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Analysis of Beach Nourishment Schemes

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ABSTRACT

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The erosion of a nourished beach may be conveniently described as the sum of the linear coastal retreat and a surcharge which decreases exponentially in time. Application of this model to the data from eight nourishment projects in north-western Europe has shown that on average only 52 percent of the nourished volume becomes a permanent part of the coastal volume. Allowing for an initial loss of some 10 per cent, the results obtained indicate that in practice computed nourishment volumes should be multiplied by a factor of about 2.2, somewhat higher than previous recommendations.

ADDITIONAL INDEX WORDS: *beach replenishment, coastal erosion, artificial beaches, coastal management.*

INTRODUCTION

For the design of an artificial beach nourishment, it is possible to follow the straightforward method as described by VERHAGEN (1992). This method is only valid in those cases where the coastal erosion is large with respect to the quantity of the nourishment. Also, data have to be available regarding the previous erosion rate. In the method, a multiplier is used to account for all "losses" of sand. A value of 40% extra is suggested. In this note, the results from a number of nourishment projects are evaluated in order to obtain support for the suggested value of 40% and further insight into the behaviour of nourishment as a function of time.

The method described in this note is limited to the evaluation of a restricted part of the beach. Usually nourished sand moves out of the nourishment area to neighbouring coastlines or to somewhat deeper water. This is called a "loss", although in the long term this sand still contributes to the stability of the coastline in general, but not at the desired location. From a geomorphological point of view the sand is not lost, because it is still a part of the littoral system, but from a point of view of the beach-manager it is a loss, because fewer square meters of dry beach are available for recreational use.

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MATHEMATICAL DESCRIPTION

The erosion of a nourished beach consists of two components: (a) the linear component of the erosion (the linear regression of the volume of sand in the coastal profile); and (b) extra erosion, arising from the new coastline being more exposed than the neighbouring profiles.

In fact, the extra erosion mentioned under (b) is caused by both longshore losses as well as adaptation of the profile in the cross-shore direction. This last phenomenon can be decreased numerically by selecting a deeper closing depth of the balance area. Unfortunately, this approach is not always possible because of non-stable breaker bars.

For a nourishment extending over a relatively long stretch of beach (the same length as the eroding area) without "adaptation losses" in the cross-shore direction, only the linear erosion needs to be taken into account:

$$V_t = V_0 - at \qquad (1)$$

In this formula, V_0 is the volume of the nourishment and V_t is the volume at given time t. For a "stable" coastline (*i.e.*, a coastline with a coastal erosion of zero m^3/m/year), with only losses in the longshore direction and "adaptation losses" in cross-shore direction, the erosion rate may be assumed to be a linear function of the extension of the nourishment into the sea. This assumption results in an exponential decay of the nourished volume (FÜHRBÖTER, 1991):

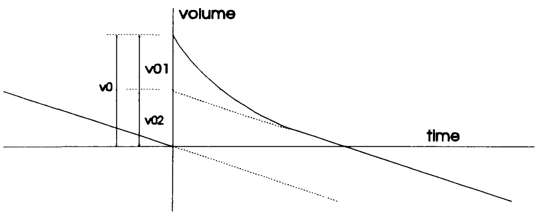

Figure 1. Change of nourished volume over time.

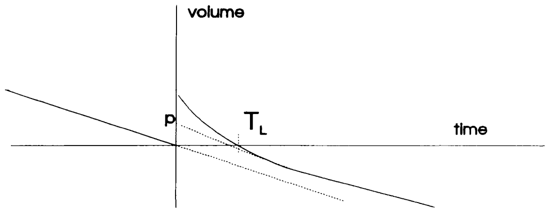

Figure 2. The value of T_L in relation to p.

$$V_t = V_0 e^{-t/T_c} \quad (2)$$

The value of T_c is a constant to be determined. Usually both situations occur at the same time:

$$V_t = V_{02} - at + V_{01} e^{-t/T_c} \quad (3)$$

with the nourished volume now partitioned into two components, V_{01} and V_{02}, as presented graphically in Figure 1.

For convenience, a parameter p may be introduced, giving the fraction of the nourished volume that becomes a permanent part of the coastal volume:

$$V_{02} = pV_0$$
$$V_{01} = (1 - p)V_0 \quad (4)$$

and consequently: Eq. (3) now becomes:

$$V_{02}(t) = pV_0 - at \quad (5)$$
$$V_{01}(t) = (1 - p)V_0 e^{-t/T_c}$$
$$V_t = pV_0 - at + (1 - p)V_0 e^{-t/T_c} \quad (6)$$

in which:

V_t = Volume of nourishment at time t (m^3/m)
V_0 = Nourished volume at t = 0 (m^3/m)
p = Fraction of the nourished volume corresponding to the natural (linear) erosion of the coastline (−)
a = Linear component of the coastal erosion (linear coastal regression) (m^3/m/year)
t = time (years)
T_c = Characteristic decay time of the nourishment (years), *i.e.*, after T_c years still e^{-1} = 37% of the nourishment remains. Instead of T_c the 50% or the 10% value can be used: $T_{50\%} = 0.693T_c$ and $T_{10\%} = 2.3T_c$.

The most effective beach nourishment is that which requires exactly the yearly loss, averaged over the erosion previous to the nourishment. Hence, a nourishment with p = 1 is the most effective. However, nourishment with p = 0 is not the least effective. Therefore, p is not a good efficiency parameter.

In order to develop a term for efficiency, E, a variable T_L is introduced, defined as the time until the moment when all nourished sand washed away (or in special cases, the moment that V_t becomes less than a predefined minimum V_{min}). The most effective nourishment has a volume $V_E = a \cdot T_L$. The efficiency is therefore:

$$E = \frac{V_E}{V_0} = \frac{aT_L}{V_0} \quad (7)$$

T_L can be calculated from:

$$pV_0 - aT_L + (1 - p)V_0 e^{-T_L/T_c} = 0 \quad (8)$$

The relation between T_L and p is sketched in Figure 2. In case of an evaluation, the unknown parameters in equation (6) are p, a and T_c. It can be assumed (VERHAGEN, 1992) that the erosion rate before and after the nourishment is the same. In some cases, the erosion rate before the nourishment is known and can be used. If linear erosion rate is not known, the assumption may be applied that near the end of the lifetime of the nourishment, there is only linear erosion left, giving a value of a. The other two parameters (p and T_c) can be determined by curve fitting (note: p is not determined by simply dividing V_{02}/V_0).

PROTOTYPE CASES

In order to evaluate out the mathematical scheme mentioned above, eight nourishments in Germany and the Netherlands were analyzed. Data from Germany were provided by KAMP (*personal communication*), data from the Netherlands from ROELSE and HILLEN (1993) and from RAKHORST (*personal communication*).

The Dutch nourishments were made in the

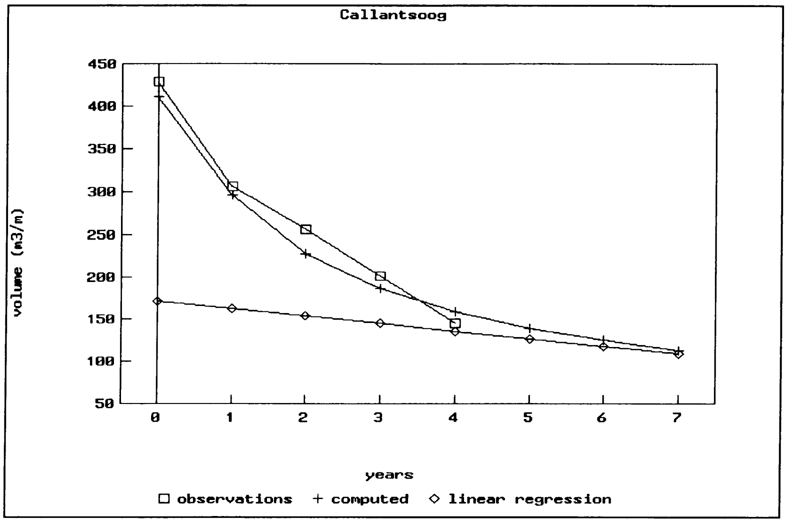

Figure 3. Nourishment at Callantsoog.

northwestern part of the country, near the villages of Callantsoog (1986), Zwanewater (1987) and De Koog (1984). The coast near Zwanewater is nearly 5 km long, and a total quantity of 1.85 million m³ of sand has been placed. The grain size of the sediment was 270–300 μm; the original beach sand was 255 μm. The slope of the nourishment was approximately 1:20 (under water) and 1:35 on the beach. The coast at De Koog (6 km) was nourished with 3 million m³ of sand with a grain size of 180 μm, while the original beach consisted of sand of 200 μm. The slope under water was 1:25, the beach slope was 1:40 to 1:60. At Callantsoog, (3 km) 1.3 million m³ of sand has been placed with a grain

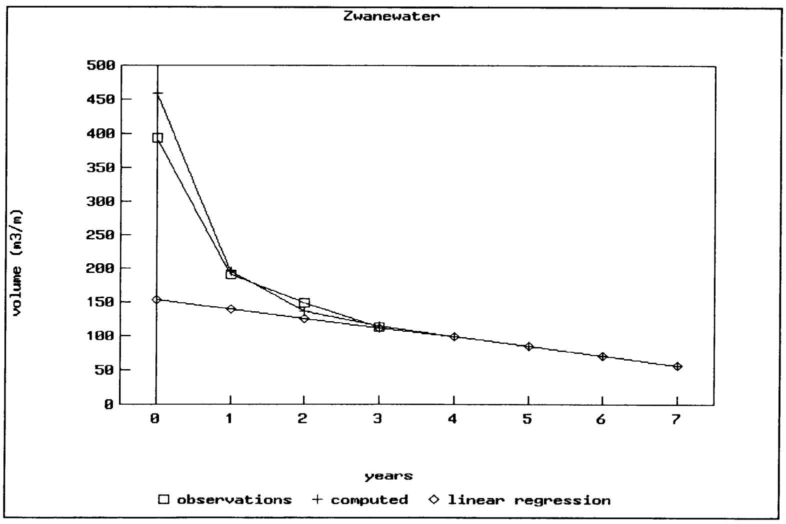

Figure 4. Nourishment at Zwanewater.

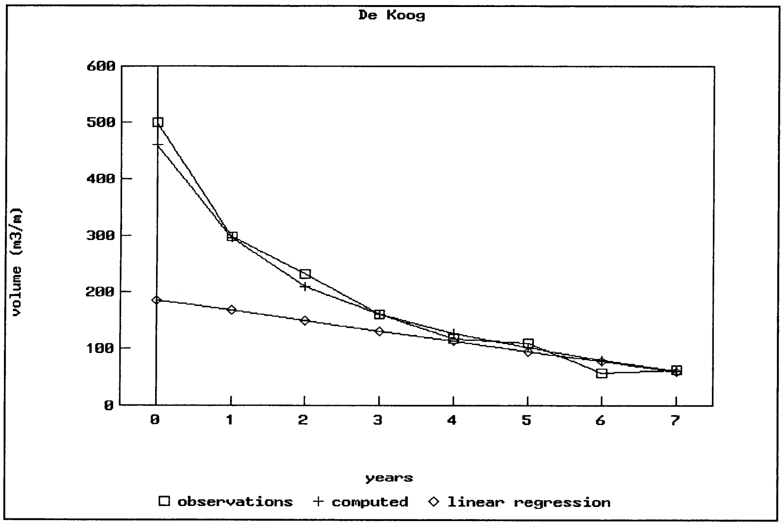

Figure 5. Nourishment at De Koog.

size of 270 μm. The original beach material here was also 255 μm. Slopes were 1:20 under water and 1:35 on the beach. The German nourishments are made on the island of Sylt, near the Danish border. The nourishment at Westerland (1972) consisted of 1 million m^3 of sand, and was placed as a stockpile of only 300 m wide. The next nourishment in Westerland (1978) was also 1 million m^3, but was placed over a total length of 900 m. In 1984 the nourishment was repeated in Westerland, 1.1 million m^3 over a total length of 1.5 km. The nourishment of Rantum was placed in

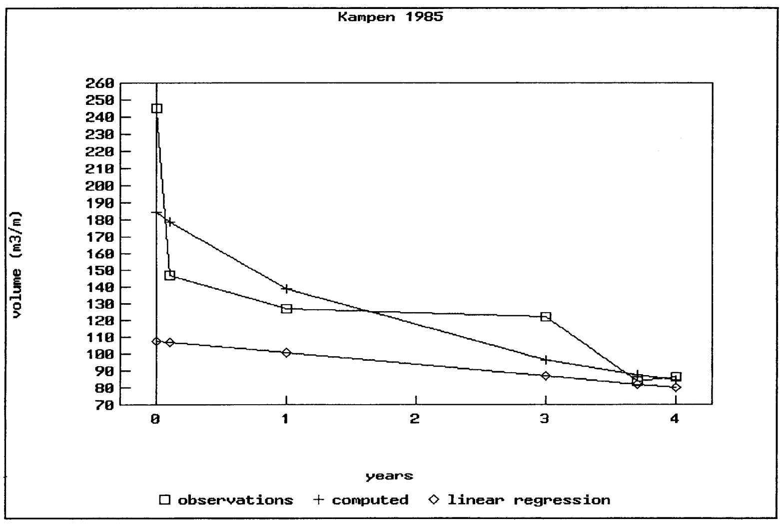

Figure 6. Nourishment at Kampen.

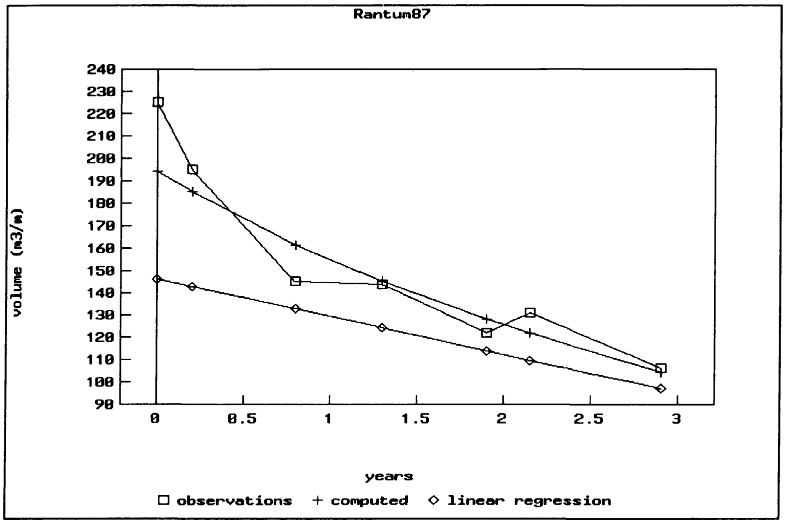

Figure 7. Nourishment at Rantum.

1987 and consisted of 1.44 million m³ placed over a beach length of 3 km. The area near Kampen was nourished in 1985 and consisted of 1.97 million m³ placed over a beach length of 4.6 km.

In the Dutch cases the erosion before the nourishment was known in detail. The following values were measured:

Callantsoog	9 m³/m/year
Zwanewater	14 m³/m/year
De Koog	18 m³/m/year

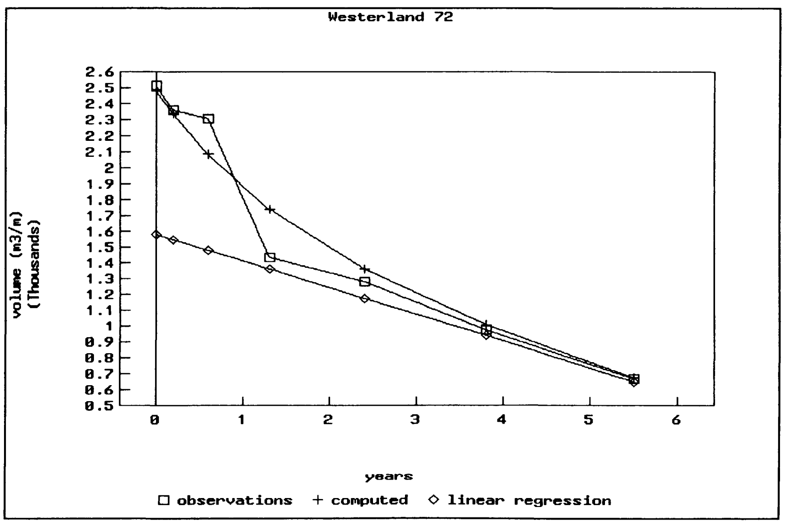

Figure 8. Nourishment at Westerland (1972).

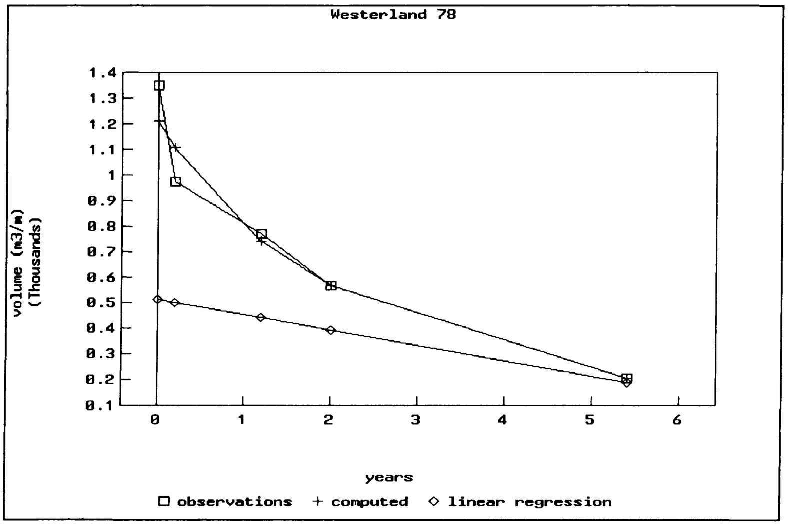

Figure 9. Nourishment at Westerland (1978).

For the German cases this value was not known, but from observations long after the nourishments, the following values have been deduced:

Kampen	7 m³/m/year
Rantum	17 m³/m/year
Westerland 72	170 m³/m/year
Westerland 78	60 m³/m/year
Westerland 84	37 m³/m/year

The extremely high erosion rate at Westerland in 1972 is not reliable. This is mainly caused by the nourishment being executed as a stockpile over a very short beach length. The data of the measured volume were analyzed using equation (6). Standard linear regression analysis was used to find the coefficients. In case of Westerland 72 and Callantsoog, the line through the points was deter-

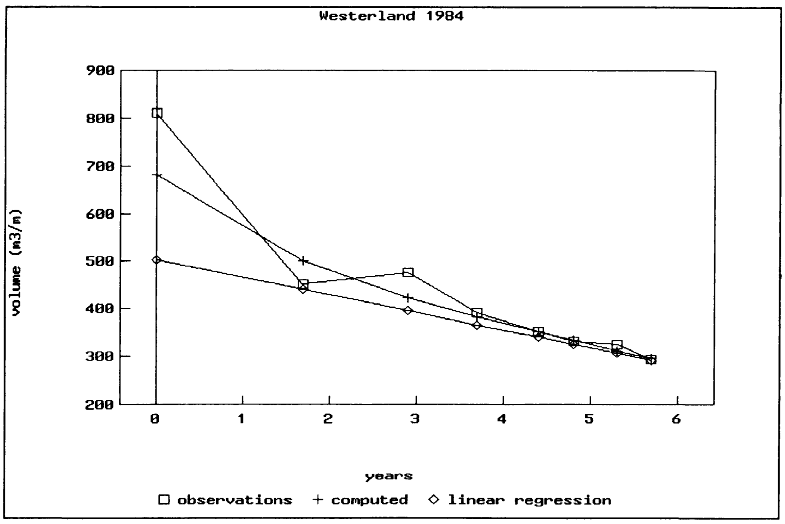

Figure 10. Nourishment at Westerland (1984).

Table 1. *Data from the analysis.*

	p	a	V_{02}	V_{01}	T_c	Corr	Initial Loss
Callantsoog	0.40	9	160	240	1.70	0.92	4%
Zwanewater	0.56	14	140	119	1.54	0.98	4%
De Koog	0.51	18	178	205	1.67	0.93	8%
Kampen	0.44	7	108	77	1.41	0.62	24%
Rantum	0.65	17	146	48	1.55	0.58	14%
Westerland 72	0.63	170	1,583	900	1.50	0.85	1%
Westerland 78	0.38	60	513	700	1.43	0.99	10%
Westerland 84	0.62	37	502	179	1.56	0.61	16%
Average	0.51				1.55		
Stand. dev.	0.11				0.10		

mined visually, not mathematically. In all cases, the correlation coefficient was determined. The results are presented in Figures 3 to 10.

SOME RESULTS

The following nourishments were analyzed with the method described above, resulting in the data of Table 1. As can be seen from the figures, in nearly all cases the computed volume at time t = 0 is less than the measured value on the beach (so it is less than the real nourished quantity). This initial loss is also indicated in the table above. As an average this loss is in the order of 10% of the total quantity. An extreme case is the nourishment in Kampen, where this percentage is up to 24%. This initial loss is decreased significantly by using deeper closing depth (in the German cases the closing depth is always 1 m below mean sea level), in the Dutch cases the closing depth is placed at approximately 5 m below mean sea level.

It is also clear that the variations in the values of p and T_c are quite small. For the design of a beach nourishment, this is an important finding. The average value of p is 0.52, which means that only 52% of the nourished sand contributes to combat the long term erosion. Because of all inaccuracies in the above analysis, one can say that the multiplier for the design is a factor of 2. However, one should add the 10% initial losses, as calculated in the last column of the table. So finally the multiplier in the cases analyzed is approximately 2.2 (the highest one is 2.9, Westerland 1978; the lowest one is 1.7 at Rantum).

CONCLUSIONS

The mathematical description of the change of a nourishment, using a linear component and an exponential component fits quite well with the observed decay of nourishment schemes in northwestern Europe. The characteristic decay time T_c is for all nourishments on the order of 1.5 years. The linear retreat is highly variable for each coast, but is rather independent from the nourishment schemes performed. The initial loss (loss in the first year) varies from 1–25 percent. This quantity, however, depends very much on the method of execution of the nourishment, as well as the closure depth for the volumetric analysis.

For a practical design of nourishments, when no data are available, the suggestion in VERHAGEN (1992) to apply a surcharge of 40% on the quantity required to combat the linear coastal regression, is not contradicted by the results from the data presented here.

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