



UNIVERSITÀ
DEGLI STUDI
FIRENZE

FLORE

Repository istituzionale dell'Università degli Studi di Firenze

Efficacy of beach dewatering - Alassio, Italy

Questa è la Versione finale referata (Post print/Accepted manuscript) della seguente pubblicazione:

Original Citation:

Efficacy of beach dewatering - Alassio, Italy / BOWMAN D; FERRI S; E. PRANZINI. - In: COASTAL ENGINEERING. - ISSN 0378-3839. - STAMPA. - 54:(2007), pp. 791-800.

Availability:

The webpage <https://hdl.handle.net/2158/220163> of the repository was last updated on

Terms of use:

Open Access

La pubblicazione è resa disponibile sotto le norme e i termini della licenza di deposito, secondo quanto stabilito dalla Policy per l'accesso aperto dell'Università degli Studi di Firenze (<https://www.sba.unifi.it/upload/policy-oa-2016-1.pdf>)

Publisher copyright claim:

La data sopra indicata si riferisce all'ultimo aggiornamento della scheda del Repository FloRe - The above-mentioned date refers to the last update of the record in the Institutional Repository FloRe

(Article begins on next page)

Efficacy of beach dewatering — Alassio, Italy

Dan Bowman^{a,*}, Serena Ferri^b, Enzo Pranzini^b

^a Ben-Gurion University of the Negev, P.O.B. 653, Beer Sheva 84105, Israel

^b Università degli Studi di Firenze, Dipartimento di Scienze della Terra, Borgo Albizi 28, 50122 Firenze, Italy

Received 13 November 2006; received in revised form 13 April 2007; accepted 14 May 2007

Available online 3 July 2007

Abstract

The goal of this study is to estimate the efficiency of dewatering operations in Alassio Beach, north Italy by following an integrated approach which included beach volume calculations, daily mapping of the shoreline position, examination of specific beach widening events and daily comparisons of morphodynamic characteristics of the drained beach versus a control section which included wave run-up, bar patterns, rip migration, evolution of the berm and cusp morphology.

Alassio beach was documented by a daily time-lapse photography, by repeated DGPS profile measurements and by an hourly wave and sea level monitoring. Following one year of draining the shoreline position and the beach volume of the drained beach and the control section showed little differences; i.e., accumulation of $0.28 \text{ m}^3/\text{m}^2$ and a shoreline advance of 1.1 m on the drained beach, whereas on the control beach the volume change was $-0.03 \text{ m}^3/\text{m}^2$ and the shoreline retreated 1.2 m. Short episodes of beach widening, 1–7 days long, which coincided with onshore bar movement and a relative low sea level, occurred simultaneously on the drained and the control sector. This data indicated the inefficiency of the draining operation.

An improved resolution for determining the draining effect was attained by the sequential snap-shot photography which showed many systematic morphological differences between the drained beach and the reference segment. The drained beach developed a berm crest and a linear, often scarped foreshore with a narrow swash zone. No such cumulative morphologies were observed on the non-drained control beach, which commonly displayed cusps that were usually absent on the drained foreshore.

The wave data showed recurrent medium wave events of $H_s=1\text{--}2 \text{ m}$, which repeatedly interrupted the calms thus “cutting-off” the beach evolution. The draining in Alassio was unable to promote beach accumulation by counteracting the erosive effect of the medium interrupting storms.

© 2007 Published by Elsevier B.V.

Keywords: Beach drain; Beach morphodynamics; Italy coast

1. Introduction

Beach groundwater dynamics (Horn, 2002) show positive correlation between elevated beach groundwater table and intensified erosion (Turner and Leatherman, 1997). Field experiments have shown that a high water table reduces swash infiltration and corresponds to enhanced offshore sediment transport (Hegge and Masselink, 1991). Draw down of the water table below the beach face promotes infiltration and reduces the duration, the volume and the mean and maximal

flow velocities of the backwash and thus promotes deposition and steepening of the foreshore. When fluctuations of the capillary fringe extends to the beach surface, following wave run-up, fluctuations in the pore pressure may occur which do not reflect the magnitude of the rise and fall of the water table (Turner and Nielsen, 1997).

Percolation into the unsaturated beach face during the sudden arrival of the uprush causes reduction in the strength of the backwash, inducing downward directed pressure gradients which increase the stabilizing drag on the sediment (Masselink and Puleo, 2006). However, the infiltration has opposing effects (Nielsen et al., 2001): When the boundary layer is reduced, following increased infiltration, the turbulence is maintained closer to the bed in the thinned boundary layer, thereby

* Corresponding author. Tel.: +972 545 225 491; fax: +972 8 6472821.

E-mail addresses: dbowman@bgu.ac.il (D. Bowman), serena.ferri@unifi.it (S. Ferri), epranzini@unifi.it (E. Pranzini).

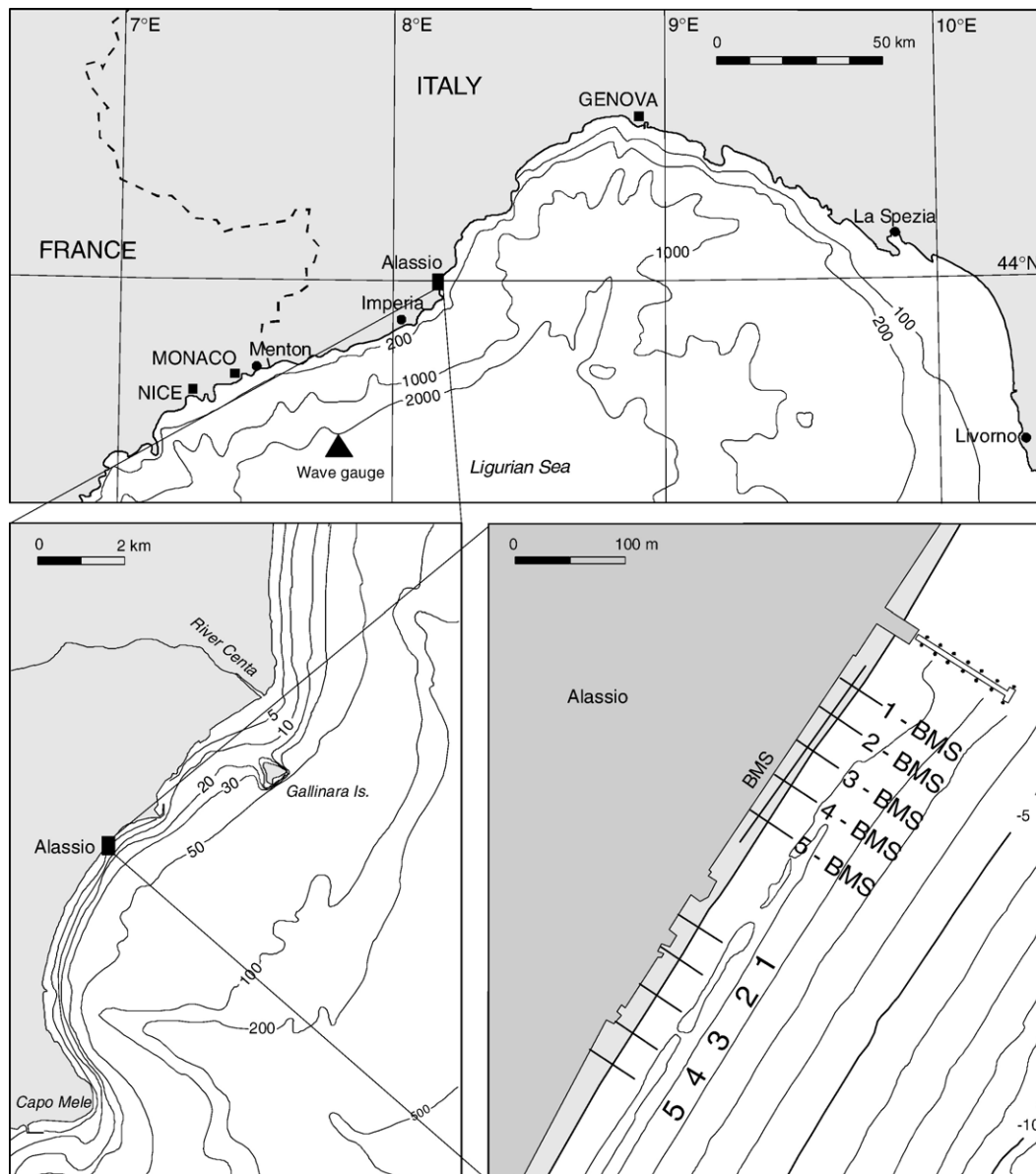


Fig. 1. Location maps of Alassio on the Gulf of Genoa: The study area includes the drained beach with the BMS and a southern control section. The promenade and the front of the city are indicated at the backshore. The cameras were located on a hotel protruding towards the waterline between the two studied beach segments.

increasing the potential shear stress and the sediment entrainment. Conley and Inman (1994) demonstrated that during backwash, exfiltration will thicken the boundary layer and thus bias the net transport onshore.

The beach draining systems in former experiments have been installed 2–3 m below mean sea level and 5–15 m inland (Vesterby, 1994), the position of the water table was monitored, beach profiling was undertaken and the volumetric beach changes were calculated. However, contrasting results have been obtained in different test sites. In some field experiments (Dean, 1990) positive results have been obtained and beach accretion reached $30 \text{ m}^3/\text{m}$, whereas in other cases no beach response was observed (Turner and Leatherman, 1997).

Although some morphological response was frequently observed in former experiments such as increase in beach elevation and in the steepness of the swash zone, the field evidence remained inconclusive. Bruun (2005) concluded that dewatering sites should at present be regarded as experimental, rather than a solution to beach erosion.

The goal of this study is to estimate the efficiency of the dewatering operations in Alassio Beach, north Italy, by following an integrated approach which includes monitoring the beach volume and the shoreline changes and comparing the morphology of the drained beach versus a control section. Our rationale is to proceed by examining specific beach widening episodes and finally to focus on the morphodynamic beach behavior.

2. Study area

Alassio beach is located on the Italian Western Riviera in the Gulf of Genoa, Lat. 44° N, L. 8.2° E (Fig. 1). It is a 3-km-long sandy beach in front of the town. The backshore is constrained by a promenade and buildings. The nearshore, within the 8 m contour, slopes approximately 1.5° and becomes 4.5° at a water depth of 10 to 20 m, where some bedrock outcrops. The beach and the nearshore are linear and regular, without alongshore topographical variations.

In February 2004, a 198-m-long Beach Management System (BMS) was installed in the beach at a depth of 1.5 m, 45 cm below MSL, and became operative on 1 March 2004. The diameter of its draining pipe was 160 mm and the volume which was drained ranged 60–100 L/s making the maximal drain 0.5 L/s/m beach front.

A 140 m-long pier for pedestrians is located to the north of the study area. Except for the nearest 20 m which are of concrete, the pier is built on piles (Fig. 1) and does not interfere with the longshore sediment flux. Shoreline mapping during the study period and daily snap-shot photography confirmed that neither accumulation nor erosion occurred south to the pile-based pier, except at the immediate surrounding of the concrete. The drained segment did therefore not include the beach section by the concrete. A 200-m-long control beach was defined to the south of the drained section.

Long-term wave data for Alassio is available from KNMI (Koninklijk Nederland's Meteorologist Institute), based on ship observations during the period 1961–1980. In the Western Ligurian Sea, waves of $H_s < 0.81$ m make up to 80%, and 99% of the waves are of $H_s < 2.5$ m. The fetch for the highest waves is centered on 240° . The tidal range in the Ligurian Sea was in 2003 0.32 m, measured in Imperia.

A detailed reconstruction of the shoreline migration in Alassio for the period 1973–2004, based on air photos and beach surveys, showed that the shoreline migrated 1.6 m seawards and 0.9 m landwards, making a total range of 2.5 m without any systematic trend. Such shoreline behavior indicates an equilibrium state.

Alassio beach is dominated by fine sand (2–3 phi) and is well to very well sorted ($\sigma_1 < 0.5$). Good sorting of beach

sediments enhances permeability (Norstrom, 1992; Masselink and Li, 2001) which may increase the rate of run-up infiltration losses. A typical bar and trough morphology is demonstrated by the spatial distribution of the coarsest sand percentile and by sorting.

3. Methods

Six hundred and twenty meters of Alassio beach were monitored on a daily basis during one year, from March 2004 to March 2005. Time-lapse photography was used during daylight hours by two cameras, deployed simultaneously on the roof of a hotel on the beach between the drained segment and the reference beach to its south (Fig. 1). Oblique instantaneous snap-shots and long time exposures were taken daily within the hours 7:00–8:00, 11:00–12:00, 15:00–16:00.

All photos were geocoded to plan view in the Gauss-Boaga UTM reference system. The photos discerned in detail the preferred breaking over the nearshore bars and revealed, by the foam pattern, the number, position, linearity and the rhythmicity of the bars and the troughs. The gaps in the bars and the erosional bays along the shoreline enabled to record the rip channels, their pattern and migration. Bars in the very shallow inshore, by the shoreline, were often directly visible on the photos. The beach width and the cusp morphology were measured on the geocoded photos. In order to avoid, as far as possible, the shortcoming of subjective visual morphodynamic definitions, no use was made of pictures which did not clearly show the above mentioned details.

The shoreline was defined as the mid-swash zone and was traced daily on the rectified photos along the reference beach and the drained segment. The validity of the shoreline mapping was tested by comparison to a ground truth shoreline located by DGPS. The results showed a deviation in the range of ± 0.7 m. The shoreline mapping was therefore held accurate to a 1 m resolution.

The morphology which was shown in the camera-derived images revealed the nearshore evolution simultaneously on the drained and on the reference beaches. The beach morphology was related to the wave climate through hourly monitoring during the

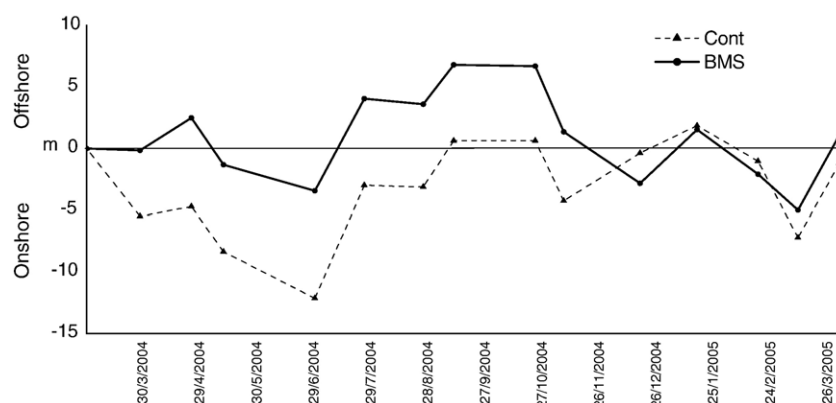


Fig. 2. Migration of the shoreline at the drained beach compared to the reference section.

entire study period of H_s , T_s and the barometric pressure, recorded at the nearest buoy station in the Ligurian Sea, by the Cote d'Azur buoy of the Meteo-France organization, located 73 km south-west of Alassio, at $43^\circ 22.89'N/07^\circ 49.68'E$, at a water depth of 2300 m (Fig. 1). The deep-water wave data was collected by a Datawell BV model Mark II. Travel time of the waves from the buoy to Alassio beach was 1.5–2.5 h. The longest storm waves reached the coast within less than 1 h.

Beach and nearshore sediments were sampled twice: 142 samples on 12 February 2004 and 144 samples on 19 November 2004. Sampling was done along a grid of 16 cross-shore transects to a water depth of 6 m. The samples were sieved in 1/2 phi intervals and the statistical parameters were calculated following Folk and Ward (1957). On the beach more than 2000 points were surveyed with Javad DGPS, using the RTK procedure. This data set served to extract 5 profiles, up to 25-m-long, across the foreshore of the drained and the control beaches, in February 2004 before the installation of the drainage system, in June and December 2004 and on March 2005, after one year of operation. A 1×1 m grid was generated to produce DTMs for each survey and calculate the volume changes.

Based on the hourly wave data throughout the year, we grouped the wave heights into three categories: calms ($H_s < 1$ m), medium wave energy ($1 \text{ m} < H_s < 2$ m) and storms ($H_s > 2$ m). A monthly mean calm shoreline was mapped, based on five consecutive calm days each month. The mapping showed that under calm wave conditions the BMS was located on the foreshore, 5–12 m from the shoreline. We further mapped the mean shoreline of 14 days of medium wave energy and of 15 storms. All shoreline elevations

included astronomical and barometric tides, superimposed on the wave setup. Swash marks of 6 storms have been mapped which indicate the total water level (Gourlay, 1992), which is a combination of the swash fluctuations superimposed on the tide elevation and on the wave induced set up.

4. Results

4.1. Overflooding of the foreshore and the BMS

The range of shoreline migration during the study period was 13 m. After one year the drained beach showed a net advance of only 1.1 m/year whereas the control beach regressed 1.2 m/year (Fig. 2). The daily shoreline mapping, when related to the hourly wave data, showed that run-up triggered by calm wave events of $H_s < 1$ m did not reach the BMS. Shorelines reached the BMS but did not significantly overrun it during medium events (Fig. 3). Shorelines which overran the BMS were triggered by storms of $H_s > 2$ m (Figs. 3 and 4). However, not all the medium wave events reached the BMS and not all the storms overran it. Former data from natural beaches that showed positive relation between extreme run-ups and the incident significant wave heights, demonstrated similar great scatter and a very low regression coefficient $r < 0.1$ (Holman, 1986).

Our data suggests the 2-m wave height as a rough threshold for significantly overflooding the foreshore including the BMS. The annual hourly wave data indicated 1075 h of such and higher waves, i.e., the foreshore including the BMS were overflooded

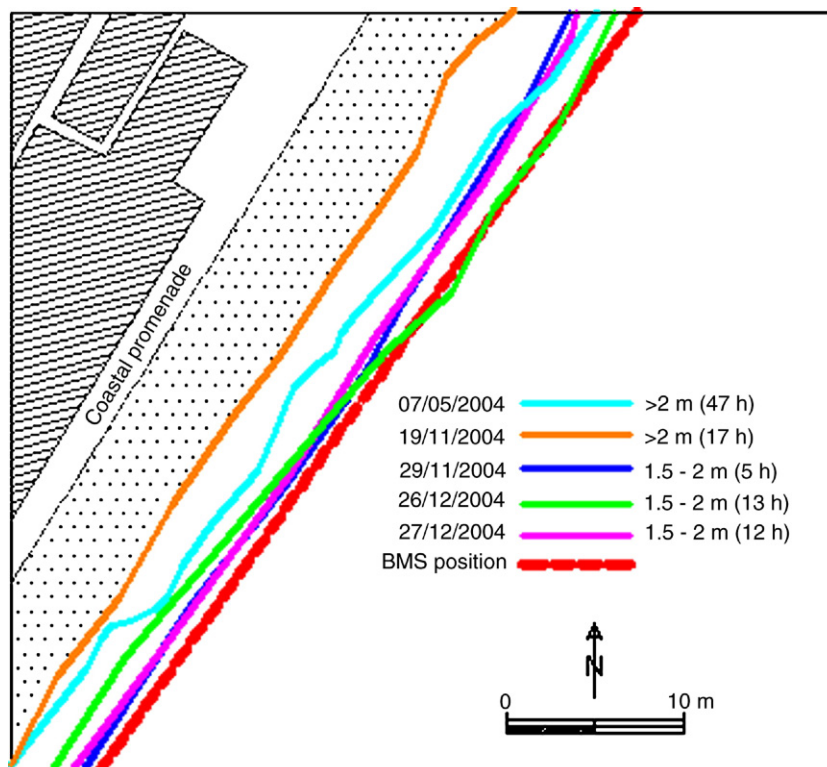


Fig. 3. Shoreline mapping: During medium wave energy ($1 \text{ m} < H_s < 2 \text{ m}$) the waterline reached the BMS without significantly over running it. During storms ($H_s > 2 \text{ m}$) the waterline reached higher up.

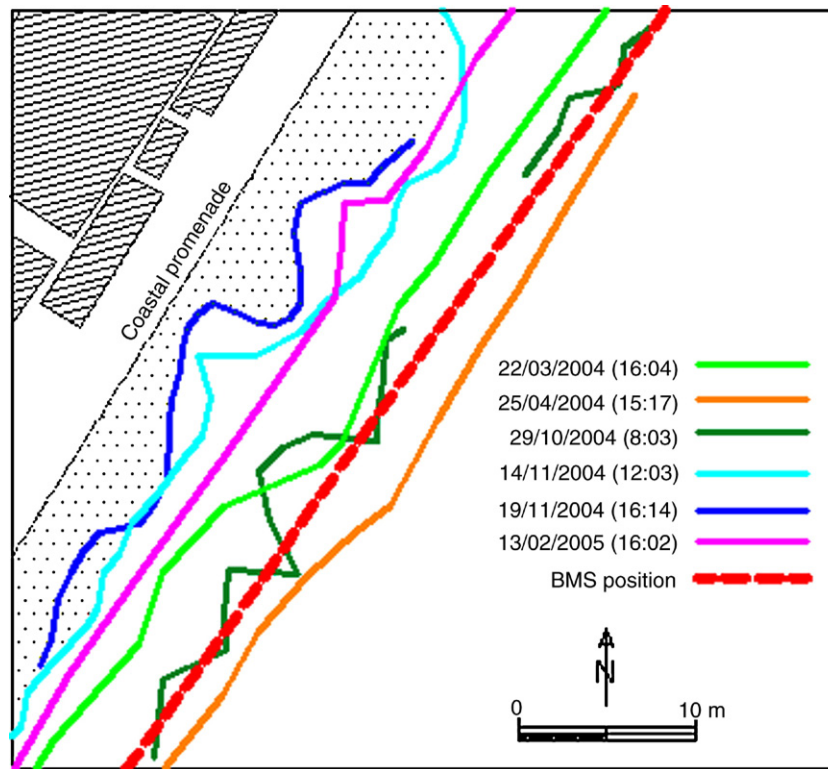


Fig. 4. Swash marks mapping: Those which over ran the BMS and reached the berm were of storms ($H_s > 2$ m). The swash marks of April and October relate to events with $H_s = 1\text{--}1.3$ m.

during 12% of the year. As the BMS system is not designed for draining below water level, these overflowing events, which provide the largest potential for beach erosion, were not counteracted by draining.

4.2. Beach widening following calm conditions

Beach widening was often reported following calm periods (Wright and Short, 1984; Short and Aagaard, 1993). In Alassio a very long calm period occurred during mid-summer (13/7–12/8/2004) and induced a widening of about 2 m. Another calm, almost 3-week-long, caused beach widening of 3–5 m. The widest beach in the drained segment (21 m) was formed during a long calm (Fig. 5). These beach widening episodes occurred simultaneously on both the drained and on the reference beach when the Transverse Bar and Rip (TBR) and the Rhythmic Bar and Beach (RBB)

morphodynamic modes dominated (Short, 1979; Short, 1999; Wright and Short, 1984). Bars often became attached to the lower foreshore, composing the Low Tide Terrace (LTT) or the Ridge and Runnel morphodynamic mode. Pronounced shoreline undulations, composed of rhythmic rip bays and horns, caused a great variability in the position of the BMS in relation to the swash zone.

4.3. Short widening episodes

We focused on two short widening episodes: a) widening of beach horns between rip embayments which occurred simultaneously along the dewatered and the control beach and coincided with a sea level fall of 15 cm. This episode widened the beach by 11 m, which is an extreme change, compared to all previous widening events. It lasted 1 week (15 ÷ 21/5/04, Fig. 6) after which the beach returned to its former width. b) A second

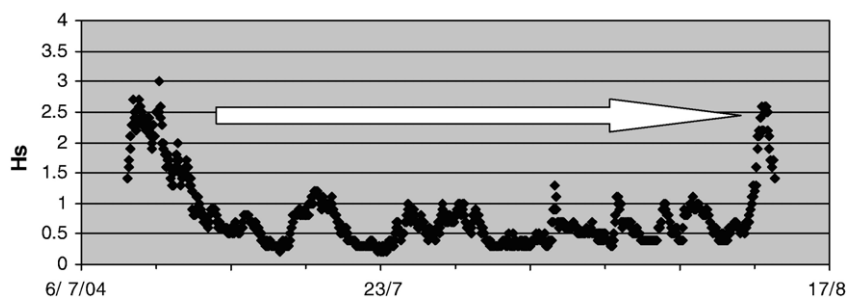


Fig. 5. Time series of deep-water significant wave heights covering the calm period 13/7–12/8/04 (arrow) which was dominated by the TBR morphodynamic mode and formed the widest beach in the drained section.

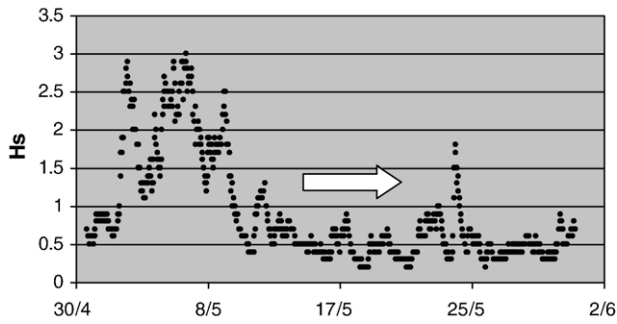


Fig. 6. Time series of deep-water significant wave heights, covering the beach widening episode of 15–21/5/04. The arrow indicates the calm period ($H_s < 1.0$ m).

episode which lasted only one day (30/8/2004) also coincided with a low sea level and widened the beach by 4 m.

4.4. Beach morphology

Comparisons of the beach segments before the draining started (February 2004) and after one year of draining (March 2005), based on five profiles on the drained and the control beach, demonstrated that within 5 m from the waterline the drained beach gained in all the transects 30–40 cm in altitude (Fig. 7). The control beach showed after one year a small net erosion.

The daily photography during the draining period showed a high-crested berm with a steep foreshore (Fig. 8A), more frequently on the drained beach than on the control beach which exhibited a wide flat and wet foreshore. The crest on the drained

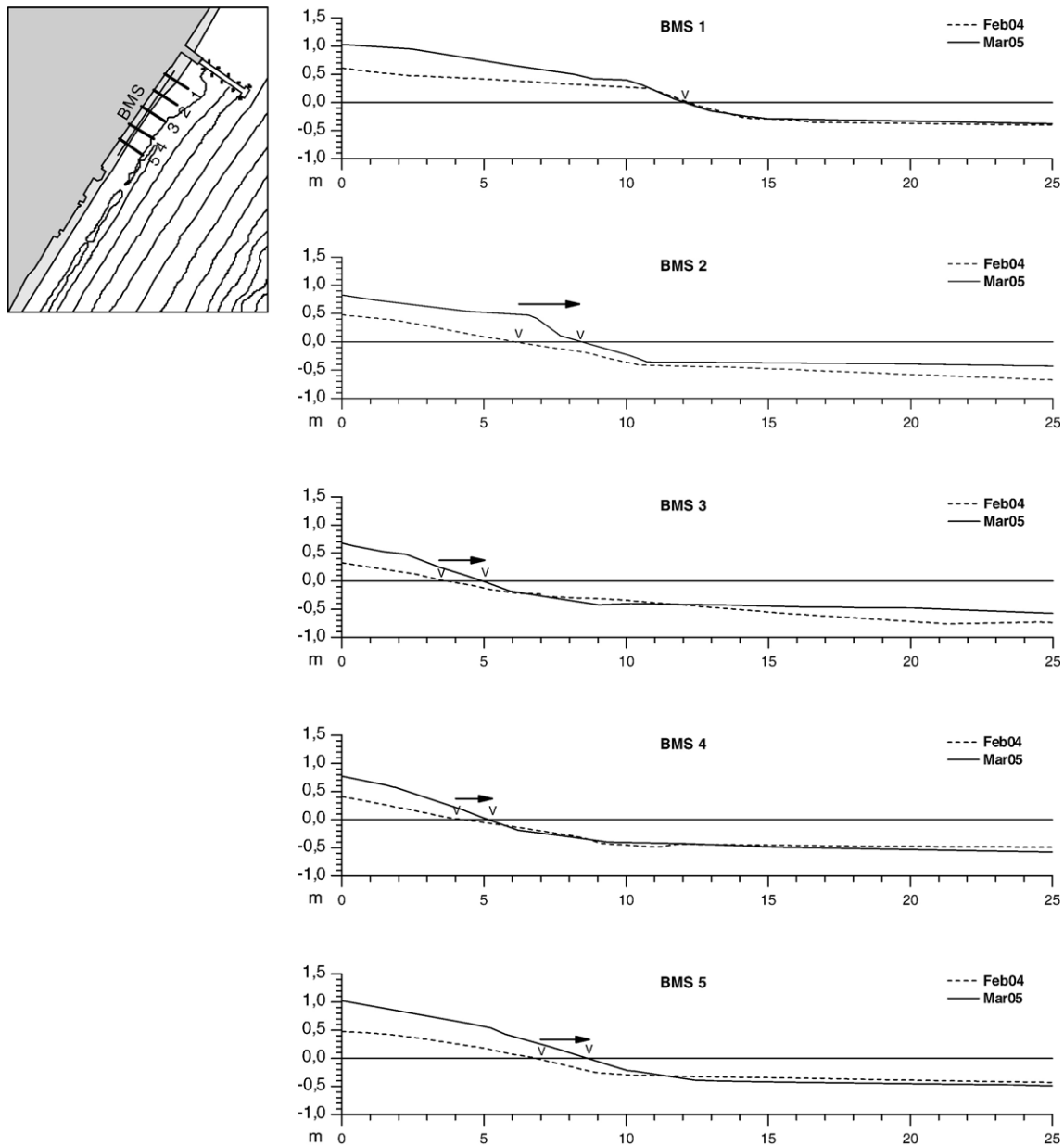


Fig. 7. Foreshore profiles across the drained beach and the control segment showing the annual net change during the study period (February 2004 compared to March 2005). Note a berm formed on the drained beach and a small (< 2 m) progradation. The control beach shows a small retreat.

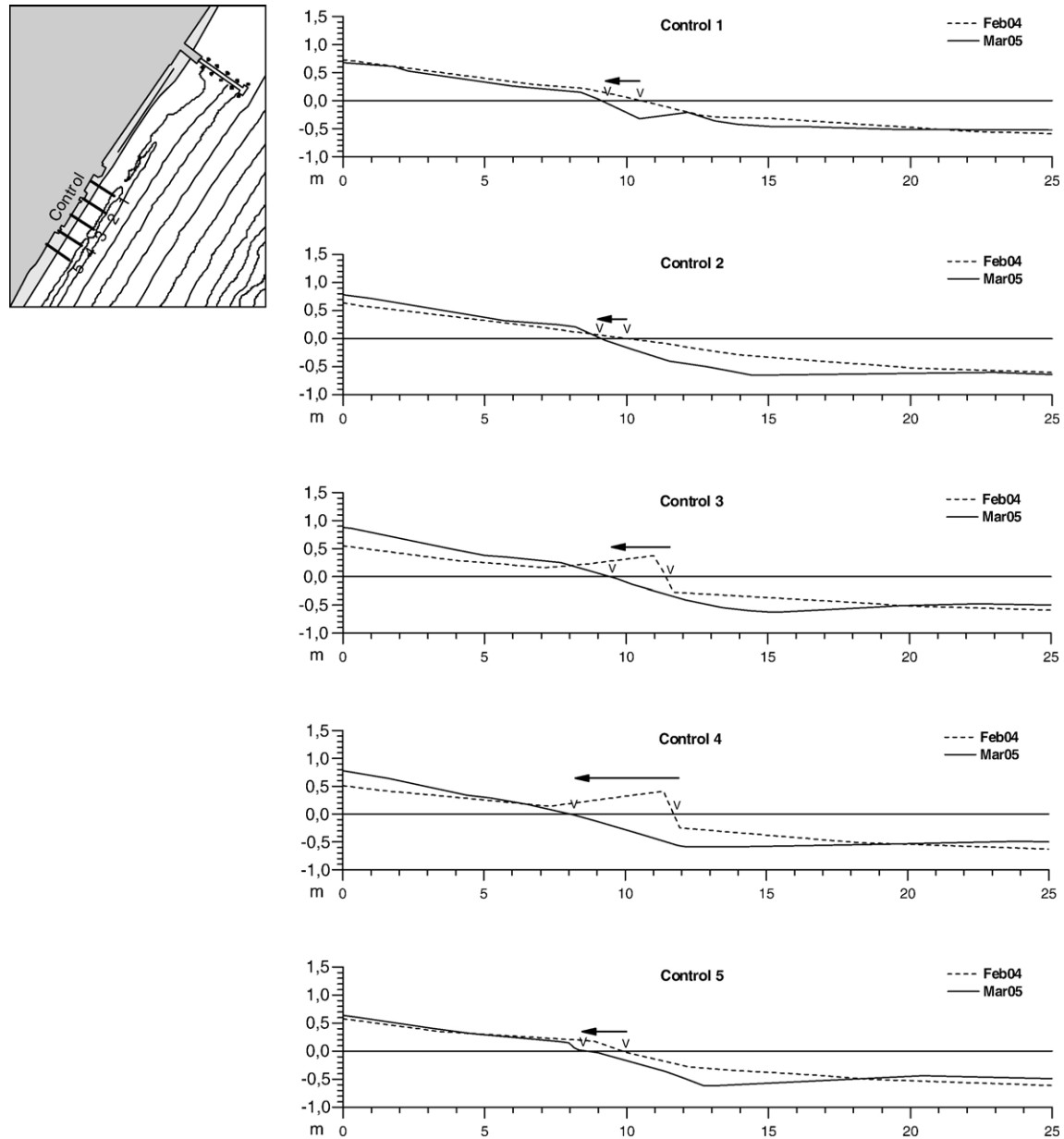


Fig. 7 (continued).

berm was usually narrower, sharper and more continuous. In the most accumulative periods, sharp crests were, however, also observed on the reference beach.

The drained beach developed a linear, often steeply scarped berm front. Beach scarps were almost never observed on the southern reference beach. The berm surface of the experimental beach became often whitish, pointing to desiccation and its run-up zone was systematically narrow. These characteristics were neither observed along the non-drained reference segment (Fig. 8B) nor along other beach segments in front of the town.

4.5. Cusp formation

Regularly-spaced, rhythmic swash cusps were observed on 35 days. In 9 cases, when the wave climate was stormy with

$H_{smax}=2\text{--}4.5\text{ m}$, the swash cusps were formed on both the drained and the reference beaches. The main group of 22 cusp events occurred only on the reference beach, while the drained segment remained completely cusp-free (Fig. 9A,B). The typical significant wave heights during these cusp events were mainly in the medium, $0.8\text{ m} < H_s < 2\text{ m}$ range (Fig. 10). The cusps were 6–15 m in length and looked as backwash furrows, starting to cut the beach face.

5. Summary and conclusions

After one year of monitoring, the volumetric beach change on the drained beach amounted to $+0.28\text{ m}^3/\text{m}^2$ whereas on the control section the change was negligible $-0.03\text{ m}^3/\text{m}^2$. The drained beach advanced only 1.1 m whereas the control beach regressed 1.2 m (Fig. 2). These are small quantitative

differences which indicate neither significant gain in beach area nor increase in the sediment volume.

In addition to the shoreline mapping and the calculation of the beach volumes, we applied morphodynamic observations which improved our resolution to estimate the draining effect. The Webcam showed that Alassio gained its maximal beach width by welding of transverse bars onto a cuspidal shoreline with extended embayments and horns. The onshore bar migration in the surf, which caused the widening, could not be controlled by draining. Furthermore, the sea level fluctuations, caused by tide and barometric pressure, ranged during the study period ± 0.4 m. The short beach widening events fit periods of relative low sea levels (Fig. 11), suggesting that the low sea caused the exposure of the onshore moving bars and “widened” the beach. In their study of the flat beaches of the Ebro Delta, Jimenez et al. (1997) reached similar conclusions. They showed that in very gentle and shallow nearshore conditions, small meteorological water level oscillations may produce fictitious shoreline displacements.

We conclude that the simultaneous widening of the drained and the non-drained beaches suggests the irrelevance of the

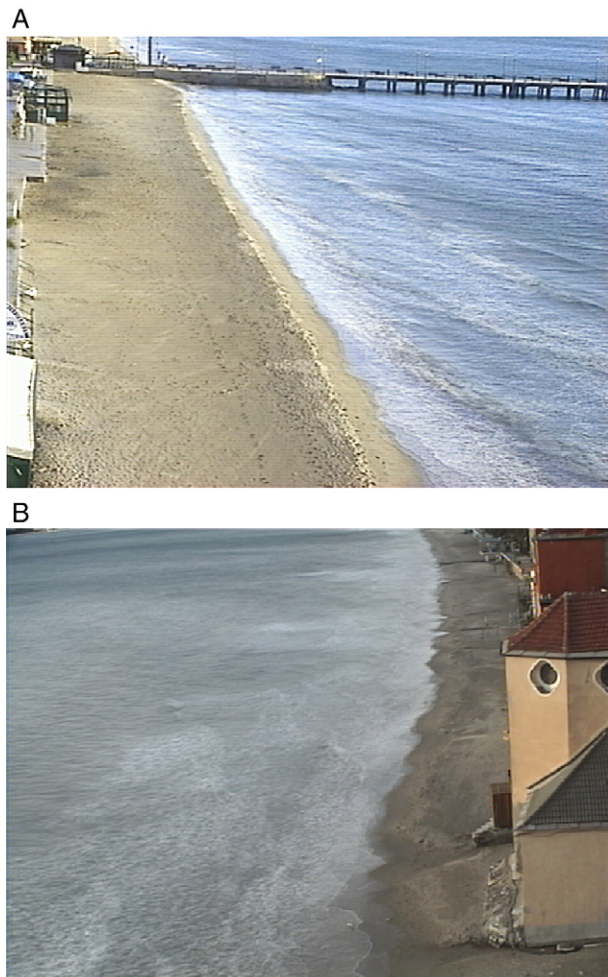


Fig. 8. 31/10/04 at 08:03, A: The typical berm of the drained beach with a sharp crest and a narrow swash zone. B: None of these characteristics is observable simultaneously on the reference beach.



Fig. 9. 28/9/04 at 8:03: A: Typical swash cusps over the reference beach compared to B: the simultaneous foreshore of the drained segment.

draining operation. The brief widening, the coincidence with the morphodynamic TBR stage of onshore moving bars and with the low sea level events contributes an explanation.

In spite of the inefficiency of the dewatering to trigger significant beach accumulation, we observed draining effects. Shoreline migrations on the drained beach showed less regression in the spring and more progradation in summer compared to the control section, although in winter no differences could be observed (Fig. 2). The Webcam provided many examples of systematic morphological differences between the drained and the reference beach. The drained segment typically demonstrated accretional features whereas the reference beach was systematically flatter, although accretion was here also not completely absent. Images of the drained beach often showed a steep foreshore and a dry berm surface. Citizens reported inconvenience in crossing the steep foreshore of the drained beach, claiming that they did not experience such hardship before. The swash zone of the drained beach was narrow and cusps were observed less frequently. Simultaneously, the non-drained reference beach demonstrated systematically a truncated, flat, wide and wet foreshore, usually without a sharp berm crest

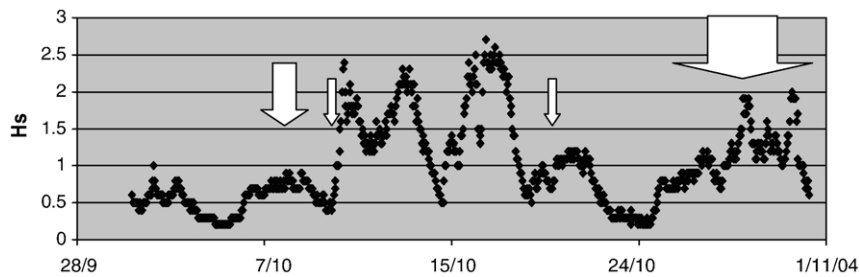


Fig. 10. Occurrence of swash cusps (arrows) during October 2004. The cusp formed in the wave climate range of $0.8 \text{ m} < H_s < 2 \text{ m}$.

and often with cusps. Similar results, i.e., development of a berm and steepening of the beach face, were observed in two-dimensional draining experiments by Ogden and Weisman (1991) and Weisman et al. (1995).

Episodes of shore-attached bars and a rhythmic shoreline (RBB and TBR beach modes) with a beach widening of 2–5 m developed in Alassio following calms of 2–4 weeks (Fig. 5). In Duck, at the Outer Bank of North Carolina (Lippmann and Holman, 1990), with $H_{s, \text{mean}} = 0.58\text{--}1.75 \text{ m}$, development of these morphological modes required similar length of post storm calms. In both cases a minimum calm period of about 2 weeks was necessary for some beach widening. In Alassio, the reoccurring two or three medium wave events or storms per month (Figs. 6 and 10) left 10 days or less of continuous calm, which are not enough for a significant onshore movement of bars and for beach widening. The morphodynamic evolution in Alassio was “cut off” by medium wave events and storms which the draining operation was unable to counteract. Such events, which intermittently prevented the evolutionary beach widening, were defined as “resets” by Ranasinghe et al. (2004) and “complex cycles” by Short (1979). The inefficiency of the dewatering system to counteract the erosive effect of these reoccurring medium storms and thereby failing to “lengthen” the calm interval, must have contributed to the poor beach widening of Alassio.

Previous studies highlighted erosion as the main cusp-forming mechanism (Smith and Dolan, 1960; Miller et al.,

1989). Cusp formation by edge waves (Guza and Inman, 1975; Inman and Guza, 1982) is also an erosive process. The breaching of the beach ridge or berm, as a trigger for cusp development was suggested by Sallenger (1979), Dubois (1978) and Pyokari (1982). Cusps, although not as small as ours, have been also reported by Wright and Short (1983) as indicators of the early stage of beach front truncation. However, other studies attributed cusp formation to accretion processes only (Sato et al., 1992; Masselink et al., 1997). In Alassio, the relative absence of cusps on the drained segment is suggested as an indication of the efficiency of the draining to prevent erosion on the foreshore during some medium wave energy events of $H_s < 2 \text{ m}$. At such wave energy cusps are expected to form (Short, 1979; Holland, 1998).

Masselink and Li (2001) reported on some indications in the literature (Bagnold, 1940; Dubois, 1972) that swash infiltration starts playing a significant role when the beach sediment is relatively coarse and that in relatively fine sediments, swash infiltration does not control the beach face morphology. Their numerical model (Masselink and Li, 2001) firmly substantiates the claim that swash acting on beaches with coarse sediments produces enhanced swash infiltration. The threshold hydraulic conductivity that emerged in their study corresponds to a sediment size of 1.5 mm, i.e., swash infiltration has negligible effects on sandy beaches, where the sediment grain size is usually less than 1 mm. This data suggests that in Alassio, as in similar former draining experiments, the accretion effects of swash infiltration were not sufficiently large partly because of the too low hydraulic conductivity of the too fine sandy beaches.

The Alassio experience suggests that it is not only the physical processes within the shoreface which should be investigated in depth (Turner and Leatherman, 1997). It is important as well to determine the storms which mark the threshold for an effective draining. Morphological monitoring during draining operations can contribute in resolving the draining efficacy.

References

- Bagnold, R.A., 1940. Beach formation by waves: some model experiments in a wave tank. *J. Inst. Civ. Eng.* 15, 27–52.
- Bruun, P., 2005. Beach drain. In: Schwartz, M.L. (Ed.), *Encyclopedia of Coastal Science*. Springer, pp. 138–140.
- Conley, D.C., Inman, D.L., 1994. Ventilated oscillatory boundary layer. *J. Fluid Mech.* 273, 261–284.

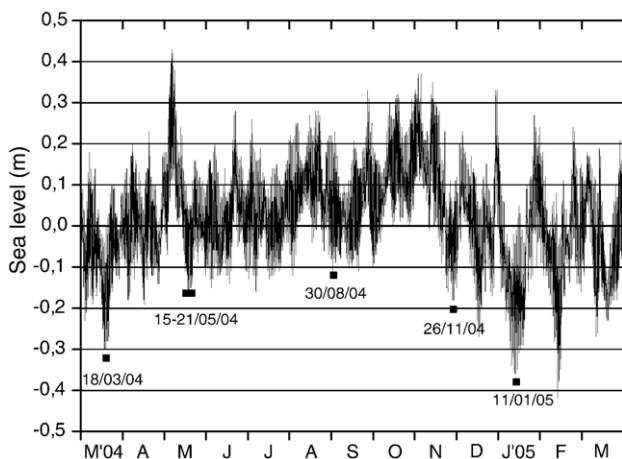


Fig. 11. Brief episodes of beach widening during the study period, related to the sea level fluctuations recorded by the Italian mareograph at Imperia, west to Alassio. In many cases the beach widening episodes fit low sea levels.

- Dean, R.G., 1990. Independent analysis of beach changes in the vicinity of the Stabeach system at Sailfish Point, Florida. Report Prepared for Coastal Stabilization Inc. (16 pp).
- Dubois, R.N., 1972. Inverse relation between foreshore slope and mean grain size as a function of the heavy mineral content. *Geol. Soc. Amer. Bull.* 83, 871–876.
- Dubois, R.N., 1978. Beach topography and beach cusps. *Geol. Soc. Amer. Bull.* 89, 1133–1139.
- Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. *J. Sediment. Petrol.* 27, 3–26.
- Gourlay, M.R., 1992. Wave set-up, run up and beach water table: interaction between surf zone hydraulics and groundwater hydraulics. *Coast. Eng.* 17, 93–144.
- Guza, R.T., Inman, D.L., 1975. Edge waves and beach cusps. *J. Geophys. Res.* 80, 2997–3012.
- Hegge, B.J., Masselink, G., 1991. Groundwater-table response to wave run up: an experimental study from Western Australia. *J. Coast. Res.* 7, 623–634.
- Holland, K.T., 1998. Beach cusp formation and spanning at Duck, USA. *Cont. Shelf Res.* 18, 1081–1098.
- Holman, R.A., 1986. Extreme value statistics for wave run up on a natural beach. *Coast. Eng.* 9, 527–544.
- Horn, D.P., 2002. Beach groundwater dynamics. *Geomorphology* 48, 121–146.
- Inman, D.L., Guza, R.T., 1982. The origin of swash cusps on beaches. *Mar. Geol.* 49, 133–148.
- Jimenez, J.A., Sanchez-Acrilla, A., Bou, J., Ortiz, M.A., 1997. Analysing short-term shoreline changes along the Ebro Delta (Spain) using aerial photographs. *J. Coast. Res.* 13, 1256–1266.
- Lippmann, T.C., Holman, R.A., 1990. The spatial and temporal variability of sand bar morphology. *J. Geophys. Res.* 95, 11,575–11,590.
- Masselink, G., Li, L., 2001. The role of swash infiltration in determining the beach face gradient: a numerical study. *Mar. Geol.* 176, 139–156.
- Masselink, G., Puleo, J.A., 2006. Swash-zone morphodynamics. *Cont. Shelf Res.* 26, 661–680.
- Masselink, G., Hegge, B.G., Pattiaratchi, C.B., 1997. Beach cusp morphodynamics. *Earth Surf. Processes Landf.* 22, 1139–1155.
- Miller, J.R., Miller, S.M.O., Torzynski, C.A., Kochel, R.C., 1989. Beach cusp destruction, formation and evolution during and subsequent to an extra tropical storm, Duck, North Carolina. *J. Geol.* 97, 749–760.
- Nielsen, P., Robert, S., Moeller-Christiansen, B., Oliva, O., 2001. Infiltration effects on sediment mobility under waves. *Coast. Eng.* 42, 105–114.
- Norstrom, K.A., 1992. *Estuarine Beaches*. Elsevier. (225 pp).
- Ogden, M.R., Weisman, R.N., 1991. Beach stabilization using drains: an experimental model study. *Proc. Coastal Sediments '91. Am. Soc. Civ. Eng.* 1955–1969.
- Pyokari, M., 1982. Breaching of a beach ridge and the formation of beach cusps. *Can. Geogr.* 26, 332–348.
- Ranasinghe, R., Symonds, G., Black, K., Holman, R., 2004. Morphodynamics of intermediate beaches: a video imaging and numerical modeling study. *Coast. Eng.* 51, 629–655.
- Sallenger, A.H., 1979. Beach cusp formation. *Mar. Geol.* 29, 23–37.
- Sato, M., Kuroki, K., Shinohara, T., 1992. A field experiment on the formation of beach cusps. *Proc. 23rd Inter. Conf. on Coast. Eng. ASCE*, pp. 2205–2218.
- Short, A.D., 1979. Three-dimensional beach stage model. *J. Geol.* 87, 553–571.
- Short, A.D., 1999. *Handbook of Beach and Shoreface Morphodynamics*. Wiley. (379 pp).
- Short, A.D., Aagaard, T., 1993. Single and multibar beach change models. *J. Coast. Res.* 15, 141–157.
- Smith, D.J., Dolan, R.G., 1960. Erosional development of beach cusps along the Outer Banks of North Carolina. *Geol. Soc. Amer. Bull.* 71.
- Turner, I.L., Leatherman, S.P., 1997. Beach dewatering as a “soft” engineering solution to coastal erosion—a history and critical review. *J. Coast. Res.* 13, 1050–1063.
- Turner, I.L., Nielsen, P., 1997. Rapid water-table fluctuations within the beach face: implications for swash zone sediment mobility. *Coast. Eng.* 32, 45–59.
- Weisman, R.N., Seidel, G.S., Ogden, M.R., 1995. The effect of water table manipulation on beach profiles. *J. Waterw. Port Coast. Ocean Eng.* 121, 134–142.
- Wright, L.D., Short, A.D., 1983. Morphodynamics of beaches and surf zones in Australia. In: Komar, P.D. (Ed.), *Handbook of Coastal Processes and Erosion*. CRC Press, Boca Raton, Florida, pp. 35–64.
- Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. *Mar. Geol.* 56, 93–118.
- Vesterby, H., 1994. Beach face dewatering—the European experience. Alternative technologies in beach preservation. *Proceedings of the 1994 National Conference on Beach Preservation Technology*, St. Petersburg, FL, pp. 53–68.