 10000 m^3/year. Of course this wave does not occur during the whole year. On an hourly basis this is 1.14 m^3/hr. So during a day of 5 hours this is 6 m^3day, or 2100 m^3/year. This amount of longshore transport is not very impressive. However, one should realise that on global terms, the sea at Cartagena is extremely calm, and there is no storm activity.

Applying the CERC formula, the same approach results in a sediment transport of 16000 m^3/year. However, it is quite questionable if the CERC formula can be applied in these cases.

Because there are hardly any other waves approaching the coast of Cartagena, all sediment transport is caused by the sea breeze generated waves. The tourist beaches of Cartagena have been protected by groynes, with a long terminal groyne. From the above calculation follows that regularly sand is moving, changing the orientation of the coastline, and finally causing some sediment transport along the tip of the groynes. Because the low value of the transport, the system is rather stable, and the tourist beaches do not suffer from severe erosion.

Comparison with other wave data

Commonly sediment transport is computed using ocean wave data, either observed on ships or from remote sensing. The Atlas of the Oceans [YOUNG AND HOLLAND, 1996] provides global information. For sea in front of Cartagena in figure 3 the waves and wind direction are presented.

Table 1: mean and maximum temperature in Cartagena

month	*MeanMax*	*Mean*	*ΔT*
January 1997	30.4	26.5	3.9
February 1997	30.7	26.9	3.8
March 1997	30.5	26.3	4.2
April 1997	30.6	27.2	3.8
May 1997	31.7	28.7	3.0
June 1997	31.8	28.4	3.4
July 1997	32.2	28.6	3.6
August 1997	32.4	28.7	3.7
September 1997	32.5	28.9	3.6
October 1997	31.9	28.5	3.4
November 1997	31.9	28.5	3.4
December 1997	31.1	27.8	3.3
January 1998	31.3	27.4	3.9
February 1998	31.8	27.9	3.9
March 1998	31.0	27.6	3.9
April 1998	31.6	28.5	3.4
May 1998	31.8	28.9	2.9
average			3.5

According to these data, much higher waves occur in the region. But, the direction of the waves is always in offshore direction. So these waves never approach the coast of Cartagena itself. And consequently, these waves do not influence the sediment transport along the coastline.

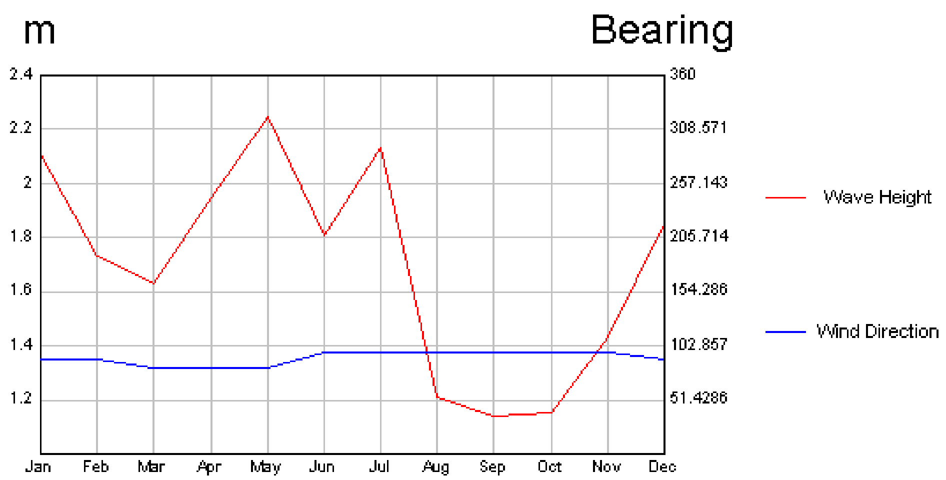

Figure 4: Wave and wind data off Cartagena [YOUNG AND HOLLAND, 1996]

Variation over the year

Analysing the data of a full year (see table 1) shows that indeed the variation during the year is negligible, and that the above figures give a good value for a whole year. So one may expect in Cartagena only very few effects of seasons.

In countries where there is a clear seasonal difference, the effect is completely different. For example along the Bulgarian coastline, in the winter period (including spring and autumn) severe storms may occur. These storms cause significant sediment transport, and at some places also significant erosion. Part of the erosion is combatted by several means, for example construction of longshore protection and groynes.

In the summer period there are no storms, and if one would look only to the "deep water" wave climate, sediment transport during the summer period has to be zero.

Sea breeze conditions along the Bulgarian Black Sea Coast

Sea breeze can be observed along the Bulgarian Black Sea Coast from May until September. Assuming the variations of sea breeze occurrence in the long run one may consider as a rough approximation that most significant sea breeze effect on coastal morphology takes place for five months per year. This statement is based on data from Wind Observation Station at Varna presented in Table2.

Table 2: Occurrence of sea breeze upon observation at the Varna International Airport

Velocity range m/s	Wind direction		Total occurrence % of time
	East	South-East	
Long term, for the whole year			
1-5	15.69	11.78	27.47
6-9	3.06	2.99	6.05
Total			33.52
Long term, Spring			
1-5	19.73	13.79	33.52
6-9	4.15	3.53	7.68
Total			41.2
Long term, Summer			
1-5	16.17	15.68	31.85
6-9	4.34	5.42	9.76
Total			41.61

Contrary to the regions with tropical climate where conditions for sea breeze development are steady during the year, in areas with continental climate, parameters of generated sea breeze depend on the variation of temperature difference between air and sea water which may range between 5 and 10 °C. This difference is subject of seasonal variation. It also depends on the global meteorological conditions. It often happens in June to have a wind from south-eastern direction with speed of 15 m/s blowing out of the warmed sea water. During such a weather which may last from a couple of days to one week, temperature difference may reach 10 °C. Coastal water circulation is important as long as there is significant difference between temperature at the bottom and at the surface as it can be seen from table 3.

Table 3: Air and Sea Temperature off the Black Sea Coast (degrees centigrade)

Month	April	May	June	July	Aug.	Sept.
Air temp	10	15.5	20	22.5	22.5	19
Sea temp	Winter			Summer		
Surface	5-7			21-22		
Bottom	8-9			9-12		

The influence of this parameter is demonstrated by sample calculation on Figure 4, where one can see, that the maximum sea breeze velocity may range from 4 to 8 m/s. This difference from the case with tropical climate is the reason why the range for sea breeze velocity in Table 2 was chosen between 1 and 10 m/s. The duration of sea breeze also depends on the temperature difference and according to the given example it is between 5 and 10 hours. As far as the average velocity and the average duration of sea breeze are used later in sediment transport computation it is clear that more thorough study of local sea breeze phenomena is needed.

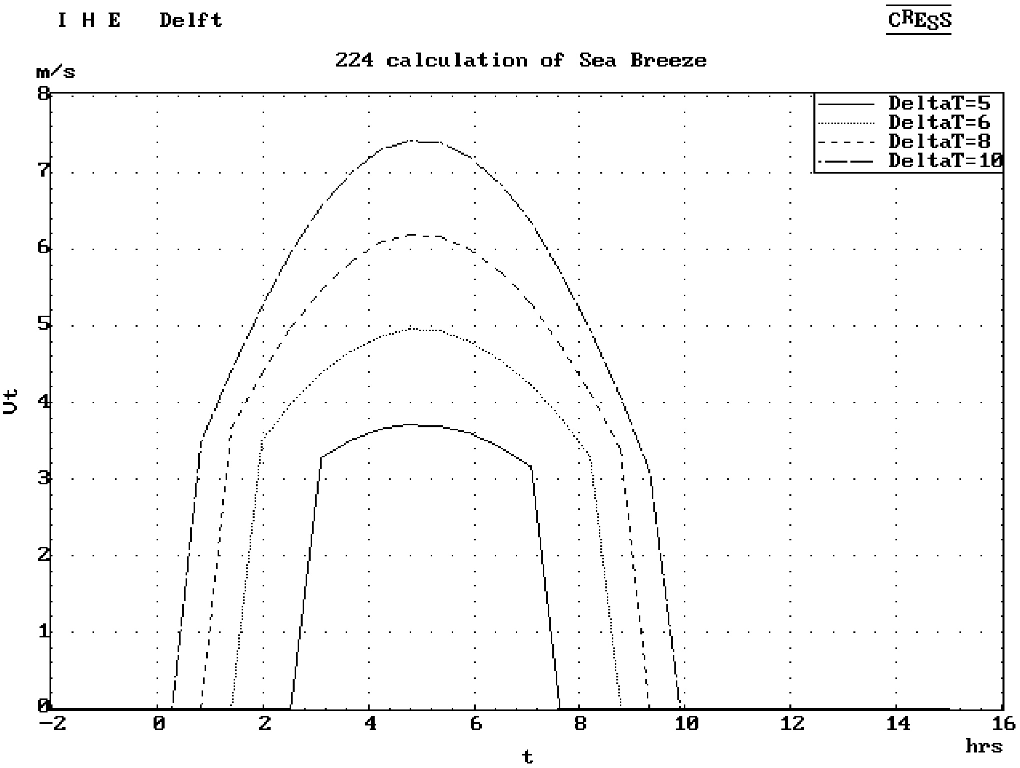

Figure 4: Example calculation of sea breeze for the Bulgarian coast

Some data recorded at the wind observation stations shown on Table 4 help to define the percentage of time of the year when the sea breeze is important for the beach morphodynamics.

Comparison of data given in Table 4 leads to conclusion that average daily occurrence of wind with velocity in the order of 4-6 m/s is practically the same for the first two stations. It is realistic because both are located close to each-other and conditions are the same. For the third station (Tzarevo) average daily occurrence of wind with velocity 4-6 m/s is less.

Practical experience and visual observation in the region located to the south of Sozopol however create an opinion that it is important to take into account also the wind with velocities up to 12 m/s. According to data from Table 4 [IVANOV & SAVOV, 1992] wind from all direction with velocity in the range 4-6 (12) m/s occur for 20 % of the time. The records at Varna International Airport show that 2/3 of the wind measured blows from

Table 4: Occurrence of wind with "sea breeze"-velocity

Station "Obzor", range 4-6 m/s	
Season	hours
Winter	439
Spring	466
Summer	375
Fall	448
1728/365=4.7 hrs/day (20%)	

Station "Emine", range 4 - 6 m/s	
Season	hours
Winter	356
Spring	402
Summer	447
Fall	415
1620/355=4.4 hrs/day (19%)	

Station "Tzarevo"			
Range, m/s	4-6	4-10	4-12
Winter	303		
Spring	243		
Summer	249	404	424
Fall	305	342	603
Total	1100	1292	1573
Hours per day	3	3.5	4.3

East and South-East. For the later calculation of the sediment transport we assume that in 13% of the time sea breeze occurs with velocity of 7 m/s.

Beach changes due to sea breeze

According to the program for the protection of Bulgarian Black Sea Coast for the period 1980-1990, coastal structures were built at many locations along the coast [IVANOV & SAVOV, 1992]. At number of coastal protection sites transverse structures were erected. The layout of these structures in most of the cases was based on engineering intuition rather then on calculations for the possible morphodynamical effects. Therefore at certain locations unexpected effect on nearby beaches took place. In the coastal engineering practice at that time only extreme events like storms were considered important for the stability of the coast and the "every day " wave climate was usually disregarded.

There are two coastal sites along the southern Bulgarian coast (near Sozopol) where significant changes of beach morphology took place after the construction of jetties was completed. The first one is the bay *St. Agalina* were a small marina was built . The sedimentation of the basin started from the beginning of the construction in 1985. At this

Figure 5: Sedimentation in the fishing harbour of Alepu

time (1999) the basin is completely filled up with sand. As long as sand deposition developed at the lee side of the structure it is clear that sand was driven to the north from the nearby large beach. The second case is at the beach *Alepu* where a jetty (Figure 5) was built to function as a fisherman's wharf. The effect of similar process can be observed.

An idea for the rate of the sediment transport can be achieved by a sample calculation for the site given in figure 5. This sand cannot be transported into the wharf area due to storms, because storms come from different directions. Assuming a temperature difference of 10 degrees the see breeze velocity becomes 7 m/s and has a duration of 5 hours (see above). Using the Bretschneider formula for wave growth in deep water, this results in a wave height of 0.7 m with a period of 2.8 seconds. These values can be included in a longshore sediment transport formula.

Table 5: Sediment transport calculation

Input values				Output values kg/m^3			
H_s	Significant wave height	0.7	m	S	Queens transport	735	m^3/yr
T	Wape period	2.8	s	S	CERC transport	5230	m^3/yr
φ	Deep water angle	79	degr				
γ	breaker index	.65	-				
α	beach slope	1:50	-				
ρ_s	sediment density	2650	kg/m^3				
ρ_w	water density	1018	kg/m^3				
p	porosity	0.40	-				
%	Occurrence	6	%				
Q	Queens constant	50000	-				

The calculation is presented in Table 5. A calculation has been performed using both the Queens and the CERC formula. In this case the Queens formula is more applicable. Because the sea breeze occurs only 5 hours per day, and only during 4 month per year, the total occurrence of the see breeze induced waves is 6 %.

For 15 years this would result in an accumulated sedimentation of 11300 m^3 according to Queens and 78500 m^3 according to CERC. The observed accumulated sedimentation in figure 5 is in the order of 15000 m^3. The result shows that the quantity of sand is not great, but on the scale of a small harbour or a marina, the effects can be considerable. More confident results might be achieved if reliable local observation of wind and air/water temperatures are collected and analyzed.

Conclusion

Using easily accessible climatic data, a good estimate can be made of the sea breeze induced waves and the sediment transport caused by these waves. For coasts without severe wave action, most transport is caused by sea breeze induced waves.

For coast with a calm season, during the calm season minor beach changes will occur due to sea breeze. On the long term morphology of these coasts, the sea breeze induced effect can be neglected, but for operational use of the beaches in the tourist season, the effect of sea breeze should not be neglected.

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