Beach Nourishment Alternatives for Mitigating Erosion of Ancient Coastal Sites on the Mediterranean Coast of Israel

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Abstract: Since 2011, beach nourishment has become the preferred solution for mitigating coastal erosion along the Mediterranean coast of Israel, as it is considered “soft” and environmentally friendly. However, using fine sand for nourishment in Israel without supporting measures is problematic due to the high wave energy and strong longshore currents in the littoral zone that tend to drift the sand away. This would require ongoing, multiyear, costly, and never-ending maintenance. In the present study, we analyzed sand and pebble alternatives for nourishment of the eroded beach in front of Tel Ashkelon, an important coastal archaeological site in southern Israel that suffers from severe erosion. Based on Pranzini et al. (2018), we analyzed the alternatives, evaluated their cost and efficiency, and assessed their potential environmental impacts. The study concluded that for protecting the southern part of Tel Ashkelon beach, pebble nourishment is the optimal solution, mainly regarding durability and cost. Using this material for nourishment will better absorb the storm wave impact and protect the foot of the archaeological Tel from erosion, and require lower maintenance cost than using finer sand nourishment.

Keywords: coastal processes; dredging; nourishment durability; unit sand volume; pebbles; Levant; Tel Ashkelon

1. Introduction

The Mediterranean Sea is rich in unique cultural assets and is considered to be the cradle of many civilizations, religions, and cultures [1,2]. Ancient empires and cultures have left a wealth of remains, including coastal settlements, harbors, and anchorages.

Some of the most important ancient sites, which represent the mutual relation between man and the sea, are located on the Mediterranean coast of Israel [3–5]. During the 20th century, Israeli ancient coastal sites such as (from south to north) Tel Ashkelon, Yavneh-Yam, Apollonia, Caesarea, Dor, Atlit, and Akko (Acre) (Figure 1: top inset), have been severely eroded, mainly due to modern marine construction, as well as sea level rise, and storm waves [1,4,6,7]. If these processes continue, a significant portion of the marine heritage of humanity will disappear, and archaeological and touristic assets of great cultural, scientific and economic value will be lost [1,4]. This coastal erosion may also affect the unique intertidal ecosystems at these sites [8].
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Figure 1. Ashkelon coast, the main marine constructions and Tel Ashkelon site (Photo: Google Earth image, 28 January 2016) (EAPC—Eilat-Ashkelon Pipeline Company); The Mediterranean coast of Israel and its main ancient coastal sites (top left inset); The Nile littoral cell longshore sand transport direction (black arrows), from the Nile Delta to Haifa Bay (bottom right inset).

One of the most important archaeological sites on the Israeli coast is Tel Ashkelon (ancient Ashkelon) [9–11], situated within the Ashkelon National Park, adjacent to the southern part of the modern city of Ashkelon (Figures 1 and 2). The most prominent ruins seen today in Tel Ashkelon are the Crusader fortifications (638-1187 CE) [12–14]. These remains include several sections of the old city wall and a short part (40 m long) of its seaside wall (i.e., the Columns wall) (Figure 3). The latter was reinforced by the Crusaders, who reused granite columns taken from Roman/Hellenistic monumental structures [15].
Because of the importance of the archaeological remains along the coast of Tel Ashkelon, it is our duty to preserve them for the sake of future generations. Several plans have been proposed in the last 15 years by governmental agencies; however, only one project aimed at protecting the Columns wall has been completed so far. The Columns wall was protected by building a ‘sacrificial’ layer of stones (3 m high and 1 m thick) on its seaward side. The project was carried out by the Israel Antiquities Authority in 2005.

Beach nourishment is one of the commonest ‘soft solutions’ for coastal erosion [16–21], and it was found more appropriate from environmental and economical perspectives, than ‘hard solutions’, such as seawalls, revetments, detached breakwaters, and groins [22]. Studies have revealed that a clear definition of the aims of beach nourishment and a well-based knowledge of the local physical conditions (e.g., coastal morphology, native sediment grain size, wave regime) are crucial for a successful coastal protection project [21]. Furthermore, to achieve a successful nourishment, a cost-effectiveness approach is needed, together with an analysis of alternative solutions, effective planning and monitoring, and using compatible sediment for nourishment [21,23,24].

The present study analyzes sand and pebble alternatives for nourishment of the eroded beach in the vicinity of the Columns wall in Tel Ashkelon. The study evaluates the cost and efficiency of each
alternative, examines their potential environmental impacts, and suggests the optimal solution as a case study for ancient coastal sites protection.

2. Study Area

2.1. Tel Ashkelon: Historical and Archaeological Setting

Tel Ashkelon is located adjacent to the ancient Via Maris, which connected Egypt with the south Levant coast and also served as the sea gate to the ‘spice route’, connecting the Far East with the Mediterranean coast [9–11]. This location endowed it with commercial and strategic advantages, and the city was an important urban center and a sea gate to international trade from the Middle Bronze Age (ca 2000–1700 BC) through the Crusader period (12th–13th centuries CE). The Crusaders conquered Ashkelon in 1153 CE, and ruled it with intervals until 1247, when it finally fell to the Muslims, to be demolished by the Mamluks in 1270 [12–14].

Underwater surveys off Tel Ashkelon have yielded numerous archaeological remains, including shipwreck remains and cargoes at a water depth of 3–4 m, architectonic elements (building stones, granite columns, marble statues, etc.), and sections of the Crusader seawall found in shallow water adjacent to the shoreline at a water depth of 0–1.5 m. These are the remains of sections of the city wall and structures from the Tel suffering erosion by the sea [25–27].

Sections of the sea-side city wall were primarily built on a sandy layer and the wall was originally located a few dozen meters from the shoreline, indicating that it was at a safe distance from the coastline and the builders were not concerned about marine erosion [15]. A traveler’s book from the 19th century noted a distance of 40 steps between the wall and shoreline [28], and aerial photographs from the second half of the 20th century show a relatively wide (20–30 m) and stable beach that stretched along the Tel until the mid-1980s. However, in contrast to this stability, severe erosion has occurred along the coast of the Tel during the past 20 years, and a steep escarpment rising to 20 m has developed [29] (Figures 2 and 3).

2.2. Ashkelon Coast: Physical Setting

Ashkelon is a modern city in the Southern District of Israel, about 50 km southwest of Tel Aviv (Figure 1). The Ashkelon shoreline is straight and exposed to the West. Its orientation varies from 32° in the south to 30° in the north. Most beaches are flat and sandy, and range in width from 20 to 50 m. In some parts, the beach is backed by a steep kurkar (local term for aeolian carbonate-cemented, quartz sandstone) cliff. In these places, the beach is generally less than 20 m wide and sometimes narrows to only a few meters during the winter.

The Ashkelon National Park coast extends about 2.85 km (Figure 1: green arrows). Morphologically, it can be divided into two main sections: (a) The southern section is a sandy beach 15–20 m wide, which is poorly defended from wave action by beachrock outcrops, and backed by an escarpment up to 10 m high (poorly cemented kurkar overlain by a sand dune a few meters thick), stretching about 1350 m from the northern fence of the EAPC area to the remains of the old city wall (i.e., southwestern coastal fortifications) (Figure 4), and: (b) The northern section (Tel Ashkelon coast) is about 1100 m long and is backed by a steep unstable coastal escarpment composed of archaeological remains of the ancient city.
In the present study, the Tel Ashkelon coast is divided into two parts. The southern part, in the vicinity of the Columns wall, is an eroded beach 400 m long (Figures 2 and 3). This beach, which is the focus of the present study, is narrow (0–15 m) and most of the time is covered by fine sand and coarser sediment, some kurkar and beachrock出crops, and scattered archaeological remains originating from the Tel layers. The seaward side of the Tel suffers from severe landslides and collapses of the archaeological strata, structures, and installations [30] (Figure 3). During the winter, when storm waves occur, most of the fine sand is drifted away from the backshore and nearshore, and large areas of kurkar and beachrock outcrops, as well as very coarse sediment (pebbles, cobbles, and boulders) are exposed. These seasonal changes also affect the coastal fauna and flora.

The northern part of the Tel beach (700 m in length) (Figure 2) and further north to the park boundary is a relatively wide (30–50 m) sandy beach that includes bathing beaches with commercial amenities.

From the sedimentological perspective, the Tel Ashkelon coast and its inner shelf (from the shore to about 30 m water depth), is considered part of the Nile littoral cell [31]. Sand from the Nile Delta is carried eastward by longshore currents to northern Sinai [32–35], and continues northeast to the Gaza Strip and north along the Israeli coast up to Haifa Bay (Figure 1: bottom inset) [36–40]. The estimated net average northward wave-induced longshore sand transport rate at Ashkelon is about 300,000 m³/year [41].

The Israeli Mediterranean wave climate has two seasons: summer (April through October) and winter (November through March). During the summer season, the wave climate is characterized by a relatively calm sea, with wave heights rarely exceeding 2 m (Hs < 2 m). In the winter season, the wave climate has alternating periods of calm seas and storm events with up to 5 m significant wave height (Hs) [34,35]. The prevailing wave direction is west-northwest (W-NW), but the predominant wave direction is west, corresponding to the longest fetch. During the last 25 years, four major storms (in 2001, 2002, 2010, and 2015) with Hs > 7 m have struck the Israeli coast. These extreme events expose the Israeli coast to relatively high waves and consequently severe coastal erosion [21].

2.3. Morphological Impact of Ashkelon Port

A small service harbor for the Eilat-Ashkelon Pipeline Company (EAPC) was constructed about 3 km south of Tel Ashkelon in 1972–1973. The harbor was built on a straight sandy coastline, and its main breakwater projected about 260 m offshore to 4 m water depth.
A few years after this construction, the adjacent seashore had suffered severe erosion of 10–20 m as far as 1.5 km north of the harbor [42–44] (Figures 1 and 4). At the same time, the coast south of the harbor had widened by tenths of meters.

In 1986–1987, a new main breakwater was built around the small EAPC harbor to create a larger oil port (Ashkelon Port) as well as a water-cooling basin for a new power plant (Rutenberg Power Station) (Figures 1 and 4). The port’s main breakwater projected about 450 m offshore, with its head located in 6 m water depth. A few years after this construction, the erosion continued further north and reached the Tel Ashkelon shore. As a result, a sand layer about 2 m thick was eroded from the beach and the surf zone in front of the southern part of the Tel. The shoreline had retreated by as much as 25 m [45], and the seaside city wall was badly eroded with its ruins scattered in the shallow water [1,3–5] (Figures 2 and 3).

2.4. Tel Ashkelon Seafront: Previous Protection Plans and Nourishment Activities

In 2007, the Israel Antiquities Authority recommended a series of protective measures for the Tel Ashkelon seafront, including: stabilizing the slope with terraces, vegetation, and nets; modifying the drainage on the Tel and its sea-side slope; protection of the seafront by a seawall and boulders and/or nourishing sand [4,6,7]. The Columns wall was partly protected, but no other measures were carried out. In 2009, 2011, 2012, and 2016, up to 60,000 m$^3$/year of a fine sand were dredged from the Ashkelon Port area and dumped at 6 m water depth offshore Tel Ashkelon (31°39'00" N, 34°31'45" E). No monitoring took place and no evidence of the dumped sand now remains.

In 2016, The Mediterranean Coastal Cliffs Preservation Government Company Ltd. (MCCP), recommended protecting Tel Ashkelon seafront by sand nourishment and a series of submerged detached breakwaters, built from geotextile tubes filled with sand, in a water depth of 4 m [46]. However, these plans have been not implemented.

2.5. Environmental Aspects

Tel Ashkelon beach is characterized by the following life forms, typical of sandy and rocky beaches of the Eastern Mediterranean: a diversity of beach birds, reptiles, the tufted ghost crab, tunnels of the Mysid crustacean, Gastroscus sanctus, and black and red ants. From spring through midsummer, female green turtles, Caretta caretta, and brown turtles, Chelonia mydas, may be seen on the sandy beach at night laying eggs [47].

The underwater habitat is usually sandy, but it also includes exposed kurkar and beachrock and sea bottom covered with pebbles and rock slabs that are often exposed due to erosion. Fauna and flora typical of sandy and rocky habitats are common on the sea bottom including fish, crustaceans, and alga. Beach nourishment may permanently bury habitats and organisms. The long-term impacts include formation of an unnatural beach, turbidity that affects light penetration and filtering organisms, as well as changing the sediment composition, which can alter the types of organisms that inhabit the nourished beach [19].

3. Methods

To assess the cost of alternatives for successful beach nourishment, grain-size and volume considerations for different sand sources, as well as coarser sediment (such as pebbles), were analyzed. The cost of each alternative was calculated in order to determine the best practice.

3.1. Grain Size Analysis

The following sediment samples from Tel Ashkelon beach (near the Columns wall) and from three quartz sand source sites were collected and analyzed:

1. Tel Ashkelon beach—Four samples (T1–T4) of the native sand were taken in December 2019 from the backshore near the Columns wall (Figure 5). The samples were dried at 50 °C for 48 h and
then analyzed for grain size through American Standard Test Sieve Series (ASTM) sized from 63 to 2000 μm in the Sedimentology Laboratory of the University of Haifa.

2. Rotem Plain sand quarry—Located in the Negev Desert, about 90 km southeast of Tel Ashkelon beach. Four samples were taken in August 2019 from the gathering area of the imported sand used for the north Ashkelon beach nourishment project [21]. The samples were analyzed using the above methodology.

3. Ashkelon Port—Six samples were taken in July 2017 from the port’s navigation channel at water depth of 6–8 m (Figure 1). The samples were analyzed through a set of ASTM sieves sized from 63 to 2000 μm by KTE Co., Technologies & Enterprises representative of ALS Global Laboratory at Haifa.

4. Offshore Ashkelon—A grab sample was taken at water depth of 20 m offshore Ashkelon, as a part of the Israeli sediment survey in August 2011. The samples were analyzed with a Malvern Mastersizer-2000 laser diffraction particle size analyzer in a range of 0–2000 μm in the Sedimentology Laboratory of the Geological Survey of Israel [48].

![Figure 5. Native sand sample (T1–T4) locations in Tel Ashkelon beach near the Columns wall. View to southwest, about 3 km from Ashkelon Port. (Photo: Orthophoto Israel, 16 July 2014).](image)

It should be noted that all sand sources have color compatibility with the native sand. In order to examine sediment alternatives for mitigating the erosion of the southern section of Tel Ashkelon beach, pebble versus sand nourishment alternatives were evaluated. For the current case study, dolomite pebbles 16–64 mm in size (that would allow a good passage for walkers on the beach), from the closest quarry to the nourished site, were analyzed. This grain size had proved to be successful for protecting the built area of Marina di Pisa in Tuscany [49].

3.2. Stability Index

In order to evaluate the compatibility and economic alternatives of the sand sources for Tel Ashkelon beach, the Pranzini et al. probabilistic approach [50,51] was used. This approach is based on the hypothesis that the stability of each grain size fraction (μm) nourished on the beach (Fbi) is inversely proportional to that fraction’s value in the cumulative distribution curve of beach native sediment (Cni). By assessing the stability index of the sand alternative, it is possible to grade the compatibility of each alternative with the native sand. Low stability will require a greater volume of
sand for nourishment than sand with high stability (details of the cost calculation are presented in Section 4 below).

The stability index (\(Si\)) (see Section 4 below) ranges between 0 and 1.0, where 0 means that all the imported sand is finer than the smallest granulometric fraction of the native sand. However, an \(Si\) of 1.0 represents the opposite situation, i.e., all the imported sand is coarser than the coarsest native sand; and an \(Si\) of 0.5 means that the imported and native grain sizes are identical.

### 3.3. Pebble Alternative

Sand is the most commonly used sediment for beach nourishment world-wide [16,17] However, for pebble (gravel) beaches, gravel nourishment is a common method for mitigating coastal erosion [16,49,52,53]. It is widely agreed that a coarser material, such as granules, pebbles, and cobbles, may effectively extend beach fill longevity [54]. In general, most researchers agree that coarser grain sizes produce steeper, more stable, and longer-lived fills [55–57]. Pebble beaches that have usually been built to protect coastal facilities and buildings [58], have proved cost-effective [49], and have sometimes provided increased space for recreation. Another application for pebbles is to cover eroded beaches of fine sediment located in front of archaeological sites, in order to protect them from storm waves [53]. A successful example of this application was applied in the archaeological site of the Apollonia Crusader castle, some 65 km northeast of Ashkelon (Figure 1: top inset). An artificial beach berm 300 m long, consisting of pebbles, cobbles, and boulders, was constructed along the cliff toe of the archaeological site (Figure 1: top inset) in 2009. This project included a 3 m high revetment that defended the cliff toe directly, and a very coarse sediment berm nourished by a volume of 20 \(m^3\) which cost €780,000 (adjusted for May 2020). In the last 10 years, the berm and revetment have survived several storms with extreme waves; the berm settled down, and sand and coarse sediment, such as crushed shells and kurkar pebbles (from cliff collapse) filled the berm matrix (Figure 6).

### 3.4. Nourishment Unit Voulme and Cost Estimation

The unit volume of sand used for nourishment is expressed as \(m^3/m\) of the beach length. According to a recent study [21], the suggested unit volume of sand for the Mediterranean coast of Israel is 400–500 \(m^3/m\). For the present study, 500 \(m^3/m\) was assumed. For the pebble alternative, however, the unit volume of 90 \(m^3/m\) used for nourishment at Marina di Pisa (Tuscany coast, Italy) [53], was adopted for the Tel Ashkelon beach. No \(Si\) calculation was made for this alternative, because its grain size was far coarser than the native one.

Detailed operations and direct cost estimation for the alternatives are as follows:

1. Rotem Plain sand quarry—Royalties for quarry sand; loading sand on 20 \(m^3\) trucks; transportation cost from Rotem Plain to the gathering area near Tel Ashkelon beach; maintenance of the gathering site; construction of facilities for transporting the sand to the beach; bulldozing the sand on the beach. The total cost for these operations is about €52/m³ [47].

2. Ashkelon Port—Rainbowing the sand via a discharge pipe at the bow of a dredging vessel (trailing suction hopper dredger), anchored at a water depth of 6 m. The dredging vessel conducts up to four cycles per day, about 800–1600 \(m^3\) of sand per load; bulldozing the sand onto the nourished site. The total cost is about €31/m³ (EDT Marine Construction pers. comm. 2020).

3. Offshore Ashkelon—Operations and costs as for Ashkelon Port.

4. Pebble alternative—Imported pebbles from Etziona quarry located about 52 km from nourishment site, including cost of pebbles, handling, transportation, and bulldozing on the site. The total cost is about €34/m³ (Etziona quarry CEO pers. comm. 2020).
The Apollonia Crusader castle, some 65 km northeast of Ashkelon (Figure 1: top inset). An artificial beach berm 300 m long, consisting of pebbles, cobbles, and boulders, was constructed along the cliff toe of the archaeological site (Figure 1: top inset) in 2009. This project included a 3 m high revetment that defended the cliff toe directly, and a very coarse sediment berm nourished by a volume of 20 m$^3$/m which cost €780,000 (adjusted for May 2020). In the last 10 years, the berm and revetment have survived several storms with extreme waves; the berm settled down, and sand and coarse sediment, such as crushed shells and kurkar pebbles (from cliff collapse) filled the berm matrix (Figure 6).

**Figure 6.** The Apollonia site (Crusader castle) coast and the main part of the nourished coast at the cliff toe: (a) about two years before nourishment operation (i.e., October 2009); (b) four months after the coast was nourished by pebbles, cobbles, and boulders; and (c) about 10 years after nourishment. (All images photographed by Dov Zviely).


4. Results and Discussion

4.1. Alternatives Evaluation

For a successful nourishment, compatibility of the nourishing (imported) sediment with the nourished site (native) sediment is vital [23,24]. The use of sediment coarser than the native material enhances the longevity of the nourished beach. Wave action and coastal currents will easily erode sediment if the grain size of the imported material is finer than that of the native material [16,17,19,20,59–63].

Four sediment alternatives for nourishment of Tel Ashkelon beach were analyzed in the present study, each with its unique characteristics, as follows (Summarized in Tables 1 and 2):

1. Terrestrial sand quarried from Rotem Plain—The mean grain size is 384 µm, which is coarser than the native 290 µm by ratio of 1.34. The stability index of the sand is 0.57, which means that almost 60% of the imported grain size is coarser than all native sediment, and its durability cost score is 1.0. The volume of sand as assumed above is 200,000 m$^3$ (500 m$^3$/m length of beach). As the estimated cost for this sand nourishment is €52/m$^3$, the expected total cost for this alternative is €10,400,000.

2. Marine sand dredged from the Ashkelon Port area—The mean grain size, 282 µm, is a little finer than the native one, but the stability index of this sand is 0.27, which means that only small part of the material is compatible with the native one. The durability cost score is 2.1, which means that with regard to the terrestrial sand, this sand needs about twice the sand volume to obtain the results as the terrestrial sand. Although the direct cost of this sand per m$^3$ is lower, it is uneconomic to use, as it needs a great quantity.

3. Marine sand dredge offshore Ashkelon at a water depth of 20 m—This sand is completely incompatible with the native one; its stability index is very poor, and it should be rejected.

4. Dolomite and limestone pebbles from Etziona quarry—Pebbles are much coarser than the native grain size, and this solution is economic. Its cost estimation is €34/m$^3$ for the case study site and the expected total cost of this 36,000 m$^3$ project is €1,224,000.

Table 1. Stability index calculation of the three alternative sand sources.

| Sieve Size | Tel Ashkelon Weight | Cumulative Weight $Cn_i$ | $S_f_i$ | Rotem Quarry $Fb_i$ | Ashkelon Port $Fb_i$ | Offshore Ashkelon $Fb_i$ |
|------------|---------------------|--------------------------|--------|--------------------|----------------------|------------------------|
| µm         | %                   | %                        | $Fb_i$ | $Fb_{i,S_f}$       | $Fb_i$               | $Fb_{i,S_f}$           |
| 2000       | 0.59                | 0.59                     | 2.32   | 1.37               | 3.94                 | 2.32                   | 0.00                   | 0.00                   |
| 1000       | 0.41                | 1.00                     | 4.05   | 4.02               | 2.41                 | 2.39                   | 0.00                   | 0.00                   |
| 500        | 14.63               | 15.63                    | 28.92  | 7.60               | 6.97                 | 0.00                   | 0.00                   |
| 250        | 77.36               | 92.99                    | 22.64  | 29.70              | 13.57                | 14.15                  | 6.47                   |
| 125        | 6.01                | 99.00                    | 43.20  | 1.69               | 79.55                | 3.19                   |
| 90         | 0.06                | 99.06                    | 10.30  | 0.10               | 0.91                 | 0.01                   |
| 63         | 0.00                | 99.06                    | 8.60   | 0.08               | 5.37                 | 0.05                   |
| Si         | -                   | -                        | -      | -                  | -                    | -                      |
| $d_{50}$ (µm)| 290                | -                        | 384    | 282                | 138                  | -                      |
| Durability Cost Score | -                   | -                        | 1.0    | 2.1                | 5.7                  | -                      |
Table 2. Costs of alternatives for nourished imported sediment for Tel Ashkelon beach.

| Alternative                        | m³/m Length of Beach | Total Nourished Volume (m³) | Stability Index | Coefficient of Durability Cost | Cost for 1 m³ of Sediment (€) | Total Cost –1000€ |
|-----------------------------------|----------------------|-----------------------------|----------------|-------------------------------|-------------------------------|------------------|
| Terrestrial Sand from Rotem Plain Quarry | 500                  | 200,000 *                  | 0.57           | 1                             | 52                            | 10,400           |
| Marine Sand Dredged in Ashkelon Port | 1050                 | 420,000 **                 | 0.27           | 2.1                           | 31                            | 13,020           |
| Marine Sand Dredged offshore Ashkelon | Not Relevant         | Not Relevant               | 0.1            | 5.7                           | 31                            | Not Relevant     |
| Pebble                            | 90                   | 36,000                      | 1 ***          | <1.0                          | 34                            | 1224             |

* Total nourished volume: 200,000 m³ = 400 m beach length (Tel Ashkelon beach) × 500 m³/m. ** Total nourished volume: 420,000 m³ = 200,000 m³ × 2.1 (Coefficient of durability coast). *** The stability index of Pebble was not calculated, as its grain size is far coarser from sand.

Table 1 represents the stability index calculation according to the above approach (Section 3.2) expressed by:

\[ Si = \text{Sum of } (Fbi \times Sfi/100), \]  

where \( Fbi \) is the frequency (%) of each fraction in the imported (borrowed) sand sample, and \( Sfi \) is the stability factor of each native grain size fraction, expressed in the following equation:

\[ Sfi = \left[ 100 - \frac{(Cn_i + Cn_{i-1})}{2} \right] / 100, \]

where \( Cn_i \) is the cumulative weight of each fraction in the native sand sample.

The highest calculated \( Si \) in the current study determined as durability cost score 1.0 (i.e., the higher the score, the higher volume of sand and cost; 0.57 = 1.0, 0.57/0.27 = 2.1, 0.57/0.1 = 5.7). It was found that sand from Rotem Plain quarry has the highest \( Si \) (Table 1).

4.2. General Environment Consideration and Possible Negative Environmental Impacts

The type of sediment to be used for nourishment should be considered depending on the aim of the planned beach. Therefore, different grain sizes are considered to be used for nourishing: e.g., fine or medium sand for a bathing beach, and coarse sand, gravel, or pebbles for protecting backshore infrastructures.

The environmental impacts of beach nourishment derive from the source of the nourished material (i.e., terrestrial or marine dredging) according to the following criteria:

- Sediment that has more than 10% silt/clay composition may exacerbate the biological impact on beach biota [64]. Fine sediment that reduces water clarity may decrease photosynthesis in marine plants, and can also decrease feeding efficiency of birds [65].
- The biota of sandy beaches may be affected, or even eliminated under the imported sediment [66].
- The use of heavy machinery to redistribute the sediment can limit the necessary movement of fauna along the beach [67].
- Turbidity at the target beach can result from resuspension of sediment at the discharge pipe, and from sediment winnowing from the nourished beach into the surf zone, which can be carried in the longshore direction or seaward with waves and currents [68–70].
- Physical changes along nourished beaches include formation of steep berms, or scarps, which can prevent turtles from reaching preferred nesting sites along the beach. As a result, eggs may be laid closer to the water, where they are more likely to be swept away by incoming tides and waves [71]. Nourished beaches are often harder (increased shear resistance) than the natural beaches, preventing attempts of nesting [71,72] and recover adequately within two to three years after project completion [71] and even up to seven years [73].
• Oil waste from substandard ship maintenance activities take in ports, may endanger all kinds of life forms on the beach [59].

5. Conclusions

(1) Sediment used for a soft solution mitigation of beach erosion should be derived mainly from the nourishment aims, and the planned beach uses. Different sediment types (i.e., sand, gravel, pebbles) might be used for developing recreation beaches or protecting coastal infrastructures.

(2) The stability index calculation grades sand alternatives for nourishment and durability.

(3) Although the direct cost of marine sand for nourishment in the present case study is lower than that of terrestrial sand, its low stability makes its use inefficient and uneconomic in the long term. In the present study, we confirmed that the coarser the sand grain size is than the native one, the better is the stability of the nourished material.

(4) The pebble solution is preferable for the specific purpose of protecting the southern part (400 m long) of Tel Ashkelon beach for the long run. It has the disadvantages of changing the biotic characteristics of the beach, and creating a new type of habitat. However, compared to the ever-changing beach in the eroded section, which is sometimes sandy and sometimes rocky, the pebble beach is a more stable habitat.

(5) Terrestrial sand quarried from the Rotem Plain is incompatible with the native one (coarser and not from marine origin) and may result in a steeper and harder beach, which will disturb turtle nesting.

(6) Marine sand dredged from Ashkelon Port area may include oil waste from ship maintenance activities in the harbor area.

(7) Marine sand dredged offshore Ashkelon at a water depth of 20 m contains a high percentage of silt that may endanger the biota on the beach and the near shore.

(8) Dolomite and limestone pebbles will prevent turtle nesting, and disturb bathing. Recovery of the beach for any present biota can hardly be expected. There is, nevertheless, the opportunity for the development of new and different types of biota that are adapted to the new gravel habitats.

(9) Monitoring of the environmental impacts post-nourishment is crucial for further research and better practice.

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