Coastal Dynamics 2017
Paper No.222

BYPASS IN GROYNE FIELDS: CASE STUDY ALONG THE LOBITO SPIT

Sten Esbjørn Kristensen[1], Nils Drønen[2], Rolf Deigaard[3], Berry Elfrink[4]

Abstract

The Lobito spit, in Angola, is fronted by a groyne field along the entire length of the spit. The groynes were intended to halt the development of the spit, by lowering the littoral drift along the spit. The stability of the spit itself appears however to be threatened because beach sections along the downstream end are narrow, thus suggesting that the supply of sediment from the longshore transport cannot balance offshore losses. Aerial images from 2004 to 2015 show also a gradual filling of downdrift empty groyne compartments. Sediment budgets are formulated to support the two observations, 1) tendency for half-empty groyne compartments in downdrift end and 2) gradual filling of empty groyne compartments. The sediment budgets rely on an empirical expression for the bypass transport in groyne fields, which is based on modelling of 2D shoreline morphology of idealised groyne fields.

Keywords: Groyne field, bypass transport, numerical modelling.

1. Introduction

Coastal structures constitutes a perturbation to the natural morphological system. By investigating and understanding the natural response to such structures, we can learn much about the natural system and e.g. obtain knowledge about how to develop a morphological design that both reflects the coastal communities' need for defences against erosion and flooding and is line with the rules of nature.

The present study concerns a groyne field located along a sandy spit, where the groyne field has modified the littoral drift conditions and thereby changed the stability of the spit itself. The effect of the groynes on the stability of the spit are investigated by estimating the littoral drift conditions in the groyne field by use of an empirical expression for the bypass transport, which was recently formulated in Kristensen et al. (2016) in terms of aggregated characteristics of the littoral drift and the groyne dimension.

Finally a box-type morphological model is used to illustrate the long-term effect of offshore losses of sand to the degree of filling of the groyne field.

2. The Lobito Spit

2.1. General description of the area and of the wave conditions

The Lobito spit is a sandy spit with a length of about 5 km. The spit was created by littoral transport supported by large angle of wave incidence, which causes instabilities to grow in time. The dominant offshore wave direction is from SW but turns clockwise to a westerly direction at the 25 m depth contour. The average significant wave height at the 25 m depth contour is 0.53 m and the significant wave height rarely exceeds 1 m. Linear refraction of the nearshore waves to the 2 m depth contour which is considered to be the closure depth, results in a wave direction of 305 deg. N. The overall orientation of the coast normal of the spit is 322 deg. N, which means that the littoral drift is northwards, and the angle between approaching waves and the overall coast normal is about 17 deg. i.e. the shoreline is located in the stable regime from a morphological point of view at least for short-term and medium-term time scales. For long-term time scales the spit is however located in the unstable regime because avalanching processes allows for accumulation of sediment below the closure depth.

[1] DHI, Agern Alle 5, DK-2970 Hørsholm, Denmark skr@dhigroup.com
[2] DHI, Agern Alle 5, DK-2970 Hørsholm, Denmark nkd@dhigroup.com
[3] DHI, Agern Alle 5, DK-2970 Hørsholm, Denmark rd@dhigroup.com
[4] DHI, Agern Alle 5, DK-2970 Hørsholm, Denmark bre@dhigroup.com

Sand is transported from the mouth of the river Catumbela, located approximately 10 km south of the spit to the northern end of the spit where it accumulates thus causing gradual migration of the spit towards north. The littoral drift is estimated to about 260,000 m^3/year in a previous DHI study.

The natural spit migration was about 18 m/year, (LNEC, 1974). Groyne construction was commenced in the 1960'ies because it was estimated that the natural development of the spit would lead to closure of the lagoon in the 1990'ies, (LNEC, 1974). The spit is currently protected by a large number of groynes, which have halted the spit migration. The groynes are approximately 100 m long and are spaced by about 300 m.

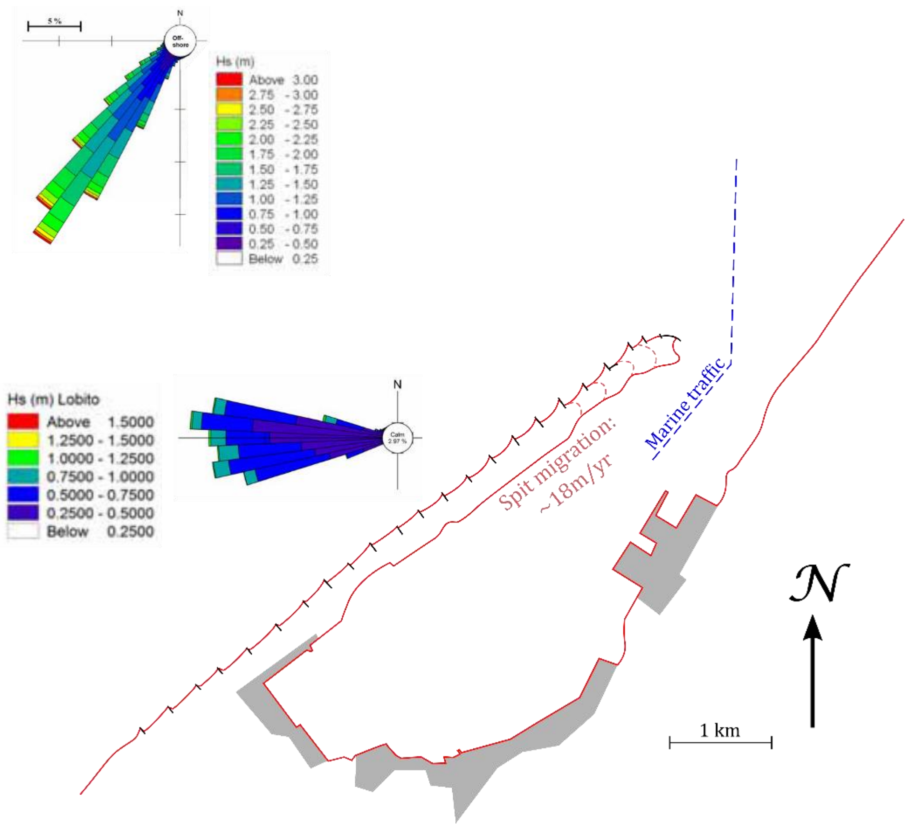

Figure 1.The Lobito spit. Wave roses cover the period 1979-2012. The nearshore wave rose is on 25 m depth.

The stability of the spit appears to be threatened, because the beaches along the downdrift groyne compartments are generally narrow thus indicating that the supply of sediment to these parts of the spit is insufficient to negate offshore loss of sand. Offshore transport is expected to occur during storm conditions due to cross-shore transport and due to rip-currents located upstream of each groyne.

Based on analyses of typical profiles it is hypothesized that the sand transported offshore is lost permanently due to avalanching along sections of the coastal profile located below the depth of closure. At these sections, a local bed slope up to 22 deg. is observed thus indicating that sand may be deposited in this area during storms and subsequent permanently lost during an avalanche when the slope exceeds a critical value.

Aerial images of the area from 2004 to 2015 show that the groyne compartments fill successively as shown in Figure 2. The successive filling of the downstream groyne compartments suggests that the offshore loss of sand is event based while a steady supply of sand from south fills up the groyne compartments more gradually over time. Despite a decade of filling of groyne compartments, the downdrift groyne compartments appear to be less filled than the upstream compartments, which can be caused by a more continuous offshore loss of sand as will be shown in Section 4 by application of the box-type morphological model.

Figure 2. Northern tip of the Lobito spit, Angola West coast of Africa. Historic shorelines are extracted from Google Earth.

2.2. Volumetric analysis of shoreline changes along the groyne field

The groyne fill ratio, defined as the ratio between the planform area of dry beach and the area contained between two neighbouring groynes, is determined for groyne compartments number 6 to 24 in order to quantify volume changes in the groyne field. The identification of the groyne compartments is shown in Figure 3 against the Google Earth image from 2004-07-28 and Figure 4 shows two examples of the analysis used to determine the groyne fill ratio. The left panel in Figure 4 shows the case for groyne compartment 10 with a groyne fill ratio of 0.67 and the right panel shows the case for groyne compartment 18 with a groyne fill ratio of 0.22.

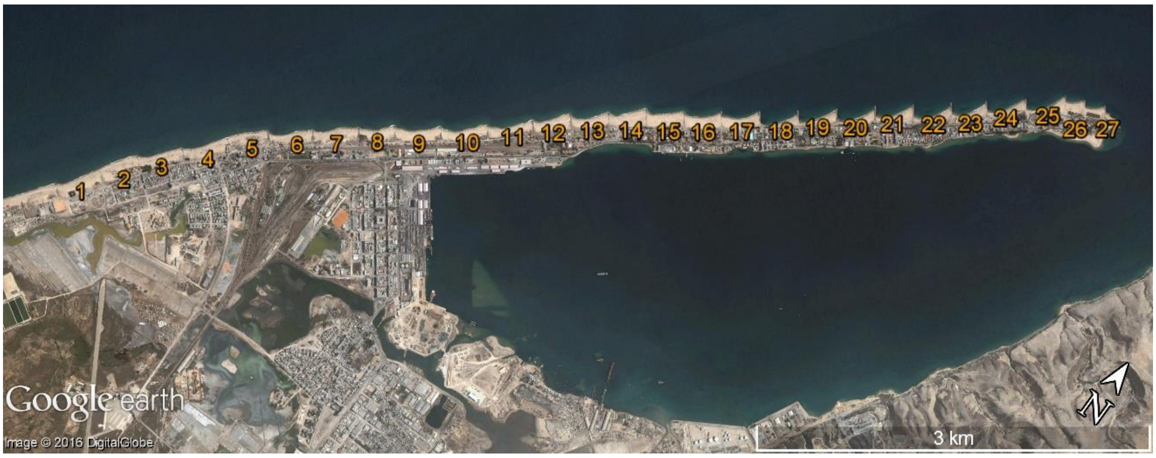

Figure 3. Assignment of an identity to the groyne compartments. Background image from 2004-07-28.

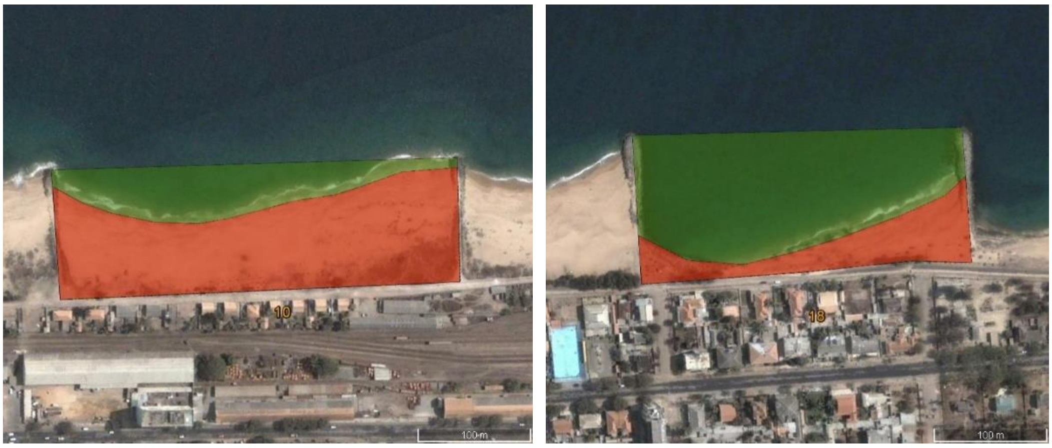

Figure 4. The groyne fill ratio is defined as the plan form area of dry beach relative to the total area between two neighbouring groynes. Left: Groyne compartment 10. Right: Groyne compartment 18. Both from 2004-07-28.

The groyne fill ratio distributions derived from the first and last of the aerial images are shown in Figure 5. The figure shows how the groyne field 6-16 were full in 2004, while the groyne compartments 17-24 were sediment starving in 2004. In 2015, accumulation of sediment has filled the groyne compartments 17-22, while the groyne fill ratio of the groyne compartments further upstream is more or less unchanged. It appears that the groyne compartments 6-16 have reached an equilibrium state, where the sediment volume in these compartments does not change in time.

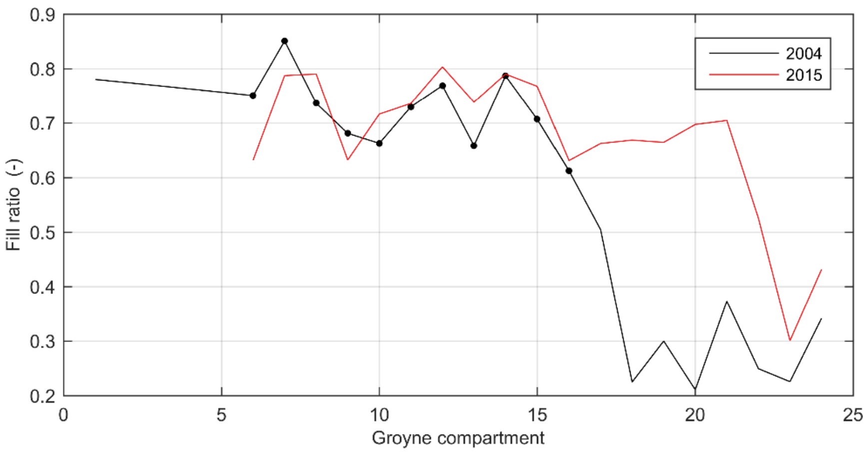

Figure 5. Groyne fill ratio derived from aerial image analysis. Groyne compartments 6-16 (highlighted with black points) are used for assessing upstream sediment supply and offshore sediment loss in Section 3.4.

The accumulated sediment volume in groyne compartments 17-22 between the observation in 2004 and the observation in 2015 corresponds to a volume of about 28,000 m^3/year when assuming an active height of 5 m. The rate of accumulation is remarkably low when considering that the bypass of sand to groyne compartments further downstream must be close to zero, which therefore suggests that either, the:

- Offshore loss along the half-empty cells is relatively high when they start filling up (rip-current)
- Upstream supply of sediment is only about 28,000 m^3/year

An empirical model for sediment bypass is used to assess the littoral drift conditions along the groyne field in order to weigh the two above possibilities.

3. Modelling sediment bypass

3.1. Background

The sediment bypass model is developed in Kristensen et al. (2016). The sediment bypass model is an empirical correction to the geometric bypass, Q_{geo}, which is defined in Figure 6 as the amount of transport occurring seaward of the groyne tip. The correction to the geometric bypass is based on the observation that:

- The geometric bypass is the minimal bypass
- Shoreline changes can increase the bypass

The geometric bypass aggregates information on the shape of the coastal profile, the width of the active transport zone and the magnitude of the minimum bypass rate.

The bypass area, Q_{byp}, increases because a turning of the shoreline up against the waves will shift the transport zone seawards at the updrift side of the groynes. The seaward shift will depend on the angle of the approaching waves, the distance between the groynes and the geometric bypass, i.e. if the groynes are short (Q_{geo} is similar to the undisturbed transport, Q_0), then shoreline changes will be subtle regardless of the angle of wave incidence or the groyne spacing. Conversely, if the groynes are long (Q_{geo} is close to zero), then the turning of the shoreline can be significant. However, turning of the local coast normal will also reduce the angle between the incident waves and the shoreline normal, thus approaching the zero transport orientation.

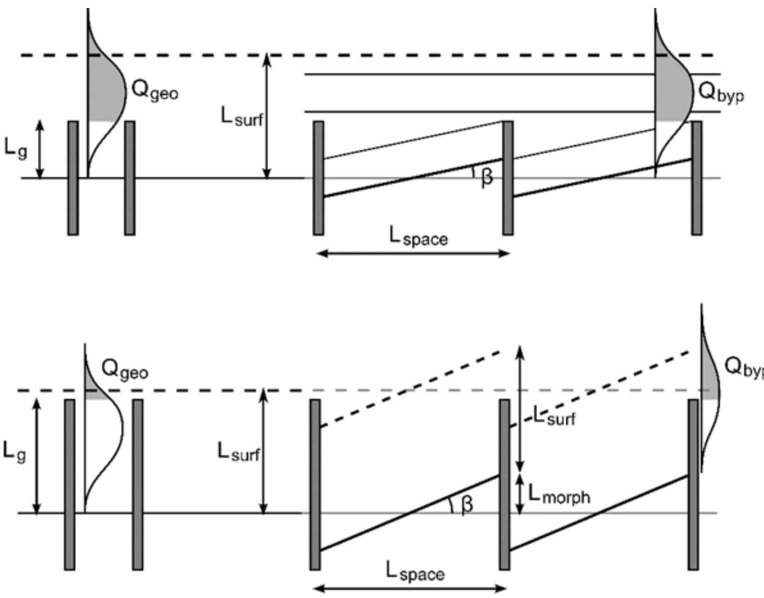

Figure 6. Definition of variables. β is the angle between waves and coastline normal at closure depth.

The empirical correction developed in Kristensen et al. (2016) to the geometric bypass is formulated by comparing simulation results from a set of different idealized cases where the principal groyne dimensions (length and spacing) were varied along with variations in the wave input (wave height and direction). The simulations included morphological evolution in a periodic domain by use of a developer version of DHI’s new model, MIKE 21 Shoreline Morphology FM.

Figure 7 shows an example of the bathymetry and transport field for a case with 200 m long groynes located every 500 m alongshore at the stage where equilibrium conditions have been obtained. The cross-shore integrated littoral drift distribution for the same case is shown in Figure 8 where it is clearly seen that the model can reduce gradients in the littoral drift. The black point indicates the geometric bypass rate, which is lower than the final equilibrium rate estimated by the use of the morphological model, which supports the understanding that the geometric bypass rate is a minimum value for the actual bypass rate.

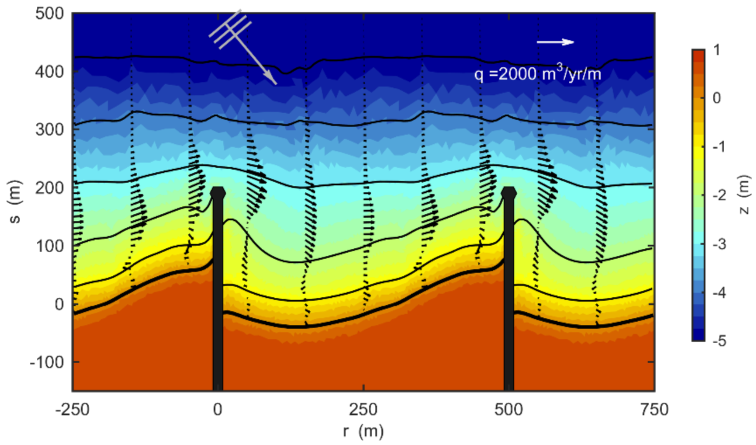

Figure 7. Example of simulated equilibrium conditions for a groyne field with 200m long groynes. From Kristensen et al. (2016).

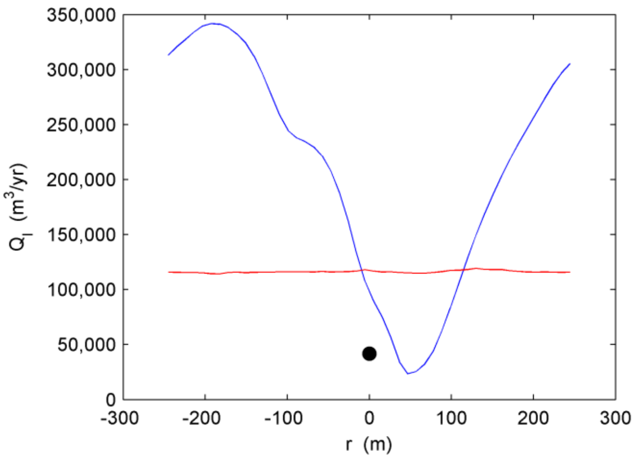

Figure 8. Example of simulated littoral drift distributions for groyne field shown in Figure 7. Blue curve: Initial time step. Red curve: Equilibrium conditions. Black point: Geometric bypass (based on undisturbed transport calculation). From Kristensen et al. (2016).

A synthesis of the results lead to a formulation where the sediment bypass is formulated as a function of the relative (normalized) geometric bypass (Q^*_{geo}) and the ratio between L_{morph} and L_g. L_g is the groyne length and L_{morph} is a length scale that depends on the groyne distance and the angle of wave incidence at the closure depth (see Figure 6).

$$\frac{Q_{byp}}{Q_0} = Q^*_{geo} + \left(1 - Q^*_{geo}\right)\left(1 - \exp\left(-0.8\frac{L_{morph}}{L_g}\right)\right) \tag{1}$$

The functional formulation of the relative bypass is compared with the calculated bypass rates in Figure 9. The solid lines indicate the equilibrium bypass rate according to eqn. 1 and the points represent model results. Colours indicate the relative geometric bypass ratio.

The figure shows that for the case where the geometric bypass is zero, i.e. a case where the groynes block the transport completely (blue curve in Figure 9), the bypass transport is zero for cases where L_{morph}/L_g is close to zero while the bypass transport tends towards the undisturbed transport when L_{morph}/L_g increases. For the case where the geometric bypass is zero, the actual bypass transport can vary quite a lot depending on the groyne length, groyne spacing and the predominant wave climate. Conversely if the geometric bypass is high (e.g. the red curve in Figure 9, where Q^*_{geo} = 0.87), the corrected bypass transport is bound in a much more narrow band and therefore not as sensitive to the groyne length, groyne spacing or wave climate.

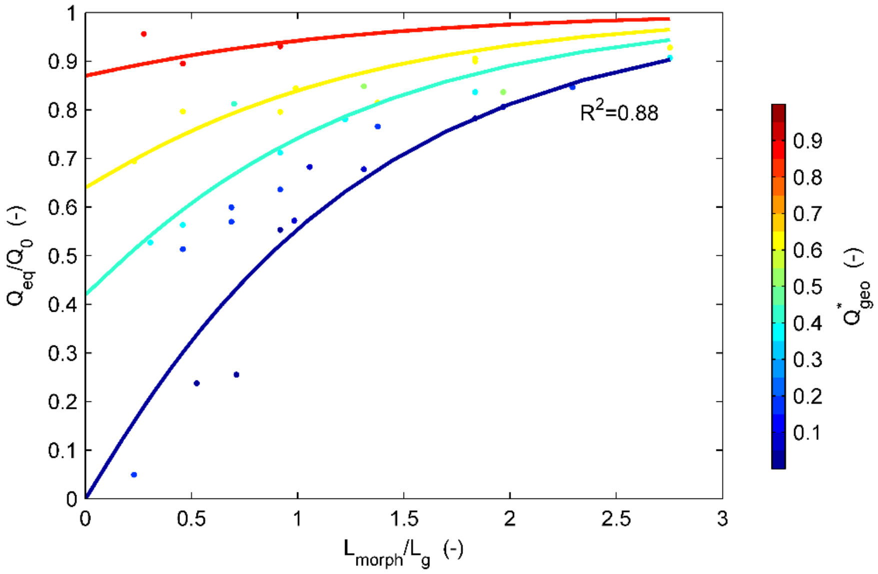

Figure 9. Simulated equilibrium bypass rates (points), functional form from eq. 1 is indicated with the curves for Q^*_{geo}: 0, 0.42, 0.64, 0.87.

3.2. Bypass rate at Lobito

A previous DHI study of the area has estimated the average undisturbed littoral drift to be about 260,000 m^3/year and that the majority of the drift occurs in a 30 m narrow band along the coast. The littoral drift distribution for the undisturbed case is depicted in Figure 10, both in terms of the longshore drift distribution over the profile (red curve) and in terms of the cumulated littoral drift distribution over the profile (blue curve).

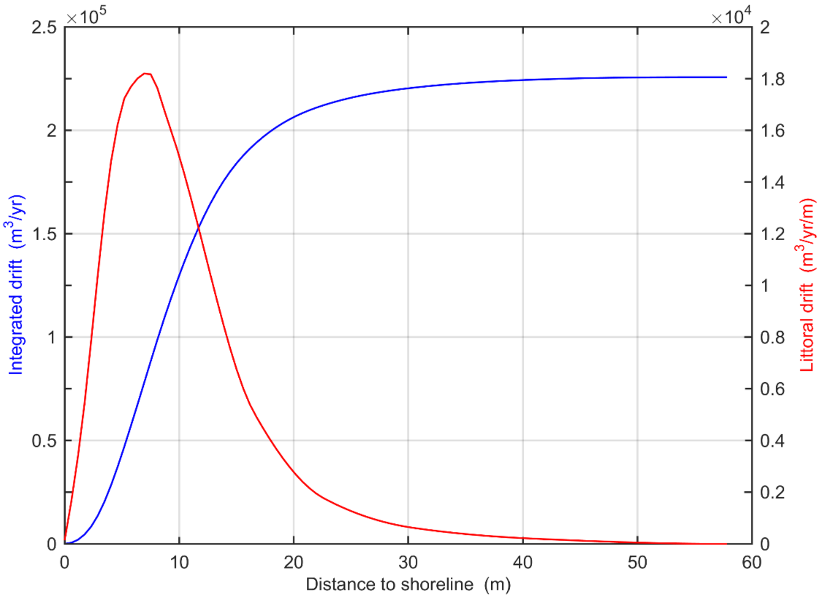

Figure 10. Littoral drift distribution.

The geometric bypass rate (Q^*_{geo}) is derived directly from the littoral drift distribution shown in Figure 10 in combination with the groyne length and the degree of filling of the groyne compartment.

The bypass formulation from Kristensen et al. (2016) was based on cases where the fill ratio of the groyne compartments was maintained, and the morphological model only redistributed sediment internally. In the present application, the sediment volume inside a groyne compartment will evolve in response to sediment supply/loss. Thus, in order to understand the bypass rate at Lobito as function of the degree of filling of the groyne compartments, eq. 1 is used to calculate the bypass rate. The calculated bypass rates are shown in Figure 11 for three different angles of wave incidence (angle between predominant wave and the overall coast normal). The curve relevant to conditions at Lobito is the red curve, where the angle between the approaching waves and the coast normal is 17 deg. The geometric bypass rate is also shown in the figure.

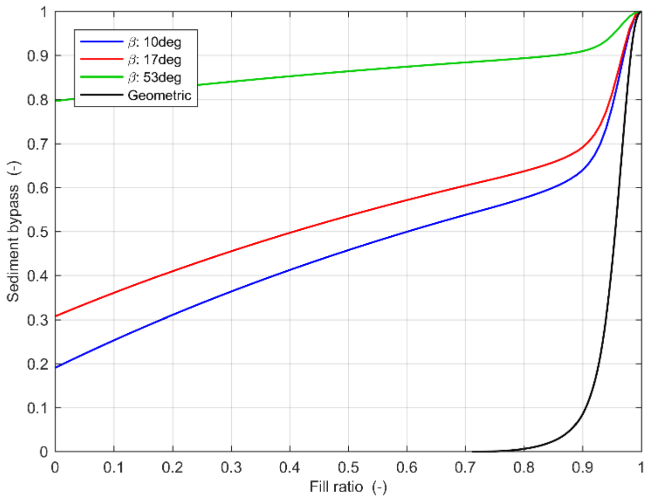

Figure 11. Bypass transport following the formulation from eq. 1 for a 100 m long groyne with a 300 m spacing.

The figure shows that there are two distinct regimes of bypass rate in terms of the sensitivity of bypass transport to changes in groyne fill ratio. The two regimes appear distinct because the width of the littoral transport zone at Lobito is narrow compared to the groyne length. The first regime is associated with the geometric bypass rate and is found along cases where the groyne compartment is nearly full. The bypass transport is here quite sensitive to changes in groyne fill ratio. The second bypass regime is associated with the morphological evolution of the coast inside the groyne compartment and the bypass transport is for this regime less sensitive to changes in groyne fill ratio.

The red curve in Figure 11 is used directly to assess bypass conditions at Lobito. For the two examples with groyne compartments shown in Figure 5, the bypass is thus estimated to be about 156,000 m^3/year (60% of Q_0) for groyne compartment 10 and about 104,000 m^3/year (40% of Q_0) for groyne compartment 18. The first bypass estimate seems reasonable, but the bypass transport for the half-empty groyne compartments appears to be over-estimated since the beach in this compartment is turned more or less up against the approaching waves.

The overestimated bypass from the empirical expression in eq. 1 may be linked to the fact that the expression was developed for cases where the surf zone was mostly comparable or wider than the groyne length. For the case at Lobito, the groynes are about three times longer than the surf zone when the groyne compartment is empty.

3.3. Sediment budget for downstream end of Lobito spit

The sediment budget for the downstream end of Lobito spit is formulated based on the empirical bypass estimate. The budget is shown in Figure 12 and covers groyne compartments 17-22 for the period 2004-2015. The sediment supply from upstream is according to the empirical bypass estimate about 150,000 m^3/year, which results in an offshore loss of about 120,000 m^3/year. The large offshore loss is attributed to offshore rip currents along the upstream side of the groynes in the compartments being filled, because this alone can explain how the gradual filling of the compartments occurs successively but at a much lower rate than the supply of sand.

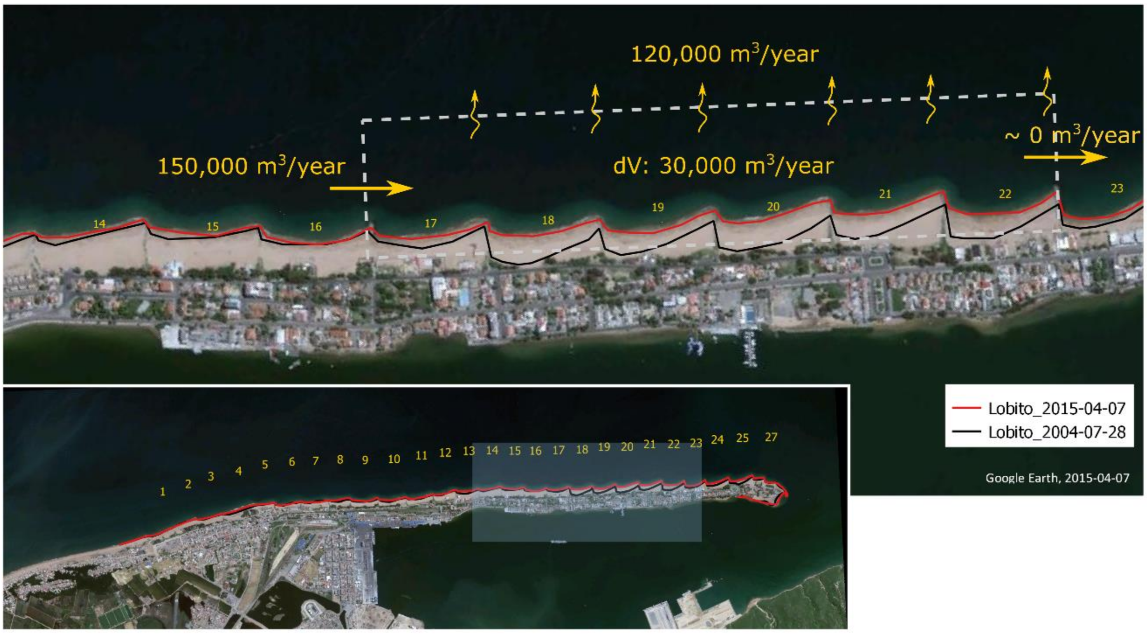

Figure 12. Sediment budget for groyne compartments 17-22 from 2004 to 2015.

3.4. Sediment budget for upstream end of Lobito spit

The littoral drift distribution for the 2004 fill ratio distribution is assessed by use of the empirical bypass expression along the upstream end of Lobito spit where the groyne compartments are partly full. The drift estimate is shown in Figure 13. It is noted that the transport estimate along the downstream end (beyond groyne 16) is also shown in the figure but it is believed to over-estimate the actual bypass rate.

In order to obtain a smooth assessment of the upstream sediment supply a linear distribution to the drift rates is fitted to the calculated drift for groyne compartments 6-16. The resulting linear drift distribution is indicated by the grey curve and it shows that the drift at the first groyne compartment is about 66 % of the undisturbed transport, i.e. 170,000 m^3/year and that the littoral drift should decrease gradually along the spit. The gradual decrease is the result of the groyne compartments tending to be less full downstream compared to further upstream.

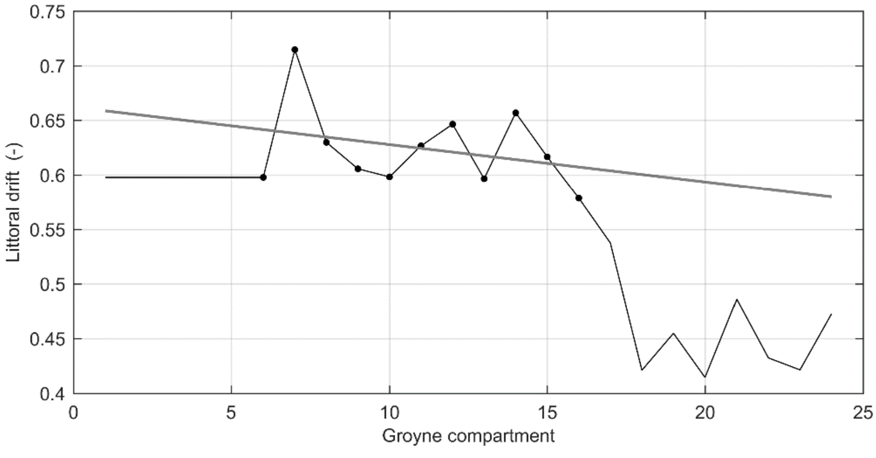

Figure 13. Black: Littoral drift distribution along the groyne field based on the 2004 groyne fill ratio. Grey: LS-fit to drift rates at groyne compartments 6-16, extrapolated across entire groyne field.

The evolution of the fill ratio along the upstream end of Lobito spit suggests that the volume is about constant. Thus, the decreasing littoral drift along this part of the spit must be balanced by a moderate offshore sand loss of 20,000 m^3/year.

4. Modelling long-term behaviour of Lobito spit

The long-term behaviour of the groyne field at Lobito spit is analysed by use of a simple box-type morphological model as illustrated in Figure 14. The morphological development is quantified by modelling the average beach width inside each groyne compartment, s_i using a mass balance equation. The formulation of the bypass rate, $Q_{L,\,i}$ is calculated using the empirical bypass expression from eq. 1. The offshore loss $Q_{off,i}$ is derived from the sediment budget along the upstream end of the spit, because the observed gradual filling of the downstream compartments will eventually fill also the sediment starving compartments.

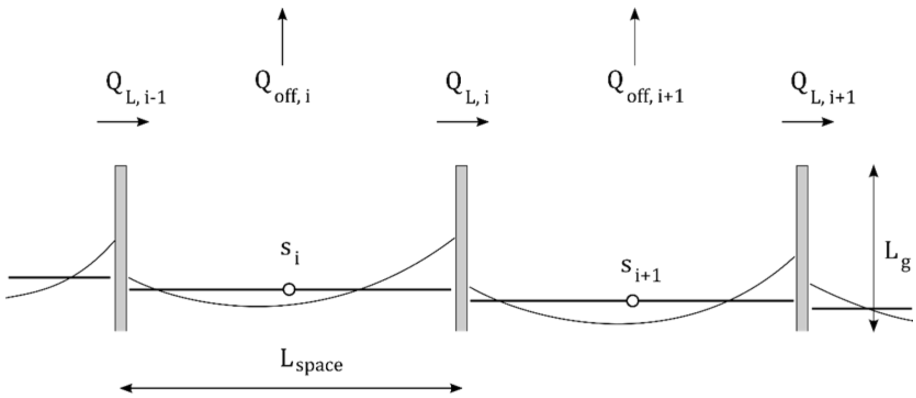

Figure 14. Box-type morphological model. The free parameter *s* defines the beach width within a groyne compartment.

Figure 15 compares the simulated fill distributions against the observed fill ratios. The model does not capture the successive filling of groyne compartments as the observations suggest. This is attributed to the over-estimation of bypass for the half-empty groyne compartments. Conversely, the offshore loss of sand in the filling groyne compartments is not included in the model and it appears to cancel out the over-estimated bypass such that the filling of the groyne compartments is described reasonably well.

The observed groyne fill ratios tend also to contain more temporal and spatial variation compared to the simulation results, as would be expected when using average conditions for model forcing as is done here.

The long-term equilibrium conditions exemplified by simulated fill-ratios after 50 years are shown in the figure for two cases. One, where offshore loss of sand is included and one where the offshore loss of sand is excluded. The figure shows that the offshore loss leads to a decreasing fill ratio along the groyne field. The offshore loss of sand decreases the littoral drift alongshore; hence, the groyne fill ratio must decrease.

The implication of the modelled results is that an offshore loss of sand along an otherwise stable groyne field is balanced by an equivalent decrease in littoral drift. The fill ratio along the groyne field must decrease along the groyne field in the direction of the littoral transport in order to facilitate such a decrease in littoral drift. Hence, the offshore loss of sand will make the downstream groyne compartments sensitive to erosion and rising water levels. Furthermore, gradual filling of groyne compartment that have previously been subject to sudden erosion events, will occur at a lower rate.

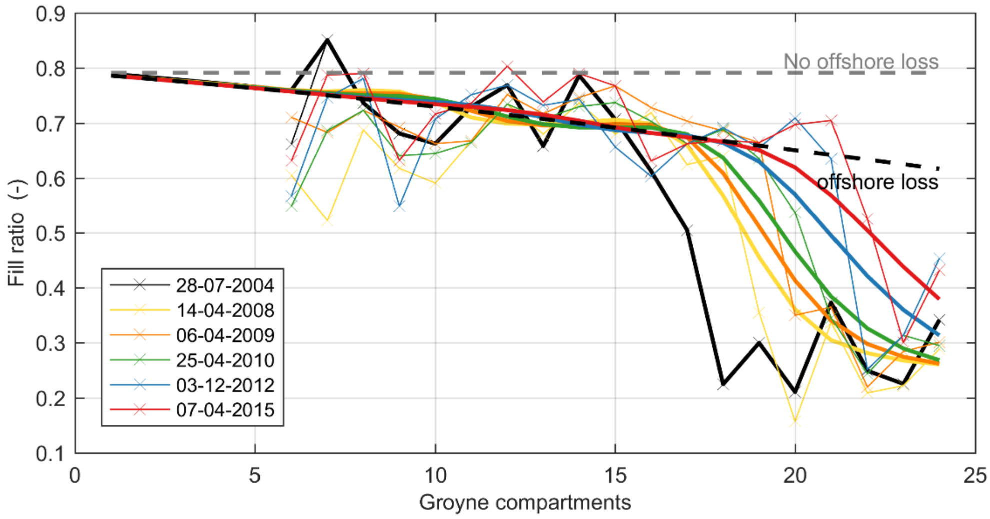

Figure 15. Comparison between modelled and observed groyne fill. Bold curves are simulated, thin curves with "x" are observations. The long-term solution is shown as dashed curves.

5. Conclusion

Aerial images of Lobito spit from 2004 to 2015 suggest that the upstream groyne compartments tend to be filled to a greater extent than the downstream groyne compartments. Furthermore, successive filling of empty downstream groyne compartments has occurred over the period covered by the aerial images.

An empirical bypass formulation derived from detailed 2D simulations is used to estimate the bypass conditions in the groyne field. The bypass description is closely related to simpler geometric considerations often seen in traditional 1-line models but includes also effects of streamline contractions, thus providing a better representation of the bypass. The bypass estimate appears however to over-estimate bypass for conditions where the groyne compartment is half-empty.

A sediment budget is formulated for the downstream end of the groyne field where the groyne compartments are filling up. From the budget it appears that the majority of the littoral drift supplied into the area is lost offshore probably due to rip currents along the upstream side of the groynes.

A sediment budget for the upstream end of the groyne field indicates that the offshore loss along this section is much smaller, probably because the groyne compartments along this section are partly full.

The example at Lobito spit shows that the groyne field combined with offshore loss of sediment can lead to sediment starving groyne compartments along the downstream end of the groyne field. This may be the case both if offshore loss of sand occurs infrequently or if the offshore loss of sand occurs continuously. If the offshore loss occurs infrequently, the downstream groyne compartments will be sediment starving because filling of the compartments occurs from the upstream end of the groyne compartment. Conversely, if the offshore loss of sand occurs as a continuous process then it is shown that the equilibrium fill distribution will tend to have upstream groyne compartments filled and downstream groyne compartments less filled.

Regardless of whether the offshore sand loss occurs continuously or during discrete events, it is clear, that problems with narrow downstream groyne compartments can be mitigated by removing the cause the offshore sand loss, e.g. by changing the design of the groyne structures.

6. Acknowledgements

This work has been supported by the Danish Agency for Science, Technology and Innovation, under DHI's GTS Core Research contract 2016-2018.

7. References

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