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# Longshore sand transport estimates along the Mediterranean coast of Israel in the Holocene

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**Abstract**

The Nile littoral cell, one of the world's longest, runs 650 km along the southeastern Mediterranean, from Abu Quir Bay near Alexandria, Egypt, to Haifa Bay on the northern Israeli coast.

Haifa Bay constitutes the northernmost final depositional sink of Nile-derived quartz sand, transported from the Nile delta by longshore currents generated by approaching breaking waves. The northward net sand transport along the Mediterranean coast of Israel results from larger waves approaching from west–south–west and south–west compared to their counterparts from west–north–west and north–west.

This study utilizes an extensive new database gathered from sediment drill cores, marine geophysical maps and field observations to measure the volume of sand deposited in Haifa Bay and the adjacent Zevulun Plain during the Holocene. It then compares this volume to recent data, including measurements of sand accumulation along Haifa Port's main breakwater (constructed in the southern entrance of the bay) as well as longshore sand transport estimates along the northern Carmel coast.

Research findings estimate the annual average quantity of sand transported to Haifa Bay throughout the period at 80,000–90,000 $m^3$. The findings further conclude that this amount has not changed appreciably over the past 75 years. Evaluating calculated values over the long term, it is suggested that the characteristics of longshore sand transport along the coast of Israel have not changed significantly during the past 7900–8500 years. It is obvious that this conjecture should be treated with reservations.
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*Keywords:* Haifa Bay; Nile littoral cell; longshore sediment transport (LST); sand; coastal processes; paleo-coastlines

## 1. Introduction

The sand supplied from the Nile and carried by longshore currents throughout the Nile littoral cell helps protect this sensitive shoreline and provides a key resource for economic growth. Blockage of Nile River sand flow precipitated by the construction of Aswan High Dam, coupled with sustained, heavy demand in Israel raised concerns about sand depletion within the cell — and prompted the need for further analysis of coastal morphological changes and clearer understanding of present longshore sand transport (LST).

The Nile littoral cell, one of the world's longest, runs 650 km along the southeastern Mediterranean, from Abu Quir Bay near Alexandria, Egypt, to Haifa Bay on the northern Israeli coast (Inman and Jenkins, 1984)

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(Fig. 1). Until the construction of the High Dam at Aswan, this cell's primary source of sand was the Nile River. The dam's emplacement in 1964, however, effectively blocked this flow, and forced the longshore currents to take sands from the Nile Delta coast and its seabed instead (Sestini, 1976; Summerhayes et al., 1978; Toma and Salama, 1980; Said, 1981; Coutellier and Stanly, 1987; Frihy, 1988; Smith and Abdel Kader, 1988; Frihy et al., 1991b; Fanos, 1995; Stanley, 1998; El-Raey et al., 1999; White and El Asmar, 1999). Despite erosion in some sectors of the Nile Delta coast, sand continued to reach the up-drift beaches and inner continental shelf of northern Sinai (Coleman et al., 1981; Inman and Jenkins, 1984; Stanley, 1989; Frihy et al., 1991a; Frihy and Lotfy, 1997) as well as the Israeli coast (Goldsmith and Golik, 1980; Rohrlich and Goldsmith, 1984; Carmel et al., 1985; Perlin and Kit, 1999) up to Haifa Bay, the final depositional sink (Pomerancblum, 1966; Nir, 1980; Zviely et al., 2006).

It should be stressed that the volume of sand taken by the longshore currents depends largely on the radiation stress caused by breaking waves. While waves can be affected by climatic variations, there is no indication that the marine climate has changed significantly during the last century.

To date, no direct measurements have been gathered to gauge actual LST along the southeastern Mediterranean coast. In Israel, early LST estimates were theoretical, derived mostly from wave refractions (Emery and Neev, 1960; Goldsmith and Golik, 1980) and supported by coastal and seabed morphological observations (Golik, 1993, 1997; Shoshany et al., 1996; Golik et al., 1999; Golik, 2002). These studies theorized that: a) wave-induced currents carry sand from Rafah northward and from Carmel headland southward, converging between Tel-Aviv and Herzliya on the Israeli coast; b) sand beyond the breaker zone is driven northward along the entire inner shelf of Israel, mainly by the frequent northerly currents; and c) sand from the inner shelf supplies the beaches by wave on-shore transport. Other empirically-based studies (Carmel et al., 1985; Perlin, 1999; Perlin and Kit, 1999; Zviely, 2006) concluded that the region's net sand transport is directed northward along the Israeli coast until Haifa Bay. Estimates made by Perlin (1999), Perlin and Kit (1999) and Zviely (2006) are based on detailed, directional wave measurements conducted during the last 15 years in the Ashdod and Haifa regions. They used coastal and seabed morphological evidence (Zviely, 2000; Zviely et al., 2000; Klein and Zviely,

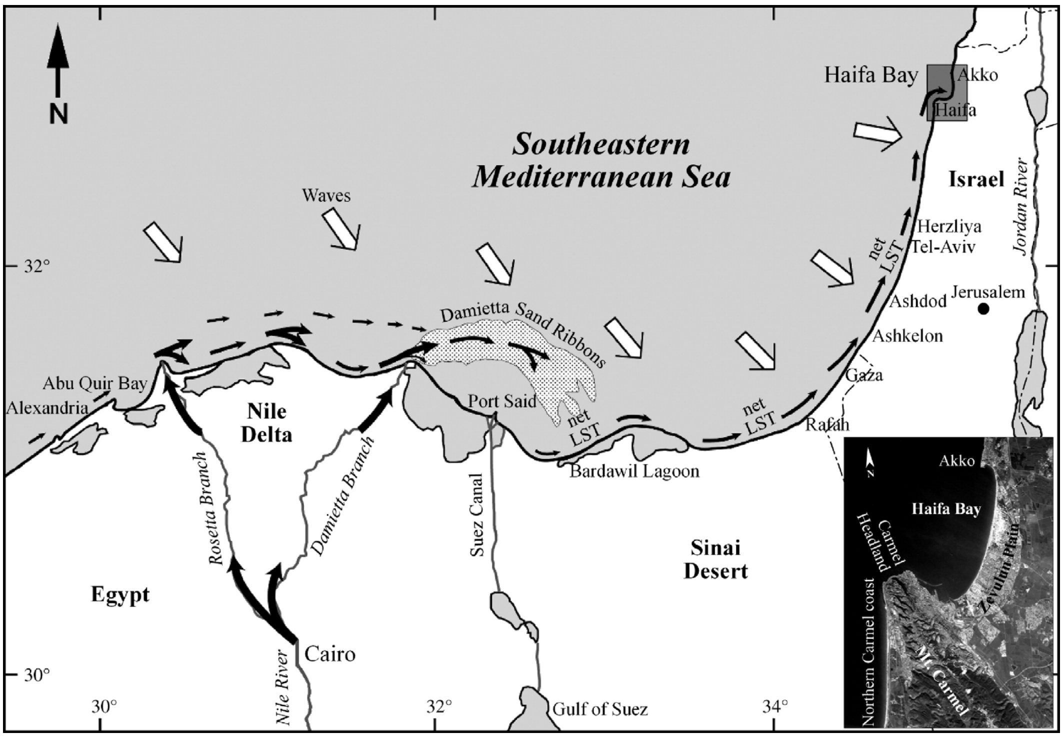


Fig. 1. The net LST dominant flow direction on the Nile littoral cell. Modified after Inman (2003).

2001; Zviely et al., 2006; Zviely, 2006) and a field experiment (Klein et al., 2004, in press) to support their claims.

This paper utilizes an extensive new database gathered from sediment drill cores, marine geophysical maps and field observations to measure the volume of sand deposited in Haifa Bay and the adjacent Zevulun Plain during the Holocene (Fig. 2). These data cover the last 7900–8500 years, and help explain the pattern of LST and its volume. These measurements further shed new light on the net LST estimates along the entire Israeli Mediterranean coastline and inner sandy continental shelf.

## 2. The study area

The study area consists of Haifa Bay and the adjacent Zevulun Plain. Haifa Bay is the most significant morphological feature on the southeastern Mediterranean coast. It opens to the west, and is bordered by Carmel headland to the south, Zevulun Plain to the east, and Akko (Acre) promontory to the north (Figs. 2 and 3). The bay's 18 km long coastline is crescent-shaped, with 5 km of artificial coast in the southern part, and 13 km of natural, sandy beaches on the eastern part. The beaches, which start 1 km north of the Qishon River outlet, are relatively wide and were backed by dunes until the

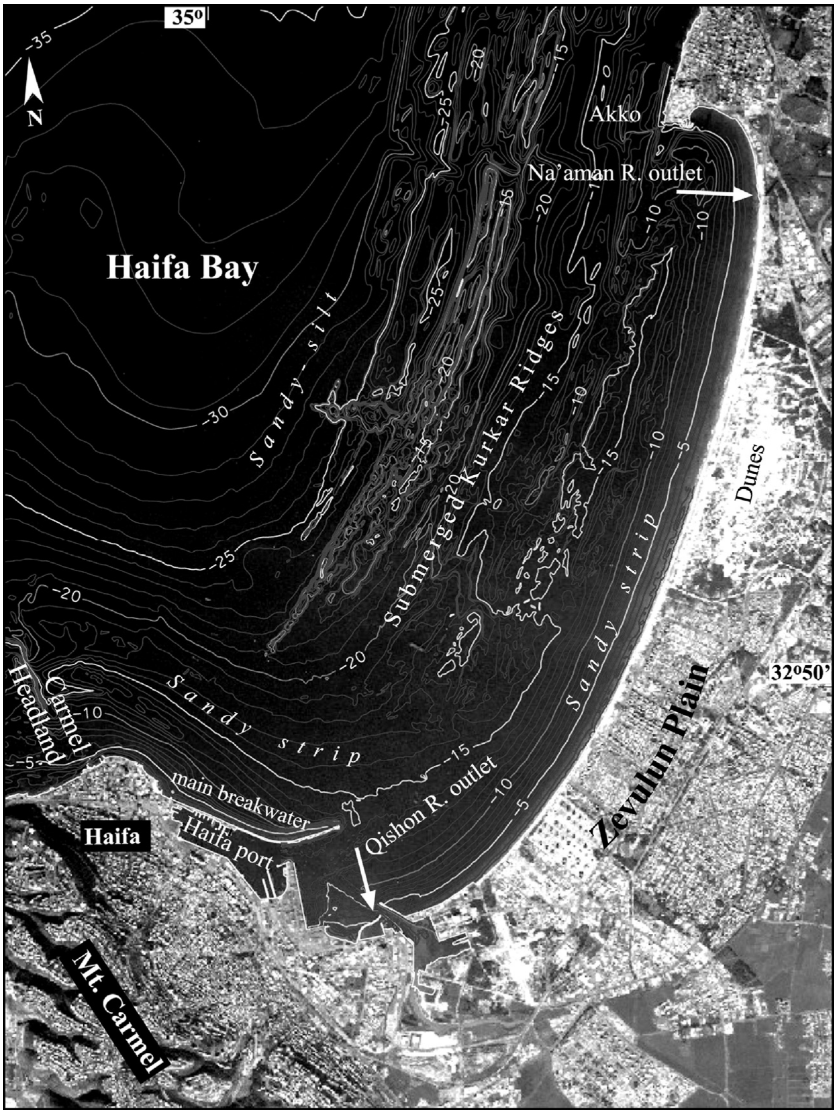


Fig. 2. Photograph of Haifa Bay area — the final depositional sink of the Nile-derived quartz sand, includes detail bathymetry. The photograph modified after: NASA, Earth Sciences and Image Analysis. Johnson Space Center, Houston, Texas, U.S.A. Astronaut Photography of Earth, Mission ISS001, Roll: ESC: Frame 5982, Date: 28.12.2001, Time: 084321 (*HHMMSS*).

beginning of the 20th century. Zevulun Plain is traversed by two rivers, the Na'aman in the north, and the Qishon in the south (Fig. 3). During the rainy season, both rivers transport large amounts of silt and clay sediment to the coast (Sandler and Herut, 2000). At present, most of the area is built-up.

Morphologically, the bay's floor can be divided into three sub-areas: a) the central and northern portions, which range from 10 to 25 m deep, and feature calcareous sandstone (locally termed *kurkar*) ridges (Figs. 2 and 3) (Bakler, 1975; Hall, 1976); b) the southern and eastern portions of the bay, which are 0 to 20 m deep, and contain a strip of Nile-derived quartz sand (Nir, 1980; Zviely, 2006); and c) the portion west of the submerged kurkar ridge area, which has a depth of 25 to 30 m and a smooth floor covered with fine sediment.

Haifa Bay and the Zevulun Plain form a geological graben, bordered to the north and south by the Ahihud and Carmel faults, respectively (Kafri and Ecker, 1964) (Fig. 3). The Holocene chrono-stratigraphy and lithology of Haifa Bay and Zevulun Plain have been

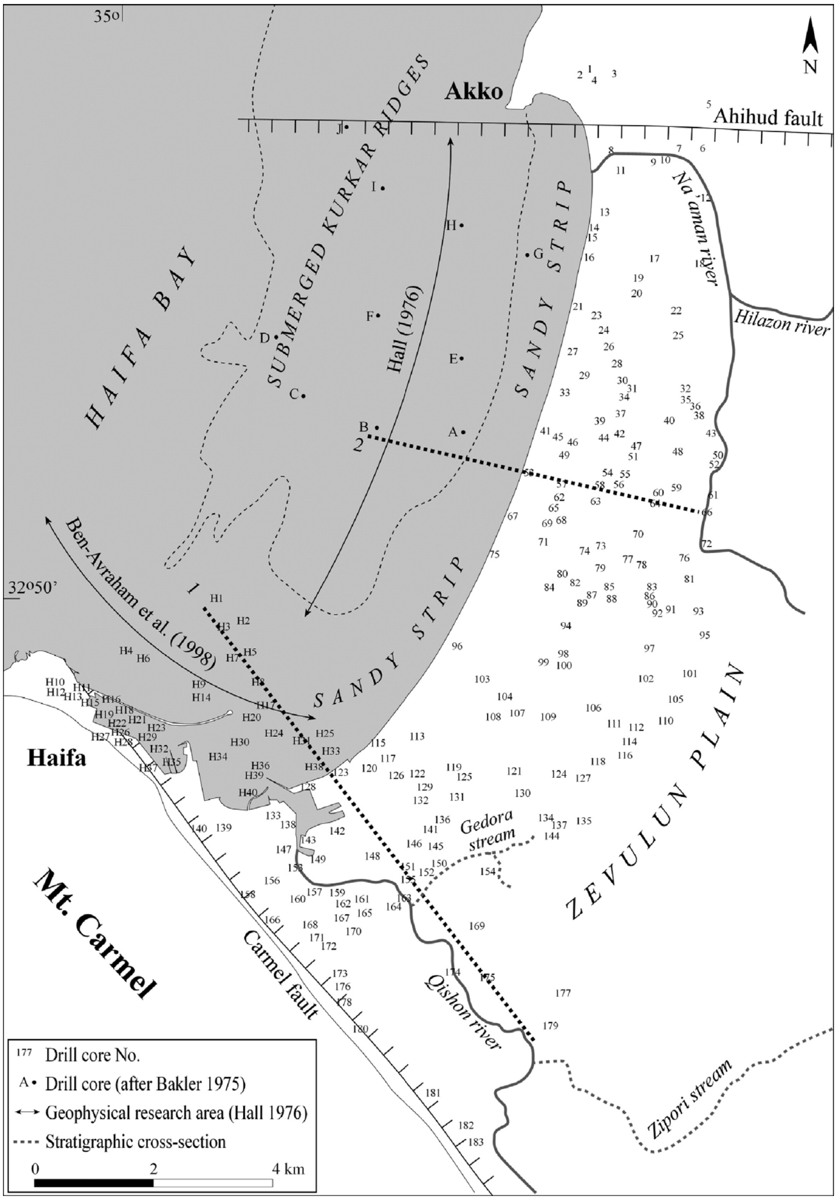


Fig. 3. Haifa Bay and Zevulun Plain showing major fault lines. Numbers indicate location of the drill cores used in the current research and the marine geophysical surveys areas. Modified after Zviely et al. (2006).

described in detail by Slatkine and Rohrlich (1963), Zviely (2006) and Zviely et al. (2006). Three coastal and shallow marine Nile-derived sand types as well as partly cemented aeolian Nile-derived sand were identified (Fig. 4).

## 3. Methods

The Holocene stratigraphy and lithology of Haifa Bay and Zevulun Plain are based on detailed analysis of 224 drill cores recovered during 1934–2004 (Zviely, 2006; Zviely et al., 2006) (Fig. 3). Approximately 70% of these drillings were for construction projects; the rest were for hydrological and geological research. Most of the drillings have a depth of 10 to 50 m. The lithological units and chrono-stratigraphy of the bay area were identified by color, granulometry, mineralogy, faunal assemblages and dating (Slatkine and Rohrlich, 1963; Figs. 4 and 5). In addition, geological data concerning the subsurface of the marine area were obtained from geophysical maps (Hall, 1976; Ben-Avraham et al., 1998) (Fig. 3).

Estimates of Holocene sand volumes in the Zevulun Plain were based on thickness of sand units found in the inland drillings, while those in Haifa Bay were deduced mainly from marine geophysical maps. In the eastern part of the bay, the thickness of the sand layer that covers the Late Pleistocene to Early Holocene bedrock was derived from a fill isopach map (Hall, 1976: their Fig. 7). This map was constructed using four high-resolution, continuous seismic reflection surveys carried out in the northern two-thirds of Haifa Bay in 1974–1976. Two sub-bottom profiling systems were acquired for the work: an E.G and G. Uniboom™ pulse boomer, and an O.R.E. Model 1036 sub-bottom profiler. Over 800 km of profiles were used to make detailed bathymetric, unconsolidated sediment isopach and bedrock structural maps covering an area of about 45 km$^2$ (Hall, 1976). A similar process was used to evaluate the southern part of the bay by Ben-Avraham et al. (1998). In addition to the marine drilling data, an isopach map for Late Pleistocene to Early Holocene terrestrial clay bedrock (H2 reflector) was used to measure sand layer thickness (Ben-Avraham et al., 1998: their Fig. 15). The map was based on seismic data acquired with a Datasonics CAP-6600 CHIRP acoustic profiling system. The data included more than 1300 km of seismic lines collected in November and December, 1997 (Ben-Avraham et al., 1998).

The drilling core sand thickness data were located on a 3D digital-vector map and combined with sand layer thickness contours obtained from marine geophysical

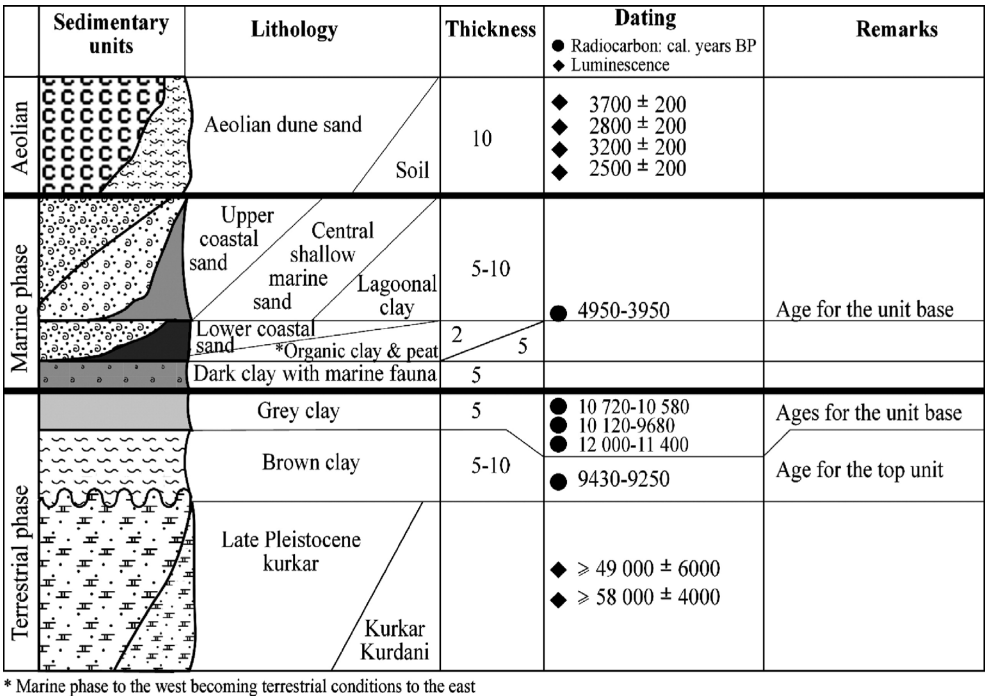


Fig. 4. Generalized stratigraphic sequences of Haifa Bay area showing the Holocene unconformably positional above the Late Pleistocene to Early Holocene terrestrial bedrock. The Holocene sequence consists of two main sedimentary cycles: marine and eolian Nile-derived quartz sand, After Zviely et al. (2006).

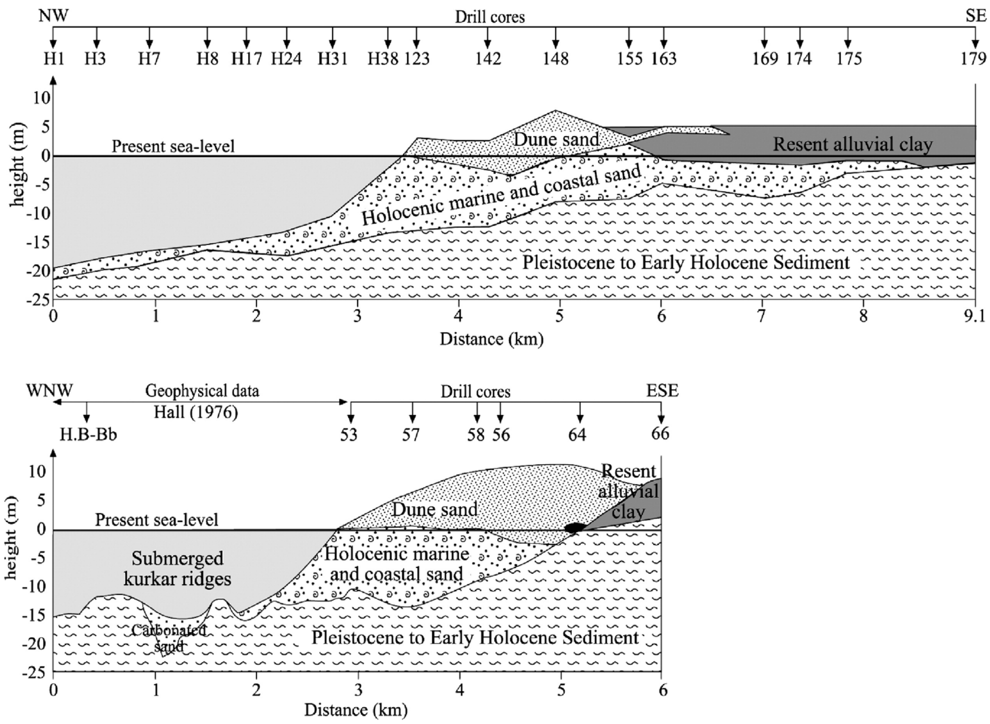


Fig. 5. Stratigraphic cross-sections in the Haifa Bay area. (A) 9 km long cross-section, from the vicinity of Haifa Port along the main breakwater to the Qishon river valley inland. The geological data obtained from marine and land drill cores. (B) 6 km long cross-section, from the submerged kurkar ridges in the central part of the bay to the Na'aman river valley inland. The sea side data is based mainly on marine geophysics survey (Hall, 1976), while the land side is based on data obtained from drill cores.

maps. All the data were than imported into a mapping software program (Microstation Java, 2000) to produce a high-resolution Digital Terrain Model (DTM) grid. Then the total Holocene sand volume in the bay area was calculated using the "Volumes" prismoidal application of GeoTerrain software (GeoTerrain, 2000), run in a Microstation Java environment (Zviely, 2006).

## 4. Results and discussion

### 4.1. Paleogeography of Haifa Bay during the Holocene

At approximately 9500 to 9000 cal. yr BP, the global sea-level reached a stand of about 35 to 30 m below its present level (bsl) (Fairbanks, 1989; Bard et al., 1990, 1996; Lambeck and Bard, 2000; Lambeck et al., 2002, 2004), and invaded the bay of Haifa (Fig. 6a). With this event, the region became a marine morphological feature (Zviely, 2006; Zviely et al., 2006). The sea continued to rise, and by about 8500 to 7900 cal. yr BP, when it was about 15 m beneath present sea-level, most of the bay was already submerged (Fig. 6b). Archaeological and geomorphological findings from the Carmel coast, Israel, support the global and regional sea-levels mentioned above (Galili et al., 1988, 1993; Nir, 1997; Sivan et al., 2001; Galili, 2004; Galili et al., 2005). It was at this point that the bay became the northernmost depositional sink of the Nile littoral cell; it remains so to this day. Between 8000 and 7150 cal. yr BP, the rising sea advanced across the present-day coastline and began to flood the Zevulun Plain, forming ria landscape. It is unknown when the sea reached its maximum inland penetration, but about 4000 years ago the shoreline was still east of its present location, up to 3 km into the center of Zevulun Plain and as far as 4.8 km into its southeastern portion (Fig. 6c). When the coastline began to retreat westward, the filling up of the sea coastal region within the bay was followed mainly by rapid deposition of coastal and shallow marine sand and aeolian dunes (Fig. 6d).

### 4.2. Sand accumulation in Haifa Bay area during the Holocene

The current research findings show that during the Holocene, 700 million $m^3$ of sand accumulated in the Haifa Bay area (Fig. 7a). Two-thirds (470 million $m^3$) were coastal and shallow marine sands (Fig. 7b), of

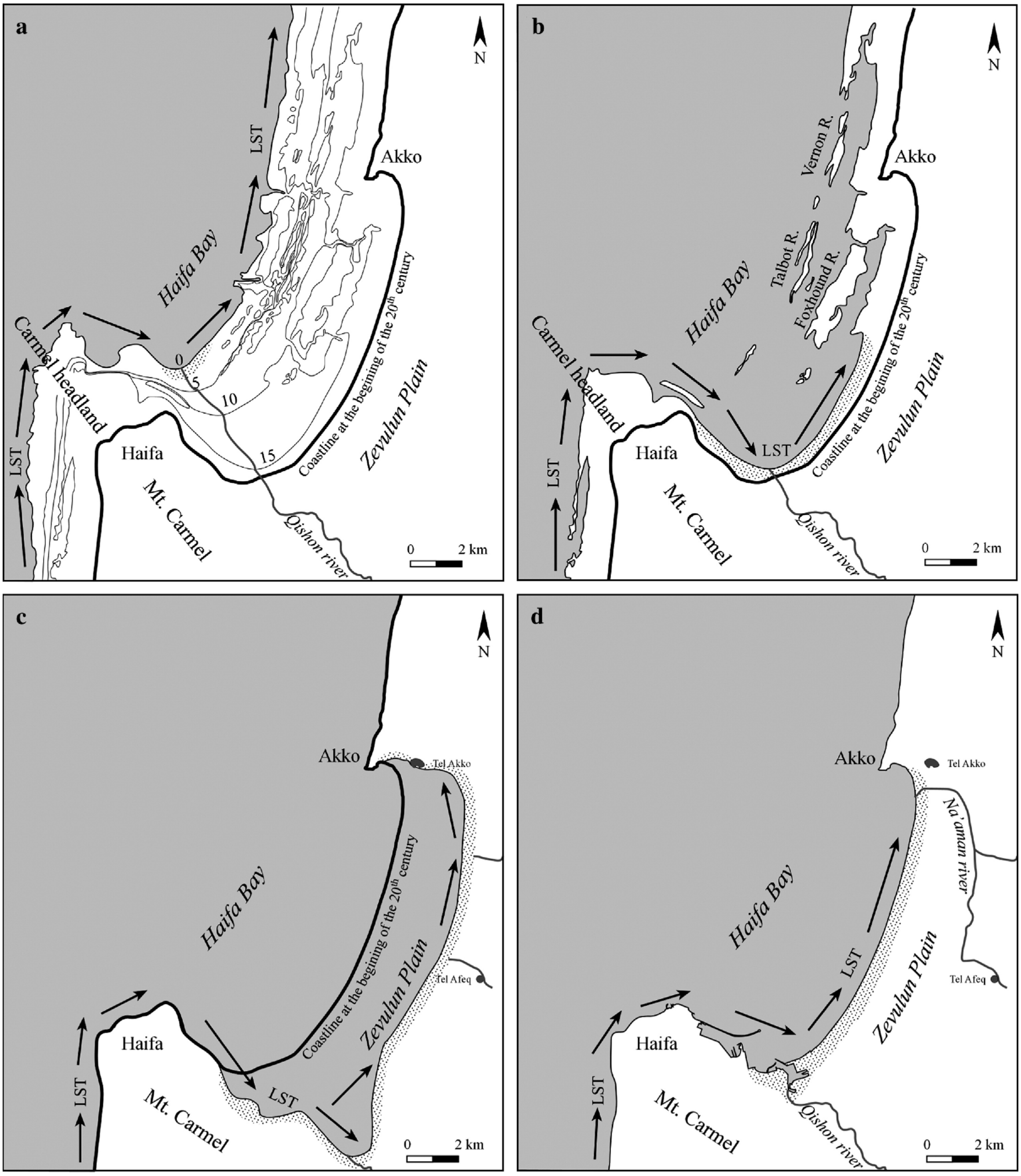


Fig. 6. The location of the palaeo-coastlines and the LST dominant flow direction at Haifa Bay and its vicinity during the Holocene. Modified after Zviely et al. (2006). (a) ~9500 to 9000 cal. yr BP when the sea-level reached a height of about 35–30 m bsl (below sea-level). The contours indicate the topography from the palaeo-coastline landward up to the present-day coastline. (b) ~8500 to 7900 cal. yr BP when the sea-level reached a height of about 15 m bsl. (c) Maximum sea invasion landward. The exact date is still unknown, but it seems to have been between 4000 and 3000 cal. yr BP. (d) Maximum sea penetration landward, the coastline started to retreat westward to its present position because due to bay reclamation.

which 135 million $m^3$ settled in Haifa Bay and 335 million $m^3$ settled in Zevulun Plain. The remaining third (230 million $m^3$) was aeolian sand deposited in dunes (Fig. 7c). According to Nir (1980) and Zviely (2006), the coastal and shallow marine sands in Haifa Bay contain 70–85% quartz and 15–30% local carbonate, while the dunes contain 85–95% quartz and only 5–15% carbonate (Denekamp and Tsur Lavie,

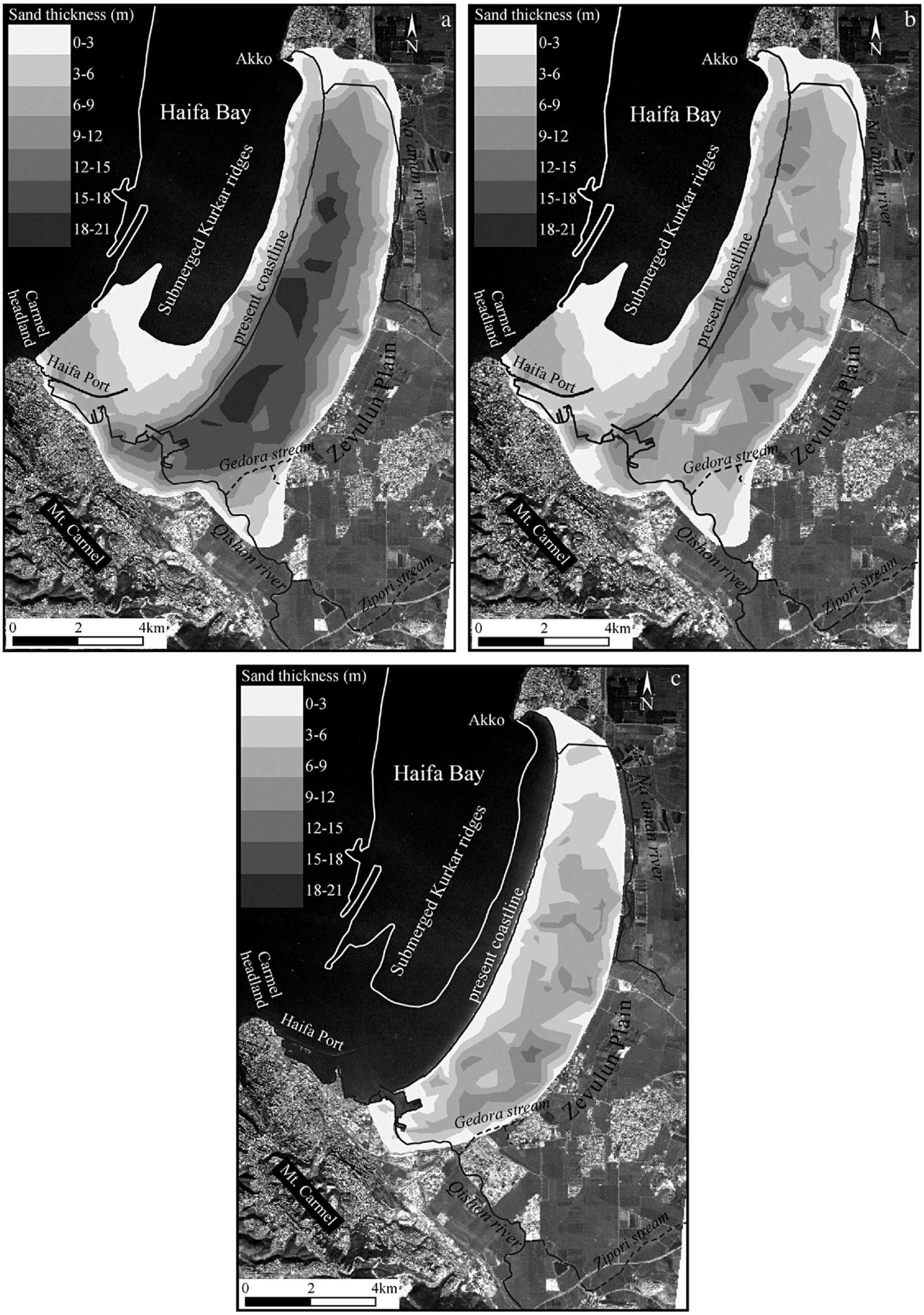


Fig. 7. Three dimensions sand units accumulation maps of the Haifa Bay area during the Holocene period. (a) Total coastal and shallow marine sands and dunes accumulated in the Haifa Bay and Zevulun Plain in the last 8500 to 7900 cal. yr BP. (b) Only the total coastal and shallow marine sands accumulated in the bay area during the time of period mentioned above. (c) The total dunes sands accumulated in the Zevulun Plain during the last 4000–3000 years ago, since the sea-level reached it present-day height (Galili et al., 1988; Nir, 1997; Sivan et al., 2004; Galili, 2004; Galili et al., 2005).

1981a,b). Overall composition of this considerable volume consists of 525–620 million $m^3$ of Nile-derived quartz sand and 80–175 million $m^3$ is of local carbonate sand.

### 4.3. LST at the southern entrance to Haifa Bay

Under typical weather conditions, the Carmel headland area at the southern entrance to Haifa Bay provides a natural barrier that prevents sand from entering northward into the bay. Only rare, high, south–west breaking waves can produce the strong northerly currents needed to penetrate the headlands and move sand eastward into the bay. In addition, the shape of the headland area (where the gentle curve of the Israeli coast is interrupted) together with its lack of a sandy beach preclude the viability of traditional LST estimate techniques. For example, straightforward use of the CERC formula in this area shows that the net sand drift should be southerly. Since there is no sand available in this area to move in this direction, sand can only be moved as described above.

### 4.4. Sand accumulation in Haifa Bay during the past 75 years

Prior to the construction of Haifa Port – and its main breakwater – by the British (1929 to 1932), sand that was able to penetrate the Carmel headland barrier flowed freely along the bay's coast. But the completion of the port's breakwater created a large trap for migrating sand entering the bay's breaker zone — and a bar of fine grain sand immediately began to accumulate (Civil and Marine Engineering Co., 1960; Golik et al., 1999). By 1938, the bar had reached the main breakwater head (Fig. 8a); by the late 1950s, it ran along the entire length of the breakwater, bypassing its eastern head and penetrating into the port's main entrance (Fig. 8b). In the early 1960s, the Haifa Port Authority dredged 1.3 million $m^3$ of sand from the sandbar (Civil and Marine Engineering Co., 1960) for reclamation and construction of a new passenger quay. At the end of the 1970s, the main breakwater was extended by 600 m to protect the new eastern quay from northwest approaching waves. Since this massive dredging, the sandbar continued to accumulate sand carried by wave-induced currents (Fig. 8c). The total amount trapped along the port's main breakwater between 1929 and 2004 (75 years of sand transport) is estimated at about 5 million $m^3$, or an average of 66,000 $m^3$/yr (Zviely, 2006). Additional amounts of sand that have bypassed the main breakwater during this

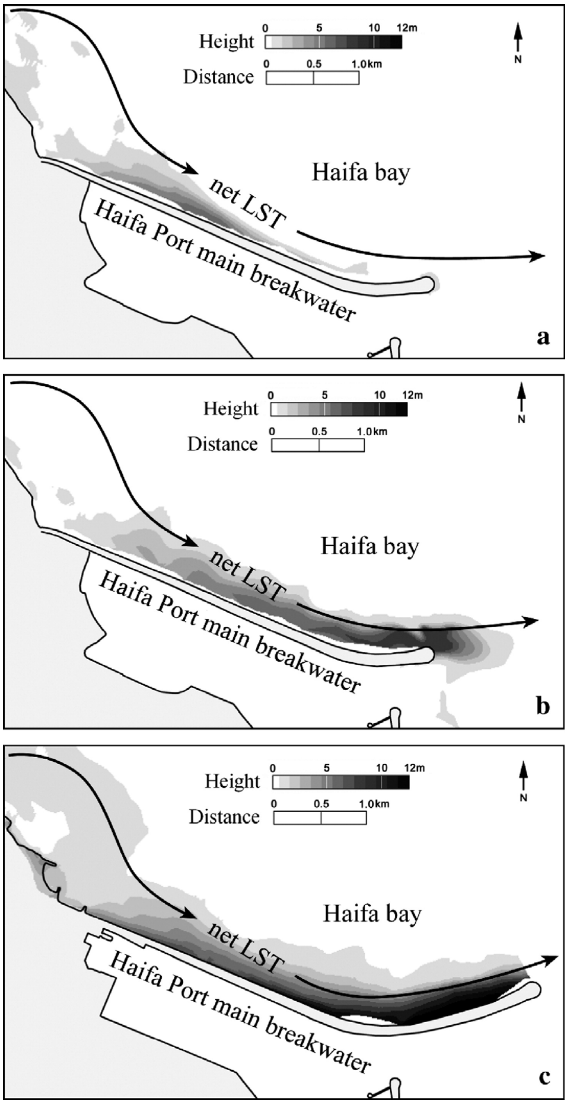


Fig. 8. Developed of the sandbar up-drift Haifa Port breakwater, see Fig. 2 for location: (a) 10 years after construction (1929–1938). (b) 30 years after construction (1929–1959). (c) 70 years after construction (1929–1998).

period and drifted eastwards into the bay are estimated at 8000–10,000 $m^3$/yr (DHI— Danish Hydraulic Institute, 2000).

### 4.5. Recent net LST estimates along the Israeli coast

A survey of recent LST measurements along the littoral cell shows an ongoing decrease as the longshore currents move east and north up the coast. Inman et al. (1976) estimated the rate of the eastward wave-induced LST at the Damietta eastern promontory of the Nile Delta at about 860,000 $m^3$/yr. This rate decreases to about 500,000 $m^3$/yr along the outer Bardawil lagoon sand bar at the northern Sinai coast (Fig. 1). Further to the northeast, an updated estimate by Perlin and Kit (1999) shows that the average net LST along the southern Israeli coast decreases from 450,000 $m^3$/yr at Ashkelon, to about 200,000 $m^3$/yr at Ashdod. Moving north, the rate decreases to approximately 100,000 $m^3$/yr at Tel Aviv, and diminishes to 60,000–70,000 $m^3$/yr at the south boundary of the northern Carmel coast just before reaching Haifa Bay, the northern end of the Nile littoral cell. Past this boundary, the lack of a sandy beach and the sharp curvature of the coast make accurate LST measurements difficult to obtain. The LST estimates by Perlin and Kit (1999), were obtained using (1) the modified CERC formula (Koutitas, 1988), and (2) the LITDRIFT module of one-line package suite developed by Danish Hydraulic Institute (LITPACK, 1998).

To develop the approximate directional statistical distribution of waves, they used high-quality directional wave data measured at Haifa and Ashdod (110 km apart) starting from 1994 (Fig. 9) by CAMERI — The Coastal and Marine Engineering Research Institute on behalf of the Israel Ports Authorities. Correlation analysis and further linear interpolation was then used to derive characteristic wave direction estimates for various sites in between. Their analysis shows that LST is strongly dependent on the relative angle between characteristic wave direction and shoreline azimuth. An updated estimate of LST for the northern Carmel coast was carried out by Zviely (2006) based on Perlin and Kit's (1999) analysis, and on long-term sets of directional wave data collected between 1994 and 2004. The new estimate yielded an average net LST of sand to the north of 72,000 $m^3$/yr, during the years 1994–2004, confirming the previous estimate of wave-induced LST in the vicinity of Haifa Bay.

The results of the this study do not support previous claims that net LST in the surf zone from Carmel headland to central Israel runs southward. Such claims – if correct – would require a convergence zone between Tel-Aviv and Herzliya, where huge amounts of sand would have been accumulated. Coastal and seabed observations in this region (Zviely, 2000; Zviely et al., 2000; Klein and Zviely, 2001; Dror, 2005) fail to detect any such accumulation.

### 4.6. Sand accumulation balance in Haifa Bay area

Using the above data, which cover the Holocene and isolate the past 75 years, we can derive and compare average annual sand budgets in the Haifa Bay area for both periods.

a) The Holocene — given the volume of deposited in the Haifa Bay and Zevulun Plain during the past 7900–8500 years – 700 million $m^3$ – we can calculate an annual average of 82,000–89,000 $m^3$/yr.
b) The past 75 years — we can add together three components to estimate this figure. The first component is the 5 million $m^3$ of sand trapped along Haifa Port's main breakwater — an average of 66,000 $m^3$/yr. The second is sand that managed to bypass the breakwater and drift eastward into Haifa Bay, estimated at 8000–10,000 $m^3$/yr by DHI researchers (2000). The third component is offshore sand transport generated by wind-induced currents (Kit and Sladkevich, 2001; Kunitsa, 2000; Kunitsa et al., 2005), which are not captured by LST measurements taken from wave induced currents in the breaker zone. The wind directional distribution was obtained by Israeli Oceanographic and Limnology Research (IOLR) and is presented in Fig. 10. The northerly transport due to wind-induced currents occurs between 10–30 m depth, and may result in an additional 10,000–20,000 $m^3$/yr of sand into Haifa Bay. Thus, average annual accumulation during this period can be estimated at 80,000–90,000 $m^3$, similar to the average for the past 7900–8500 years.

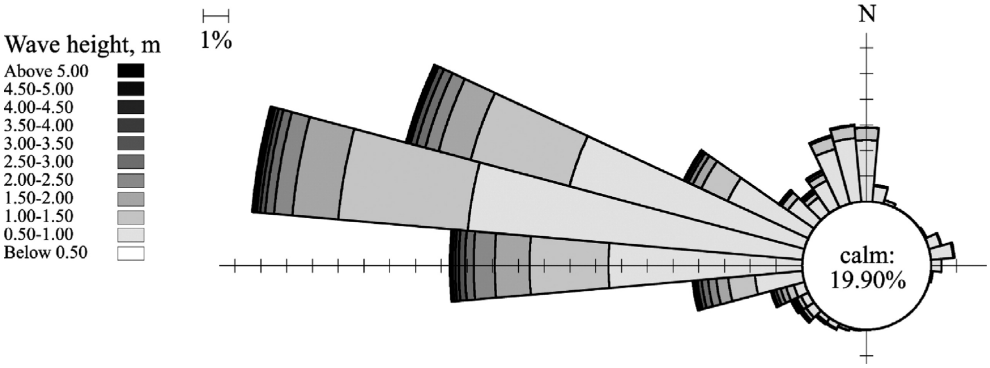


Fig. 9. Directional wave distribution measured using directional buoy in Haifa area during 1994–2005.

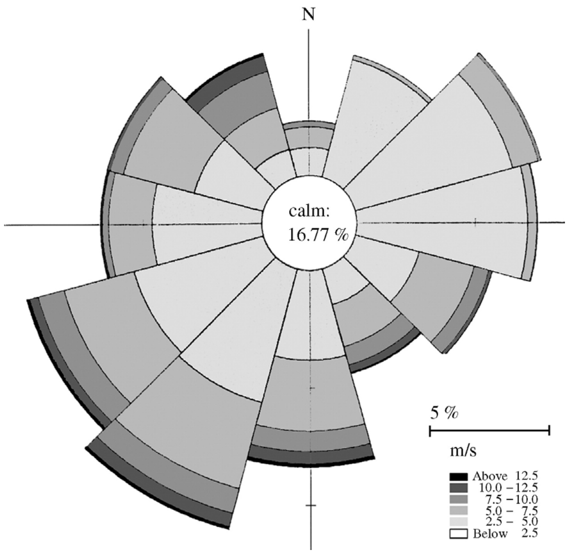


Fig. 10. Directional wind distribution measured at Hadera coal unloading terminal during 1994–1998.

Therefore, while we cannot exclude the possibility of substantial changes in volume and direction of sand transport during the past 8500 years, as suggested by Stanley (1978) and Stanley and Galili (1996), we can otherwise assume – with some reservations – that the characteristics of net LST along the coast of Israel have not changed significantly throughout the period, including the last 75 years.

## 5. Conclusions

The assessment of LST presented in this research is based on the huge amount of Nile-derived quartz sand deposited in the Haifa Bay and Zevulun Plain, sand accumulation near the Haifa Port breakwater after its construction and sand transport calculations derived from detailed, accurate, directional wave data.

Evaluating calculated values over the long term, it is suggested that the characteristics of net LST along the coast of Israel have not changed significantly during the past 7900–8500 years.

This research refers to the average, annual net LST. It is well-known that longshore currents (and the sand transported by them) are active in both directions, subject to the wave climate (wave directions) along the southeastern Mediterranean coast. It is further known that in a relatively narrow band within 100 m from the shore, net transport runs to the south (Perlin and Kit, 2002: their Fig. 3). Therefore, one may find clay and other sediments that are not from Nile sources. Nevertheless, global net transport across the entire bottom profile (a band about 500 m wide) affected by all breaking waves, runs to the north.

The near total blockage of Nile River sand caused by Aswan High Dam forced the currents to take sand instead from the Nile Delta coast, and led to significant erosion in this area. The sand taken from the Delta coast, however, has compensated for the reduction of Nile River sand and prevented sand shortages further up the Nile littoral cell coastline. Rohrlich and Goldsmith (1984), however, assert that that within approximately 400 years, the reduction will ultimately affect the Israeli coast.

The present study indicates that on the global regional scale during the 20th century there have no been changes in the LST processes along the coast of Israel. This is based primarily on considerable volume of sand that has accumulated along the Haifa Port breakwater during the past 75 years. The annual accumulation has not changed throughout the period, despite the construction of significant marine structures such as Ashdod Port, Herzliya Marina, and Ashkelon and Hadera cooling basins from the 1960s onward.

This assertion is supported by findings from morphological analysis of the changing coastline of Haifa Bay in the 20th century. These show that until construction of Haifa Port, sandy beaches of Haifa Bay extended westward until port's main breakwater was built. Since that time, only small morphological changes have been observed at the beaches, stemming mainly from seasonally variable impacts. Had the port of Haifa not been built, the sandy beaches of the bay would have probably continued the expansion they began 4000 years ago (Zviely, 2006).

Man-made disturbances along the Israeli coast during the 20th century (ports, marinas, detached breakwaters, sand mining) have undoubtedly altered coastal morphology and affected the fragile environment. Yet, their impacts appear largely contained and localized — and there is no indication that they have affected sand transport processes on the inner sandy continental shelf of Israel between 0 to 30 m in depth. The effects of the most significant project in the cell – the High Dam at Aswan – have not yet reached the Israeli coast.

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