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The Coastal Geomorphological Development of the Skagen Spit, Jutland, Denmark. Its Fate During the Next Century. Coastal Erosion and Accretion.

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ABSTRACT

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This paper is written in continuation of 3 earlier papers published by the JCR on the Skagen Spit in Jutland, Denmark. The first paper, JCR 9(4), 1993, addressed the geological development, as a result of glacial moraines generated by glaciers from 3 different directions. The second paper, JCR 9(4), described the advance northward of the spit from about 6,000 years BP and up to now in relation to the relative rise of the land due to glacial rebound in relation to the rise of the sea level. The Skagen Spit model built in 1995 is mentioned in JCR 14(1), which gives details on the development of the spit modeled in scale 1 in 5,000 and presented from a platform driving in imitated elevation 15,000 meters.

This (fourth) paper attempts to predict the development of the spit up to year 2,100 including the erosion of the west and east sides and the large accumulations on the tip of the spit, Grenen (The Branch). Coastal protection efforts by groups of groins have, as it could be expected, not been very successful and nourishment has so far been minor in scale. Huge accumulations of the order of 1 million cubic meters per year take place at the Grenen. The present rate of shoreline movement, which is about 6–8 meters per year, can be expected to increase to 8–10 meters per year as a result of a worsening of the weather climate increasing the erosion. The spit, therefore, is becoming "slimmer" and only major artificial nourishments will be able to protect the spit.

ADDITIONAL INDEX WORDS: *Skagen Odde, Skagen Odde Model, sea level rise, coastal protection, artificial nourishment.*

NATURAL EROSION

This (fourth) paper on the Skagen Spit (Figure 1) looks beyond present conditions in an attempt to describe the shore development through the next century, based on assumptions of a worsening of the weather climate with more severe and more frequent storms in the North Sea. The winds generally turning more counter-clockwise causing more SW winds and wave action with the accompanying higher tides (information the Danish Meteorological Institute, *personal communication*). At the same time we are facing an increase in sea level rise as documented by exact tide level recordings all over the world (LISLE and DOLAN, 1993) although its intensity is highly variable. The rise is rather small along Danish shores, or from 0 to 2mm/year (as mentioned by FRICH, 1993 and FENGER, 1993).

The North Sea shores have during the last two decades experienced more severe storms than ever recorded in history. Dune recessions have been up to 30 meters in one very severe storm (Coastal Directorate, Lemvig) causing breakthroughs of the dune line. The erosion by sea level rise, however, is less in Denmark than in Germany, Holland and France, but it may increase, as glacial rebound vanishes. Just 2mm rise per year, however, may increase shoreline recession by about 0.2 meters per year. A 6mm annual rise, as predicted by the international IPCC organization on Climate Change may cause an increase of shoreline and dune recession of 0.5 to 1.0 meter per year of shores like the Skagen Spit's western sections. They are already eroding rather heavily with maximum dune recessions exceeding 1 meter per year in an area between Gl. Skagen and Kandestederne (Figure 1). This, in turn, means that in 50 years the present vegetated shore dune system will have vanished on several kilometers of shore and been replaced by sand drift areas. The sand is partly lost to the ocean and partly carried by the wind over sparsely vegetated low areas behind the dune line leaving irregular deposit "fans". The "gray" (vegetated) dunes do not migrate. They suffer front-erosion and breakthroughs as seen on the shore northeast of Kandestederne. Further south at Tversted (Figure 1) dunes are wider, but areas at Kjul Strand have recently been subject to severe dune erosion, now apparently stabilizing again, possibly a result of offshore nourishment.

MAN-MADE EROSION PROBLEMS

Man-made erosion is caused by man's activities in the Littoral System (BRUUN, 1995). That may appear in the form of structures like groins and jetties (breakwaters) or as dredged navigation channels to ports, in all cases producing a littoral

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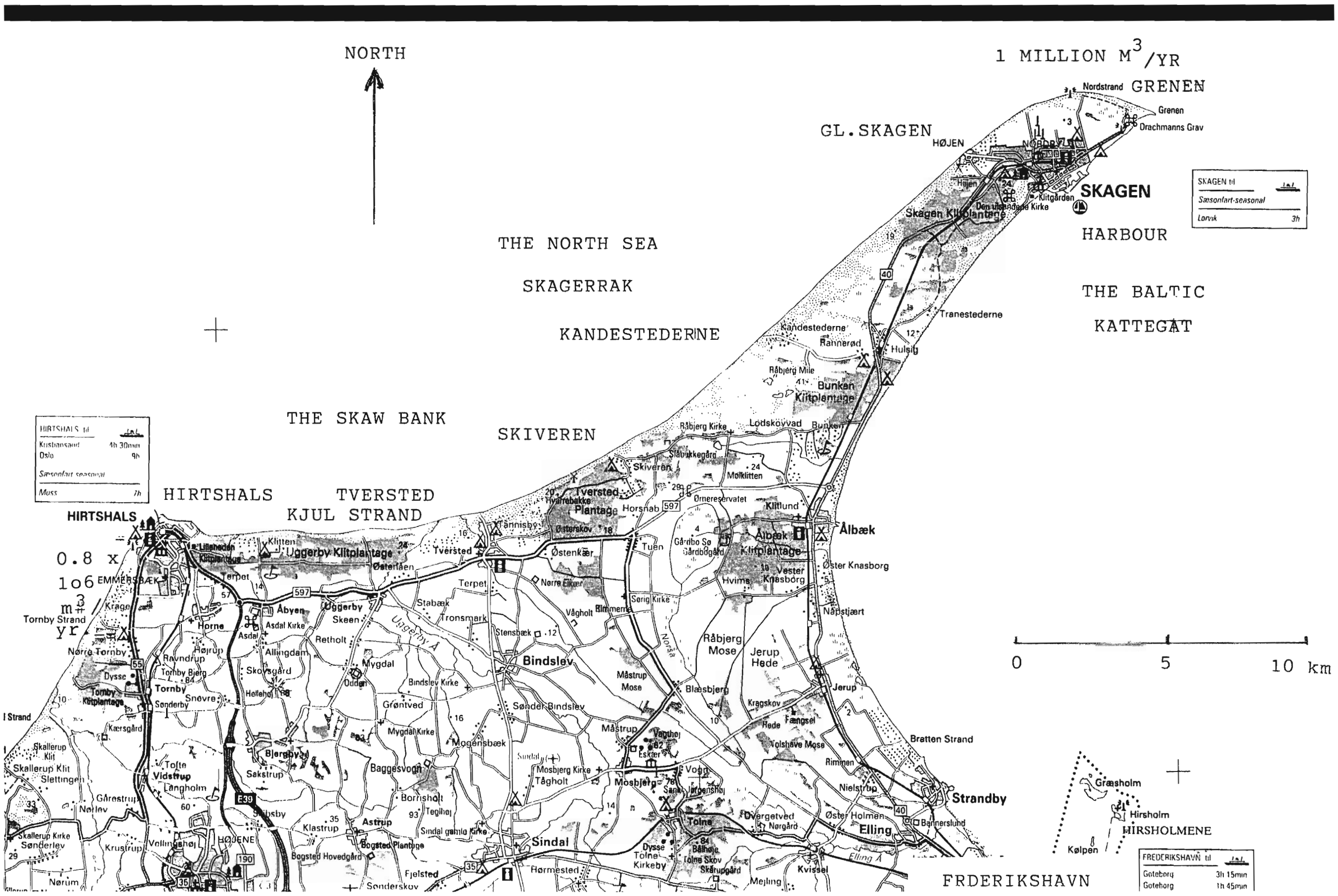

Figure 1. Map of the Skagen Odde, Province Vendsyssel, Jutland, Denmark, Danish Geodetic Institute.

drift barrier visible above sea level as accumulation of material on the updrift side and erosion on the downdrift side of the barrier. Such barrier-effects unfortunately are too common on our shores. They have caused severe damages to dunes, to properties and to the environment in general, including the aesthetics. In the state of Florida, such barrier-effects are prohibited by law. The Florida Coastal Law of 1986 says:

Re: 161,142 Declaration of Public Policy Relating to Improved Navigation Inlets:

(1) "All construction and maintenance dredging of beach quality sand should be placed on the downdrift beaches or, if placed elsewhere, an equivalent quantity of sand from an alternative location should be placed on the downdrift beaches".
(2) "On an average annual basis, a quantity of sand should be placed on the downdrift beaches equal to the natural annual longshore sediment transport". Denmark does not have similar laws or regulations, but efforts are being made to change this unfortunate situation. At entrances on the North Sea coast at Hvide Sande and Torsminde transfer of sand across the entrance has been undertaken for 15–20 years (up to about 250,000 m^3/year). At Hirtshals, where the North-going drift is of the order of about 0.8 to 1.0 million m^3 per year material dredged in the entrance channel is dumped downdrift in shallow water. It may not all reach the beach—but instead it drifts northeast-ward nourishing the shore of the Skagen Spit. The harbour works at Hirtshals located on a headland, are probably responsible for a total loss of the order of about 500,000 m^3 per year, part of which may settle on the Skaw Banks (Figure 1). Looking further North the accumulation on Grenen and the Skagen Reef is about 800,000 m^3 annually causing a deficit of 1,000,000 less 500,000 less 800,000 = −300,000 m^3 sand which must then be picked up from the shore mainly between Gl. Skagen in the North and south of Skiveren in the South (Figure 1).

Such long-range effects are known from other cases (Bruun, 1995). The problem can best and most economically be solved by a direct input or material from the offshore using hydraulic pumps.

The 4,000m long Grenen reef is developing further northward. Heavy wave action on the reef causes rapid changes of depths with periods of accretions followed by periods of erosions—still with an overall continued deposit. The reef is very dangerous to seafarers and the outer parts of the Skagen Spit

Figure 2. Groins at Gl. Skagen, 1960.

are plugged with innumerable shipwrecks buried down in the ground.

A long-range effect of the harbour at Hirtshals may be responsible for the increase of erosion at Gl. Skagen starting in the 1950's or about 25 years after the completion in the 20's of most of the harbour jetties and a navigation channel at Hirtshals (BRUUN, 1995). At Gl. Skagen, six groins were built at the beginning of the 1950's (Figure 2). They were effective, but caused severe downdrift erosion. Starting in 1977 another 16 short T-groins were built northeastward. They lowered the shoreline recession considerably but also caused further extension of leeside erosion. The total length of erosion infested shore from Gl. Skagen and northeastward is now about 2,500 meters. Some place close to the location of the North Lighthouse (Figure 1) the erosion is replaced by accretion increasing northeast ward towards Grenen which during recent years has experienced offshore shoreline movements of 6–8 meters per year as explained in a following paragraph.

DISCUSSION ON THE FUTURE DEVELOPMENTS

IS IT POSSIBLE TO IMPROVE THE EROSION SITUATION ON THE SKAGEN SPIT?

The answer is—of course—but funding is the problem. The extensive groin-fields on the Skagen Spit is shown in Figure 1 but it is obvious that groins per se have not been successful in the overall picture. They have rather, by their downdrift effect, caused more erosion than accretion. Groins can delay—but not solve the problem. Groins are also dangerous to bathers and they do not improve the aesthetics.

Let's look at the bottom profile at Gl. Skagen (Figure 3). It has 3–4 offshore bars with crest depths from 1 to 4 meters and distance from shore of about 50 to about 550 meters vary-

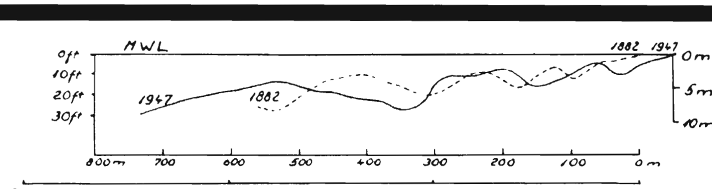

Figure 3. Bottom profiles at Gl. Skagen (BRUUN, 1954).

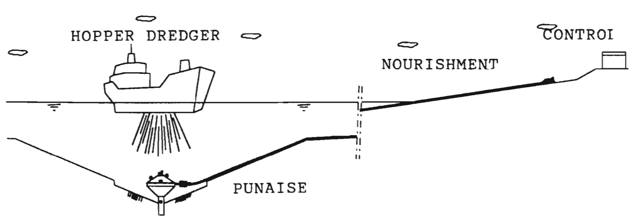

Figure 4. Skagen Harbour.

ing somewhat with the wave conditions. Waves of 5–6 meters offshore break on all bars and may finally reach 1 to 1.5 meters at the beach.

Regarding coastal protection the adamant requirement in 1999 is:

(1) The protection shall stabilize and improve beaches and dunes.
(2) The protection must not have any adverse effects on neighboring shores.
(3) The protection shall provide good aesthetics and a pleasing recreational beach.
(4) Artificial nourishment of the beach shall be by suitable material, no pollutants accepted. Grains must be as coarse or coarser—up to a limit—as the existing beach sand.
(5) The material used for nourishment shall be secured without causing any damage to the environment.
(6) The artificial nourishment operation shall be as economic as possible considering advanced experiences, as they become available.

THE CONDITION AT GL. SKAGEN (Figures 2 and 3)

Preliminary samplings have indicated that material on the outside of bar #3 from shore at depths of 4–5 meters, about 550 meters from shore, apparently is as coarse or coarser

Figure 5. The Punaise placed in the bottom for pumping of sand to shore (VISSER and BRUUN, 1997).

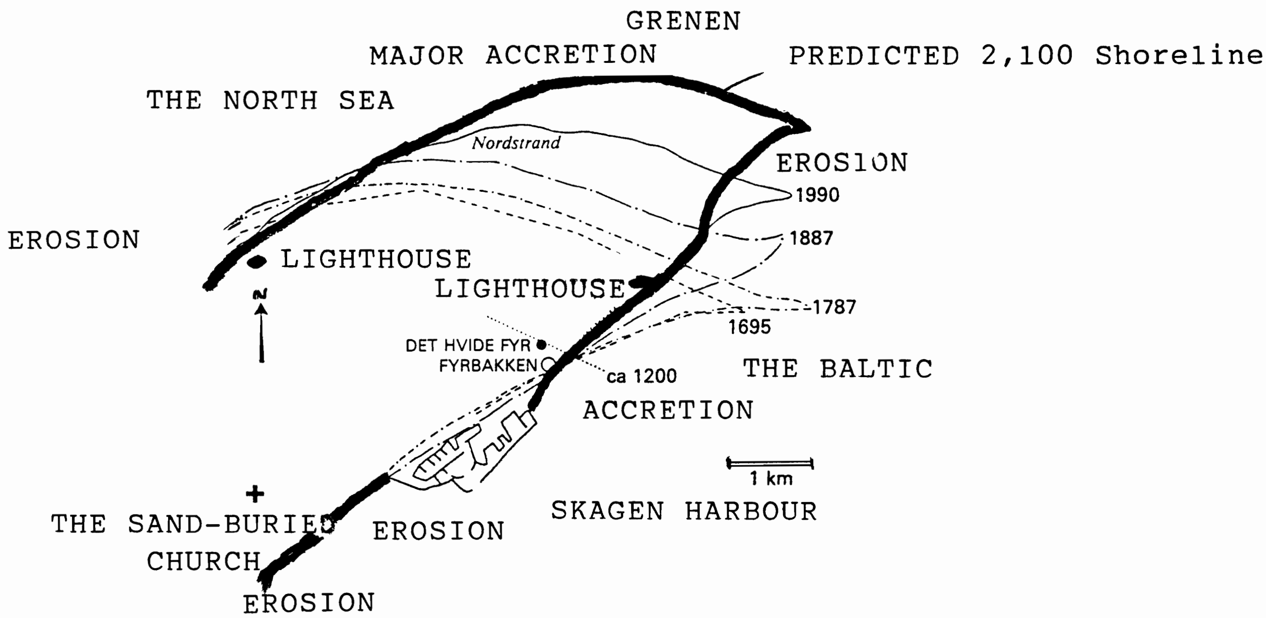

Figure 6. Various historic shorelines, 1695–1990 (Skalk no. 4, 1997) and the computed 2100 shoreline (BRUUN, 1998).

than the beach sand. It is under heavy wave attack during severe storms. Beach sand includes some eroded (finer) dune sand. Good coarse sand is also found further NE-ward on the ocean bottom and may include some gravel. Comparing conditions at Bovbjerg on the straight North Sea coast, south of Thyboron, sand on the beach at Bovbjerg is coarser than sand on the single offshore bar. As a good luck sand of 0.3 to 0.5 mm is found offshore at 20 meters depth, 2–3 kilometers from shore, comprising meltwater sand from the last glacial period. It is excellent for beach nourishment, but the nourishment period is restricted to some spring and summer months, when dredgers are able to work in milder wave action. About 3 million cubic meters are nourished every year on about 80 km of shore.

HOW DO WE BRING THE SAND TO THE SHORE?

This can be done fairly easily by hydraulic equipment used in a hopper dredger which first loads itself at the source and next steams to shore unloading directly on the beach by "rainbowing" over the bow or through a short pipeline tied to an unloading buoy offshore as it is done further down the coast. The method preferred depends upon the bottom profile steepness and upon the equipment itself. The cost by large hopper dredgers will vary from \$2.5 to \$4.5 per m^3 depending upon the location of the source of material. In the Netherlands a submerged pump called "The Punaise" (thumb-tack) buried in the bottom discharges to shore through a pipeline from the pit, which is kept filled by dumping of material by a dredge with bottom-doors as shown in Figure 4 (VISSER and BRUUN, 1997).

In the case of *e.g.* Gl. Skagen such underwater pumps may be placed in the 3rd bar and perhaps be operated automatically. Some tests are needed to confirm the ultimate design and capacity. A third method is the use of a "Crawl Dog" that is a barge with hydraulic pumps working on crawlers or floating with spuds that are hydraulically operated supporters. It discharges through a pipeline to shore and is launched from the beach (BRUUN, 1996) at low cost. Such equipment has been tested in Australia and in South Africa, with luck. More comprehensive nourishments should be spaced in time to produce optimum economy. If the quantity needed per year *e.g.* is 150,000m^3, this could be obtained by nourishment of 500,000m^3 once every 3 years. This would lower the unit price as mentioned later in the paper. If at Gl. Skagen the quantity is 500,000m^3/three years, the unit cost would be about \$3/m^3 or about \$1.5 million or \$0.5 million per year, in Danish crowns 4 million per year with conventional pumping. But the price could become kr. 3 million per year with an underwater pump as described. This price still is rather high for a single location of limited length of shore, but as discussed later it might still be an economic undertaking.

THE CONDITION SE OF GRENEN ON THE KATTEGAT (BALTIC) SIDE

The SE-side of the spit has during the last 40–50 years in particular experienced severe erosion. To protect the Grenen lighthouse (Figure 1), a group of 6 groins, later expanded to 39 short T-groins, have been placed on about 2,200 meters of shore towards the harbour of Skagen. Very little nourishment, however, has been done with the result that about 500 meters of shore no longer has a beach. And offshore depths would anyhow prohibit the use of nourishment for such section. The about 1,000 meters long shore east of the harbour is almost stable with some accumulation just east of the harbour providing the most used recreational beach at Skagen. See Figure 5. West of the harbour (left on the figure) which is an almost perfect littoral drift barrier, erosion started upon completion of the harbour works in 1907. About 12 groins were built in the 1920's on 750 meters of shore. They are now abandoned, as they did not function due to the lack of nourishment. Further west of the Royal Residence, "Klitgaarden", the "Dune Castle", 7 small T-groins were built recently on a 400 meter long shore—causing leeside erosion further down the shore (Southwest). See Figure 1. Some feeding of the dune toe slope and the upper beach has been undertaken at Gl. Skagen as well as on the eastern side of the spit, but in small quantities providing mainly a kind of weak revetment on the dune slope. Nourishment in a larger scale will be effective east of the harbour and west of the groins on the west side of the harbour.

For reasons of consideration to economy, future nourishment could include all 3 areas: Gl. Skagen and the 2 areas east of the Grenen, thereby increasing the annual nourishment to 50,000m^3 or 150,000m^3 every three years. Together with Gl. Skagen this would make a total of 500,000 + 150,000m^3 = 650,000m^3 once every three years at a price of \$1.95 million, Danish crowns 16 million. That is about 4 million Danish crowns per year, but it could be less, if new type equipment is used (VISSER and BRUUN, 1997). Such a program could become of immense importance for the "tourist industry" in Skagen.

HOW WILL GRENEN LOOK BY THE YEAR 2100 OR 100 YEARS FROM NOW?

Its morphology would probably be as it is today, but Grenen would have continued its movement north and northeast. A preliminary quantitative appraisal may be undertaken realizing that it depends upon the weather climate and of the water depths north of Grenen.

Annual accumulation on Grenen and the Reef about 800,000m^3 due to increased erosion becoming about 1,000,000m^3 of sand accumulated on about 4,000 meters of shore (Figure 1). With depth limit for deposit 25 meters the shoreline will move out a distance $x = 1{,}000{,}000/25 \times 4{,}000 = 10$ meters a year. With depth limit 35 meters $x = 1{,}000{,}000/25 \times 4{,}000 = 8$ meters per year.

Figure 6 leaves an impression of a movement towards the north by Grenen of about 1,000 meters on average by the year 2100. The figure also shows the results of some earlier surveys (Skalk, NO. 4, 1997). On the east side of Grenen accumulations east of the harbour will decrease slowly. West of the harbour erosion will continue moving westward, if no "real" nourishment is undertaken. So far it has not been done.

CONCLUSION

(1) The Skagen Spit is facing a period of increasing erosion due to adverse changes in the weather climate. The spit is "slimming down". A continued sea level rise will contribute further to erosion.
(2) Its shores are suffering from the loss of sand. Eroded material is mainly deposited on Grenen and its reef. We may expect an increase in the quantities deposited by which about 4,000 meters of Grenen shoreline will move out in the ocean at rates increasing to 8–10 meters per year in the years to come.
(3) More efficient measures of protection technically as well as economically, are available at lower unit costs, but this cost may still be prohibitive for major operations in the nearest future. Socio-economic considerations may, however, become more important than they are at present while "naturalists" do not mind to see the whole thing go to pieces!
(4) Finally, it is mentioned that the Skagen Spit model, exhibited at the harbour of Skagen, gives a rather thorough description of the fate and behavior of the Skagen Spit. Videos show wave motions and wave attacks on the shore. A wind-flume of 12 meters length gives an impression of sand drift by wind and you see the spit from 15,000 meters elevation from a platform driving over the model.

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