HYDROLOGY AND COASTAL MORPHOLOGY AT SÃO TOMÉ

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Abstract: The Democratic Republic of São Tomé and Principe is an archipelago comprised of two main islands and several islets located in the Gulf of Guinea 350 km off the west coast of Africa. Villages of in the archipelago are built close to the coastline and have historically suffered from high rates of river and coastal inundation and erosion. Flooding and erosion appeared to have increased in recent years due to climate change. Moreover, the economical and social evolution of São Tomé and Principe, closely linked to the colonial past of the country, has lead to a slowly impoverishment and lack of infrastructures at these villages.

The objective of the study consists in performing a coastal geomorphological and hydrological study to help identifying and analyzing coastal risks faced by local communities, accounting for possible climate change impact.

Keywords: climate change; hydrology; wave climate; coastal morphology; coastal zone management.

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INTRODUCTION

In most islands around the world, people, agricultural land, tourist resorts and infrastructures are concentrated in the coastal zones, and are thus especially vulnerable to any change in climate and rise in sea level. The Democratic Republic of São Tomé and Príncipe, is an archipelago comprised of two main islands respectively named São Tomé and Príncipe, and several islets located in the Gulf of Guinea 350 km off the west coast of Africa (Fig. 1). Given its small size, isolation, susceptibility to natural disasters and limited capacity to achieve sustainable development, São Tomé and Príncipe is highly vulnerable to the effects of climate variability and change. The country is one of Africa’s smallest nations with a total area of 1.001 km$^2$ and a population size of 166,000.

![Fig. 1. (Left panel) Map of the island of São Tomé with the location of the village of Ribeira Afonso. (Right panel) Location of the island with respect to the African continent.](image)

Tadross and Tummon (2009) found a general trend toward increasing aerosol concentration and precipitation during the December-February season in the area where the island is located. This trend appears to be consistent with fishermen’s reports that the fog season has changed in intensity and shifted in time since the early 1980s. In the last years, some of the coastal communities have begun to approach the Government, asking to help them in solving problems related to fishermen safety threatened by the decrease in visibility caused by the fog, the increase in river flooding and the extensive coastal erosion. Such vulnerability to present climate variability will tend to increase in the future due to the expected increase in extreme weather events which, to some degree, have already been observed.

This study is part of an on-going project which aims at evaluating and prioritizing a number of climate-related issues, for several villages located around the São Tomé coastline. In this paper, the main findings for one the villages are described: Ribeira Afonso. More details on the study and extensions to the other villages can be found in UNESCO-IHE and Deltares (2011) and Giardino et al. (2011). The prioritization of problems is defined based on measurement analysis, observations and interviews to local community members. Based on this analysis, and after consultation meetings with the local communities, a number of possible adaptation options are proposed.

DATA DESCRIPTION AND ANALYSIS

Given the large spectrum of problems characterizing the communities on the island, different data sets were used to carry out the study. The almost complete lack of measurements available made
impossible the setting-up of complex modeling tools, which require a high number of input parameters. Moreover, the few time series recorded (e.g. sea level) were not sufficiently long to derive long term trends, possibly related to climate change. Therefore, this study can be seen as a collection of practical solutions, which can be used to give a first description of the functioning of the coastal physical systems and to draft preliminary solutions to eventual problems.

**Topographic and bathymetric data**

No digital elevation map, neither detail bathymetry data of the island are available. The hydrological modelling of the island was carried out using “strm data” (http://srtm.csi.cgiar.org). The resolution of the DEM is 90x90 meter.

Bathymetry data at the two villages were collected using an echosounder (Plastimo echotest: resolution 0.1 m – maximal measurable depth = 80 m). Three profiles were collected at the village of Ribeira Afonso. Bathymetry data were corrected for tidal influence and referred to mean sea level.

**Precipitations**

The large topographic gradients caused by the presence of a volcanic formation in the middle of the island which reaches the altitude of 2024 m, lead to extremely large variations in precipitations (Fig. 2). The northern part of the island is characterized by a very dry climate with averaged annual precipitations far below 1000 mm/year, and in the south-western part reaching peaks above 7000 mm/year. Given these large differences in rainfall between catchments, rainfall data at several locations around the islands would be necessary for a good understanding of the hydrological system at catchment level. Moreover, given the small scale of the catchments, high temporal resolution would also be required to reproduce peaks of the flooding events. Unfortunately, rainfalls data at the moment are only collected at the airport, which is located in the northern part of the island where the annual precipitation is very low (925 mm/year), and with scarce temporal resolution (1 measurement/day). Therefore, to drive the hydrological model in the catchment of interest, satellite TRMM data were used (Kummerov et al., 2000; Simpson et al. 1996) available for the period 1999-2008, which overlaps to the airport data. This data set, despite the very poor spatial resolution (0.25 × 0.25 degrees), has the advantage of covering the all island. The data was corrected to reduce the bias with respect to measurements at the airport, and to account for gradients in rainfall within the island. These are very crude approximations, and therefore results need to be looked with a critical eye. However, given the total lack of data in the catchment of interest, this was the only possible approach to be used to drive the hydrological model, and to have a first estimate of the discharges and their variability in the year, in conjunction with possibly expected changes in the future.
Waves

No wave data is recorded at the moment around the island. ECMWF (European Centre for Medium-Range Weather Forecasts) were used in this study. The data are available on a 2.5 degrees resolution grid for the period 1957-09-01 until 2002-08-31. The data set contains information on significant wave height ($H_s$), mean wave period ($T_m$), and mean wave direction ($\theta_m$).

Winds are mostly directed from south to north during the year (Tadross and Tummon, 2009). Moreover, the African continent creates a sort of natural protection in the North and East side of the island, leading to the wave climate in Fig. 3. The wave rose shows that waves approaching the islands are mainly coming from SSW direction.

An extreme event analysis was performed based on the wave height data set. The results of this analysis are shown in Fig. 4. In particular, wave heights for return periods of 30, 50 and 100 years are respectively equal to 2.88 m, 2.95 m and 3.07 m.

Caires et al. (2006) computed the present global wave height for waves with return period of 20 years and estimated the seasonal relative change between 1990 and 2080. According to their estimation, at the location of São Tomé an increase in wave height up to 5 % might be expected before 2080.

Tide and surge

One tidal gauge located in the Baia de Ana Chaves, where the capital is situated, supplies hourly information on tidal levels. Data can be required through the website (http://www.brest.ird.fr/pirata/sao_tome.php). Hourly data were collected continuously from 2004 until now. Older data (between 2000 and 2004) were also available but referred to a different reference system and therefore not used in the present analysis. Based on this data set a tidal harmonic analysis was carried out. Unfortunately, given the limited length and resolution of the time series, long term tidal harmonic components could not be identified. Neither, information on sea level rise could be extracted by the data.
The analysis showed that the island is subject to a microtidal regime with a tidal range between 0.30 m and 1.80 m, and with predominance of the semidiurnal components.

To separate the effect of the surge from the tidal signal, the tide reconstructed from the main tidal components was subtracted from the original signal. Moreover, the obtained signal was filtered with low pass filter with window size equal to 48 hours (typical duration of a storm). An extreme event analysis was carried out with the final signal. Surge levels for three return periods (30, 50 and 100 years) were computed and respectively equal to 0.50 m, 0.53 m and 0.57 m. Despite the high uncertainty band due to the short time span of the measurements, this shows that the influence of surge it is quite limited due to the high water depth surrounding the island.

The latest IPCC scenario (SREF A1F1 as shown in the IPCC 4th assessment report) suggests a global sea level rise between 0.26 to 0.59 m, between the present (1980–1999) and the end of this century (2090–2099). This second value should be increased by 0.2 m to account for uncertainties in climate-carbon cycle feedback and include the full effects of changes in ice sheet flow. In relative terms this means that these values are quite important and their effect on the communities living close to the sea comparable to that one of a surge with return period of more than 100 years.
STUDY AREA

**Geomorphological characterization of the area**

The village of Ribeira Afonso counts approximately 2000 inhabitants (Ottow and Filatova, 2011). At the sea side (east), the village is delimited by a pocket beach approximately 30 m wide (Fig. 5). The beach width, when compared with historical maps, seems not to have remarkably changed in time. This would suggest a beach in equilibrium condition. However, some erosion most likely due to storm is visible on the upper part of the beach profile, where a sea wall and a rudimentary revetment with rocks have been built (Fig. 6). The bathymetry was measured along three profiles down to a water depth of about 15 m, showing similar slopes of about 1:25.

![Fig. 5. Plan view of Ribeira Afonso. The three yellow lines represent the transects at which bathymetry measurements were collected.](image1)

The beach is mainly characterized by alluvial deposits with volcanic origins. Sediment is predominantly gravel in the southern side with a $D_{50}$ of about 80 mm. The rest of the beach is characterized by sand with diameter of approximately 0.5 mm in the middle and 0.35 mm in the North.

![Fig. 6. Beach in front of Ribeira Afonso](image2)
On the southern side the village is delimited by a river with a section approximately 15 m wide. At the river mouth a bar about 2 m high constituted by gravel with diameter between 5 and 20 cm blocks almost completely the river.

Based on observations and communication with local people, a priority list of problems was drawn. According to this list the main engineering problems for the people living in the village are:

- Floods from the river and not maintained / under dimensioned drainages.
- Floods from the sea

The World Bank has defined as reference line, a yearly number of 23.5 days in which the village is flooded.

RESULTS

Hydrological modeling

The size of the catchment of the river was defined based on supervised automatic delineation on outlet location and estimated equal to 20.5 km$^2$. The hydrological model was run based on the corrected TRMM data as input. For potential evapotranspiration the ERA Interim dataset was used (Simmons et al., 2007). Daily, monthly averaged and monthly maximum discharges (Fig. 7) were computed. Moreover, the impact of a possible increase or decrease of 10% in precipitation due to climate change was also evaluated. The simulated values show the high variability of discharges during the year, due to the high variability in precipitations along the year. This also stresses the importance of defining adaptation measures which should withstand this wide range of hydrological conditions.

Coastal morphological modeling

This part of the study involved the definition of the present sediment budget, and the impact of climate change (i.e. increase in storminess and sea level rise) on the erosion potential and coastal retreat.
Based on the offshore wave climate and the bathymetry data collected at the three transects, the nearshore hydrodynamics and sediment transport was computed.

A simple wave model including refraction, shoaling and depth induced breaking was used to transform the offshore wave climate to nearshore. The effect of diffraction induced by the headland in the south of the coastal cell was accounted for by including a diffraction coefficient to the wave height at the breaker line, according to Kamphuis (2000). Moreover, the effect of refraction induced by the curvature of the coastline and consequent divergence of wave energy was considered multiplying the obtained wave height by a factor equal to 0.9. The obtained wave induced longshore currents range between 0 and 0.6 m/s, according to the different wave condition. The contribution of tidal currents was estimated equal to 0.1 m/s.

Based on the local hydrodynamics, the sediment transport due to the combined effects of currents and waves was estimated according to the formulation of Van Rijn (2005):

\[
Q_{t,\text{mass}} = K_0 K_{\text{swell}} K_{\text{grain}} K_{\text{slope}} (H_{s,br})^{2.5} V_{\text{eff,L}}.
\]

where:
\(Q_{t,\text{mass}}\) = longshore sand transport
\(K_0\) = dimensionless coefficient (Van Rijn suggests a value of 42)
\(K_{\text{swell}}\) = correction factor for swell waves (equal to 1)
\(K_{\text{grain}}\) = particle size correction factor
\(K_{\text{slope}}\) = bed slope correction factor
\(H_{s,br}\) = significant wave height at breaking
\(V_{\text{eff,L}}\) = effective, tidal and wave-induced longshore velocity in the surf zone

Sediment transport was computed at the three measured transects (Fig. 5), for each one of the wave classes defining the wave climate, and then added up to give an estimation of the total annual longshore transport (Table 1). The Table shows an increasing sediment transport capacity moving from transect 1 to transect 3, which could lead to a potential erosion of the coast.

Moreover, few additional considerations should be added to draw a complete sediment balance of the coastal cell:

- Sediment input from the river in the south of the village. No measurement of sediment transport in the river was available. However, based on previous studies carried out in rivers with similar discharge (e.g. Morehead et al., 2003; Bartnik et al. 1992) we estimated a yearly transport of about 11500 m\(^3\). We are fully aware that this value is a very rough estimate and that difference in sediment transport in different rivers can be up to some order of magnitude.

- Sediment input from the three drainage systems crossing the village. Despite smaller than the main river, the three drainages bring to the sea a not negligible volume of sediment, especially during high rainy periods. We can estimate this in the order of 4000 m\(^3\) per year.

- It is important to mention that these formulations have been derived assuming a straight coast and that longshore currents need a certain distance before reaching a situation of equilibrium condition.
The highest sediment transport capacity at transect 3, is only an index of a potential sediment transport. Most likely, all this transport is blocked by the headland in the north of the cell and will remain in the coastal cell.

Table 1. Estimate longshore transport at the three transects for each one of the significant wave condition (positive transport from South to North)

<table>
<thead>
<tr>
<th>Case</th>
<th>Wave height (m)</th>
<th>Direction (°)</th>
<th>Frequency (day/year)</th>
<th>Transport Tr.1 (m³/year)</th>
<th>Transport Tr.2 (m³/year)</th>
<th>Transport Tr.3 (m³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45</td>
<td>195</td>
<td>6</td>
<td>0</td>
<td>21</td>
<td>61</td>
</tr>
<tr>
<td>2</td>
<td>0.75</td>
<td>195</td>
<td>123</td>
<td>0</td>
<td>1916</td>
<td>5499</td>
</tr>
<tr>
<td>3</td>
<td>1.05</td>
<td>195</td>
<td>150</td>
<td>0</td>
<td>6111</td>
<td>17570</td>
</tr>
<tr>
<td>4</td>
<td>1.35</td>
<td>195</td>
<td>56</td>
<td>0</td>
<td>4561</td>
<td>13129</td>
</tr>
<tr>
<td>5</td>
<td>1.65</td>
<td>195</td>
<td>14</td>
<td>0</td>
<td>1979</td>
<td>5703</td>
</tr>
<tr>
<td>6</td>
<td>1.95</td>
<td>195</td>
<td>3</td>
<td>0</td>
<td>684</td>
<td>1975</td>
</tr>
<tr>
<td>7</td>
<td>2.25</td>
<td>195</td>
<td>0.7</td>
<td>0</td>
<td>236</td>
<td>682</td>
</tr>
<tr>
<td>8</td>
<td>0.75</td>
<td>225</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>1.05</td>
<td>225</td>
<td>2.5</td>
<td>0</td>
<td>0</td>
<td>68</td>
</tr>
<tr>
<td>10</td>
<td>1.35</td>
<td>225</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>163</td>
</tr>
<tr>
<td>11</td>
<td>1.65</td>
<td>225</td>
<td>1.3</td>
<td>0</td>
<td>0</td>
<td>123</td>
</tr>
<tr>
<td>12</td>
<td>1.95</td>
<td>225</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>46</td>
</tr>
<tr>
<td>13</td>
<td>2.25</td>
<td>225</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>158</td>
</tr>
<tr>
<td>14</td>
<td>0.45</td>
<td>165</td>
<td>0.04</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0.75</td>
<td>165</td>
<td>1.05</td>
<td>0</td>
<td>35</td>
<td>34</td>
</tr>
<tr>
<td>16</td>
<td>1.05</td>
<td>165</td>
<td>1.8</td>
<td>0</td>
<td>157</td>
<td>155</td>
</tr>
<tr>
<td>17</td>
<td>1.35</td>
<td>165</td>
<td>0.4</td>
<td>0</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>18</td>
<td>1.65</td>
<td>165</td>
<td>0.04</td>
<td>0</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>19</td>
<td>1.95</td>
<td>165</td>
<td>0.07</td>
<td>0</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>20</td>
<td>2.25</td>
<td>165</td>
<td>0.04</td>
<td>0</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>15845</td>
</tr>
</tbody>
</table>

Based on these considerations, an estimate sediment balance of the coastal cell was drawn in Fig. 8.

Fig. 8. Sediment balance of the coastal cell in Ribeira Afonso (values in m³/s)
To get a validation of these computations based on morphological observations, the theory of spiral beaches was applied to the Ribeira Afonso beach (Hsu et al., 1989). The theory allows to compute the equilibrium profile of a beach delimited by two headlands, given a most common wave direction. The difference between the actual shape of the beach and the equilibrium profile is an index of the erosion potential of the beach. These calculations show that the north part of the beach is in fact close to equilibrium. The southern part shows a potential for erosion, if there was no import of sediments from the river and the drainage systems, which helps maintaining the beach in long term morphological equilibrium.

The long term coastline retreat due to sea level rise was computed with the commonly used Bruun rule (Bruun, 1962):

\[
\text{Retreat} = \frac{\text{Sea Level Rise}}{\text{Active profile slope}} \text{ (m)}
\]

This resulted in a potential coastline retreat due to sea level rise respectively equal to 9 and 19 m for 2050 and 2100 sea level rise scenarios.

The potential of the coastline to storm erosion was computed by means of the state-of-the-art model \textit{Xbeach} (Roelvink et al., 2009), for storms with return period of 30 and 50 years and in conjunction with different sea level rise scenario (Table 2). The Table shows that for a storm (surge + waves) with return period of 30 years, the coastline in 2050 might retreat of 24 m. This values might increase up to 27 m in 2100. Theoretically, the values are practical the same for a storm with return period of 50 years, in view of the fact that the computed storm surge levels and wave height are very similar for the two return periods.

Table 2. Projected future storm erosion. The values given in the table indicates the retreat (i.e. landward movement) of the 0 m (MSL) contour for a storm with return period of 30 years.

<table>
<thead>
<tr>
<th>Sea level rise</th>
<th>Retract distance (m)</th>
<th>T = 30 years</th>
<th>T = 50 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>2050 SLR (0.35 m)</td>
<td>24</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>2100 SLR (0.79 m)</td>
<td>27</td>
<td>27</td>
<td></td>
</tr>
</tbody>
</table>

Potential to sea flooding

Based on the estimated values of storm surge and wave height for return periods of 30 and 50 years, the future potential to inundation was computed by adding the contribution from storm surge, wave runup (Hunt, 1959) and sea level rise (Table 3).

Table 3. Future inundation potential due to a combined effect of storm surge, wave runup and sea level rise for return periods of 30 and 50 years

<table>
<thead>
<tr>
<th></th>
<th>Height above MSL (m)</th>
<th>T = 30 years</th>
<th>T = 50 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm surge (m)</td>
<td>0.53</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>Wave runup</td>
<td>0.51</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Sea level rise (2050)</td>
<td>0.35</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Inundation potential (2050)</td>
<td>1.39</td>
<td>1.43</td>
<td></td>
</tr>
</tbody>
</table>

These values are significantly important, in relation to the fact that houses are built nearly on the beach (Fig. 6), stressing the necessity of taking immediate action to counteract the flooding events, before the problem might become even more serious in the future. Moreover, flooding events from
the sea usually coincide with flooding from the river and drainage systems further increasing the problem of draining the village during high discharge events (Fig. 7).

**DISCUSSIONS AND CONCLUSIONS**

A complete hydrological and coastal morphological study was carried out for the village of Ribeira Afonso, located on the eastern coast of the island of São Tomé. The study is part of a bigger climate adaptation study, involving several pilot villages located on the island of São Tomé and Principe, and aiming at assessing and prioritizing climate related issues at these villages.

The study has shown that flooding from the river and the bad maintained drainage system, in addition to flooding from the sea, are the main problems for the community of Ribeira Afonso. These threats might become even more serious in the future when scenarios of sea level rise, increase storminess and precipitation intensity are considered. A possible increase in precipitation of 10 %, might lead to a maximum change in river discharge of more than 20 %.

Despite this stretch of coastline appears to be in long term morphological equilibrium for the present condition, the effect of sea level rise might lead to a coastal retreat of almost 20 m by the year 2100, when the most drastic IPCC scenarios are considered. The effect of short term erosion due to storms is already visible now and might become even more important in the future, leading to a possible coastal retreat of more than 20 m by year 2050, for a storm with return period of 50 years. Storm surge levels might also increase in the future, reaching values close to 1.5 m by year 2050 m.

If we consider the geographical location of the houses and infrastructures in the village, which are built nearly on the beach, these values assume a drastic tone, and urgent measures need to be taken by the Central Government.

We would also like to underline the fact that all study was undertaken without nearly any measured data since this information was not available. This approach might be useful to understand the physical system and prioritizing the existing problems. However, we would kindly advice the Central Government to start a complete monitoring program, which would help in refining the analysis and properly dimension the adaptation measures.

At last, we are also aware that climate change is just one of the aspects influencing the present issue for the communities of São Tomé and Principe. The past colonial history of the island (UNESCO-IHE and Deltares, 2011) can explain why many of these communities decided to settle in an area so close to the sea, more sensible to the impact of natural forcing and climate change. Therefore, this study should be seen as a support tool of a large scale coastal zone management of the island, where the Central Government should play a major role, with involvements of the local communities during the implementation of the different adaptation options.

**ACKNOWLEDGEMENTS**

The study was carried out by a combined Deltares and UNESCO-IHE team. The study was financed by the Global Environmental Facility (Grant No. TF 096127). The World Bank was the implementing agency for this project.
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