Investigating the effects of sea-level rise on morphodynamics in the western Giens tombolo, France

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Abstract. Rising sea level along with the occurrence of greater and more frequent storms would cause not only coastal flooding, but also beach erosion and shoreline retreat problems. The Almanarre beach along the western Giens tombolo is socio-economically and heavily vulnerable to accelerated sea level rise due to its high touristic value and low-lying topography. Therefore, it is necessary to quantify the impacts of sea level rise (SLR) on the morphodynamics in this area, e.g. to evaluate the relationship between the beach erosion and SLR. Coupled hydrodynamic and sediment transport numerical models are used to investigate the changes in current, wave and sediment dynamics when sea level rises. A total of 16 scenarios with and without SLR are simulated. The effectiveness of the coupled model is assessed by comparison of simulated values with available field measurements. The results presented in this work should be useful in the investigation of other coastal regions.

1. Introduction

The western branch of Giens double tombolo is located in Provence, South East of France (Figure 1). It has been the object of both accretion and erosion processes due to natural causes such as waves, winds and storms, or due to human interference. Courtaud [1] studied the shoreline evolution of Giens tombolo with the aid of aerial photographs and some field surveys, using imagery digital processing techniques. During the period from 1950 to 1998, the northern part of Almanarre beach, located between Landmark B01 to B23 (Figure 2), suffered an average retreat of -6.4 m/linear meter corresponding to an erosion area of -13,900 m², whereas the southern part between Landmark B23 and B46 was accreted with an average advance of +19.8 m/linear meter corresponding to an accretion area of +41,100 m². With the same technique, Than [2] estimated that the average annual rate of shoreline erosion is (-0.01 to -0.63) ± (0.27 to 1.82) m/year in the northern part and the shoreline accretion is (0.02 to 2.01) ± (0.14 to 5.1) m/year in the central and southern parts over the period from 1920 to 2012. By using numerical simulation, [3] indicated that the disappearance of Posidonia in Giens Gulf would cause a significant increase of current speed, significant wave height and sediment transport rate. In the other hand, by 2100, the global SLR due to climate change, forecasted to be around 44 cm, may have serious impacts on coastal regions [4]. According to Brunel [5], all the beaches of Provence underwent an average shoreline retreat of 5.8 (± 3.5) m due to a relative SLR of +11 cm between 1896 and 1998. If an increase in sea-level of about +44 cm is predicted in the end of this century, Brunel [5] also estimated an average retreat of -20 (±2) m, with values varying between -12 (±2) and -41 (±2) m. It suggests that SLR will exacerbate coastal the erosion problem in the study area. In this paper, the numerical models are used to present a quantitative analysis of the effects of SLR on hydrodynamics and sediment transport along Almanarre beach.
2. Data and Methods

2.1. Study area
Almanarre beach runs through the studied area with an overall direction of north-south and extends about 4.5 km along the Salt Road. Unlike a normal straight coast, the bathymetry in this area is highly complex due to the presence of submerged shoals and cross-shore deep troughs (Figure 2). The wind data of Hyères station (Figure 1) reveals that the west and southwest winds have strong influence on the wave agitation and the coastal morphology in Giens Gulf. These winds maintain the frequency of 25.66% of the observed time with the maximum speed of 21.47 m/s in the west direction. On the other hand, wave data of the buoy 08301 located approximately 1.8 km south of Porquerolles Island (Figure 1) reveals that the studied area is exposed to dominant west and southwest waves with respective frequencies of 36.92% and 28.84%. Waves are the main hydrodynamic process along the coast of Giens tombolo, as the maximum tidal variation is less than 0.3 m [6]. The seabed of the Gulf of Giens is covered by Posidonia seagrass - with an area of about 1800 ha [7], the most important endemic seagrass species in the Mediterranean Sea. It has a strong impact on the local morphodynamics, viz. dissipation of wave energy, reduction in current speed, promoting the accumulation of suspended sediment, and the reinforcement of the sandy soil [8]. The first mapping of the Posidonia was conducted in 1993 by the G.I.S. Posidonie. The results showed that the upper limit of Posidonia is on average from -2 to -3 m depth and its lower limit from -30 to -35 m (Figure 3).

2.2. Numerical modeling

2.2.1. Model descriptions
In the present study, the MIKE21 coupled modules of Hydrodynamic (HD), Spectral Wave (SW), and Sand Transport (ST) developed by DHI [9] are applied to model hydrodynamics and sediment transport along the western Giens tombolo under the impact of sea level rise. Particularly, the HD module is used to compute surface elevation and currents which are induced by waves, whilst the SW module is used for transformation of wind-generated waves and swell from offshore and description of the detailed near-shore wave field. The ST module is used to estimate the sediment transport field and the morphological evolution [3]. The computational domain, about 9 km², has only one western open-sea boundary and a shoreline-land boundary enclosing remainders (Figure 2). The coupled model system is solved on a flexible 2D grid including 21,048 triangular elements. Accordingly, a coarser mesh with the largest grid cell area of 5000 m² is used for the offshore area and very fine mesh with the smallest one of about 40 m² in nearshore area along Almanarre beach (Figure 2).
2.2.2. Model calibration

The model calibration was done by adjusting some main input parameters, viz. Manning’s number, $M$, Nikuradse’s roughness height, $k_s$, and the median grain size, $D_{50}$ [3]. The simulated wave and current results are compared with the data measured at Almanarre beach from 31st October to 12th November 2000. The computed wave heights at the water depth of 3.5 m are reasonably close and show good agreement with measured values (Figure 4). The RMSE is about 0.12 m, corresponding to the difference SI of 22% (Table 1). Furthermore, the comparison of computed and measured current speed is displayed in Figure 5. The statistical scores for this comparison are $R^2 = 0.64$, RMSE = 0.02 m/s, and SI = 41%, respectively.

The morphological evolution obtained from the ST model is compared with the bathymetry which was measured by E.O.L [10] in November 2008. Figure 6 shows the difference between the measured and simulated beach profile at Landmark B25 of Almanarre beach. The model setup has resulted in BSS of 0.39, which is on reasonable level according to Van-Rijn [11].
2.3. Study scenarios

In order to clarify and quantify the impacts of SLR in the studied area, different wind directions and different levels of storms are modeled. The input data of the numerical simulations in SLR conditions are described in Table 2. For annual scenario, the sea level is about 0.5 m above CM which was determined by sum of average sea level over many years (+0.39 m) and the minimum rate of sea level variation at Marseille by 2040-2050 (0.11 m) [12]. On the other hand, sea levels in remainders are the same values as shown in present sea level conditions (No SLR) but adding 35 cm caused by the phenomenon of sea level rise between 2010 and 2060 [13]. Regarding the wave parameters, they were referred from the reports of ERAMM [14] and CEREMA [15].

Table 2. A summary of study scenarios for the western Giens tombolo.

| No. | Scenarios        | Sea level (m) | Wind Speed (m/s) | Wind Direction | Hs (m) | Tp (s) | MWD (°) |
|-----|------------------|---------------|------------------|----------------|--------|--------|--------|
|     |                  | No SLR        | SLR              |                |        |        |        |
| 1   | Annual           | 0.39          | 0.5              | 5.8            | 200 (S)|        |        |
|     |                  |               |                  | 7.5            | 200 (S)|        |        |
|     |                  |               |                  | 6.48           | 200 (S)|        |        |
|     |                  |               |                  | 8.69           | 200 (S)|        |        |
| 2   | Decadal storm    | 0.95          | 1.3              | 12.55          | 230 (SW)| 6.56   | 9.12   | 225    |
| 3   | Tri-decadal storm| 1.00          | 1.35             | 19.83          | 230 (SW)| 7.1    | 10.3   | 225    |
| 4   | Semi-centennial storm | 1.15       | 1.5              | 29.59          | 230 (SW)| 7.34   | 11     | 225    |
| 5   | Centennial storm | 1.50          | 1.85             | 36.43          | 230 (SW)| 7.64   | 12     | 225    |

3. Results and Discussion

3.1. Effects of SLR on waves

The coastal morphology of the western Giens tombolo is influenced by four main wind directions, viz. northwest, west, southwest, and south. The change of wind direction accompanied with the SLR phenomenon can provoke the significant modification of wave field. It is clearly seen that the southwest winds cause the highest waves in the Almanarre beach, whereas the lowest waves are generated by the south winds (Figure 7), regardless of SLR. Particularly, the mean significant wave heights, \( H_s \), found at the water depth of 3.5 m near Landmark B08 under the impacts of southwest and south winds are about 0.6 m and 0.57 m, respectively (Table 3). However, all the wave heights decrease gradually when they approach the shallow water areas and are dissipated by the bottom friction. In addition to generating the highest waves, the southwest winds also induce the largest radiation stresses i.e. \( S_{xx}, S_{yy} \) and \( S_{xy} \) (Table 3). When the sea level rises, deeper water areas enable larger waves to reach and break closer to the coastline, resulting in greater wave heights in nearshore zones. Indeed, the mean wave heights near Almanarre beach are increased by 1.22%–1.59% (Table 3). The southern winds induce the largest increase of wave height up to 1.59% at Almanarre beach, compared with the other wind directions. As sea level increases, the propagation of larger waves over
the shallow waters results in higher radiation stresses, boosted by 2.2%-5.1% at a water depth of 3.5 m in front of Almanarre beach when sea level rises about 11 cm (Table 3).

Figure 7. Modeled cross-shore variations in wave heights under the impact of SLR and variation of wind direction at Landmark B08.

Figure 8. Modeled cross-shore variations in wave heights under the impact of SLR and variation of storm scale at Landmark B08.

Figure 8 depicts the simulated cross-shore variations in wave heights at Almanarre beach under the influence of different storms as well as SLR. It is noticeable that the higher level of storm causes the larger and stronger impacts on wave fields, regardless of SLR. Particularly, the mean significant wave height without SLR increases from 1.15 m in decadal storm to 1.46 m in centennial storm; while its value ranges from 1.31 m in decadal storm to 1.59 m in centennial storm (Table 3). Greater water depths due to storm surges with SLR reduce bottom friction and increase water depth relative to the wave height, resulting in larger and more energetic waves that could reach the beaches. As a result, the nearshore significant wave height is intensified by 8.91%–13.39% at the water depth of 3.5 m near Landmark B08 (Table 3). When SLR occurs along with storms, an increase in wave heights would generate a corresponding raise of radiation stresses. An increasing trend in wave heights is found in all the stormy scenarios, but the maximal increase occurs in the decadal storm and it reduces when the storm levels increase. The radiation stresses are boosted by 20.27%-32.88% at Almanarre beach, compared with those cases without SLR.

3.2. Effects of SLR on currents

In the Giens gulf, both the winds and waves induce the longshore currents [6]. Therefore, the variation of wind directions and the different wave climate were simulated in this work in order to investigate their effects on the current field. Figure 9 presents the modeled cross-shore variations in current speed \( (V_c) \) at Landmark B08 in Almanarre beach, caused by different wind directions and different sea levels. Even though the southwest winds induced the highest significant wave height in the studied area (Figure 7), the northwest winds have the strongest impacts on the current speed along the western Giens tombolo. This is valid for both no SLR case and SLR case. Specifically, the highest mean current speeds of 0.22 m/s and 0.23 m/s at the water depth of 3.5 m at Almanarre beach generated by the north-western winds are higher than other winds about 20%-36% in the nor SLR conditions and 14%-28% in the SLR conditions (Table 3). This paradox may come from the terrain of the studied area. In addition, the southern waves are blocked or limited by the presence of the rocky outcrop of Madrague (Figure 1). This paradox also confirms that the nearshore currents along Amanarre beach are mainly governed by the wind and the wave only plays a secondary role in the development of these currents. When sea level rises, the currents are stronger than those in the cases of no SLR conditions. For instance, the current speed at the water depth of 3.5 m near Landmark B08 is increased by 4.56%-16.1% (Table 3).

The impacts of storms along with SLR on the modelled cross-shore variation in current speed at Almanarre beach is illustrated in Figure 10. It is noted that the current speed is reduced from 150 m seaward of the shoreline to 350 m seaward of the shoreline before gradually increasing again to reach the coast. Similar to the annual conditions, this cross-shore evolution of current speed would be attributed to the seabed change. Without SLR scenarios, the higher level of storm usually causes the larger current speed at Almanarre beach, except for the centennial storm case. Specifically, the current speed of 0.2 m/s at the water depth of 3.5 m near Landmark B08 in the decadal storm condition is
increased up to 0.42 m/s in the semi-centennial storm condition and significantly decreased to 0.39 m/s in the centennial case (Table 3). This sudden reduction would be explained by the fact that the sharp increase of 35 cm in the centennial storm could cause the local water volume expansion and the extensive submergence of low-lying areas. As sea-level rises, most of current speeds influenced by the storms are increased by 33.3%-86.7% at Almanarre beach. Apart from the cases of the semi-centennial storm, the current speed at the water depth of 3.5 m near Landmark B08 is reduced to 3.4% (Table 3).

3.3. Effects of sea-level on sediment dynamics

The sediment transport in the study area is carried out by the current of longshore drift induced by the oblique waves striking the coast from the north to the south and from the west to the east [1]. Similar to the study of hydrodynamics, the effect of SLR on sediment transport rates ($Q$) was investigated by elevating the mean sea level (+0.5, +1.3, 1.35, 1.5, and 1.85 m). Figure 11 plots the modelled cross-shore variation in the sediment transport rates under the impacts of various winds along with SLR. It reveals that the higher wave-induced radiation stresses and current speeds (Figure 9) close to shore resulted in a narrow band of sediment transport concentrations along the shoreline. It is clearly seen that the northwest winds always have the strongest impact on the sediment transport rates, regardless of SLR. They induced the highest sediment transport rates of $4.5 \times 10^{-5} m^3/s/m$ at the cross-shore of Landmark B08 in Almanarre beach. By contrast, the lowest sediment transport rate of about $2.13 \times 10^{-5} m^3/s/m$ is generated in the south winds. It strongly confirms that the pattern of the sediment transport rates mostly depends on the current speed distribution (Figure 9). When taking into account the SLR, the sediment transport rates are intensified along Almanarre beach, regardless of wind direction. Particularly, at the water depth of 3.5 m near Landmark B08, the total load is increased by about 3%-23% probably due to the raise in nearshore current speed when taking into account the SLR phenomenon (Table 3). The maximal increase of 22.9% is observed in the southwest winds probably due to the highest waves along with sea level rise, while the minima increase of 3% is caused by the northwest wind.

Figure 12 shows the cross-shore variation in sediment transport rate under the impacts of storms with and without sea level rise. It is noticeable that the cross-shore distribution of sediment transport rates starts reducing from 350 m seaward of the shoreline to 150 m seaward of the shoreline at Almanarre beach, corresponding to the decrease of current speed (Figure 10), regardless of SLR. In addition, it verifies that the high storm level induces the largest total load of sediment. The maximum sediment transport rate of over $1.7 \times 10^{-4} m^3/s/m$ is reported in the centennial storm scenario. The current speed plays a decisive role in the sediment transport along the western Giens tombolo. Indeed, when sea level rises, the increase of current speed results in the boost in the total load at Almanarre beach. The total load is added by 13%-282% if SLR is taken into account (Table 3). The maximal increases are of 244.4% and 281.8% in the decadal and tri-decadal storm conditions, respectively. Whilst the minimal rise of 12.9% occurs under the impact of semi-centennial storm with SLR.
Figure 11. Modeled cross-shore variations in sediment transport rates under the impact of SLR and variation of wind direction at Landmark B08.

Figure 12. Modeled cross-shore variations in sediment transport rates under the impact of SLR and variation of storm scale at Landmark B08.

Table 3. Effect of sea level rise on hydrodynamic parameters and sediment transport in Almanarre beach.

| Scenario         | $H_s$ (m) | $S_{xx}$ ($m^2/s^2$) | $S_{xy}$ ($m^2/s^2$) | $S_{yy}$ ($m^2/s^2$) | $V_c$ (m/s) | $Q$ ($m^3/s/m$) |
|------------------|-----------|----------------------|----------------------|----------------------|-------------|----------------|
| **No SLR**       |           |                      |                      |                      |             |                |
| Northwest        | 0.582     | 0.182                | 0.048                | 0.127                | 0.217       | 4.49E-05       |
| West             | 0.593     | 0.183                | 0.049                | 0.129                | 0.174       | 3.28E-05       |
| Southwest        | 0.603     | 0.184                | 0.050                | 0.131                | 0.141       | 2.40E-05       |
| South            | 0.570     | 0.165                | 0.045                | 0.118                | 0.139       | 2.13E-05       |
| Decadal          | 1.152     | 0.667                | 0.167                | 0.416                | 0.200       | 3.30E-04       |
| Tri-Decadal      | 1.246     | 0.789                | 0.189                | 0.473                | 0.222       | 4.34E-04       |
| Semi-Centennial  | 1.337     | 0.923                | 0.211                | 0.512                | 0.415       | 1.60E-03       |
| Centennial       | 1.457     | 1.107                | 0.251                | 0.613                | 0.389       | 1.72E-03       |
| **SLR**          |           |                      |                      |                      |             |                |
| Northwest        | 0.591     | 0.188                | 0.050                | 0.130                | 0.227       | 4.62E-05       |
| West             | 0.600     | 0.187                | 0.051                | 0.132                | 0.187       | 3.47E-05       |
| Southwest        | 0.612     | 0.191                | 0.053                | 0.136                | 0.163       | 2.95E-05       |
| South            | 0.579     | 0.171                | 0.047                | 0.122                | 0.156       | 2.44E-05       |
| Decadal          | 1.307     | 0.881                | 0.222                | 0.540                | 0.373       | 1.14E-03       |
| Tri-Decadal      | 1.376     | 0.995                | 0.247                | 0.597                | 0.411       | 1.66E-03       |
| Semi-Centennial  | 1.456     | 1.110                | 0.270                | 0.651                | 0.401       | 1.80E-03       |
| Centennial       | 1.591     | 1.338                | 0.327                | 0.772                | 0.518       | 3.18E-03       |
| **Difference (%)** |         |                      |                      |                      |             |                |
| Northwest        | 1.57      | 2.88                 | 3.62                 | 2.95                 | 4.56        | 2.96           |
| West             | 1.22      | 2.18                 | 3.14                 | 2.40                 | 7.87        | 5.96           |
| Southwest        | 1.58      | 3.81                 | 5.10                 | 3.97                 | 16.08       | 22.88          |
| South            | 1.59      | 3.35                 | 4.42                 | 3.45                 | 11.73       | 14.25          |
| Decadal          | 13.39     | 31.93                | 32.88                | 29.80                | 86.68       | 244.36         |
| Tri-Decadal      | 10.38     | 26.07                | 30.34                | 26.05                | 85.60       | 281.80         |
| Semi-Centennial  | 8.91      | 20.27                | 27.89                | 27.31                | -3.38       | 12.86          |
| Centennial       | 9.23      | 20.93                | 30.60                | 25.90                | 33.15       | 84.84          |

4. Conclusions
Numerical models have been developed successfully to quantify the impacts of SLR on hydrodynamic parameters and sediment transport in the Giens gulf. The results of this work strongly confirm that SLR leads to significantly increased wave heights, current speeds and sediment transport rates. The
impact of SLR on morphodynamics in the stormy conditions is about ten times greater than that in the annual conditions. Particularly, the mean wave heights near Landmark B08 are increased by 1.22%-1.59% in annual conditions, whereas they are boosted by 8.91%-13.4% in the extreme events, comparing to those without SLR. In the stormy conditions, the nearshore current speed is intensified by 33.2%-86.7%, while it is only increased by 4.56%-16.1% in the no SLR scenarios. The raise in the current speed mainly leads to a corresponding increase of sediment transport rate by 2.96%-22.88% in the annual cases and by 12.86%-281.8% in the stormy cases. This would be explained by the fact that deeper water areas due to SLR along with storm surge allow larger waves to reach and break closer to the shoreline, resulting in more wave energy impacting the beach profile and taking sediment offshore.

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