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Numerical simulation versus in-situ sedimentary flux on sandy beaches as a function of the breaker parameter

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***Abstract*—This paper discusses the abilities of numerical models to predict bed morphodynamics and longshore sediment transport on multi-barred sandy beaches. The sediment transport model used in this study solves the bed evolution equation in conjunction with several sediment transport formulas. The flow field and the water depth are calculated using the depth-averaged hydrodynamic model TELEMAC-2D[1]. The work consisted in setting up three different methodologies of calculation. The principle is to make an internal coupling of three codes where Tomawac models swell propagation; Telemac2D calculates the currents and Sisyphe determines the morphodynamic evolution. These models were used in the framework of a simulated meteorological cycle describing the seasonal evolution of hydrodynamic factors.**

I. INTRODUCTION

Compared to the beaches where the tide plays only a low or moderate role, macrotidal beaches have been only a few studies attempt to measure it sandy transport [3, 4, and 5]. This type of beaches are characterized by a strong tidal with sand bar which results in a large variability in hydrodynamic processes with a horizontal translation of shoaling, breaking and surf zone [6]. These variations lead to more difficulties to simulate and understand all the process in action.

The amount of sediments transported by longshore drift it mainly determined by the height of the waves at breaking but this measurement can be difficult to realize due to tidal and waves conditions. In simulation, the McCOWAN [7] theoretical breaking index of 0.78 is commonly used but many studies show that wave can break for different values and this ratio Hs/h (Hs=wave height (m),h=water depth(m)) depends particularly on the slope of the beach [8, 9]. Smaller coefficient (Hs/h between 0.3 and 0.5) are proposed for macrotidal beaches [10, 4] but there are only a few in-situ measurements with high tides.

This article presents the results of a study in macrotidal beaches of the southern North Sea and eastern English Channel that analyze the impact of the breaker parameter over wave height and the longitudinal sediment transport. Three different formulas available in Telemac-mascaret have been used to simulate sediment transport, Bijker, Bailard and Soulsby Van-Rijn.

To calibrate the different sediment transport formulas integrated in the numerical model, our simulations of sediment flux were compared with in-situ data of sediment transport measured on macrotidal beaches of the southern North Sea and eastern English Channel. Longshore sediment transport measurements were obtained using streamer traps deployed at several locations across shore-perpendicular transects, following the method proposed by Kraus [2], which enables to estimate sediment flux at several elevations through the water column. Hydrodynamic measurements have also been realized with six devices place on beaches. The results had shown that the wave breaking occurs at a ratio Hs/h between 0.2 and 0.4 and have a maximum ratio Hs/h around 0.5. This comparison between in-situ data and simulation showed that the breaking index is a major indices on the validity of the results.

II. STUDY AREA AND METHODOLOGY

A. *Study site*

This study was conducted on a sandy beach (D50 = 0.17 mm) at Zuydcoote on the coast of northern France (Fig. 1A). The measurement site is characterized by a low slope (tan β= 0.014), approximately 450 m wide, marked by the presence of several intertidal bars with variable height and width (Fig. 1B). Beach Zuydcoote faces the North Sea and is exposed to surges with low to moderate power due to refraction on their pre-littoral sand banks and low slopes that characterize the

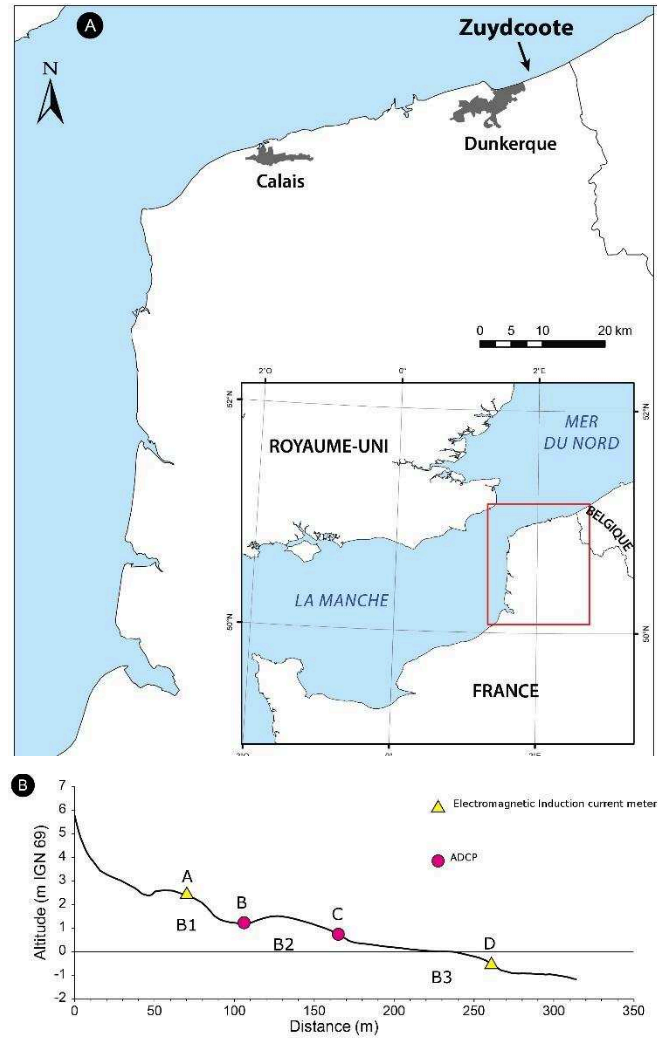

Figure 1. A) Location of the study site; B) Position of measurement devices in the intertidal zone and position of the bar B1, B2 and B3.

shoreface [11]. The tide is semi-diurnal and tidal is macrotidal, mean tidal range in Dunkirk being about 5.5 m whitewater and 3.5 m in still water. This high tidal range is responsible for strong tidal currents flowing parallel to the shore in the coastal area, but whose intensity strongly decreases from bottom to top of the beach [12].

B. In-situ measurement Methodologie

The method used is based on the simultaneous acquisition of hydrodynamic data and in situ measurements of sediment fluxes using sediment traps. Hydrodynamic measurements were performed in June 2013 using two electromagnetic current-wave recorders and two current profilers (ADCP) arranged in three intertidal bars and a tarp along a radial perpendicular to the coastline (Figure 1B). These devices make it possible to obtain measurements of wave parameters (significant wave height (Hs), period and direction) and current (speed and direction of the average current speed of transverse and longitudinal component of the current), and the average height of the water column. Currents were measured near 0.15 m above the bottom in the case of electromagnetic induction current meters and 0.2 m for the ADCP (height of the first cell above the unit). The acquisition frequency hydrodynamic data was 2 Hz for all devices that have been programmed to record data every 15 minutes for 8.5 minutes (electromagnetic current) and 10 minutes (ADCP). Two ADW S4 current meter were placed parallel to the beach at a depth of ten meters to obtain wave parameters far away from the other devices and to have initial condition for wave generation in the simulations. They also helped to adjust tidal current as explained latter.

Measurements of sediment fluxes has been done using sediment traps to measure suspended sediment transport at several levels in the water column and near the bottom with five nets of a mesh of 63 microns distributed regularly on a height of 1.43 m. Sediment traps are placed facing the longitudinal current for a period of 10 minutes. Sediment flows were determined at each trap, and then integrated over the water column following the procedure recommended by Rosati and Kraus [1]. All flux measurements were carried out closed to the current meter devices.

A camera was installed at the top of the dune behind the beach at a height of 10 m above mean tide level to take a picture every 10 seconds. Images corresponding to an average of 60 consecutive shots allow to locate the surf, breaking and shoaling area during each period of hydrodynamic which allowed to know what type of hydrodynamic processes was at each measurements device during each registration period.

The bathymetric measurements were performed on the entirety of the study area using DGPS.

C. Simulations Methodologies

In situ measurements of sediment fluxes were compared with the results of modelling of sediment flux based on the coupling of three codes (TOMAWAC for wave propagation, 2D Telemac for current and Sisyphe for sediment transport) and use of three transport equations: Bijker [13],Bailard [14] and Soulsby Van-Rijn [15, 16, 17].

Tidal currents are generated by imposing a difference in sea level at each side of the simulation domain. This difference is calculated using data from three tide gauges: one at Calais and one at Dunkirk in west Zuydcoote and one in Oostende, at east from Zuydcoote. The water depth given by the two ADW S4 current meter allowed us to optimize this sea level difference by comparing their water depth at rising and falling tide. The simulation are done with Telemac-2D which resolve Barré de Saint-Venant equation in two dimension.

Data of the ADW S4 devices are also used for the generation of waves at boundary layer by giving waves height and period. These waves are propagated by Tomawac software by solving the balance equation of the action density directional spectrum. The total energy induced in waves is the sum of dissipated and induced energies produced as a result of physical interactions (1):

$$Q=Qds + Qnl + Qbf + Qbr + Qtr \quad (1)$$

Where

- Qds = Whitecapping-induced energy dissipation
- Qnl = Non-linear quadruplet interactions
- Qbf = Bottom friction-induced energy dissipation
- Qbr = Bathymetric breaking-induced energy dissipation
- Qtr = non-linear triad interactions

These terms are numerically modelled and different methods have been proposed by researchers for calculating their values. In this study we did not use actually wind for waves generation. The breaking model choose is the Battjes and Janssen's model [18] which is based on the analogy with a hydraulic jump. It assumes that all the breaking waves have a maximum height Hs(m) compute by (2).

$$\mathrm{Hs} = \gamma_2 \mathrm{h} \quad (2)$$

Where γ_2: a factor which depends of the type of beach.

The total energy dissipation term $D_{br}$is expressed as follows (3)

$$D_{br} = -\frac{\alpha Q_b f_c H_S^2}{4} \quad (3)$$

where $Q_b$is the fraction of breaking wave, f_c is a characteristic wave frequency and α is a numerical constant of order 1. $Q_b$is estimated as the solution of the implicit equation (4)

$$\frac{1-Q_b}{\ln(Q_b)} = \frac{H_{s0}}{2H_S^2} \quad (4)$$

where $H_{s0}$is the significant wave height

Sediments fluxes are calculated through Sisyphe. Sisyphe is a sediment transport and morphodynamic simulation module which is part of the hydrodynamic finite elements system Telemac. In this module, sediment transport rates, decomposed into bed-load and suspended load, are calculated at each grid point as a function of various flow (velocity, water depth, wave height, etc.) and sediment (grain diameter, relative density, settling velocity, etc.) parameters. The bed load is calculated by using one of the classical sediment transport formulae from the literature. The suspended load is determined by solving an additional transport equation for the depth-averaged suspended sediment concentration. Three different formulas have been used in this study, Bijker, Soulsby – Van Rijn, and Bailard. All of them take into account the interaction with the waves to calculate sediment flux.

For Bijker's method, the two components (the bedload Q_b and the suspended load Q_s)are computed separately.

The bedload transport rate is (5) :

$$Q_b = b\theta_c^{0.5}\exp\left(-0.27\frac{1}{\mu\theta_{c\omega}}\right) \quad (5)$$

where $\theta_c$is the non-dimensional shear stress due to currents alone, $\theta_{c\omega}$ is the non-dimensional shear stress due to wave-current interaction, and μ is a correction factor which accounts for the effect of ripples and $b = 2$ is a constant value.

The suspended load transport is solved in a simplified manner, by assuming the concentration profile to be in equilibrium. The inertia effects are not modelled and it is assumed that no exchange takes place with the bed load layer. After depth-integration and by assuming a Rouse profile for the concentration and a logarithmic velocity profile for the mean velocity profile ([13] and see Sisyphe user guide[19])

For Soulsby-Van Rijn's method the transport rate due to the combined action of waves and currents is provided by the following equation(6):

$$Q_{b,s} = A_{b,s}U\left[\left(U^2 + 2\frac{0.018}{C_D}U_0^2\right)^{0.5} - U_{cr}\right]^{2.4} \quad (6)$$

This formula can be applied to estimate the components of the total sand transport rate (bedload and suspended load), and it is suitable for beds covered by ripples. $A_{b,s}$ is a coefficient function of d_{50}, gravity and water and sediment density. U is the depth-averaged current velocity, U_0 is the RMS orbital velocity of waves, and C_D is the quadratic drag coefficient due to current alone. This formula has been validated assuming a rippled bed roughness with ks = 0.18 m. U_{cr} is the critical entrainment velocity.

Bailard's formula is based on the energetic approach. The bedload and the suspended load components of the sand transport rate are expressed respectively as the third- and fourth-order momentum of the near-bed time-varying velocity field, ,$\overrightarrow{U(t)}$ as follows (7, 8) :

$$Q_b = \frac{f_{c\omega}}{g(s-1)}\frac{\epsilon_c}{\tan\varphi}\langle|\vec{U}|^2\vec{U}\rangle \quad (7)$$

$$Q_S = \frac{f_{c\omega}}{g(s-1)}\frac{\epsilon_s}{W_S}\langle|\vec{U}|^3\vec{U}\rangle \quad (8)$$

with $f_{c\omega}$ the friction coefficient which accounts for wave-current interactions, ϵ_s = 0.02, ϵ_c = 0.1 empirical factors, φ sediment friction angle ($\tan\varphi = 0.63$) and $\langle\cdot\rangle$ time-averaged over a wave-period. g is the gravity and s the relative density (ρ_s/ρ_0, ρ_s sediment density and ρ_0 water density) and W_S is the fall velocity of the sediment.

The time step for Telemac is of 2 seconds and it is coupled with Tomawac and Sisyphe every 10 and 2 time step respectively. Morphodynamics evolution is taken into account to calculate currents and waves and currents are also taken into account for waves' generation.

III. RESULTS

A. In situ results

The measurement's campaign was characterized by conditions of moderate wave energy, wave height have ranged from less than 0.20 m to 0.93 m, the maximum height has been reached on the B3 bar down the beach .Waves heights show high variability across the foreshore, the heights decreasing to the upper beach due to the dissipation of waves energy when they are spread over the lower depths of the foreshore and because of their breaking on intertidal bars.

It is observed almost exclusively lifting of the waves in the troughs because the waves are reformed into depression following the flood on the lower bar. Hs/h reports are generally higher on the bars, because the thickness of the water layer is lower than in the troughs, but also because the wave height increases with the breaking that occurs preferentially on bars. This is particularly the case at bar B1, which was exclusively subject to breaking process and surf during these measurements. Only the device on bar B3 and B2 which were subject to all the process and have enough water depth can give a good estimation of the maximum ratio Hs/h (Fig. 2) which is about 0.5.

B. Simulations results

By extracting the waves' height, frequency and direction from the ADW S4 devices we can generate waves with a good precision. Multiple simulations were accomplished by varying the breaking index of the Battjes and Janssen's model (Fig .3, 4 and 5). These figures show that when γ_2= 0.25 (Fig. 3) the waves cannot propagate and growth properly and the breaking point occurs before the bar B3 and B2 which leads to small waves height over it with an error of more than 20%. For γ_2= 0.78 (Fig. 5) the waves seem to be in accordance in bar B3 but they do not break soon enough and grow too much at B2 with an error of 11%. The simulation with γ_2= 0.5(Fig. 4) gives results consistent with in situ measurements over each bar with an error lower than 5%. Simulations results for the sedimentary flows are summarizing in Tab .1, 2 and 3.

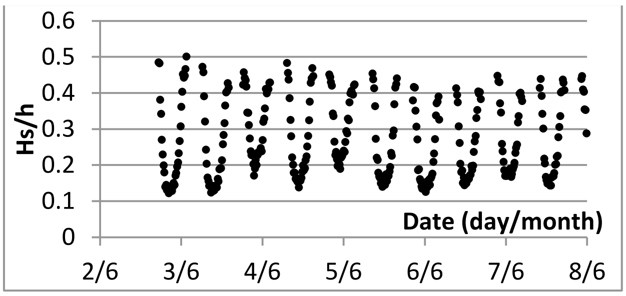

Figure 2. Hs over h for the bar B3

Bijker (Tab. I) and Bailard (Tab. II) formulas seem to overestimate the sedimentary flux in all position and for every γ_2 coefficients tested. Soulby -Van Rijn formulation (Tab. III) is more in line with in-situ results and the better values are obtain for γ_2=0.5 as for the waves simulation.

TABLE I. SEDIMENT FLUX WITH BIJKER FORMULA

Device	Sedimentary flux (kg/s/m)			
	Experimental	Simulation		
		Hs/h = 0.25	*Hs/h = 0.5*	*Hs/h = 0.78*
A	5,14E-03	2,52E-01	8,43E-01	2,06E+00
B	2,98E-03	1,34E-01	9,74E-01	2,74E+00
C	3,25E-02	4,63E-01	1,04E+00	4,43E+00
D	3,99E-02	1,61E-01	6,43E-01	1,39E+00

TABLE II. SEDIMENT FLUX WITH BAILARD FORMULA

Device	Sedimentary flux (kg/s/m)			
	Experimental	Simulation		
		Hs/h = 0.25	*Hs/h = 0.5*	*Hs/h = 0.78*
A	5,14E-03	2,88E-01	5,92E-01	4,17E+00
B	2,98E-03	3,34E-01	2,04E+00	2,35E+00
C	3,25E-02	4,24E-01	2,69E+00	2,15E+00
D	3,99E-02	9,13E-02	1,17E+00	3,71E+00

TABLE III. SEDIMENT FLUX WITH SOULSBY VAN RIJN FORMULA

Device	Sedimentary flux (kg/s/m)			
	Experimental	Simulation		
		Hs/h = 0.25	*Hs/h = 0.5*	*Hs/h = 0.78*
A	5,14E-03	1,86E-03	6,15E-03	8,40E-02
B	2,98E-03	1,05E-03	8,44E-03	1,45E-01
C	3,25E-02	2,05E-04	2,32E-02	5,67E-02
D	3,99E-02	6,27E-05	2,87E-03	6,19E-02

The results obtain for device A which correspond to bar B1 are less accurate than the other, this can be explained by the small water depth that never exceeds 1.0 m.

IV. CONCLUSION

The results obtained in this study show that the wave's breaking on a beach with intertidal bars and low slope occurs at lower indices breaking than those provided by a theoretical index such as McCowan. The comparison of fluxes measured in situ with the calculated flow highlighted the importance of choosing index breaking in transport modeling this type of beach, the best simulations results have been obtained with indices γ_2= 0.5, which correspond to the maximum Hs/h experimentally obtained during the measurement campaign. Results obtain with Sousby – Van Rijn's equation are in agreement with experimental but these obtain with Bijker and Bailard formulas are not accurate on such beaches.

The measurement campaign also provides us with wind data that have not been yet taken into account to generate current and swell.

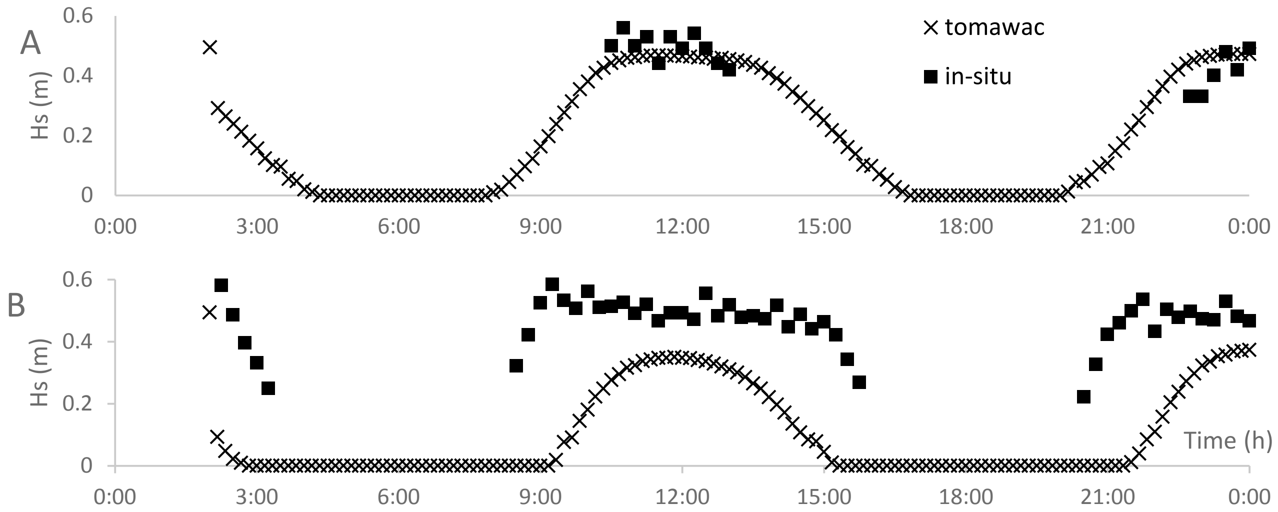

Figure 3. Wave height in function of time for Hs / h = 0.25 A) over bar B3, B) over bar B2

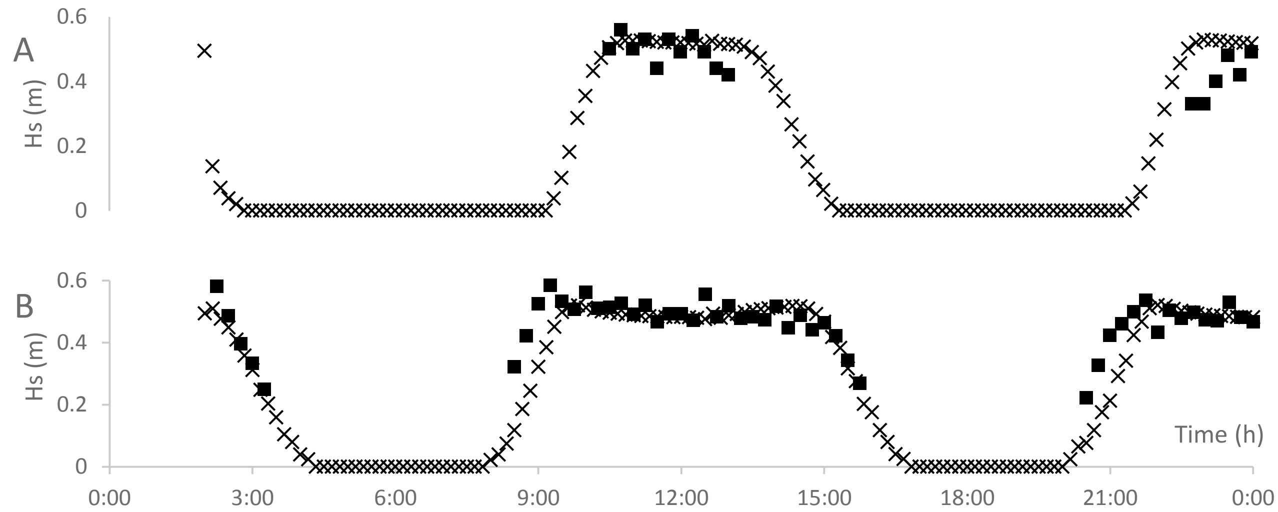

Figure 4. Wave height in function of time for Hs / h = 0.5 A) over bar B3, B) over bar B2

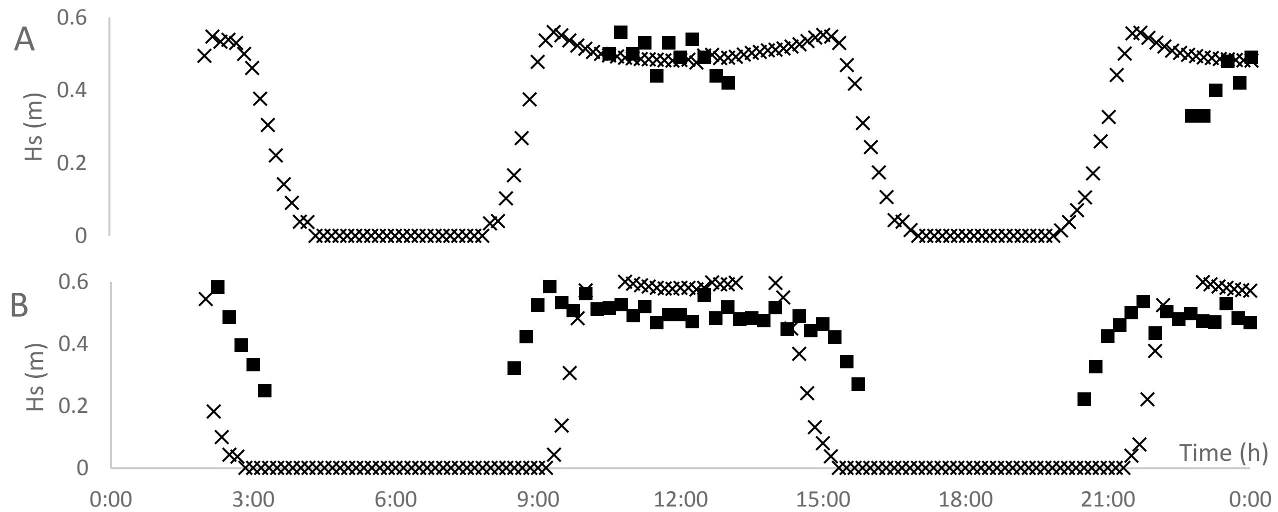

Figure 5. Wave height in function of time for Hs / h = 0.78 A) over bar B3, B) over bar B2

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