Sea wave propagation from offshore to Maputo’s coast. Application to longshore sediment transport assessment
Cristina N. A. Viola, Manel Grifoll, Jaime Palalane and Tiago C. A. Oliveira

ABSTRACT
This study aims to characterize the wave climate near the coastal region of Maputo (Mozambique), and to provide a first assessment of the sediment transport load in this area. A time-series of 13 years’ worth of offshore wave data, obtained from reanalysis products, was propagated to the coast. Wave propagation was performed using Linear Wave theory and the numerical model, Simulating WAVes Nearshore (SWAN). Propagations with SWAN were carried out considering different scenarios in order to evaluate the influence of parameters such as wind, tidal level, frequency spectrum and numerical mesh resolution on wave characteristics along the coast. The prevalent waves propagated came from between east and southwest directions. Results from linear propagation were used to estimate the potential longshore sediment transport. The Coastal Engineering Research Center formula was applied for a stretch of beach in the Machangulo Peninsula. A net potential rate of longitudinal sediment transport (of the order of $10^5$ m$^3$/year, along an extension of the coast of 21 km) was directed northwards, and was consistent with the frequent wave directions.

INTRODUCTION
Maputo’s coastal area (Mozambique) has great diverse natural environments and landscapes that are characterized by the occurrence of mangroves, submarine coral reefs, small islands and archipelagos, among others. These environments are a key element to the economy of this region as they boost economic, cultural and touristic activities, and have also contributed to the high population density in this area.

The evolution of Maputo’s coastal area is characterized by its degradation from erosion and loss of mangrove areas, as well as from the decrease in surrounding sandy beaches and dunes (Björnberg & Wahlström 2012). Part of this degradation is due to natural processes, related to the impact of severe wind-waves and anthropogenic actions. The knowledge of the wave climate and its interaction with the sandy coast are a key issue in developing coastal-management plans. In this sense, shoreline erosion is closely related to longshore sediment transport, so the quantification of this process is essential to understand and predict coastline evolution (Jiménez & Sánchez-Arcilla 2004; Khalifa et al. 2009; Silva et al. 2013). An accurate description of the wave climate (and its propagation) is required to estimate the sediment transport load in the shoreline and to design mitigation actions (Mendoza & Jimenez 2006). From an engineering point of view, wave propagation techniques are based on analytical approaches and numerical models (see review in Cavalieri et al. 2007). The wave conditions in the shoreline permit the assessment of sediment drift, and the implementation of numerical models of coastal evolution (e.g., Jiménez & Sánchez-Arcilla 2004; Cañizares & Irish 2008; Roelvink et al. 2009; Harley et al. 2011; Briganti et al. 2012; Postacchini et al. 2012; Gracia et al. 2013).

This work is focused on an area previously uninvestigated, so the primary goal of this research is to characterize the wave climate in the region adjacent to the coast of Maputo (Figure 1). The research starts evaluating the wave data available offshore from Maputo Bay, then propagating the wave conditions to the shore. Finally, we estimate the longshore sediment transport using an analytical formula in a stretch of beach in the peninsula of Machangulo (see Figure 1). The layout of this paper is as follows: the next section describes the methodology used in the study, with the subsequent section dedicated to results.
and discussion. The paper ends with the main conclusions and recommendations for further research.

**METHODOLOGY**

The methodology used in this study was based on three steps: (i) characterization of the Maputo offshore wave climate, (ii) wave propagation from offshore to onshore, and (iii) assessment of longshore sediment transport. Details of the methodology used in each of steps are presented in the next points.

**Maputo offshore wave climate**

Due to the lack of visual and instrumental data in the study area, wave data from the global numerical model NOAA Wave Watch III (NWW3) (Tolman 2002) are used. This implementation generates global wave data (including for the African East Coast) every 3 hours with a spatial resolution of 1.25° longitude and 1.0° latitude (approximately 138.75 km × 111 km). The NWW3 model solves the spectral action density balance equation for wave number-direction spectra. The growth, refraction and decay of each component of the complete sea state, for each specific frequency and direction, are solved. The main physical processes involved in ocean wave generation and propagation are included in the model, specifically: refraction and straining of the wave field due to temporal and spatial variations of the mean water depth and of the mean current, wave growth and decay due to the actions of wind, nonlinear resonant interactions, dissipation by white-capping, and bottom friction (Tolman 2002).

In this study, 13 years of wave data (Hs – significant wave height, Tp – Pick Period and Dr – mean direction) from 1997 to 2010 are used. Wind data from the Global Forecast System project are used in NWW3 as an input. To perform the present study, a point (P) 600 km offshore from the Maputo coast was used as the reference point to take results from NWW3. Figure 1 illustrates the point (P) located at 26°S 38°45’E.

Figure 2 presents the directional histogram of wave height for point P. Predominant wave directions are from SSW (30%) with significant wave height predominantly in the interval of 2–3 m. Waves with direction from ESE represent 22% of the total waves.

**Wave propagation**

**Propagation based on linear wave theory**

Propagation based on linear wave theory is used in this study to propagate waves from offshore to the onshore breaking point. This method takes into account shoaling and refraction, and is based on Snell’s law, the wave energy conservation principle and on the assumption that waves propagate on a constantly slope bathymetry parallel to the shoreline. The depth-induced wave breaking criteria \(H/h = 0.78\) (McCowan 1894) is used to identify the breaking
All the 17,528 wave cases correspondent to the 13-year offshore wave regime are considered in the propagation. However, some of the waves cases registered offshore were not propagated because they are not effective according to the sediment transport estimations. These cases correspond to waves that are not traveling to the coast.

**Numerical propagation with Simulating WAves Nearshore (SWAN)**

In order to propagate waves from offshore to the coast, the open source numerical model, SWAN (Booij et al. 1999), was used. SWAN is a well-known model in the field of coastal engineering. The SWAN model takes into account a large number of actions and processes that influence wave propagation: (i) wave propagation in time and space, shoaling, refraction due to current and depth, and frequency shifting due to currents and non-stationary depth; (ii) wave generation by wind; (iii) three- and four-wave interactions; (iv) white-capping, bottom friction and depth-induced breaking; (v) dissipation due to vegetation; (vi) wave-induced set-up; (vii) propagation from laboratory up to global scales; (viii) transmission through, and reflection (specular and diffuse) against, obstacles; and (ix) diffraction. SWAN computations can be made on a regular or curvi-linear grid, and a triangular mesh in a Cartesian or spherical co-ordinate system.

Two regular meshes with different geographic limits were tested in the numerical experiments (M1 and M2 in Figure 1). A spatial discretization of 1,600 m in both directions was used in the wave simulations in order to limit the computational costs for M1. Wave parameters are provided to M2 mesh boundaries (with a spatial resolution of 600 m) from M1 model outputs. Bathymetry data were derived from the database, General Bathymetric Charts of Ocean (GEBCO) (see Figure 3). The bathymetric in GEBCO was generated by combining quality-controlled ship-depth soundings, with predicted depths between the sounding points guided by satellite-derived gravity data (Smith & Sandwell 1997). In order to avoid the propagation of the entire 13-year wave regime with SWAN (17,528 wave cases), limited representative wave cases were simulated with SWAN. A set of numerical experiments using SWAN was carried out in order to evaluate the sensitivity of the outputs (wave height, wave period and wave direction) at different input parameters. In addition to the inter-comparison of the meshes, we compared the inclusion of waves and tides. A wind speed of 4.5 m/s and a tidal range between 0.2 and 3.8 m were assumed in the sensitivity test (Langa 2007). The most frequent wave characteristics were combined with the 3 directions of wind, 45, 90 and 225°.

Furthermore, a comparison considering Jonswap or Pierson–Moskowitz spectrums was carried out. The main input parameters used and tested in the simulations are summarized in Table 1.

Based on the work done by Guiloviça et al. (2011) a very energetic wave case corresponding to a 25-year return period event ($H_s = 7.63$ m, $T_p = 11.0$ s and $D_r = 90°$) was chosen and propagated with SWAN. The inclusion of this case aims to evaluate the wave energy changes induced by the propagation of an extreme wave.
The longitudinal sediment transport by the action of sea waves was evaluated using the Coastal Engineering Research Center (CERC) formulation (USACE 1984). There are not enough data available on the sediment size and inclination of the profile of the region under study; since these are the basic parameters of other commonly used bulk longshore sediment transport formulas (e.g. Kamphuis 1991; Rijn 2000), this evaluation was limited to the CERC formulation:

\[
Q_l = K \cdot H_b^{5/2} \cdot \sin(2\alpha_b) \cdot \frac{\rho \sqrt{g}}{16 \gamma^{1/2} \cdot (\rho_s - \rho)(1 - n)}
\]

where \(K\) is the CERC coefficient, \(Q_l\) is the solid flood, \(H_b\) is the breaking wave height, \(\gamma\) is the breaking criteria parameter, \(g\) acceleration of gravity, \(\alpha_b\) is the angle between the coastal normal and the wave front, \(\rho_s\) is the sediment density, and \(\rho\) is the water density.

In this study the value of \(K\) is calculated according to Mil-Homens et al. (2013):

\[
K = \left[2232.7 \left(\frac{H_b}{L_0}\right)^{1.45} + 4.505\right]^{-1}
\]

where \(L_0\) is the wave length calculated for deep water conditions. In order to evaluate the sensitivity of \(K\), calculations with a constant \(K\) value of 0.29 were also performed.

### RESULTS AND DISCUSSION

#### Propagation using the linear wave theory

The results for the propagation using the linear wave theory are presented through contingency tables, which relate the occurrence of a wave with its significant height, and wave period to a certain direction. Thus, we divided the dataset in intervals of 22.5° directions (16 intervals were obtained), significant wave heights \(H_s\) at intervals of 0.5 m, and periods \(T_p\) at 2 s intervals (nine intervals were obtained). The contingency table of the wave climate obtained from the reanalysis is shown in Table 2. The maximum significant wave is about 4 m and corresponds to 90° and 45°N directions. Table 3 shows the wave heights in the surf zone resulting from linear propagation of the offshore point. The maximum significant wave height is around 2 m and corresponds to a 90°N wave direction. The frequencies of the directions offshore and in the breaking point are shown in Figure 4. In both cases, the predominant wave direction is ESE.

#### Propagation using the SWAN numerical model

This section presents the wave propagation using SWAN. Results of the sensitivity numerical experiments are summarized in Table 4. The values correspond to the propagation at point P2. The first scenario corresponds to
the propagation of the average climate without the influence of external agents. In this case, the wave height at P2 was 1.5 m. The sensitivity test for the different wind conditions showed how the wind effect is relatively low. In this sense, differences of a few centimeters in significant wave height were obtained (see Table 4). The most unfavorable combination was with a wind direction of 45°N, with an increase of the wave height of 7%. The changes in wave direction and period were negligible. The inclusion of tides does not show a noticeable difference between the numerical results. An additional scenario is related to the variation of the standard spectrum of the SWAN model. Differences of about 8% were obtained in terms of wave height and wave period by comparing Jonsswap and Pierson–Moskowitz (PM) wave spectra.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Directionwave,0 (N)</th>
<th>Variation</th>
<th>$H_s$ (m)</th>
<th>$T_p$ (s)</th>
<th>Direction (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple propagation</td>
<td>202.5</td>
<td>–</td>
<td>1.5</td>
<td>10.5</td>
<td>162</td>
</tr>
<tr>
<td>Propagation including wind</td>
<td>202.5</td>
<td>Wind 45°N</td>
<td>1.6</td>
<td>9.0</td>
<td>158.7</td>
</tr>
<tr>
<td></td>
<td>202.5</td>
<td>Wind 90°N</td>
<td>1.4</td>
<td>9.2</td>
<td>160.0</td>
</tr>
<tr>
<td></td>
<td>202.5</td>
<td>Wind 225°N</td>
<td>1.3</td>
<td>9.4</td>
<td>159.2</td>
</tr>
<tr>
<td>Propagation including tides</td>
<td>202.5</td>
<td>High tide</td>
<td>1.6</td>
<td>10.5</td>
<td>162.4</td>
</tr>
<tr>
<td></td>
<td>202.5</td>
<td>Low tide</td>
<td>1.6</td>
<td>10.5</td>
<td>162.2</td>
</tr>
<tr>
<td>Propagation with different spectrums</td>
<td>202.5</td>
<td>Jonsswap</td>
<td>1.5</td>
<td>10.5</td>
<td>162.0</td>
</tr>
<tr>
<td></td>
<td>202.5</td>
<td>PM</td>
<td>1.6</td>
<td>9.7</td>
<td>163.2</td>
</tr>
</tbody>
</table>

Table 3 | Wave heights propagated linearly at the breaking point (in meters)

<table>
<thead>
<tr>
<th>$T_p$ (s)</th>
<th>Direction (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.5</td>
<td>45</td>
</tr>
<tr>
<td>67.5</td>
<td>90</td>
</tr>
<tr>
<td>112.5</td>
<td>135</td>
</tr>
<tr>
<td>157.5</td>
<td>180</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Directionwave,0 (N)</th>
<th>Variation</th>
<th>$H_s$ (m)</th>
<th>$T_p$ (s)</th>
<th>Direction (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple propagation</td>
<td>202.5</td>
<td>–</td>
<td>1.5</td>
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</tr>
<tr>
<td>Propagation including wind</td>
<td>202.5</td>
<td>Wind 45°N</td>
<td>1.6</td>
<td>9.0</td>
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</tr>
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<td></td>
<td>202.5</td>
<td>Wind 90°N</td>
<td>1.4</td>
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<td>1.3</td>
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<td>159.2</td>
</tr>
<tr>
<td>Propagation including tides</td>
<td>202.5</td>
<td>High tide</td>
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<td></td>
<td>202.5</td>
<td>PM</td>
<td>1.6</td>
<td>9.7</td>
<td>163.2</td>
</tr>
</tbody>
</table>
For the 25-year return period wave case, it was found that the significant wave height presents a reduction of about 34% from offshore to onshore ($H_s = 7.63$ m at P, $H_s = 5.00$ m at P2). The wave direction tends to deflect slightly from East to Southeast ($D_r = 90^\circ$ W at P, $D_r = 106.5^\circ$ W at P2) and the period also tends to reduce ($T_p = 11.0$ s at P, $T_p = 10.1$ s at P2).

**Comparison between linear propagation and the SWAN model**

Results of the linear propagation (Table 5) and propagation with the SWAN model (Table 6), were compared based on obtained wave characteristics at point P2. Through analyzing the results of these two propagation methods, differences in significant wave height are noticeable in some directions. For instance, differences of 1.5 m were obtained for waves coming from $22.5^\circ$ W. Furthermore, directions that tend to be perpendicular to the shore showed similar results. For instance, differences of 0.3 m were found for the $112.5^\circ$ N wave direction case. Linear theory tends to provide smaller values than the SWAN model; the differences in terms of wave period and wave direction were relatively smaller than the significant wave height.

**Sediment transport estimations**

The results of the wave propagation were used to study the coastal dynamic, preceding an analysis of the longshore sediment transport along a 21 km stretch of the Machangulo Peninsula. The wave conditions were propagated to P3 (see Figure 1). There are not enough data available on the sediment size and inclination of the beach profile, which are the basic parameters of the Kamphuis formulations (Kamphuis 1991) and Van Rijn (Rijn 2001). Therefore, the assessment of longshore sediment transport was limited to the CERC formulation (USACE 1984). Table 7 presents the results of the annual integrated transport according to the CERC coefficient, $K$. The most effective directions were found according to the rate of potential sediment with an evident transport northward. These correspond to directions of $112.5^\circ$ and $135^\circ$. Directions below $90^\circ$ were associated to southward longshore sediment transport.

The sediment transport rate obtained for Machangulo Peninsula seems low in comparison to locations of similar wave fetch. For instance, the gross annual transport estimated in Escuadrón Beach (Chile) was approximately $37 \cdot 10^6$ m$^3$/yr (Barrera et al. 2012) for 20 km of coastline.

Larangeiro & Oliveira (2003) and Oliveira et al. (2004) found rates of longshore sediment transport in Portugal’s coast greater than $10^6$ m$^3$/yr. Both examples present longshore sediment transport rates significantly larger than the estimations obtained for Machangulo Peninsula. Moreover, estimations in limited fetch-areas, such as the Egyptian Northern Coast (Khalifa et al. 2009), presented greater sediment transport rates (about $1.2 \cdot 10^6$ m$^3$/yr in 40 km of coastline) than the magnitudes estimated in Machangulo Peninsula. The study results seem comparable to the study carried out at Cancun Beach (Mexico) which considered different beach sections with an annual gross transport of around $70 \cdot 10^3$ m$^3$/yr (González-Leija et al. 2013). The results confirm the relatively greater variability

**Table 5 | Results of linear propagation to control point P2**

<table>
<thead>
<tr>
<th>Dir0 (°N)</th>
<th>22.5</th>
<th>45</th>
<th>67.5</th>
<th>90</th>
<th>112.5</th>
<th>135</th>
<th>157.5</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dir (°N)</td>
<td>29.2</td>
<td>47.8</td>
<td>67.5</td>
<td>90.0</td>
<td>112.4</td>
<td>134.6</td>
<td>156.7</td>
<td>169.8</td>
</tr>
<tr>
<td>$H_s$ (m)</td>
<td>2.7</td>
<td>3.8</td>
<td>2.6</td>
<td>2.3</td>
<td>3.0</td>
<td>3.0</td>
<td>2.7</td>
<td>1.7</td>
</tr>
<tr>
<td>$T_p$ (s)</td>
<td>11</td>
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<td>7</td>
<td>7</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>11</td>
</tr>
</tbody>
</table>

**Table 6 | Results of SWAN propagation model to control point P2**

<table>
<thead>
<tr>
<th>Dir0 (°N)</th>
<th>22.5</th>
<th>45</th>
<th>67.5</th>
<th>90</th>
<th>112.5</th>
<th>135</th>
<th>157.5</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dir (°N)</td>
<td>73.9</td>
<td>82.2</td>
<td>93.1</td>
<td>105</td>
<td>117</td>
<td>133</td>
<td>147</td>
<td>156</td>
</tr>
<tr>
<td>$H_s$ (m)</td>
<td>1.2</td>
<td>2.2</td>
<td>1.6</td>
<td>1.7</td>
<td>2.7</td>
<td>2.5</td>
<td>2.2</td>
<td>2.0</td>
</tr>
<tr>
<td>$T_p$ (s)</td>
<td>9</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>
in the longshore sediment transport estimations, basically due to uncertainty in the $K$ coefficient. In this sense, Larangeiro & Oliveira (2003) found that values of $K$ equal to 0.13 provided good estimations using the CERC formula in large-fretch areas such as Portugal’s coast. This value is lower than the standard value ($K = 0.77$) found by Komar & Inman (1979) for the Pacific Coast. Our ranges of $K$ values (i.e. 0.04–0.22), obtained using the Mil-Homens et al. (2013) formula, seem consistent with Larangeiro & Oliveira (2003), considering Machangulo Peninsula as a large-fetch location.

The longshore sediment transport values obtained in the current study may also be underestimated because waves used for transport were propagated to the shore based on linear theory. We have shown that linear theory tends to underestimate wave conditions in comparison to modelling outputs. In consequence, due to the noticeable variability in longshore sediment values (Mil-Homens et al. 2013), we recommend an accurate acquisition of wave data estimating breaking wave properties and a characterization of the granulometric and morphodynamic parameters to enhance the sediment transport estimations. Consequently, the results obtained in this contribution should be considered as a first assessment of longshore sediment transport not previously provided.

**FINAL REMARKS**

This paper provides a first assessment of the longshore sediment transport along the southern Maputo coast (Mozambique), near the Machangulo Peninsula, not previously estimated. The longshore sediment transport has been quantified of the order of $10^5$ m$^3$/yr. The predominant longshore transport is northward, consistent with the propagated wave climate. However, the difficulties encountered in this study suggest the need to improve some aspects related to beach characterization and wave climate data in this region. This will lead to an accurate calibration of the parameters involved in the sediment transport evaluations and wave propagation modeling. The results presented here may be useful to improve management of coastal areas, land management, and suggest appropriate solutions to the problems of coastal erosion in the area.

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