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ORIGINAL

Shoreline migration and beach-nearshore sand balance over the last 200 years in Haifa Bay (SE Mediterranean)

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Abstract Several researchers have investigated morphological changes on the south-eastern Mediterranean coast during the late Holocene. However, very few of these studies include quantitative data covering the last 200 years. In this study, topographical maps, nautical charts and aerial photographs are used to estimate the shoreline migrations and beach–nearshore sand balance over the last 200 years in Haifa Bay, Israel, the northernmost final depositional sink of the Nile littoral cell. The findings reflect two main periods. During the first period, between 1799 and 1928, human intervention along the bay's coast was negligible, a significant coastal expansion of ~50 to 150 m (averages of 0.4–1.2 m/year) was measured, and sand accumulation was estimated at ~70,000 m^3 annually in the beach–nearshore area. A dramatic change in the sedimentological pattern was observed during the second period, between 1928 and 2006, following the completion of Haifa Port's main breakwater (1929–1933). During this period, most of the bay's coast was in a steady state, with seasonal fluctuations of less than about ±20 m, and slight erosion of ~7,000 m^3 annually. These findings are consistent with previous studies which conclude that from approximately 4,000 years ago until the construction of Haifa Port, sea level remained relatively stable, and a continuous accumulation of Nile-derived sand dried up the Zevulun Plain and shifted the Haifa Bay shoreline westwards to its present location. This long-term trend ceased after completion of the Haifa Port main breakwater.

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Introduction

Coastal erosion can damage, even devastate communities, physical structures and ecosystems. Therefore, the study of erosion is critical to managing coastal resources and planning coastal engineering projects. Numerous geological, biological and archaeological investigations have studied morphological changes on the Mediterranean coast during the late Holocene. Yet, studies covering several millennia cannot adequately capture the specific impact of the last 200 years, when human activities have had their most dramatic effects on the environment.

In fact, few longer-term studies include specific quantitative data covering the post-industrial period (Schwarzer et al. 2003; Ogden 2004; Robinson 2004; Plaziat and Augustinus 2004; Forbes et al. 2004), especially in the south-eastern Mediterranean (Sestini 1976; Frihy and Khafagy 1991). During the twentieth century, however, a significant rise in sea level (Bindoff et al. 2007) and increasing human intervention have caused substantial morphological changes along the Nile delta coast (Frihy 1988; Smith and Abdel-Kader 1988; Blodget et al. 1991; Frihy and Komar 1993;

Frihy et al. 1994, 1998; Fanos 1995; El-Raey et al. 1999; El-Asmar and White 2002), the northern Sinai coast (Klein 1986; Frihy and Lotfy 1997) and the Mediterranean coast of Israel (Nir 1976, 1982a, 1982b; Rosen DS 1992, 1998; Golik et al. 1996; Shoshany et al. 1996; Golik and Rosen 1999; Zviely 2000, 2006; Klein and Zviely 2001; Zviely and Klein 2003; Klein and Lichter 2006).

Within this context, the aim of this paper is to derive quantitative data gathered from topographical maps, nautical charts and aerial photographs covering the past 200 years, in order to estimate the historic shoreline migrations and beach–nearshore sand balance in Haifa Bay, Israel (Fig. 1).

Study area

Sedimentological and geomorphological setting

Haifa Bay, in northern Israel, constitutes the northernmost depositional sink of the Nile littoral cell (Inman and Jenkins 1984; Almagor et al. 2000; Zviely et al. 2007). The sediments are composed largely of fine quartz sand (Nir 1980; Zviely 2006; Zviely et al. 2006) transported from the Nile delta (Egypt) by longshore currents, generated by breaking waves from the southwest (Emery and Neev 1960; Goldsmith and Golik 1980; Carmel et al. 1985; Perlin and Kit 1999; Zviely et al. 2007). Haifa Bay is bordered by the Carmel headland to the south, the Zevulun Plain to the east, and the Akko (Acre) promontory to the north (Fig. 2). Two rivers traverse the Zevulun Plain, the Na'aman in the north and the Qishon in the south. Both transport large amounts of silt and clay to the bay's offshore (Sandler and Herut 2000).

Morphologically and sedimentologically, Haifa Bay (0–30 m deep) consists of three sub-areas: a fine sand area (Nir 1980; Zviely 2006; Zviely et al. 2007), submerged calcareous sandstone (locally termed kurkar) ridges (Bakler 1976; Hall 1976), and a deeper area of silty sand (Zviely et al. 2006). The bay's 18-km coastline is sandy and slightly curved in the eastern part, and artificially built in the south at

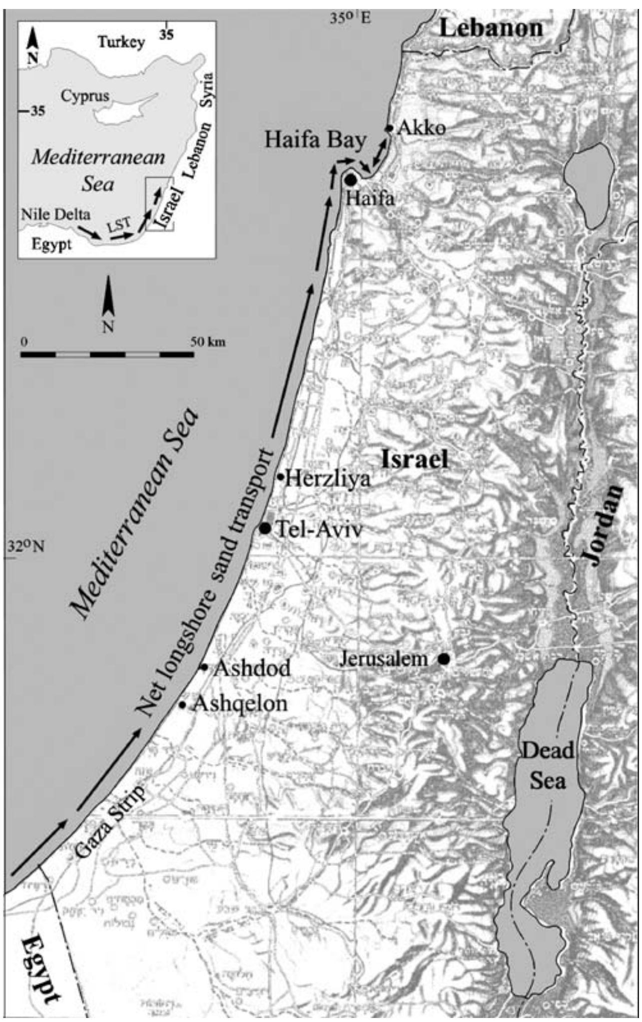

Fig. 1 Locality map of the study area (*LST* longshore sand transport)

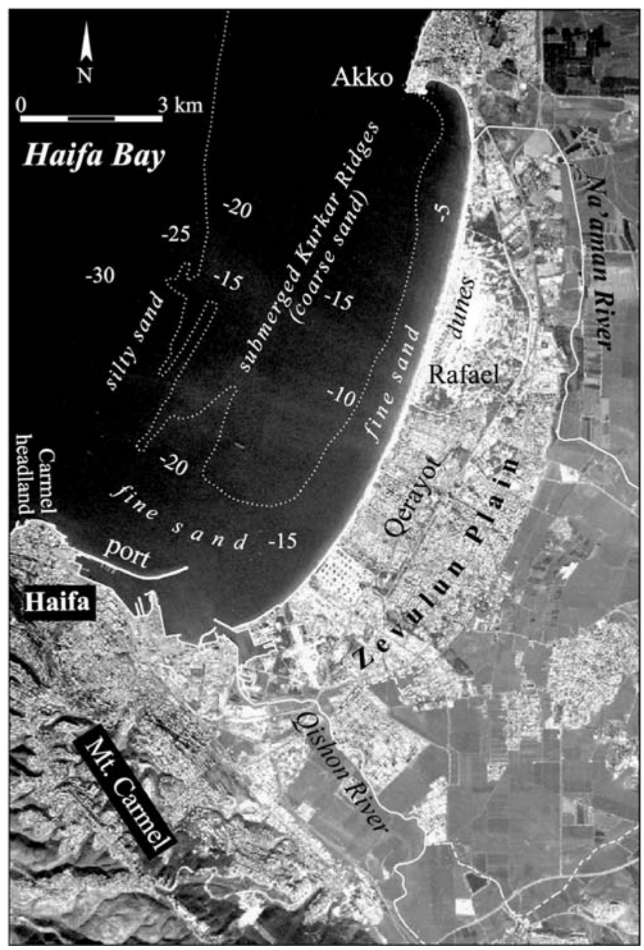

Fig. 2 Main morphological features and urban areas in Haifa Bay and the Zevulun Plain (depth contours in metres; photograph modified after NASA, Earth Sciences & Image Analysis, Johnson Space Center, Houston, TX, astronaut photography of earth, mission ISS001, roll ESC frame 5982, date 28 December 2001, time 08:43:21)

Haifa Seaport. On the Zevulun Plain are situated both Israel's foremost industrial zone and a dense, residential zone with a population exceeding half a million (Fig. 3). These industrial and residential activities compound the necessity of adequate management of the coastal zone.

Shoreline migrations during the Holocene

During the early Holocene, and for the first time since the Last Glacial Maximum (about 18,000 years ago), the Mediterranean Sea invaded Haifa Bay (Zviely 2006; Zviely et al. 2006). The sea continued to rise and, between 8,000 and 7,150 cal. years B.P., it crossed the bay's present-day shoreline and began to flood the Zevulun Plain. By about 4,000 cal. years B.P., the rising sea reached its present-day level, covering the Zevulun Plain. At that time, the bay reached its easternmost position, up to 3 km further inland than that of the present day on the central Zevulun Plain, and up to 4.8 km further inland in its south-eastern part (Zviely 2006; Zviely et al. 2006).

Since then, steady deposition of Nile-derived sand (Zviely et al. 2007) and a relatively stable sea level (changes of less than ±1 m; Galili et al. 1988, 2005; Nir 1997; Sivan et al. 2001, 2004; Galili 2004) has driven the shoreline seawards to its present location.

Longshore sand transport during the Holocene

During the last 7,900–8,500 years, the sand bypassing the Carmel headland barrier was transported unimpeded to the southern Haifa Bay coast by wave-induced longshore currents. The total amount of sand deposited in the Bay and on the Zevulun Plain during this period was estimated at an annual average of 80,000–90,000 m^3 (Zviely 2006; Zviely et al. 2007). However, the construction of the Haifa Port main breakwater (1929–1933) created a large trap for migrating sand, and a sandbar began to accumulate along its outer side (Civil and Marine Engineering Co. 1960; Golik et al. 1999).

In the early 1960s, the Haifa Port Authority dredged $\sim 1.3 \times 10^6$ m^3 of sand from the sandbar (Civil and Marine Engineering Co. 1960) for construction of the "western quay". Since this massive dredging, the sandbar has continued to accumulate sand carried by wave-induced currents (Zviely et al. 2007). Recently (2005–2007), an additional $\sim 2.5 \times 10^6$ m^3 of sand has been dredged again from the sandbar, and used for the construction of the new "Carmel Port phase A quay". The total amount of sand trapped between 1929 and 2004 has been estimated at $\sim 5 \times 10^6$ m^3, with an average of 66,000 m^3 annually (Zviely 2006; Zviely et al. 2007). Only small amounts of sand (8,000–10,000 m^3/year) bypassed the main breakwater head during this period, drifting eastwards along the bay coast.

Materials and methods

Selection of maps and aerial photographs

The current study of Haifa Bay's shoreline is based mainly on topographic maps and nautical charts from the last two centuries, collected from Israeli and European archives. Of these, eleven maps at scales of 1:10,000 to 1:100,000 were selected. Maps through the 1930s were based on geodetic field surveys; maps after the 1930s were based on aerial photographs. Five of the maps were surveyed prior to the construction of Haifa Port in 1929 (Table 1); the remainder were surveyed from 1955 to 1998 (Table 2). Digital vector maps of the Haifa Bay shoreline based on high-resolution Orthophoto represent the recent years 1994 and 2006. In addition, a series of aerial photographs from 1945 to 1995 were assessed. The northern series focuses on the coast between the Na'aman River outlet and the south-eastern walls of the old city of Akko. The southern series, first examined by Golik et al. (1999), covers the coast from the Qishon River outlet to the Qerayot coastal sector. For security reasons, no aerial photographs were available for the Rafael coastal sector.

Fig. 3 Panoramic view of the Haifa Bay area and the port (the photograph was taken from the lower part of Mount Carmel towards the east; contributed by Mr. A. Dror, 13 March 2004)

Table 1 Characteristics of the maps and charts selected for the current study

Map name	Map/sheet number	Year of survey	Map reference	Scale
Acre, Nazareth, Le Jourdain	$\mathrm{F}^{\mathrm{lle}}$ 46	1799	Jacotin (1818)	1:100,000
Bay of Acre	1585	1862	Mansell et al. (1863)	1:45,400
Acre	15–25	1929–1930	Survey of Palestine (1933)	1:20,000
Haifa	14–25	1927–1928	Survey of Palestine (1932b)	1:20,000
Carmel	14–24	1927	Survey of Palestine (1932a)	1:20,000
Akko	15–25	1955	Israel Department of Surveys (1959)	1:20,000
Haifa-East	14–25	1956	Israel Department of Surveys (1958b)	1:20,000
Haifa-West	14–24	1956–1957	Israel Department of Surveys (1958a)	1:20,000
Topo-cadastre	155–255	1966	Israel Department of Surveys (1968b)	1:10,000
Topo-cadastre	155–250	1966	Israel Department of Surveys (1970)	1:10,000
Hefa (Haifa)	1585	1998	UK Hydrographic Office (1998)	1:20,000

Reliability of historical maps

Geographical–historical studies of Israel during the nineteenth century are based on maps representing the physical and human environment of that time period. The professional French and British surveyors who produced many of these maps had a well-established record of competency and accuracy. During that time, great progress was made in the production of nautical charts, and much of their data remain in use today. Furthermore, these cartographers' instruments and methods, as well as their general objectivity were controlled for possible biases.

Jacotin maps

The Jacotin maps are the scholarly products of Napoleon Bonaparte's campaign in Egypt and Palestine (1798–1799; Godlewska 1988). Col. P. Jacotin was the senior surveyor responsible for Palestine during the Napoleonic invasion. The final mapping of his surveys was based on astronomical fixing of key points in Egypt, and possibly in Syria.

Godlewska (1988, p. 17) described the instruments used by Jacotin for his astronomical observations as the best available at the time in France. No extensive triangulation system was laid in Egypt; this may also have been so in Syria. The basic field data were procured by using plane-table drawings on which astronomical points were pre-marked, without the aid of a compass. These points were derived either from direct observation or (in several places) by triangulation. The points were used as basis for drawing "rays" to two to four (preferably) permanent features, angled at 60–90°. Then, a baseline of 1 km was measured in the direction of the next astronomical control point. By using a station at the end of this baseline, several rays were drawn which intersected the other rays. Additional points were then established and intersecting rays drawn to reach the next astronomic point. At that point, measurements were averaged, and a plane-table drawing map was positioned on the overall grid.

Table 2 Geometric registration results of the maps and charts before and after the construction of Haifa Port

Map reference	Before port construction					After port construction					
	Jacotin (1818)	Mansell et al. (1863)	Survey of Palestine (1933)	Survey of Palestine (1932b)	Survey of Palestine (1932a)	Israel Department of Surveys (1959)					UK Hydrographic Office (1998)
Scanning resolution (dpi)	400	400	300	300	300	300	300	300	300	300	400
Pixel size (m)	3.50	3.50	3.90	4.25	4.20	4.25	4.15	4.15	2.10	2.10	2.92
Number of control points	10	10	19	12	20	24	36	24	34	35	16
Standard deviation X (m)	6.36	6.36	3.04	4.63	5.90	2.43	3.45	4.54	2.12	1.57	2.65
Standard deviation Y (m)	6.52	6.52	2.39	3.16	2.87	3.50	3.80	4.46	1.65	1.31	1.70
Standard deviation XY (m)	7.11	7.11	2.74	3.82	4.54	3.80	3.57	5.00	2.08	1.71	2.55
X_{rms} error (m)	9.41	9.41	4.44	7.97	8.81	4.64	6.39	6.96	3.71	3.26	4.66
Y_{rms} error (m)	11.01	11.01	4.29	4.99	4.93	4.87	4.94	6.71	2.84	1.99	3.02
XY_{rms} error (m)	14.48	14.48	6.17	9.41	10.10	6.73	8.80	9.67	4.67	3.82	5.55
CM error (m)	11.37	11.37	4.62	7.89	6.35	4.48	4.32	5.64	2.32	2.00	4.23

A few maps of Egypt were also compiled during the campaign. After the defeat of the French army, the field data were brought to France, and the cartography was completed under Jacotin's supervision. The maps were published from 1809 to 1830 as part of a monumental set of books, the "Description de l'Égypte". Volume 8 of the 2nd edition contains an atlas of 47 maps at a scale of 1:100,000, edited by Jacotin (1818). While some historical geographers question the accuracy of Jacotin's maps (Amiran 1944; Karmon 1960; Hopkins 1968; Godlewska 1988), his survey of northern Haifa Bay (included in map no. 46, entitled Acre, Nazareth, Le Jourdain; Fig. 4) received particular attention, reflecting the French Army's focused interest in the region of Akko (Acre). In Haifa Bay, French surveyors had the tools, the time, and a clear mandate to execute meticulously and comprehensively (Zviely 2006). Their baseline was laid and measured on the plain of Akko. The survey net extends from the Valley of Esaraelon (Jezreel) up to southern Lebanon, including Haifa Bay and Mount Carmel. Accordingly, their work on Haifa Bay seems sufficiently reliable for the purpose of the current study.

Mansell charts

The Comm. Mansell nautical charts represent high-quality products of the Royal Navy's 1862 hydrographic survey in Palestine. This carefully organized and systematic survey (see Rosen B 1992; Goren 2002) was part of charting the eastern Mediterranean, and surveying strategic anchorages and harbours. The mission in Palestine used the survey steamship HMS *Firefly*, and was equipped with the best instruments available at the time (Ritchie 1967). The baseline was measured by chain onshore, and then the latitude and longitude of so-called observatory stations were charted: Acre (Akko), Atlit and Jaffa (Yafo). The latitude of each station was determined by the meridian altitude of the sun

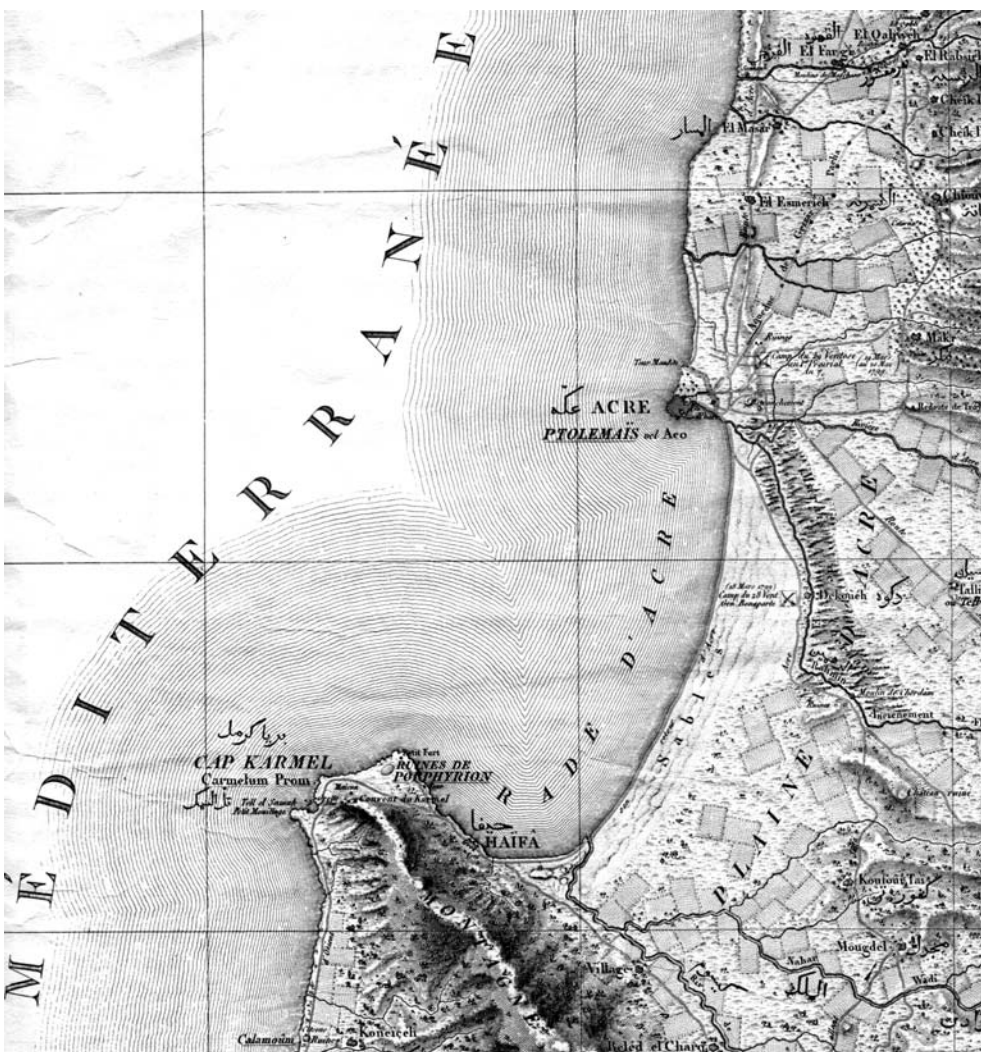

Fig. 4 Haifa Bay area in map F[lle] 46 (Acre, Nazareth, Le Jourdain), surveyed under the direction of Col. P. Jacotin in 1799, 1:100,000-scale (Jewish National and University Library, E. Laor Cartographic Collection, Hebrew University of Jerusalem)

and stars, the longitude by means of the sun and a chronometer; if needed, an artificial horizon was used. Then, the true bearing (exact celestial direction) of the baseline was determined by celestial observation combined with compass calibration. From the observatory stations, angles were measured by theodolite or horizontal sextant to all the important points. Later, the bathymetry was sounded, and the shoreline triangulated by foot. The survey yielded a new version of chart no. 1585, Bay of Acre, at a scale of 1:45,400 (Fig. 5), covering the area from the Carmel coast to Akko (Mansell et al. 1863). Another chart, no. 1242, includes two sections: the area of Akko (Acre or Akka), at a scale of 1:18,200, and the area of Haifa (Kaifa), at a scale of 1:22,800 (Bedford and Mansell 1863). Analysis of the charts shows that the shoreline was triangulated every 100 to 200 m (Zviely 2006). All indications are that the charts have been prepared in a professional manner.

Survey of Palestine maps

Due to its strategic importance, the British government had a vested interest in preparing the best possible survey of Haifa Bay. Between 1921 and 1928, they established a new triangulation net in Palestine, and published 1:10,000-scale cadastre maps which served as base for 1:20,000-scale topographical maps published in 1947 (Elster et al. 1956; Gavish 2005). Three maps cover the Haifa Bay area: Acre (Survey of Palestine 1933), Carmel (Sheet 14–24; Survey of Palestine 1932a), and Haifa (Sheet 14–15; Survey of Palestine 1932b). These maps are still used today.

Israel department of surveys maps

In its early years, the Israel Department of Surveys simply updated the British maps. Later, it conducted new surveys and

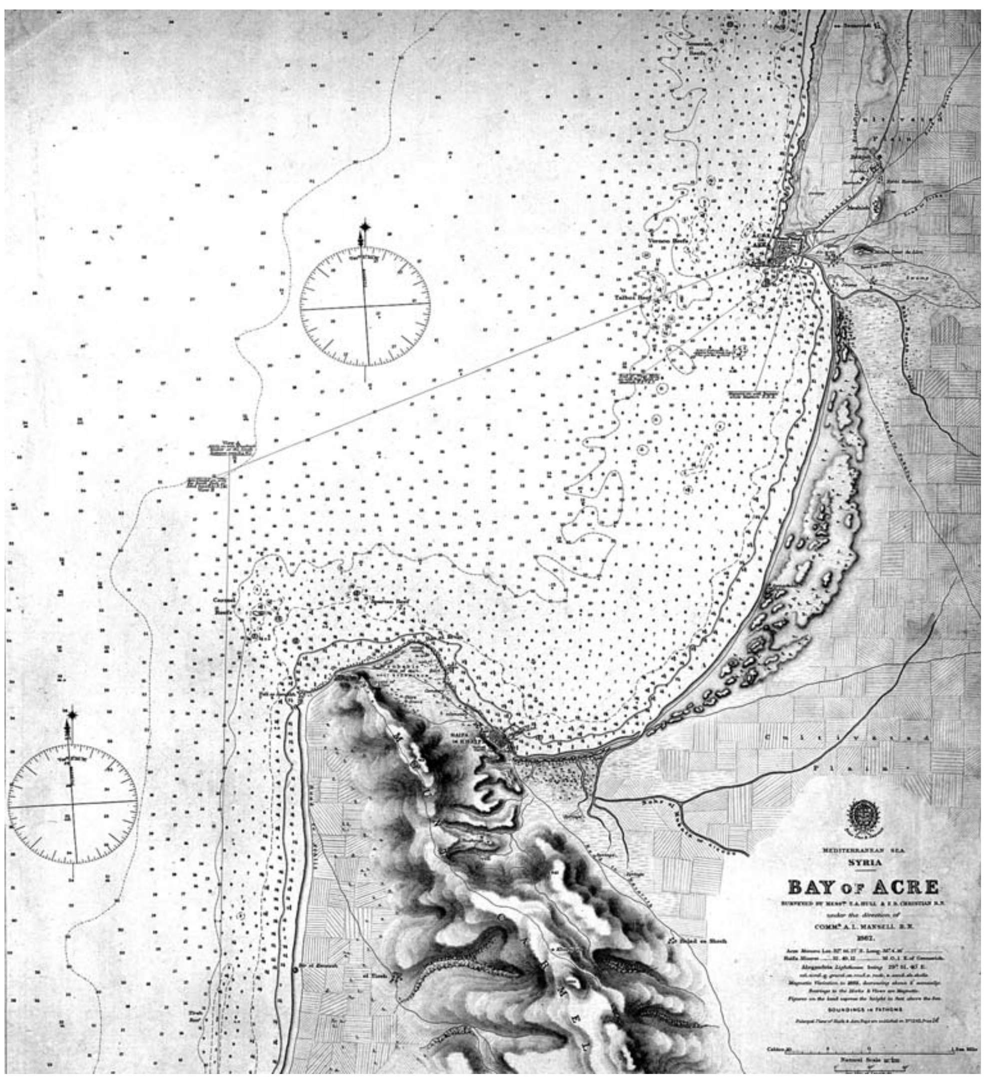

Fig. 5 Haifa Bay area in chart 1585 (Bay of Acre), surveyed by Lieut. T.A. Hull and Lieut. F.B. Christian, under the direction of Comm. A.L. Mansell in 1862, 1:45, 400-scale (soundings in fathoms; Jewish National and University Library, E. Laor Cartographic Collection, Hebrew University of Jerusalem)

published a set of topographic maps of 1:20,000-scale, using aerial photographs mainly of the coastal zone (Elster et al. 1956). Three maps cover the Haifa Bay area: Akko (Israel Department of Surveys 1959), Haifa-East (Israel Department of Surveys 1958b) and Haifa-West (Israel Department of Surveys 1958a). In the late 1960s, an additional topographical map of 1:50,000-scale (Israel Department of Surveys 1968a), and two cadastral 1:10,000 supplements (Israel Department of Surveys 1968b, 1970) were published.

UK hydrographic office charts

The United Kingdom Hydrographic Office (UKHO) conducted its last surveys of Israel's coast during 1930–1932. The resulting charts have been repeatedly updated by the Admiralty; the newest version of chart no. 1585 currently available dates from the late 1990s (UK Hydrographic Office 1998). The chart of the northern coast of Israel, Hefa (Haifa) and vicinity, is at a scale of 1:70,000, and the chart of Haifa Bay, Hefa (Haifa) at a scale of 1:20,000. The hydrographic data were derived from the best available sources, including old charts of Mansell et al. (1863) and Edgell and Officers HM Surveying Ship Endeavour (1931), depth surveys by the Israeli Ports Authority, and other Israeli charts. The shoreline was charted using corrected satellite imagery.

Mapping of shoreline position

Several advanced methods have been developed for monitoring coastline position, including geodesy, photogrametry, remote sensing, image processing, cartography and GIS (Dolan et al. 1978, 1980; Leatherman 1983; Smith and Zarillo 1990; Morton 1991; Anders and Byrnes 1991; Crowell et al. 1991; Shoshany and Degani 1992; Thieler and Danforth 1994; Morton and Speed 1998; Gorman et al. 1998; Pajak and Leatherman 2002). The methodology used in the current study is based on comparison mapping, elaborated by Shoshany and Degani (1992), as described by Zviely (2000), Klein and Zviely (2001) and Zviely and Klein (2004).

The maps were scanned at a resolution of 300–400 dpi; aerial photographs were scanned at 600 dpi, in order to preserve a surface geometric separation higher than 1 m/pixel. Geometric registration of analogue scenes was performed in two steps. For a start, the Survey of Palestine maps were geo-referenced according to the map's coordinates. Then, the other scenes were geo-referenced by means of selected ground control points from the Survey of Palestine maps. The scanned maps, aerial photographs and corresponding ground control points were imported into photogrametric mapping software (Microstation Descartes 2000). By applying a polynomial fourth-order transformation module (projective) to the raw scene files, the maps and aerial photographs were warped into the Cassini–Soldner projection and Clarke 1880 modified geodetic datum (locally termed Israel old datum). After geometric corrections, the warped scenes of the shoreline's position were mapped using vector-mapping software (Microstation Java 2000). The shoreline could then be ascertained as a mapped vector object by observing the contrasting grey-scale shades in the images. The merging of the digital vector files produced a visual timeline illustrating the trends of Haifa Bay coastal migration over the last 200 years.

Each stage of the mapping process contributed a horizontal error in the accuracy of the shoreline position, producing a maximum cumulative measurement error (CM) of the maps. The CM of the historical maps is expressed as follows (Haimi 1998; Table 2):

$$\mathrm{CM} = 2(D+R)\Big/\sqrt{N}$$

where D is the error of shoreline location in the vector mapping process, caused by low quality of the analogue maps and aerial photographs (defined as twice the maximum scene pixel length size after geometric registration, as obvious exaggeration), R the error due to the geometric registration process (defined as twice the maximum of XY_{rms}, as obvious exaggeration; rms, root mean square), and N the number of average ground control points on each scene.

The CM of the aerial photographs is expressed as follows (Table 3):

$$\mathrm{CM} = 2(D+R+I)\Big/\sqrt{N}$$

where I is the error due to shoreline identification in aerial photographs (defined as twice the worst resolution in the scanning process, as obvious exaggeration).

Measurements of shoreline migrations

For the years preceding the construction of Haifa Port (1929–1933), Haifa Bay's coastline was subdivided morphologically into five distinct sectors (Fig. 6a): the Haifa coast (Fig. 6b), Qishon River coast (Fig. 6c), Qerayot coast (Fig. 6d), Rafael coast (Fig. 7a) and Akko coast (Fig. 7b).

Shoreline migrations along Haifa Bay during the last 200 years were then measured for each sector, using virtual polygons. Each polygon was delineated by its shoreline and, on the opposite side, by a fixed baseline (Fig. 8). The choice of baseline was based on baseline permanency and unequivocal identification. Two short perpendicular lines then connected the shoreline to each baseline (Fig. 8, lines *a* and *b*). These connecting lines varied with the relative position of the shoreline to the fixed baseline. Subsequently, the area of each polygon was assessed by applying a planimetric measuring program (measure area) of Microstation Java (2000). This was repeated for each historical and contemporary data source. In a final step, the

Table 3 Characteristics of the aerial photographs which cover the north-eastern part of the bay, and the geometric registration results

Date	26 Nov. 1945	Sep. 1956	15 Jan. 1966	29 Jun. 1974	16 May 1980	4 Nov. 1995
Flight	680 PS.19	MM11	MM107	MM399	MM654	ML501
Time	Unknown	12:42	13:02	13:10	14:26	10:22
Photograph	6158	8080	7446	9615	2604	3247
Height (m)	3,000	2,470	3,110	2,350	2,260	1,840
Scanning resolution (dpi)	600	600	600	600	600	600
Pixel size (m)	2.26	2.13	1.33	1.40	1.36	1.27
Number of control points	20	17	19	18	17	17
Standard deviation X (m)	0.83	1.13	0.87	0.87	0.89	0.68
Standard deviation Y (m)	1.24	0.87	0.54	0.93	0.75	0.62
Standard deviation XY (m)	1.49	0.78	0.79	1.12	0.87	0.75
X_{rms} error (m)	1.38	0.90	0.78	0.97	0.65	0.62
Y_{rms} error (m)	2.04	1.76	1.30	1.75	1.37	1.68
XY_{rms} error (m)	2.72	1.22	1.91	1.74	1.57	1.17
CM error (m)	3.40	2.14	2.31	2.47	2.08	2.50

area of each polygon was subdivided into the length of its shoreline, resulting in what was termed the “mean width” (MW; Fig. 9) of each polygon relative to its baseline. Changes in this parameter measured over time reflect fluctuations in the distance of the polygon’s shoreline relative to its baseline. The difference in MW between two selected years, relative to their common baseline, is expressed as follows:

$$\mathrm{MW} = S1 - S2/[(L1 + L2)/2]$$

where S is the area of the polygon for a given year, and L the corresponding length of shoreline (Fig. 8).

Estimating beach–nearshore sand balance

Twelve nearshore bathymetry profiles were measured in 2002. Depths of 0–5 m below mean sea level were measured perpendicular to the shoreline, along straight cross sections extending up to 350±50 m (Fig. 9).

Assuming that the beach–nearshore bottom profiles along Haifa Bay’s sandy coasts have not change significantly over the last 200 years, shoreline migration measurements can then be used to estimate the sand balance for the study period, based on two separate volume calculations (repeated for each sandy coastal sector): (1) the difference in MW (the beach), accounting for the variation of the land extension only, and (2) the variation of the nearshore portion of the bottom profile which extends from the swash zone to the position of closure depth (Birkemeier 1985; Kit and Pelinovsky 1998; Nicholls et al. 1998).

To calculate the beach sand balance (V_{B}), a representative profile was selected for each coastal sector. Subsequently, the cross section area (A) of each such profile was estimated (repeated for each coastal sector) by applying a planimetric measuring program (Microstation Java 2000). This is the area bordered by selected profiles (Fig. 9, profiles 1, 2), and limited offshore by the difference in MW between two selected years. Finally, the cross section area (A) was multiplied by the average shoreline length between two selected years, to obtain the beach sand balance (V_{B}). This volume can be expressed as

$$V_{\mathrm{B}} = A[(L1 + L2)/2]$$

which represents that part of annual sand transport leading to the buildup of the beach.

In the following step (repeated for each coastal sector), the average shoreline length between two selected years was multiplied by the difference in MW and by the closure depth (h_{l}), to obtain the total beach–nearshore sand balance (V_{T}). This volume can be expressed as follows:

$$V_{\mathrm{T}} = V_{\mathrm{B}} + V_{\mathrm{N}}$$

and

$$V_{\mathrm{T}} = \mathrm{MW}h_{\mathrm{l}}(L1 + L2)/2$$

where MW is the mean width shoreline migration, h_{l} the closure depth, $(L1+L2)/2$ the mean length of a given coastal sector, and V_{N} the nearshore sand balance for this sector (Fig. 9). Here, use of this equation is based on the above assumption that the shape of the bottom profiles has not change significantly during the last 200 years.

Results

Historic shoreline migrations

Haifa coastal sector

During the mid-nineteenth century, the Haifa coastal sector was characterized by a narrow and steep seashore, rocky shoreline and sandy foreshore. The shoreline extended

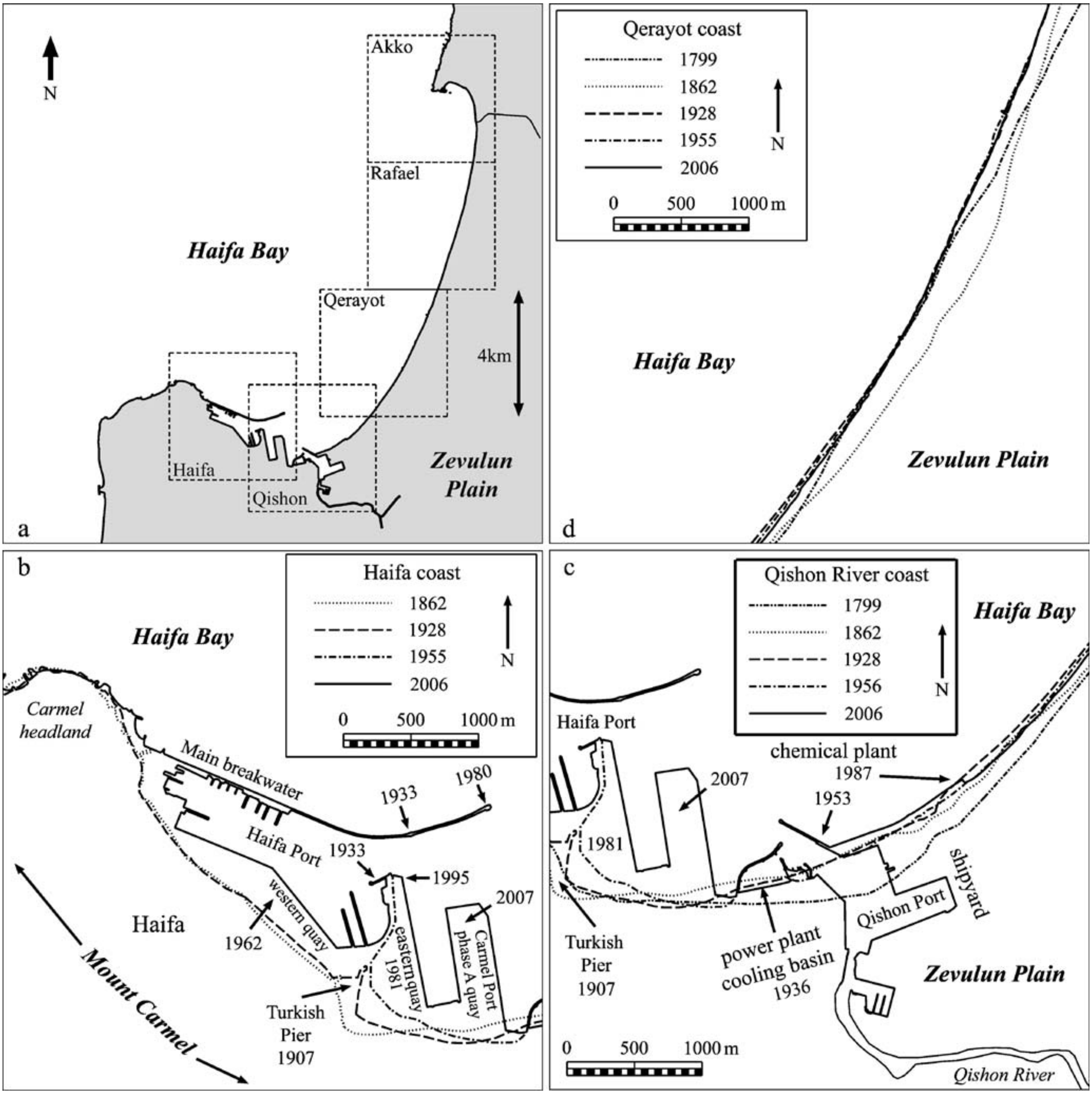

Fig. 6 Haifa Bay coastline changes between 1799 and 2006: **a** coastal sectors legend, **b** Haifa coastal sector, **c** Qishon coastal sector, **d** Qerayot coastal sector

3.4 km from the north-eastern tip of Carmel headland (Ras el Krum) to the old city walls (Bedford and Mansell 1863; Mansell et al. 1863; Fig. 10). The inland area, between the seashore and the Mount Carmel eastern slopes, was a flat plain covered with alluvial soil. At the beginning of the twentieth century, a 400-m-long northward pier was built by the Turkish authorities (Fig. 11). A few years after the construction of this pier (1905–1907), a sandbar accumulated around the pier, and dredging was needed along its eastern side (Edgell and Officers HM Surveying Ship Endeavour 1930). Between 1929 and 1933, Haifa Port was built in the south-western part of the bay, thereby artificially changing its coast (Figs. 6b and 12).

Qishon river coastal sector

At the end of the nineteenth century, the Qishon River coastal sector extended 4.4 km, from Haifa's old city walls to ~1.3 km northeast of the historical Qishon River outlet. It was characterized by a flat and relatively wide (~80 m)

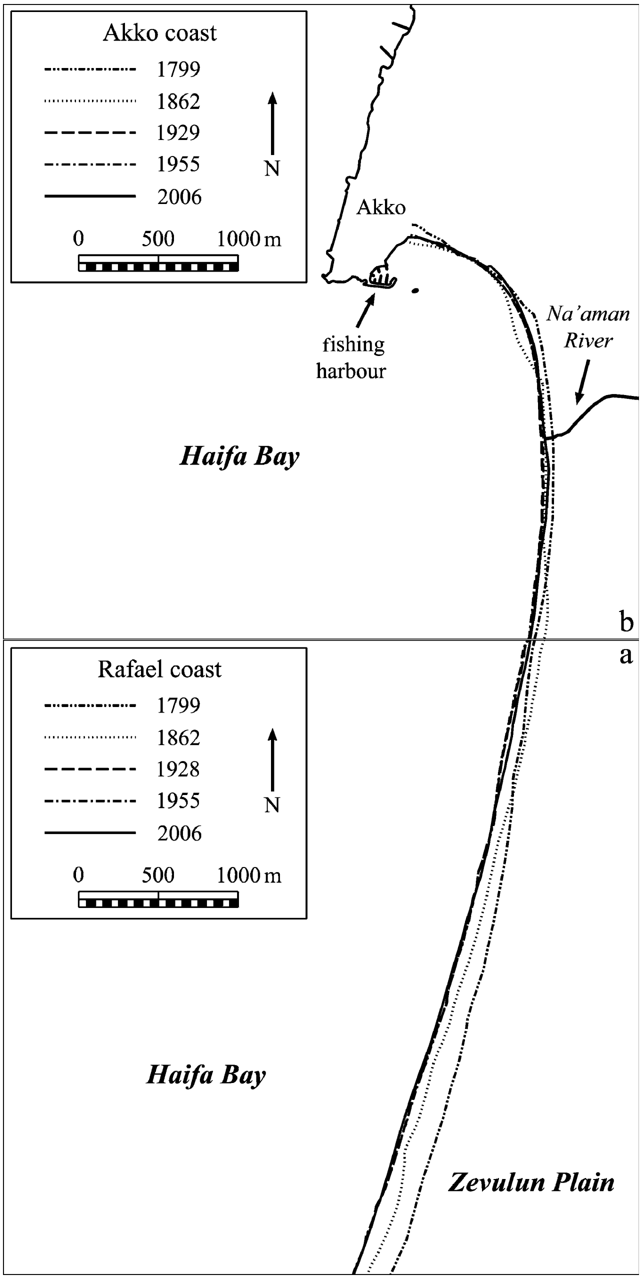

Fig. 7 Haifa Bay coastline changes between 1799 and 2006: **a** Rafael coastal sector, **b** Akko coastal sector

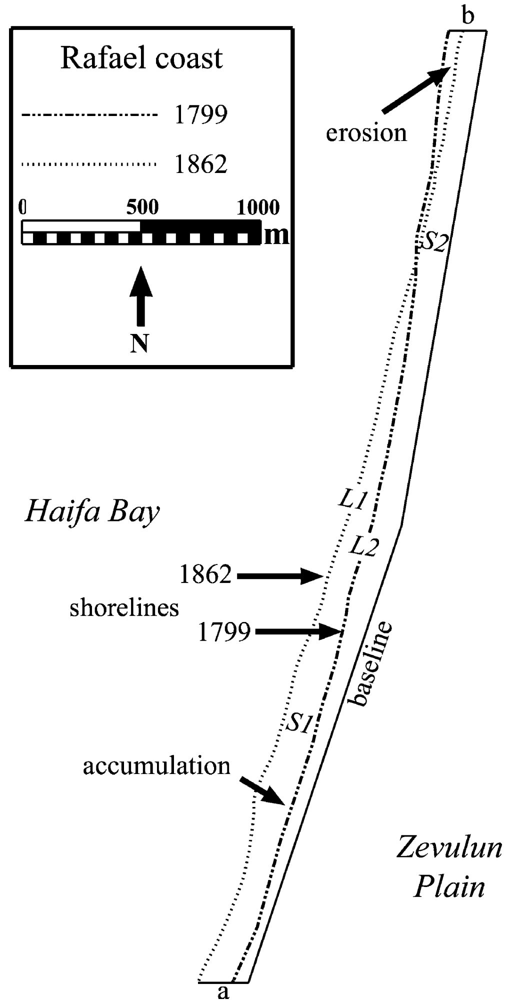

Fig. 8 Difference in shoreline position between 1799 and 1862 for the Rafael coastal sector, relative to its baseline

seashore, and backed by low dunes (less than 4 m in height; Guérin 1880) which separated the Qishon River's marshy area from the sandy seashore. The findings show that the coast widened by ~140 m during the period 1799–1862 (average of 2.2 m/year; Fig. 6c, Table 4, MW), and continued to expand slightly northwards from 1862 to 1928. Most of this expansion took place 300–1,600 m east of the Turkish Pier. In 1936, a cooling basin for the Haifa power plant was constructed ~1,100 m southwest of the natural Qishon River outlet (Fig. 13). Its main and lee breakwaters are 500 and 170 m long respectively. In 1952–1953, during the construction of Qishon Port, the river outlet was shifted artificially ~850 m southwest, towards the power plant's cooling basin. In addition, a 550-m-long groin was constructed on the north-eastern bank of the new river outlet, in order to stabilize Qishon Port's main entrance (Figs. 2 and 6c). The findings show that the Qishon River coast retreated slightly by 5 m during the period 1928–1955. Some years after the construction of the groin, erosion occurred on the adjacent north-eastern seashore. In order to prevent further erosion, a 600-m-long seawall was built in 1974. Almost immediately, however, erosion began to its northeast. Consequently, the seawall was extended in 1977 and 1987, until a 2-km-long shoreline was stabilized artificially.

Qerayot coastal sector

The Qerayot coastal sector extends 4.6 km, northeast to the Qishon coast (Fig. 14). In 1862, its sandy seashore was flat and relatively wide; the *Via Maris* road from Haifa to Akko

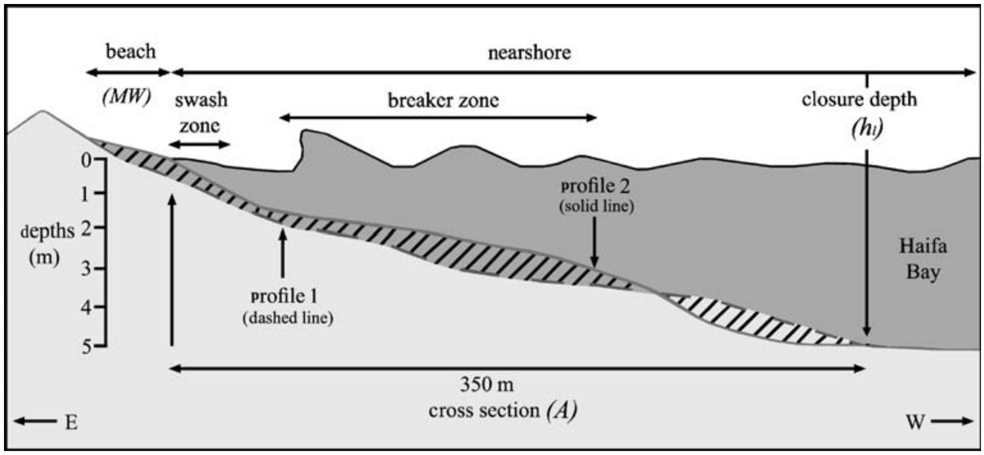

Fig. 9 Schematic Haifa Bay nearshore profiles in two selected years (profiles *1* and *2*), ending at the position of the closure depth

passed ~100 m east of the shoreline (Mansell et al. 1863). Relatively high dunes 5–11 m high stretched east of the old road (Guérin 1880; Edgell and Officers HM Surveying Ship Endeavour 1930). The findings show that the coast retreated by ~100 m (average of 1.6 m/year) during the period 1799–1862 but widened by ~180 m (average of 2.9 m/year) during 1862–1928 (Fig. 6d, Table 4, MW). After the construction of Haifa Port, the coast stabilized and, in the last 78 years, shoreline migration was limited to ±20 m per year on average (Fig. 15a). These shoreline migrations are within the magnitude of seasonal changes in Haifa Bay, and smaller than the mapping process cumulative measurement error (Table 2). Similar results were obtained by revising the data from the Golik et al. (1999) mapping study, which was based on aerial photographs taken from 1956–1995.

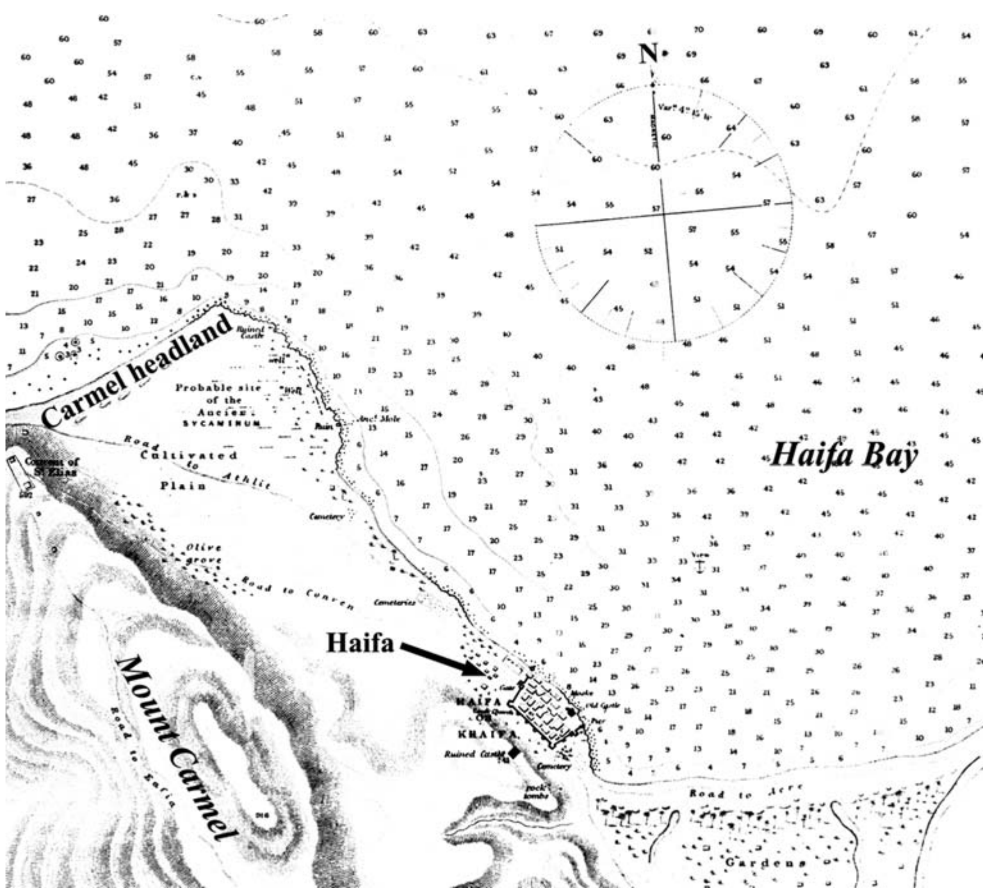

Fig. 10 The Haifa coast in chart 1242 (Haifa or Kaifa), surveyed by Lieut. F.D.G. Bedford, under the direction of Comm. A.L. Mansell in 1862, 1:22,800-scale (soundings in feet; Jewish National and University Library, E. Laor Cartographic Collection, Hebrew University of Jerusalem)

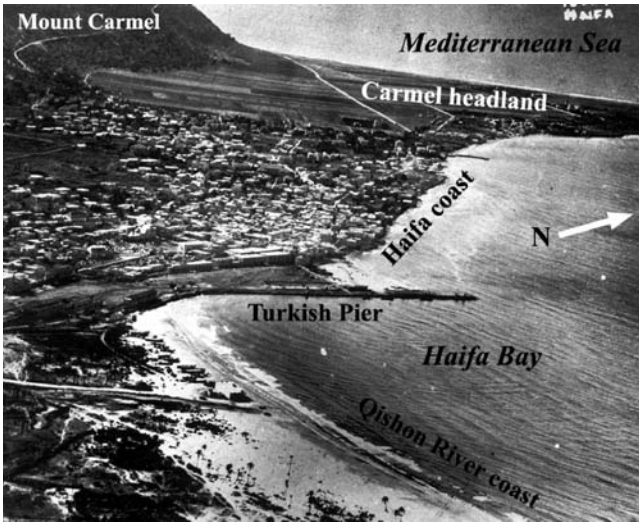

Fig. 11 Oblique aerial photograph of the Turkish Pier and the Haifa coastal sector, taken towards the west by the Royal Australian Air Force (image A-624, 1,000 feet; modified after Kedar 1991, p. 210)

Rafael coastal sector

The Rafael coastal sector extends 4.1 km, between the Qerayot and Akko coasts. Morphologically and sedimentologically, it resembles the Qerayot coast. The findings show that the Rafael coast widened by ~75 m (average of 1.2 m/year) during the period 1799–1862, and by an additional ~80 m (average of 1.3 m/year) during 1862–1928 (Fig. 7a, Table 4, MW). As in the case of the Qerayot sector, the coast stabilized after the construction of Haifa Port; in the last 78 years, shoreline migration was less than ±20 m (Fig. 15b).

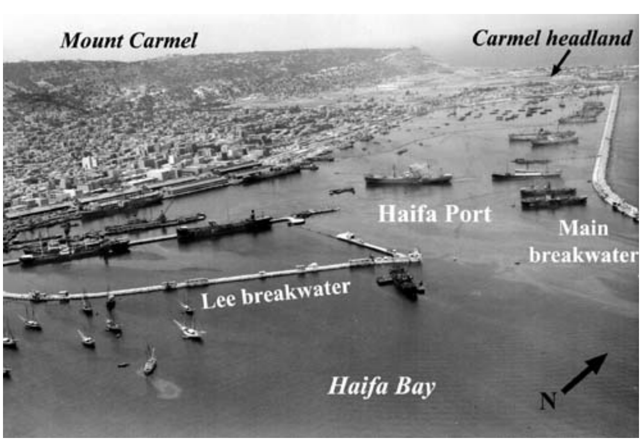

Fig. 12 Aerial photograph of Haifa Port and the city of Haifa, taken on 1 September 1947 towards the northwest by Mr. K. Zoltan (national photographs collection, Government Press Office, Prime Minister's office branch, Jerusalem, image code D820-010)

Table 4 Shoreline migration measurements and beach–nearshore sand balance estimates, over the last 200 years in various Haifa Bay coastal sectors

Year/period	Qishon River	Qerayot	Rafael	Akko
Shoreline length (m)				
1799	4,385	4,621	4,108	3,013
1862	4,194	4,592	4,172	2,971
1928	4,112	4,604	4,183	2,956
1955	5,037	4,615	4,172	2,958
1966	Built-up area	4,671	4,173	3,058
1994		4,608	4,227	3,038
2006		4,606	4,160	2,995
Difference in beach mean width (shoreline migration; MW, m)[a]				
1799–1862	141	−102	74	42
1862–1928	9	181	82	9
1928–1955	−5	−7	1	−1
1955–1966	Built-up area	−15	−8	−9
1966–1994		20	18	−4
1994–2006		−14	−12	−1
Beach sand balance (V_B, m^3/year)				
1799–1862	12,864	−7,592	3,773	744
1862–1928	85	20,639	4,367	33
1928–1955	−71	−123	2	−1
1955–1966	Built-up area	−1,397	−253	−199
1966–1994		965	506	−16
1994–2006		−1,107	−524	−2
Nearshore sand balance (V_N, m^3/year)				
1799–1862	35,126	−29,832	20,505	9,316
1862–1928	2,677	42,254	21,699	1,988
1928–1955	−1,308	−6,127	434	−560
1955–1966	Built-up area	−25,617	−15,527	−11,973
1966–1994		17,152	13,303	−2,423
1994–2006		−26,693	−20,133	−992
Total beach–nearshore sand balance (V_T, m^3/year)				
1799–1862	47,989	−37,424	24,278	10,060
1862–1928	2,762	62,893	26,066	2,021
1928–1955	−1,379	−6,250	436	−561
1955–1966	Built-up area	−27,014	−15,780	−12,172
1966–1994		18,117	13,809	−2,439
1994–2006		−27,800	−20,657	−994

The Haifa sector as such was mainly rocky prior to the Haifa Port construction (1929–1932), and therefore it is not included in the table
[a] Positive values denote sand accumulation, negative values sand erosion

Akko coastal sector

The Akko coastal sector extends 3 km, from ~1.4 km south of the present Na'aman River outlet to the eastern walls of Akko's old city. The findings show that during the period 1799–1862, the coast widened to a variable degree along its length, amounting to an average of ~40 m (0.7 m/year; Fig. 7b, Table 4, MW). For example, in the southern part of this coastal sector, a 50-m transgression was recorded, whereas in the central part (~700 m northwest of the present Na'aman River outlet) the coast widened by 150 m.

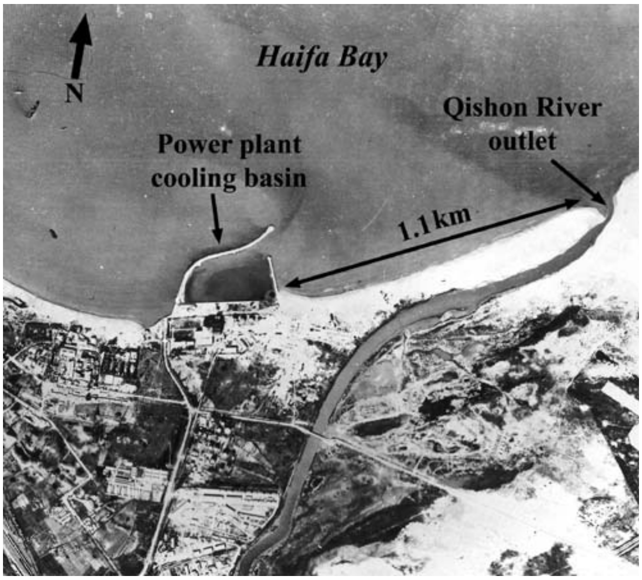

Fig. 13 Aerial photograph of the Qishon River coast on 7 January 1945 (aerial photographs collection, Survey of Israel, Tel-Aviv, flight 680, P.S.14., frame 6112, 15,000 feet)

This trend continued (albeit slightly) from 1862 to 1928, when the coast widened by an additional few meters. Between 1928 and 1955, the coast remained stable, although in the last 50 years the shoreline has retreated by 15 m (Fig. 15c). The same results were obtained from the aerial photograph mapping carried out in the current research, and covering the period 1945–1995.

Haifa Bay's closure depth

Analyses of numerous profiles which were determined from historic nautical charts of Haifa Bay (Bedford and Mansell 1863; Mansell et al. 1863; Edgell and Officers HM Surveying Ship Endeavour 1931), and contemporary bathymetric charts (Ministry of Transport–Department of Shipping and Ports 1972; Fig. 6 in Hall 1976; Oceana Marine Research Ltd 2002) show that the bay's closure depth is ~5 m deep.

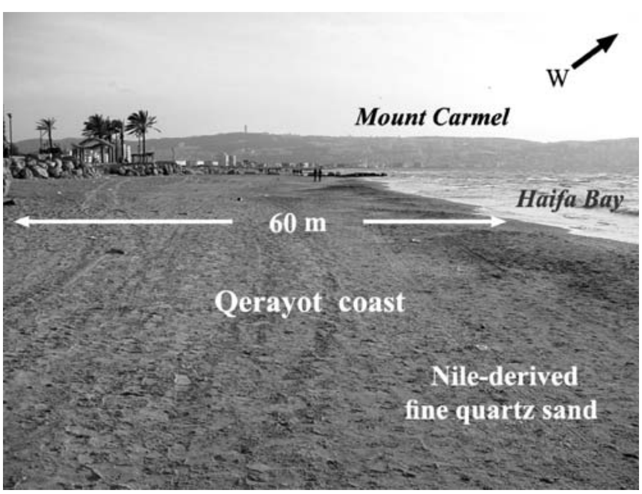

Fig. 14 Panoramic view of the Qerayot coastal sector and Mount Carmel (the photograph was taken towards the southwest, 29 March 2003)

To test this estimate, the Birkemeier (1985) expression was used:

$$h_l = 1.57 \times H_e$$

where H_e is the nearshore storm wave height exceeded only 12 h per year. Based on high-quality directional wave measurements collected during the last 15 years offshore Haifa Bay (by CAMERI, Coastal and Marine Engineering Research Institute, on behalf of the Israel Ports Authorities), 12 h annually significant wave heights of 3.0–3.3 m were estimated for the bay's breaker zone (Danish Hydraulic Institute 2000). The resulting values of h_l are 4.7–5.2 m, and closely match the closure depth estimate obtained from the charts.

Historic beach–nearshore sand balance

Assuming Haifa Bay's closure depth is ~5 m, and has not changed over the last 200 years, differences in beach mean width (Table 4, MW) were used to estimate the beach–nearshore sand balance (Table 4, V_T) for the study period. The data for the Bay as a whole are based on volume calculations for each of its sandy coastal sectors.

The findings show sand accumulation of ~48,000 m^3 annually in the Qishon River coastal sector during the period 1799–1862 (Table 4, V_T). The value reduced by an order of magnitude from 1862 to 1928, followed by slight erosion from the time of construction of Haifa Port until 1955.

For the Qerayot coastal sector, sand erosion of ~37,000 m^3 annually was estimated during the period 1799–1862 (Table 4, V_T). This erosion dramatically changed to sand accumulation of ~63,000 m^3 annually through the following period of 1862–1928. After the construction of Haifa Port, accumulation ceased and, until 1955, the area eroded slightly. The erosion trend increased through the next decade, by ~27,000 m^3 annually. From 1966–1994 erosion ceased, and sand accumulation amounted to ~18,000 m^3 annually. More recently, the trend has changed again to erosion of ~28,000 m^3 annually (Table 4, V_T). Although the sedimentological trend for the Qerayot coast changed significantly after the construction of Haifa Port, only a small amount of erosion, averaging ~2,000 m^3 annually, was recorded for the period 1928–2006.

Compared to the Qerayot coast, different sedimentological trends were estimated for the Rafael coastal sector from the nineteenth century until the 1930s. The findings show sand accumulation of ~24,000 and ~26,000 m^3 annually

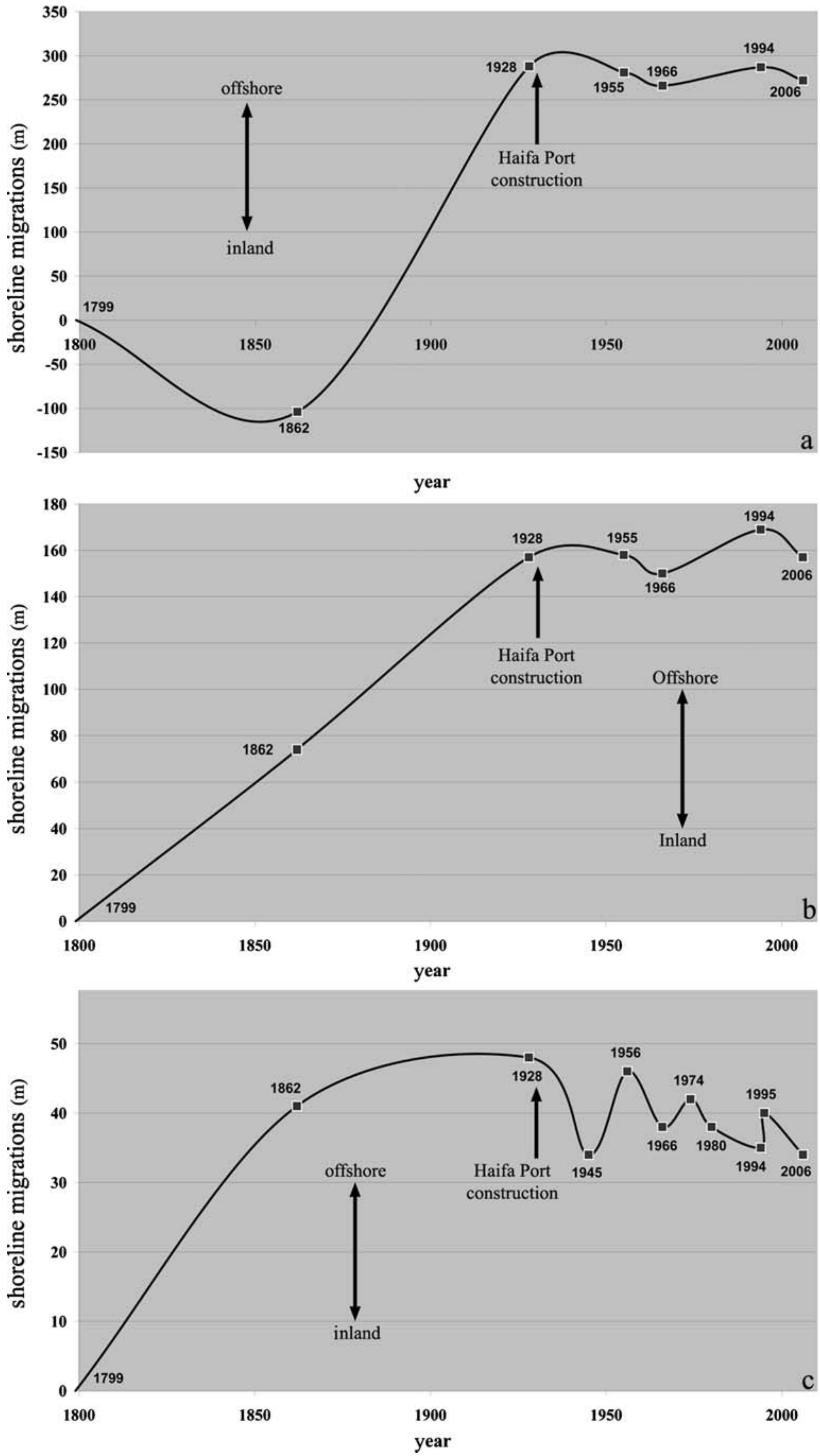

Fig. 15 Shoreline migrations over the last 200 years (relative to 1799) along the Qerayot coastal sector (**a**), the Rafael coastal sector (**b**) and the Akko coastal sector (**c**)

during 1799–1862 and 1862–1928 respectively (Table 4, V_T). Later, after the construction of Haifa Port, the Rafael dataset shows a trend similar to that recorded for the Qerayot sector, except that the total sand balance was approx. zero from 1928–2006 for the Rafael sector.

The findings for the Akko coastal sector show sand accumulation of ~10,000 m^3 annually from 1799–1862, which reduced to ~2,000 m^3 annually from 1862–1928 (Table 4, V_T). Between 1928 and 1955, the beach–nearshore area remained stable. During the last 50 years, it has continuously slightly eroded by ~3,000 m^3 annually.

Discussion

Haifa Bay shoreline migrations and sand balance between 1799 and 1928

Analyses of shoreline migrations and sand balance between 1799 and 1862 show that the Haifa Bay coastal sectors widened by ~40–140 m (average values of 0.7–2.2 m/year), and accumulated 10,000–48,000 m^3 of sand annually (Table 4, V_T), with the exception of the Qerayot coast. Based on the measurements of Jacotin and of Mansell, the latter retreated eastwards by ~100 m (average of 1.6 m/year), and eroded by ~37,000 m^3 annually. This unexpected deviation from the general trend is probably due to inaccuracy of measurements, especially by Jacotin, whose precision in conducting the Qerayot coast survey is questionable.

This accretionary trend continued between 1862 and 1928, and the bay's coastal sectors expanded, especially the Rafael and Qerayot sectors which gained an additional ~80 and ~180 m (averages of 1.2 and 2.7 m/year respectively), and accumulated significant amounts of sand, averaging 26,000 and 63,000 m^3 annually respectively. Haifa Bay's total sand balance shows accumulation of ~70,000 m^3 annually during the period 1799–1928 (Table 5, V_T).

Using shoreline migration estimates for the late Holocene (Zviely et al. 2006, 2007), and selecting the period between 1799 and 1928, the annual average coastal expansion of Haifa Bay for both periods can be derived and compared.

1. The late Holocene: given a shoreline migration of 3 and 4.8 km in the central and south-eastern parts of the Zevulun Plain respectively, during the last 4,000 years average rates of 0.75–1.2 m/year of coastal expansion can be calculated.
2. From the beginning of the nineteenth century until the construction of Haifa Port: given a shoreline migration range of 51–156 m for Haifa Bay, between 1799 and 1928 average rates of 0.4–1.2 m/year of coastal expansion can be calculated.

Table 5 Total beach–nearshore sand balance estimates, over the last 200 years along the Haifa Bay coast

Period	Result[a]
Total beach sand balance (V_B, m^3/year)	
1799–1862	9,789
1862–1928	25,124
1799–1928	17,635
1928–1955	−193
1955–1966	−1,849
1966–1994	1,455
1994–2006	−1,633
1928–2006	−371
Total nearshore sand balance (V_N, m^3/year)	
1799–1862	35,115
1862–1928	68,618
1799–1928	52,256
1928–1955	−7,561
1955–1966	−53,117
1966–1994	28,032
1994–2006	−47,818
1928–2006	−6,388
Total beach–nearshore sand balance (V_T, m^3/year)	
1799–1862	44,903
1862–1928	93,742
1799–1928	69,890
1928–1955	−7,754
1955–1966	−54,966
1966–1994	29,487
1994–2006	−49,451
1928–2006	−6,690

[a] Positive values denote sand accumulation, negative values sand erosion

The comparison shows similar annual average rates of coastal expansion in the Haifa Bay sandy coastal sectors for both periods.

Haifa Bay shoreline migrations and sand balance between 1928 and 2006

Analyses of shoreline migrations between 1928 and 2006 show that Haifa Bay's coastal sectors were in a steady state (cf. seasonal fluctuations of less than about ±20 m), with the exception of the Akko coast. The latter retreated by 15 m during this period, primarily due to human-induced modification of the Na'aman River's natural flow, and coastal structures built during the last 50 years.

Regarding the Haifa Bay total sand balance, the findings show slight erosion of ~7,000 m^3 annually during the period 1928–2006 (Table 5, V_T). This demonstrates a dramatic change to the sedimentological regime along the bay's eastern coast after the construction of Haifa Port, and corresponding stabilization of the shoreline on the long term, although during relatively short periods of time (few years) the Haifa Bay coastline in part can retreat or can shift seawards, depending on climate variations.

Conclusions

Analyses of shoreline migrations and beach–nearshore sand balance over the last 200 years in Haifa Bay show two main periods characterized by different sedimentological regimes.

From 1799 to 1928, when human intervention was negligible along the bay's coast, a significant coastal expansion of ~50–150 m (averages of 0.4–1.2 m/year) was observed, and sand accumulation of ~70,000 m^3 annually was estimated.

A dramatic change in sedimentological regime was observed from 1928 to 2006, following the completion of Haifa Port's main breakwater (1929–1933). The bay's coastal expansion trend ceased, and slight erosion of ~7,000 m^3 occurred annually.

These findings support those of Zviely et al. (2006, 2007) who reported that, from approx. 4,000 years ago until the construction of Haifa Port, a relatively stable sea level combined with continuous accumulation of Nile-derived sand have caused the Zevulun Plain to dry up, associated with a shifting of the bay's shoreline westwards to its present location. This long-term trend ceased after the construction of Haifa Port's main breakwater.

As reported in this study based on all available bathymetric charts and aerial photographs, for the last 80 years there has not been a notable shift of the Haifa Bay coastline, contrasting with its significant shift seawards for a comparable period of time prior to the construction of Haifa Port, which blocked the longshore sediment transport entering the Bay. Further research is necessary to confirm this trend, of high importance for sustainable coastal management of the Haifa Bay coastal zone. The lack of longshore sediment transport can result in an eventual coastline retreat caused by erosion due to unexpected climate changes.

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