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Assessing shelf aggregate environmental compatibility and suitability for beach nourishment: A case study for Tuscany (Italy)

Nicola Bigongiari [a,1], Luigi E. Cipriani [b,1], Enzo Pranzini [c,1], Monia Renzi [d,1,*], Giovanni Vitale [c,1]

[a] CIBM – Center of Marine Biology and Applied Ecology "G. Bacci", Viale N. Sauro 4, Livorno, Italy
[b] Region of Tuscany – D.G. for the Environment, Energy and Climate Change – Section for the Protection and Value Enhancement of Marine and Coastal Environments, via di Novoli, 26, 50127 Firenze, Italy
[c] Department of Earth Sciences, University of Florence, Borgo Albizi 28, 50122 Firenze, Italy
[d] Department of Biological and Environmental Sciences and Technologies, University of the Salento, SP Lecce-Monteroni, 73100 Lecce, Italy

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ABSTRACT

Beach nourishment practices are a key aspect in coastal management plans for stakeholders and communities. Stemming from a concrete case-study (Tuscany), this research analyzes: (i) principal problems of current law regulating dredging, (ii) gaps in technical guidelines, (iii) advantages of integrated approaches to the decision-making process, (iv) possible applicable nourishment options and their costs and benefits. Our results show that sand compatibility is driven mainly by grain-size stability due to the occurrence of lower pollution levels in off-shore deposits than in threatened beaches, thus current laws and guidelines should be improved to fill the evident gap in the evaluation process and to include a more complete approach to data evaluation and an integrated approach to ecotoxicity evaluation, which is relevant in cases of geochemical anomalies. The cost-benefit analysis performed indicates that only dredging intended to manage more than 1 million m^3 of aggregates would represent a real advantage for local communities.

1. Introduction

Coastal erosion affects approximately 100 km out of the total 200 km of continental sand beaches in Tuscany, with shoreline retreat values exceeding 10 m per year at specific sites (Cipriani et al., 2013). In order to stabilize these coastal sectors and maintain their environmental and economic value, some 2 million cubic meters of sediments are required each year (Danelon and Pranzini, 2013). Hard shore protection structures could reduce longshore and offshore sediment transport, reducing the amount of beach fill volume required, but this would increase downdrift erosion and reduce the resilience and economic value of the Tuscan coast.

The Region of Tuscany opted for an intermediate solution, reducing the amount of hard protection (currently covering approximately 30 km of sand coast) and increasing soft shore protection by means of beach nourishment.

Riverbed sediment quarrying has been prohibited in Tuscany since the 1970s, and the limited availability of aggregates in regional alluvial plain quarries induced coastal restoration designers to look for sand in the Po River plain, with high environmental (CO_2 emissions, noise, powder, traffic) and economic (€ 20–40 *per* m^3) costs.

In this scenario, the Region of Tuscany, as part of the Regional Plan for Integrated Coastal Zone Management (ICZM) in cooperation with local authorities (Provincial and Municipal Administrations) and River Basin Authorities, has coordinated and financed (with approximately € 110 million) a Programme for coastal restoration activities, beach evolution monitoring and the implementation of coastal studies (Sargentini et al., 2004). One important such study worthy of mention was a research project with the aim of searching for and characterizing sand and gravel deposits laying on the Tuscan continental shelf to be used for beach nourishment purposes. The study cost about € 2 million and allowed for the identification of four reservoirs as potential borrowing sites, with an estimated volume of approximately 129 million m^3 of aggregates (Chiocci et al., 2009). Another part of the Regional ICZM Plan (€ 1 million invested) comprises the environmental characterization of continental shelf reservoirs, aimed at evaluating potential damage to marine and coastal environments resulting from sediment extraction, transport and deposition (Cipriani et al., 2011). Chemical, biological, ecotoxicological, sediment grain-size and

* Corresponding author.
E-mail address: monia.renzi@virgilio.it (M. Renzi).
[1] All authors contributed equally.

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colour data were used to assess the compatibility of these aggregates with the native sediments of beaches experiencing severe erosion in Tuscany.

An especially important factor in this particular situation is the economic value of Italian beaches (from € 800/m^2 to € 2500/m^2 according to NOMISMA-www.beachmed.it), which generates strong local interest in managing the short-term evolution of the shoreline. The bottom-up decision-making process contrasts with the long-term and large-scale management of coastal sediments within physiographic units (Cappucci et al., 2011). Beach erosion is also a primary concern among summer tourists in the United States (Houston, 1995). The severe erosion of beaches determines a significant reduction in tourism, with adverse impacts on the local economy. Over the past few decades, the most popular approach to addressing beach erosion problems worldwide is to replace eroded sand with sand from the sea floor (Houston, 1996), a procedure on the increase in Europe as well (Pranzini and Williams, 2013). In addition, an evaluation of costs due to the effects of erosion in coastal areas resulting from climate change is crucial to the definition of adaptation strategies. Along Italian coasts, adaptation options to deal with the effects of climate change were first proposed by Cappucci in 2007 (BEACHMED, 2015). This analysis showed that defending the entire 4600 km of Italian sand coastline would not be economically sustainable. In fact, even if only the 1500 km of beaches that have already been subject to erosion were to be protected, a huge initial investment (about € 2 billion) would be necessary, along with repeated maintenance interventions over time. In this case, the amount of sediment required for beach nourishment was estimated at around 150–200 million m^3 (approximately 100 m^3 per meter of beaches), not to mention the quantities that would be necessary for maintenance interventions (BEACHMED, 2015). In Italy, beach nourishment using sand dredged from continental shelf reservoirs started in 1994 within the projects of coastal stabilization of the barrier islands protecting the Venice Lagoon; since then approximately 20 million m^3 of aggregates have been extracted, mostly to nourish beaches in Veneto, Lazio and Emilia-Romagna (Pranzini, 2013).

Many research programs are now comparing the availability (potential supply) of sand to carry out beach nourishment against the demand for sediments indicated by public authorities to contrast coastal erosion, but this analysis is still in progress (Correggiari et al., 2012). In addition, many environmental constraints specific to the Mediterranean Sea limit the possibility of reusing sediment for beneficial purposes (e.g. beach nourishment) if dredging is carried out along the coast or close to coastal infrastructures like harbours (Ausili et al., 2012; Cappucci et al., 2011; Lisi et al., 2009). The PESETA Project (Ciscar et al., 2014) used the Dynamic and Interactive Vulnerability Assessment (DIVA) model (Vafeidis et al., 2008; Hinkel and Klein, 2009) to estimate annual damage costs in 2020 and 2080 for two scenarios – low and high sea level rise (representing low and high climate sensitivity for the A2 SRES scenario, Nakicenovic et al., 2000). Total costs (*i.e.* damage and adaptation costs) were estimated first for a no-adaptation scenario, and second when adaptation (dike construction and beach nourishment) was taken into account. Total costs were found to be much higher without adaptation, thus adaptation was shown to be a highly cost-effective investment.

Based on a concrete case study carried out in Tuscany, the aim of the present research is to evaluate the compatibility of continental shelf aggregates for the nourishment of Tuscan beaches, and also to perform a cost-benefit analysis related to possible future needs due to erosion processes linked to global climate change (IPCC, 2007).

2. Materials and methods

2.1. Sediment sampling

Continental shelf sediments were collected in two different submerged sand deposits denominated "Massa", located 16 km offshore from the outlet of the Serchio river, at a water depth ranging between 40 and 100 m, and "Piombino" with water depth from 60 to 90 m but with bottom characterized by a much more irregular morphology (Fig. 1).

Sampling strategy was developed in order to characterize both vertical and horizontal variability of both sand deposits. Four georeferenced (WGS-84) replicates were located per km^2, for a total of 58 sampling stations: 36 in the Massa deposit (codified as M1÷M36) and 22 in the Piombino deposit (codified P1÷P22). In each sampling station, a 6-m-long core was collected using a SHSBD-A® core tube; three analytical levels were selected from each core at different depth levels (superficial, middle and deep samples) depending on the core length and following the sampling strategy proposed by the specific Guideline published by the Central Institute of Applied Marine Research (APAT-ICRAM, 2007). A total of 174 sediment samples were collected from the Massa and Piombino continental shelf deposits for physical, chemical, microbiological and ecotoxicological characterization.

Twenty-one beaches (codified from b. 1 to b. 21 moving from north to south) threatened by erosion were characterized along the Tuscan coast to evaluate sand compatibility with the continental shelf deposits (Fig. 1). For beach sampling, three superficial sediment samples (0–50 cm) were collected directly using a Teflon pre-conditioned spatula at each sampling site (for a total of $n = 63$ observations). Collected samples were homogenized, stored in HDPE bottles and kept at + 4 °C until the time of analyses. Analyses were performed on variables of interest as per Italian Law (Decree Law n. 319, 1996) and following the APAT-ICRAM Guideline (2007).

2.2. Textural analysis

Sediments were dry sieved at ½ phi intervals after removing and weighting fines (<0.063 mm). The compatibility of borrow sand texture with native beach sediment was evaluated by comparing grain-size distribution and computing the Stability Index (Is; Pranzini, 2002), for which values higher than 0.50 were considered acceptable. This was done both for single core, in its coarsest part, and for side cores when some lateral continuity was found in the deposit.

2.3. Colour assessment

Sediment colour assessment was performed with a Konica Minolta CR-410 colorimeter in the CIEL$^*a^*b^*$ colour space (Pranzini et al., 2010) with D65 illuminant (clear sky). Colour distance between pairs of samples was determined as Euclidean distance: $\Delta E^*ab = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$.

Compatibility was qualified as positive for $\Delta E^*ab < 10$, based on perceptions of colour differences in sand sediments ascertained through interviews with beachgoers (Pranzini and Vitale, 2010), and is now a standard for beach nourishment in Tuscany.

2.4. Chemical analyses

Trace elements (Al, As, Cd, Cr, Hg, Ni, Pb, Cu, V, Zn), macronutrients (total nitrogen, total phosphorous, total organic carbon), hydrocarbons (linear aliphatic; polycyclic aromatic hydrocarbons)