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38 YEARS OF GRAVEL BEACH EVOLUTION AND REPLENISHMENT IN NICE FRENCH RIVIERA

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Abstract – The shingle barrier of Nice –on the French Riviera- extends on 4.5 km along the famous sea-front, the “Promenade des Anglais”. This beach is exposed to a mostly low energy environment, but it suffers from erosion due to numerous coastal infrastructures, the drastic reduction of sediment inputs and a very steep shoreface. Since 1976, local authorities have been monitoring the beach width through a total of 50 transects. In order to stabilize the beach, almost 600 000 m³ of shingle were deposited. This dataset is useful to analyze the beach evolution and describe the nourishment policy.

Résumé – *Le rivage de la ville de Nice, sur la Côte d’Azur en France, est bordé par un étroit cordon de galets de 4,5 km le long de la célèbre Promenade des Anglais. Cette plage évolue dans un contexte de basse énergie, mais connaît cependant des problèmes d’érosion car elle est très artificialisée, est coupée de ses sources naturelles de sédiments et se situe au niveau d’une avant-côte très pentue. Depuis 1976, les services techniques de la mairie procèdent à des mesures de la largeur de la plage au niveau de 50 transects. Afin de lutter contre l’érosion et maintenir une largeur de plage suffisante pour les activités balnéaires, la mairie a déposé près de 600 000 m³ de matériaux de rechargement depuis 38 ans. Nous disposons donc d’une base de données pour étudier l’évolution de cette plage et décrire la politique de rechargement.*

Introduction

Beaches along seaside promenades are important elements of typical landscapes of the French Riviera (e.g. the “Croisette” in Cannes, the “Promenade des Anglais” in Nice). They play a major role in coastal defense as buffers against storms in very densely populated zones (Anthony, 1997, 2005; Nordstrom, 2013); e.g. in 2011, the city of Nice counted 344 064 inhabitants and the urban area 1 million. Because they received very few or no sediment inputs and are highly artificialized, those beaches often suffer from erosion (Anthony & Cohen, 1995, 1996; Anthony *et al.*, 1998; Groupe RAMOGE, 2002).

In the late 1960s, the local authorities of Nice implemented a beach replenishment and measurement scheme that still exists today. Beach nourishment is increasingly being performed on the sandy beaches in Europe and around the world (Hamm *et al.*, 2002; Hanson *et al.*, 2002; Finkl & Walker, 2005; Van Rijn, 2011 ;Cooke *et al.*, 2012). However, examples on shingle barriers seem to be more rare (Cohen, 1996; Bawedin & Hoeblich, 2006).

We have been working on the gravel beach of Nice for 20 years now (Cohen, 1993). Using statistical and multivariate data analysis, we have identified erosion zones and assessed beach nourishment policy (Cohen & Anthony, 2007). In our recent works treating data until 2005 (Anthony *et al.* 2011), we have demonstrated that the massive supplies of pebbles (around 558 000 m³) were successful in stabilizing and slightly enlarging the beach. However, most of these inputs have disappeared near the very steep shoreface and may be further down. In 1995 (Anthony & Cohen, 1995), we already questioned the future of the beach of Nice in case of reduction or termination of replenishments. Would it erode and become as narrow as some parts of the Baie des Anges, for instance in Cagnes-sur-Mer, a few kilometers southward? In 1996, Finkl addressed the same issue concerning the sandy coasts of the south-east of the USA in an editorial of the *Journal of Coastal Research* that has remained famous up to now. For him, the effectiveness of beach nourishment depends on the ability to maintain the beach and therefore on sediment supplies and the financial resources allocated to the program.

The objective of this paper is to describe the nourishment policy and the beach evolution and examine their correlation over 38 years using a simple statistical analysis.

General setting and beach nourishment scheme

Nice is located in the south-east of France on the French Riviera in the Maritime Alps department (figure 1). The shingle beach stretches on 4.5 km along the northeastern part of the “Baie des Anges” and the famous “Promenade des Anglais”. The hinterland is high and steep; it goes down directly into the sea with no continental shelf: the slope between the shore and the 100 m depth contour ranges from 20 to 80 %. The small valleys cutting the steep hills extend seaward forming micro-canyons. The beach is made up mainly of medium sized pebbles (5 to 10 cm). It is submitted to a microtidal range (around 50 cm at spring tide). The most frequent waves come from SW to SE (65 %). Offshore, they are usually of low energy: from 2002 to 2014, 75 % of significant heights (Hs) were inferior or equal to 0.7 m and 99 % inferior or equal to 1.9 m. However, severe storms can occur during which waves are slightly mitigated by the steep shoreface and break on the beach (figure 2). For example, on November 18 2011, waves with Hs = 3.7 m and Hmax = 6.9 m were recorded by a Datawell oceanographic buoy anchored 1.7 km offshore in the “Baie des Anges” (CEREMA, 2014).

The beach of Nice is quite narrow (average width = 28.17 m). It is characterized by a gentle slope on the upper beach and berms on the lower part (figure 1). This beach is highly artificialized. It is flanked by a wall supporting the “Promenade des Anglais”. The Promenade and the road were gradually enlarged during the twentieth century. The technical services of the city have estimated the beach width to be 50 m around 1900 and 30 m in the 1930s (Dumasdelage *et al.*, 2014). To the west, the embankment of the airport is an impassable obstacle to the sediment inputs coming from the Var river, which was the major gravel supplier in the past. The input from other small coastal streams opening on the beach (e.g. the Magnan creek and mainly the Paillon river) are also very limited due to the artificialization of their downstream part and catchment. To the east, the beach ends with a small rocky headland (Rauba Capeu). Anthony *et al.*, 2011 showed that sediment loss can therefore only occur seaward and not beyond these obstacles. 16 groynes curb the longshore sediment transport. Each year in late spring, the beach is reshaped: winter berms are flattened.

Similar patterns can be observed on other beaches in the French Maritime Alps (e.g. Antibes, Cagnes-sur-Mer, Menton) and in the Italian Liguria (e.g. Ventimiglia, Bordighera, San Remo; Groupe RAMOGE, 2002), but without replenishment being as important as it is in Nice.

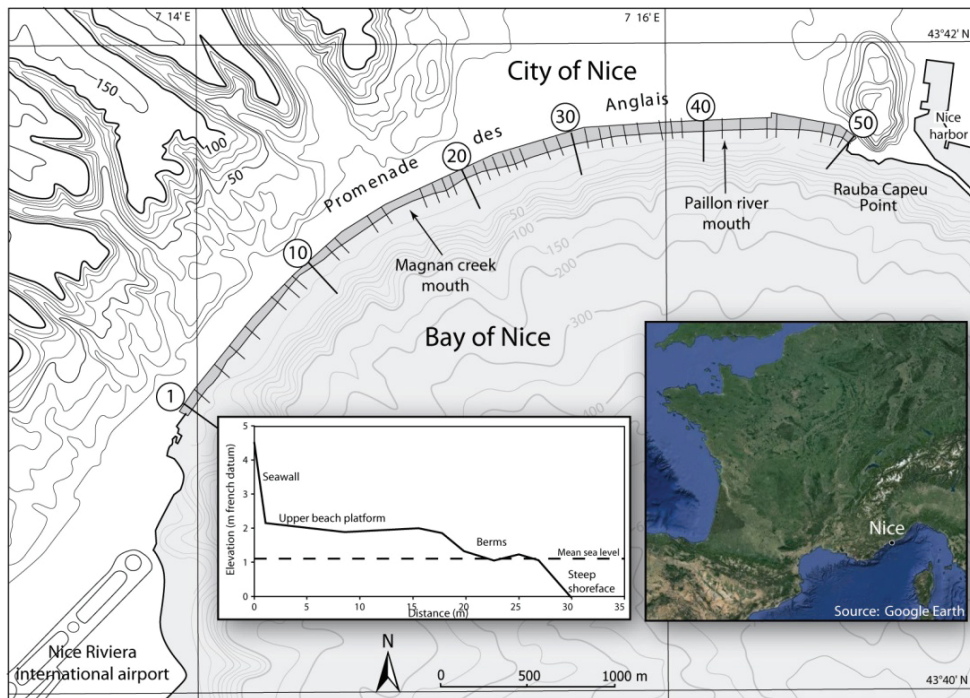


Figure 1 – Location of the study site and monitoring transects, typical beach profile.
 Figure 1 – Localisation du site, réseau de mesure et profil caractéristique de la plage.

In order to solve the beach erosion already observed, the municipal authorities began nourishment in the late 1960s. But we don't know the volumes provided in these early operations. The first volume in the database dates from 1976. Since then, an amount of 582 910 m³ or 128 m³ per linear meter has been deposited on the beach. It must be emphasized that it was an innovative policy of management at that time. This was partly made possible by the availability of free materials coming from major earthworks in the town (the hills of Nice are composed of puddingstone, a sandy matrix including pebbles) and from the cleaning of the riverbeds of small streams leading to the beach (mainly the Paillon river) whose downstream part is now channeled underground (covered with a urbanized concrete slab). Nourishments were generally brought in late winter or early spring. They were irregular in time. Figure 3a shows that most took place from 1976 to 2000 (525 910 m³). Since 2010, the municipality has had to buy the shingles from quarries in the hinterland at the price of 80 €/m³. Since then, the replenishments have been particularly concentrated on the eastern part of the beach (25 000 m³). Figure 3b shows the volumes and areas of deposition.

Since 1976, the technical services have set up a beach monitoring network. It consists of 50 transects, spaced on an average of 90 m, along which the beach width is measured (from the upper seawall to the water limit) from two to four times a year in winter, spring and autumn (figure 1). We have a database with 115 dates from 1976 to 2013 on 50 measuring points, almost without gaps. A statistical synthesis helps to analyze beach evolution and to assess the nourishment scheme.



Figure 2 – Photographs taken during a storm (april 2010) and a beach replenishment.
Figure 2 – Photographies prises pendant une tempête (avril 2010) et un rechargement.

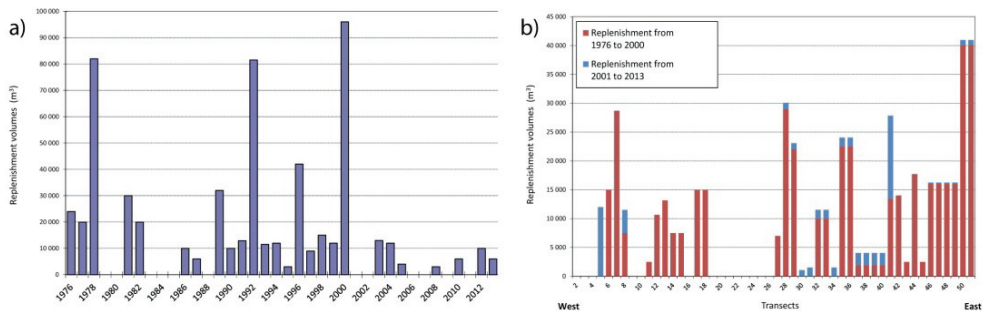


Figure 3 – Beach replenishment volumes in time and space.
Figure 3 – Les rechargements dans le temps et l'espace.

Results

Figure 4a displays the average, maximum and minimum width of each transect of the measurement network. The dotted line represents the global average beach width (28.17 m). We see that the longshore variations of the beach width are mild: they range from 21.82 to 37.1 m, but more often, they are between 24 to 33 m. On the graph a fairly regular alternation of sectors with slight variations in the average width appears. As recommended in shoreline study handbooks (Bowman & Pranzini, 2008), we computed standard deviations to characterize the temporal variability of each sector. They are represented by vertical bars on figure 4a. They are quite homogeneous. The average standard deviation is 3.3 m, the most important is 5.5 m and the smallest is 2.2 m. The most

mobile sectors are the most replenished ones (e.g. west and east); in the center of the beach, variability is lower where the nourishments are mild or null. Figure 4b presents the average seasonal widths: they are mostly smaller in autumn and winter, wider in spring and summer. These greater widths can be explained by the beach reprofiling in spring. The maximum and minimum widths are given for information. They can correspond to exceptional situations (e.g. replenishment, reprofiling or storm).

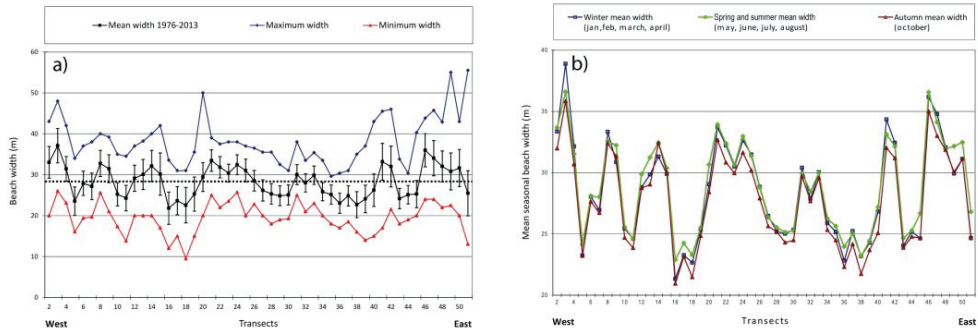


Figure 4 – Mean, maximum and minimum beach widths (a), mean seasonal widths (b).

Figure 4 – Largeurs moyennes, minimales, maximales et saisonnières.

The General temporal evolution of the average beach width from 1976 to 2013 is depicted on figure 5a. The interannual variability is clearly obvious, but using a polynomial regression of order 3, it is possible to make out two periods. Firstly a stabilization phase (mild erosion from 1976 to 1981, then a slight enlargement until 1998), secondly an erosion phase beginning in the late 1990s and continuing until now. This second period corresponds to the drastic reduction of beach replenishment. Figure 5b deals with spatial evolutions during the two phases. Here a clear longshore variability on short distances appears with a rapid alternation of sectors slightly wider or narrower than the average (28.17 m, dashed line on the diagram). The average widths for each transect and the two phases (1976-2000 and 2001-2013) were also computed and compared to the average of the whole study period. Almost everywhere (36 out of 50 transects or 72 %), the widths for the first phase are superior and the ones for the second phase are inferior to the averages of the entire study period. The replenishment distribution does not always explain this result. If the eastern part of the shore (transect 46 to 51) is one of the widest, it might be due to large nourishment volumes (211 440 m³). Some other replenished sectors (e.g. T5 to 8, T27 to 29) show nevertheless a width inferior to the average even though they respectively received 67 200 and 60 130 m³ of shingles.

To complete the analysis of shoreline changes, the annual evolution rates have to be estimated for each measurement point. Four currently-used methods were tested (Dolan et al., 1991): End Point Rate (EPR), Linear Regression (LR), Average of Rates (AoR) and Jackknifing (JK). These rates are presented on figure 6a. LR, AoR and JK methods give very similar results. EPR always over- or underestimates the rates; indeed, it is the only one that uses only two values (the first one and the last one) in the calculations and does not take the others in between into account. Consequently, we worked with the Linear Regression method that is here statistically significant and easy to compute.

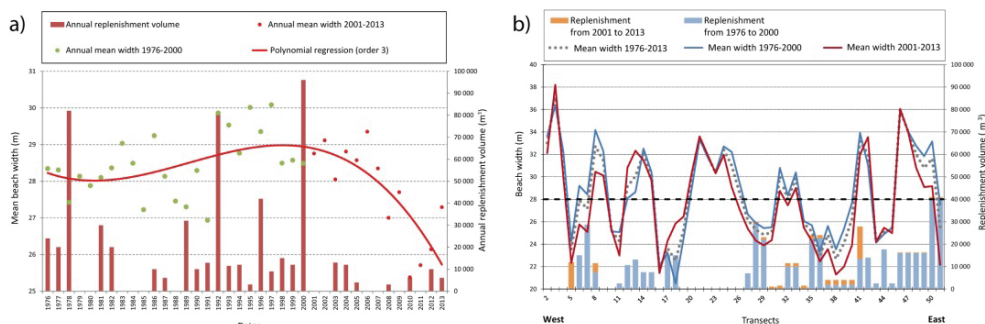


Figure 5 – Mean widths in time and space.
 Figure 5 – Largeurs moyennes dans le temps et dans l'espace.

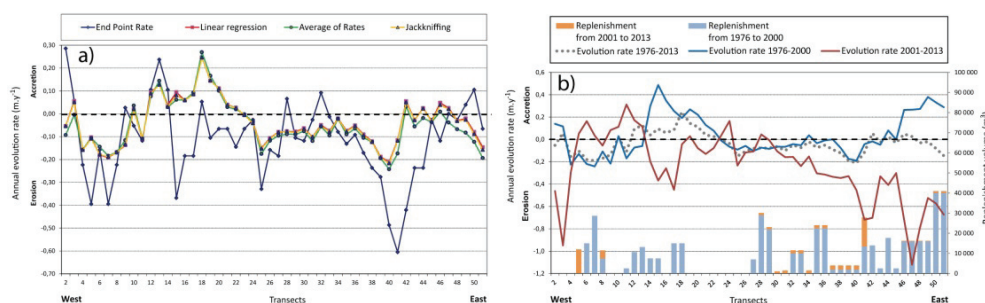


Figure 6 – Results of four methods to compute shoreline evolution rates and comparison of evolution rates of three time periods (1976-2013, 1976-2000 and 2001-2013).
 Figure 6 – Résultats de quatre méthodes pour estimer les taux d'évolution du trait de côte et comparaison des taux d'évolution de trois périodes (1976-2013, 1976-2000 et 2001-2013).

The evolution rates over the total study period range from -0.24 to $+0.20$ $\text{m}\cdot\text{y}^{-1}$. An alternation of accretion and erosion zones is obvious on figure 6 but its distribution is not as regular as the one of the beach widths. The rates for both periods were calculated (figure 6b). In 76 % of the cases, the rates of the second period are inferior to those of the first one (erosion increases or accretion slows down). This is clearly visible in the west (T14 to 23) and in the east (T30 to 51) where the beach was firstly stable or in slight accretion and then suffered from erosion with rates up to -1 $\text{m}\cdot\text{y}^{-1}$. As for the average width, it is quite difficult to put the rates of evolution in relation with the nourishment volumes. Massive inputs before 2000 seem to have resulted in shoreline progression. Their drastic reduction since 2001 seems to have led to severe erosion. However, some parts (e.g. T5 to 14) which were replenished between 1976 and 2000 were in erosion and then from 2001 to 2013 were in mild accretion although they received very few or no nourishment over that period.

In order to understand the longshore evolution of the beach, we got interested in the spatial autocorrelation of the transects. It is hypothesized that the evolutions of two directly neighbouring measurement points are strongly linked. We will see whether this linkage will be regular alongshore. To highlight this, we propose a simple statistical formula. It is based on the Bravais-Pearson correlation coefficient (r), calculated for two neighbouring transects

(e.g. T3 and T4, T4 and T5, etc.) using their beach width statistical series over the time in the original database. The coefficient value varies from -1 to +1; tending to +1, the correlation is strong, two neighbouring points are strongly dependent and evolve in the same way; tending to -1, the correlation is also high, but negative: the two transects evolve in opposite ways (e.g. the first is eroding, the second accreting). When r tends to 0, there is no statistical relation between the transects; they are considered as independent, having no mutual influence. Since the distances between transects are unequal, the correlation coefficient has to be weighed: it is divided by the spacing (in meters). The computed statistical index is dimensionless.

The results are displayed on figure 7. In the interpretation, focusing on the values exceeding plus or minus one standard deviation from the average is of great interest. Beyond plus one standard deviation ($+1\sigma$) are the sectors particularly dependent from one another; for instance, for T38 and 39, west of the Paillon river mouth where the alongshore correlation coefficient reaches its highest value. Nevertheless at this time, it is difficult to say what caused this result. But this situation is rare: the $+1\sigma$ threshold is crossed only five times. On the contrary, it is more often crossed for a value of -1σ : this could be interpreted as “breaches” in longshore dependency and explained in several ways. In the west part of the beach 14 groynes cut out longshore sediment transport and obstruct beach reprofiling and also nourishment spreading by bulldozers. These groynes create wider zones updrift and narrower zones downdrift. This is obvious on aerial photographs. But it is hardly possible to detect the influence of each groyne on the graph. On the central and eastern parts of the beach only two groynes are found. Here, the river and stream mouths (e.g. Magnan and Paillon) also can cut out the longshore transport. In the east part, a change in the upper seawall orientation causes a sudden enlargement of the beach width (figure 1) and has consequences on the calculation of statistical indicators; this could explain the low value of the coefficient for T44 and T45. Variations between plus and minus one standard deviation are still to be interpreted if possible.

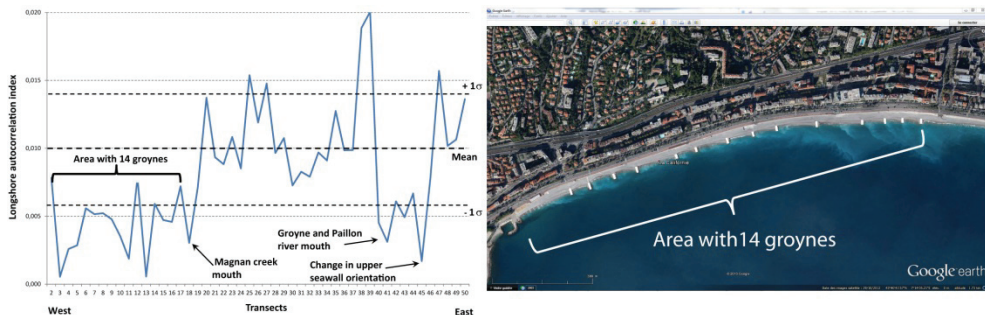


Figure 7 – Spatial autocorrelation along Nice beach.

Figure 7 – Autocorrélation spatiale le long de la plage de Nice.

Discussion and conclusions

If it is clear that massive sediment supplies have succeeded in stabilizing the beach until the end of the 1990s and that their curtailment has led to general erosion, it is

difficult to determine precisely the role of nourishment on evolution in each sector. This could be due to several parameters.

The database comprises emerged beach width measurement that we try to put into relation with replenishment volumes. The beach volume is not always proportional to its width; it depends on its shape. Beach profiles would have been more suitable for such a study. This is that kind of measurement that the technical services of the city have just set up (Dumasdelage et al., 2014). The provided data tables indicate the locations of deposition, but then the pebble supplies are spread alongshore by bulldozers and the beach is reshaped every year in late spring. The further analysis of the seasonal data could estimate the impacts of these anthropogenic interventions on the beach which might be the main sediment transport factor.

To understand the influence of variability or variation of weather and marine conditions on the shoreline, there is only little information on the entire study period. In a preliminary investigation (Anthony et al., 2011) we used ANEMOC data (Morellato & Benoit, 2010) at an annual scale: it was not sufficient to detect any temporal trend of offshore wave significant height (Hs) and to correlate it with the shingle barrier behaviour. This first stage could be completed crossing meteorological and tide gauge data to compute the evolution of potentially eroding events (Chaverot et al., 2008). In the short-term, data from the wave buoy installed in 2002 could also be taken into account (CEREMA, 2014).

In several papers (Cohen & Anthony, 2007; Anthony et al., 2011), we have discussed the role of the steep shoreface and of the microcanyons assuming that they were bottomless sediment pits and that they determined onshore waves and currents characteristics. This was recently proved by Dumasdelage et al. (2013, 2014). Using fine scale hydrodynamic models (TOMAWAC, TELEMAC 2D and SISYPHE), these authors demonstrated that there was a concentration of wave energy on small underwater headlands separating microcanyons and a convergence of longshore drift and waves induced currents into these canyons. In these works, the effect of groynes also clearly appears. A study of the correlation between modal hydrodynamic conditions and shoreline widths and evolution rates would be of great interest.

Nowadays as sediment supplies become rare, an optimization of their management is necessary. Would it be possible to store pebbles which would be available when needed and at no cost? Could underwater breakwaters similar to those built for example along the Ligurian or Tuscan coasts in Italy be an interesting solution? Studies on morphodynamics aiming to estimate the behaviour and the resilience of the gravel barrier to hydrodynamic conditions should be carried out. Beach reprofiling has to be discussed, especially the spreading down of pebbles to increase the beach width that causes sediment loss offshore (Anthony et al., 2011). The shingle beach of Nice is a priceless natural protection against storms as well as a geomorphological and touristic asset that needs to be preserved.

Acknowledgements

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