Aeolian transport of nourishment sand in beach-dune environments
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SUMMARY

Beach nourishment is used worldwide as a method for restoring and maintaining coastal areas threatened by (structural) marine erosion. Nourishment implies a direct supply of sand to a beach, so that the sand acts as a buffer against wave energy during extreme events. However, nourishment may also affect the sediment exchange rate between the beach and the dune. The aim of this thesis is to assess the impact of beach nourishment on aeolian sand transport and morphodynamics (Chapter 1).

The study is conducted on several nourishment sites along the Dutch North Sea coast (Chapters 2 and 3). On two beaches, referred to as the Ameland and the Den Helder site, field measurements of aeolian sand transport and related factors were carried out, both prior to beach nourishment and after beach nourishment (Chapters 4 and 5). The topography and foredune vegetation has been monitored for several years. Data from these two sites have also been used to apply the aeolian sand transport model SAFE and the air flow model HILL, in order to identify the response of aeolian sand transport and morphology to several fill characteristics and nourishment design parameters (Chapter 6).

The overall effects of nourishment on the development of the beach-dune system are studied on a group of twelve beach nourishments sites (Chapter 2). Nourishment is found to promote dune building. The foredune is barely eroded in the first four years following nourishment. A negative sand budget is found for the entire supratidal beach, which does not change after nourishment. One year after nourishment, erosion of the beach increased. In the same year, the rate of aeolian sand transport to the foredunes significantly increased: net aeolian deposition in the foredunes was about $14 \text{ m}^3 \text{ m}^{-1} \text{ y}^{-1}$ on average (versus about $9 \text{ m}^3 \text{ m}^{-1} \text{ y}^{-1}$ on average in a control situation). There was, however, a large spatial and temporal variation in deposition. The method does not allow for an assessment of the effects in the year of nourishment.

The increase in sand transport may be due to many factors. Several factors, relating to characteristics of the fill material (such as the grain-size distribution of the sand) and nourishment design (such as beach width and beach topography) determine the erodibility of the surface, the availability of
sand, and the erosivity of the wind and may, therefore, restrict or amplify the rate of aeolian sand transport on a nourished beach, as compared to an unnourished beach. A number of these factors and their role in aeolian sand transport has been studied in detail.

**Erodibility of the surface**

The offshore source area is often characterized by a variety in material properties in both vertical (temporal) and horizontal (spatial) direction. The sand from this source area is mixed when brought ashore. The sand frequently contains admixtures of gravel, silt, shells or organic matter, which are insubstantial in the ambient beach sand. In addition, the fill material has not been subject to marine and aeolian sorting to the same extent as the sand that normally reaches the beach. Samples from several nourishment beaches and adjacent control sites along the Dutch coast show that nourishment sand is poorer sorted, has a platykurtic and negatively skewed grain-size distribution (i.e., a coarse tail) and contains both more silt and more coarse grains or shell fragments (Chapter 3).

The grain-size distributions of the samples from nourished beaches and dunes and nearby unnourished beaches are related to the 'susceptibility' of the sediments to mobilize under controlled wind tunnel conditions (Chapter 3). The rates of aeolian sand transport depend on sorting of the sand and the amounts of shell fragments in the sand, and do not relate to mean grain-size of the sand. Shells eventually prevented further transport by forming a lag. The fill material, which is moderately sorted to moderately well sorted and contains shell fragments, is associated with low rates of sand transport during wind tunnel experiments, as compared to rates of sand from nearby unnourished beaches. At two nourished sites, however, sand is well to very well sorted, and samples from these nourishments exhibited high transport rates. For non-uniform sand, such as nourishment sand, sorting and amounts of shell fragments may therefore be more important than mean grain-size. Assuming very well sorted sand in process-response models, such as the SAFE-HILL model system, may therefore not be valid (Chapter 6).

As soon as the beach is nourished, marine and aeolian sorting processes alter the surface texture of the beach (Chapter 4). The grain-size-selective aeolian processes that take place after a beach nourishment with moderately sorted fill containing shell fragments were studied on the Ameland site. Marine reworking of the fill results in a decrease of shell fragments and a decrease in fines on the foreshore surface, with the exception of the swash mark. During aeolian sand transport, aeolian decoupling of the nourishment sand results in a backshore with surface lag deposits with moderately sorted
sand containing a substantial amount of shell fragments, silt and coarse quartz grains, alternated with superimposed patches of wind-blown sand with less shell fragments. Silt and shells were underrepresented in sand transported under moderate and strong winds, indicating high threshold friction velocities for these components. Wind-laid nourishment sand, i.e., the nourishment sand that is blown to the dunes, contains only small amounts of these shell fragments and the sand is finer and better sorted than the nourishment beach sand. Grain-size-selective processes lead to an assimilation of the grain-size distribution of the nourishment sand to the native sand, but the nourishment sand that is blown to the foredunes still deviates from the wind-laid native sand, in that it is more poorly sorted and more negatively skewed. Although the coarse material selectively lags behind, wind-laid nourishment contains more coarse material than the native beach sand and the wind-laid native sand found in the foredunes. Since a good correlation is found between the amount of this coarse material and carbonate content, this suggests that vegetation effects can be expected (Chapter 3).

Shell pavements develop especially on the backshore (Chapters 4 and 5) and on top of banquets, dune front nourishments and dune nourishments (Chapter 3). The shell pavement formed at the backshore of the Ameland beach results in a reduction of aeolian sand transport, but the sand transport does not cease (Chapter 5). During different conditions either the input of sand from the intertidal area, where the sand has been reworked by the sea, the sand supply from the shell pavement or superimposed patches of dry well sorted blown sand provide a source for aeolian sand transport. The large variability in surface characteristics probably enhances variation in aeolian sand transport over the beach.

**Availability of sand**

In order to develop a fully developed saltation layer, a critical fetch has to be exceeded. On a beach, the minimum available fetch for onshore sand transport is delimited by the beach width from the limit of run-up to the edge of the dunes. Wind direction determines the actual fetch length. Measured rates of aeolian sand transport relate to fetch of wind over beach sand (Chapter 5). Especially at the Den Helder site, measured transport rates increased with fetch. Since beach width (and fetch) is enlarged by nourishment, this suggests that larger sediment fluxes (and more erosion on the beach) can be expected as compared to before nourishment. The effect will be largest just after nourishment and will gradually decrease as the size and width of the nourishment diminish as a result of marine and aeolian processes. Sediment supply, which is influenced by surface characteristics and
conditions, is recognized as an important parameter for the effect. However, the relation between aeolian sand transport and fetch is seriously affected by, e.g., the variability in surface characteristics.

The impact of the adaptation length, relating to the distance over which sand transport adapts to a new equilibrium, and thus relating to the critical fetch, is evaluated by applying the SAFE-HILL model system: with increasing adaptation length, the development of the beach and foredune is suppressed (Chapter 6).

**Erosivity of the wind**

The SAFE-HILL model system is used to evaluate the impact of several nourishment designs on the erosivity of the wind (which is expressed in terms of friction velocity), and therefore on the pattern of erosion and deposition of the beach and foredune. The design of a beach nourishment had a limited impact on the erosivity of the wind. In addition, there are no pronounced differences in erosivity of the wind over the unnourished and nourished Ameland beach, respectively. However, the erosivity of the wind over a banquet (i.e., a dune toe nourishment) made out of well sorted, loose sand results in a dramatic adaptation of the fill. The steep, bare windward side of the banquet erodes due to wind speed-up. Most sand is deposited directly on top of the banquet (Chapter 6).

The study shows that nourishment mainly promotes dune growth by forming a buffer against wave energy (preventing dune toe erosion), and by temporally enlarging the aeolian sediment transport rate to the dunes. Nevertheless, nourishment may reduce aeolian sand transport in individual cases. The factors studied often have complex feedback mechanisms that have to be taken into account when optimizing nourishment projects from a geomorphological and ecological point of view (Chapter 7).