

Article

Six Decades of Morphodynamic Evolution Around Ashdod Port, Southeastern Mediterranean Coast of Israel

Dov Zviely 

Faculty of Marine Sciences, Ruppin Academic Center, Emek Hefer 40250, Israel; dovz@ruppin.ac.il;
Tel.: +972-52-5805-758

Abstract

Long-term morphodynamic responses to large ports are difficult to quantify when historical observations cover different periods, spatial domains, and engineering interventions. At Ashdod Port, on the Mediterranean coast of southern Israel, previous studies documented individual stages of coastal change, but the cumulative response to six decades of port development remained unresolved. This study reconstructs the Ashdod coastal system from 1957 to 2025 using historical and modern bathymetric–topographic surveys, shoreline analysis, and intervention-adjusted sediment balances. During 1965–1995, approximately $4.50 \times 10^6 \text{ m}^3$ of sand accumulated within the $\sim 2.5 \text{ km}$ sector immediately south of the main breakwater (MBW), while a comparable deficit developed north of the port. Following construction of Ashdod Marina (1995–1997), accumulation became distributed across the southern sectors, while erosion persisted north of the port and extended farther downdrift. For 1965–2021, intervention-adjusted balances were $+7.859 \times 10^6 \text{ m}^3$ south and $-7.208 \times 10^6 \text{ m}^3$ north of the port, corresponding to $+140$ and $-129 \times 10^3 \text{ m}^3/\text{yr}$, respectively. Their similar magnitude and opposite signs constrain the long-term morphological response to interruption of the predominantly northward sediment-transport system but do not constitute a direct LST estimate. Successive port expansions extended the MBW head from ~ 15 to $\sim 25 \text{ m}$ water depth, across most of the sandy inner-shelf domain extending to $\sim 30 \text{ m}$. North of the port, substantial sediment losses were accompanied by limited shoreline retreat, showing that shoreline change alone underrepresents the submerged response. Despite artificial northward transfer of $\sim 1.457 \times 10^6 \text{ m}^3$ since 2000, the downdrift deficit persisted. Historical accumulation south of the port should therefore not be equated with a presently available sand reserve. The record demonstrates the value of multi-decadal volumetric analysis for resolving cumulative port impacts and supporting sediment management on engineered sandy coasts.

Keywords: Ashdod Port; longshore sand transport (LST); littoral cell; coastal morphodynamics; sediment budget; beach nourishment; sand bypassing



Academic Editor: Juan J. Munoz-Perez

Received: 27 July 2026

Revised: 9 September 2026

Accepted: 10 September 2026

Published: 17 September 2026

Copyright: © 2026 by the author.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Large deepwater ports constructed along straight, open-shelf sandy coasts represent major anthropogenic interventions in wave-dominated environments. By modifying longshore sand transport (LST) pathways and nearshore hydrodynamic conditions, such structures commonly induce pronounced morphodynamic asymmetry, characterized by sand accumulation on the updrift side and sediment deficits and erosion along downdrift coasts. These impacts have been documented worldwide through monitoring programs, numerical and physical modeling, and theoretical analyses [1–4], including case studies

from Spain, the United Kingdom, Ireland, South Africa, and California, demonstrating the widespread morphodynamic influence of large coastal structures and the diversity of mitigation approaches, including sand bypassing and beach nourishment [5–10]. However, most previous investigations relied on short- to medium-term monitoring datasets or model-based transport estimates, thereby limiting quantitative evaluation of long-term sediment redistribution and morphodynamic evolution within littoral sediment systems.

The Mediterranean coast of Israel (Figure 1) and its adjacent inner shelf form part of the Nile littoral cell [11,12]. This coastal compartment is one of the world's longest littoral sediment systems, extending approximately 650 km from Abu Qir Bay, west of the Nile Delta near Alexandria, Egypt, to Haifa Bay in northern Israel [13–16].

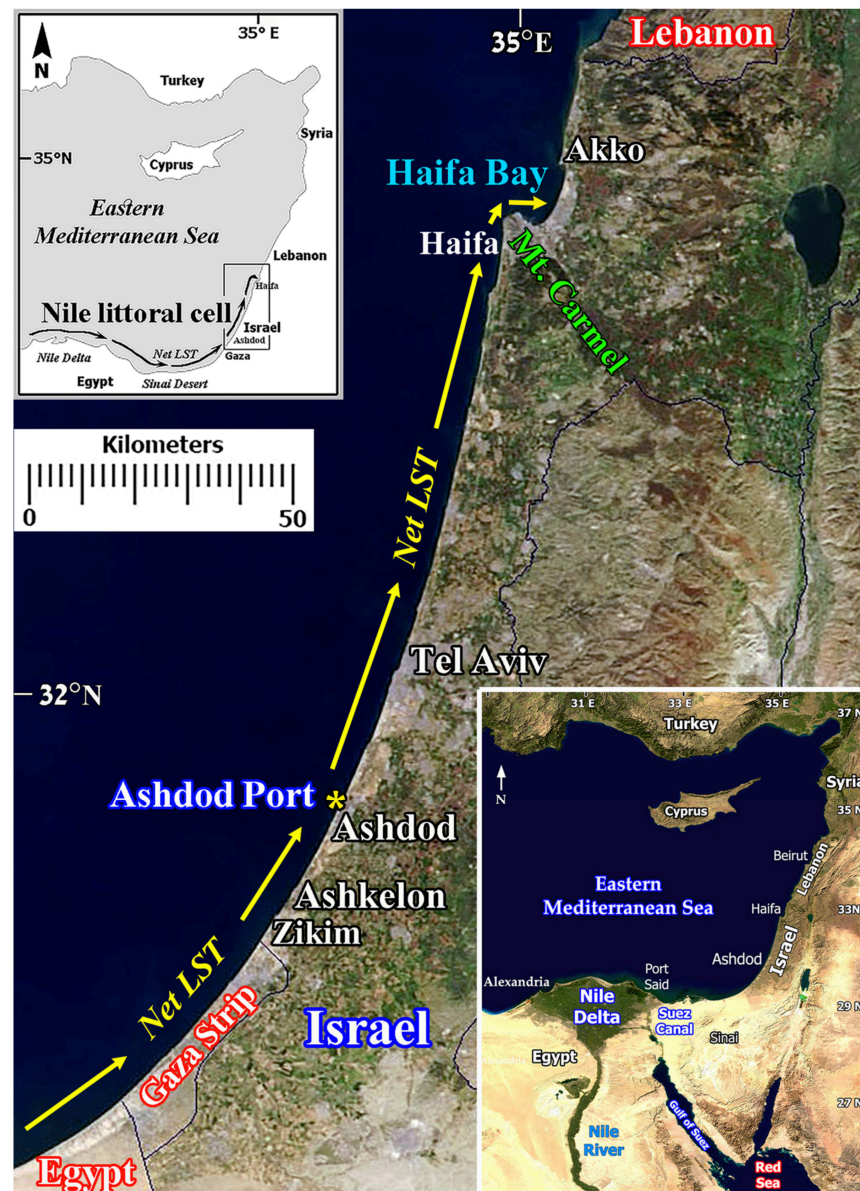


Figure 1. The Mediterranean coast of Israel, showing the location of Ashdod Port and the dominant direction of net LST, indicated by yellow arrows. Top inset: Full extent of the Nile littoral cell, including the dominant direction of net LST. Bottom inset: Key seaport locations in the southeastern Mediterranean. Background image: MiddleEast.A2003031.0820.250m.jpg, photographed by J. Descloitres, MODIS Rapid Response Team, NASA/GSFC, 31 January 2013. Image source: NASA Goddard Space Flight Center; created by Reto Stöckli, Robert Simmon, and the MODIS Groups, 14 August 2010. Available at: <https://visibleearth.nasa.gov/images/57752/blue-marble-land-surface-shallow-water-and-shaded-topography> (accessed on 27 July 2026).

Along the Israeli Mediterranean coast, major marine structures, including Haifa Port [17–19] and Ashdod Port [19–23], have substantially modified natural LST pathways and nearshore morphodynamics. The present study focuses on Ashdod Port, whose construction and subsequent offshore expansions have been accompanied by more than five decades of engineering monitoring and morphodynamic investigations.

Ashdod Port was constructed between 1961 and 1964 along a straight, wave-dominated sandy coastline within the Nile littoral cell and became operational in 1965 [19,20].

Nearly four decades later, the port underwent its first major offshore expansion between 2001 and 2005. A second major expansion followed between 2015 and 2021, further extending the main breakwater (MBW) seaward into deeper water [22,23].

The morphological evolution and morphodynamic response to construction and subsequent expansion of Ashdod Port have been investigated for more than five decades. The first generation of studies focused primarily on the immediate vicinity of the original port and relied on repeated hydrographic surveys to quantify seabed morphological changes associated with construction of the main breakwater. Early investigations used successive hydrographic surveys to estimate net LST and document seabed morphological change adjacent to the port [24–27]. These studies progressively extended the observational period from the first years following port construction to 1985 and introduced differential bathymetric mapping and volumetric analyses of accumulation and erosion. These studies established the bathymetric foundation for understanding the early morphological evolution of the original port but remained largely confined to local analyses of seabed change in its immediate vicinity.

Golik et al. [19,20] provided the first comprehensive regional assessment of the morphological effects of Ashdod Port. By integrating historical shoreline positions derived from aerial photographs with the available bathymetric surveys, they reconstructed shoreline evolution, seabed morphology, and sediment redistribution over the period 1957–1995. Their study synthesized the findings of the earlier engineering investigations within a unified regional morphodynamic framework, substantially expanding both the spatial extent and the scientific scope of previous work.

Following the regional synthesis of Golik et al. [19,20], a second generation of engineering and scientific investigations was initiated to support the environmental assessment, construction, and long-term monitoring associated with the successive expansion projects at Ashdod Port. These investigations used repeated bathymetric surveys, shoreline mapping, and sediment-budget analyses to evaluate the effects of port expansion, dredging, sand bypassing, nourishment, individual storm events, and subsequent morphological adjustment over successive monitoring periods from 2000 to 2020 [28–34].

These monitoring programs established a unique long-term database of repeated bathymetric–topographic surveys, shoreline reconstructions, and sediment-budget estimates describing the progressive morphodynamic evolution of the Ashdod coastal system during successive stages of port development.

In parallel with the engineering monitoring program, independent academic studies focused on shoreline evolution derived from historical aerial photographs. Dror [35] reconstructed long-term shoreline changes along the Ashdod and southern Palmachim coasts between 1946 and 2010, whereas Brozin [36] investigated shoreline responses to extreme wave storms using aerial-photograph-derived shoreline positions acquired between 2000 and 2019 together with offshore wave measurements collected during 1992–2023.

Although these investigations substantially advanced the understanding of coastal evolution around Ashdod Port, they remained focused on individual monitoring periods, specific engineering interventions, or shoreline analyses. Consequently, despite nearly seven decades of bathymetric–topographic surveys and more than five decades of scientific

investigations, no previous study has integrated the historical survey record into a unified quantitative reconstruction of long-term seabed evolution, shoreline migration, sediment-budget evolution, and regional sand redistribution spanning the entire 1957–2025 study period [19–36].

The present study addresses this knowledge gap by integrating a multi-decadal sequence of historical and modern bathymetric–topographic datasets spanning 1957–2025 within a unified morphodynamic framework. The analysis incorporates historical hydrographic surveys, including the previously unused post-construction bathymetric dataset reconstructed from the 1965 nautical chart, together with successive monitoring datasets collected during the long-term environmental monitoring programs associated with Ashdod Port [19–34]. Unlike previous studies, which primarily examined individual monitoring periods or shoreline evolution, the present study reconstructs long-term seabed evolution, volumetric sediment budgets, shoreline migration, and regional sand redistribution using a consistent methodology applied to the multi-decadal survey record.

Accordingly, this study addresses three principal objectives: (1) to quantify the multi-decadal evolution of seabed morphology, sediment-volume change, and shoreline migration across the principal phases of Ashdod Port development; (2) to determine the spatial and temporal relationships between subaqueous morphological change and shoreline response, particularly within the downdrift coastal system north of the port; and (3) to evaluate how the observed long-term sediment redistribution provides an observational constraint on the morphodynamic consequences of the regional LST regime and its interruption by port development and associated sand-management interventions.

2. Study Area

2.1. Morphological and Sedimentological Setting

The study area is subdivided into two main domains, extending across the coastal zone and adjacent inner shelf south and north of Ashdod Port. The southern domain extends ~6.1 km south of the port's MBW (Figure 2: left map) and includes Ashdod Marina and ~5.5 km of dissipative sandy beaches used primarily for recreation (Figure 3) [37]. Beach widths range from 60 to 100 m, and the littoral zone extends ~400 m offshore to ~6 m water depth. The bathymetry is characterized by a longshore bar–trough system. Such systems are characteristic of dissipative sandy beaches along the southern and central Israeli Mediterranean coast and exhibit marked morphological adjustment in response to changing wave conditions [38,39]. Beyond ~6 m water depth, the bathymetric contours become progressively smoother and parallel to the shoreline, except near the marina and the port's MBW, where local convergence occurs.

The northern domain extends ~6.3 km northward from the port's lee breakwater (LBW) (Figure 2: right map) and is characterized by reflective beaches with steeper and narrower profiles, generally less than 50 m wide. Along ~4 km of this area lies a prominent beachrock strip (Figure 4) extending to ~3 m water depth, representing remnants of intensive beach sand quarrying carried out until 1963 [39]. Historical beach sand quarrying substantially reduced the volume of the active littoral sand reservoir along this coastal sector prior to construction of Ashdod Port. Consequently, the northern beaches presently comprise discontinuous accumulations of predominantly coarse carbonate sand and shell fragments trapped locally landward of the beachrock, whereas the southern beaches remain dominated by fine Nile-derived quartz sand. Beyond the beachrock zone, bathymetric contours gradually realign parallel to the shoreline, although beach profiles remain considerably steeper than their counterparts south of the port.

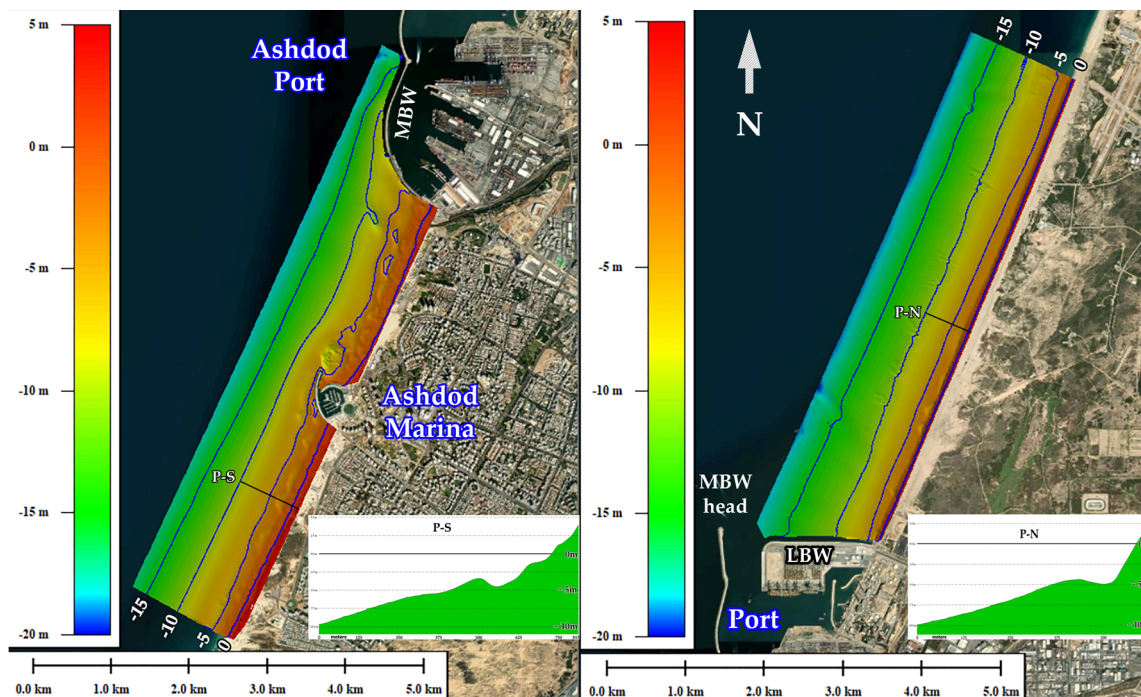


Figure 2. Shaded-relief bathymetric maps of the southern and northern study domains adjacent to Ashdod Port. The left map shows the southern domain south of the MBW, including cross-shore profile P-S, and the right map shows the northern domain north of the LBW, including cross-shore profile P-N. Elevations and water depths are referenced to the Israel Land Survey Datum (ILSD), with depth contours shown at 5 m intervals. Bathymetric-topographic data were collected in 2021 by LIA Surveying and Engineering Services Ltd. for the Israel Ports Development & Assets Company Ltd. Background image: Maxar (Vivid) satellite imagery, acquired on 18 September 2023. © Maxar Technologies. Used with permission.



Figure 3. Fine sandy beach located between Ashdod Marina and Ashdod Port, photographed on 18 June 2019.

Both domains are up to ~1.4 km wide, extending from the shoreline, defined as the 0.0 m contour relative to the ILSD, offshore to water depths of ~18–20 m (Figure 2). In this study, the term “Ashdod coastal system” refers to the investigated domains south and north of Ashdod Port, encompassing the subaerial beach, shoreline, coastal zone, and adjacent inner shelf.

The coastline is generally straight, although the shoreline azimuth gradually changes from ~26° at the southern boundary of the study area to ~23° at its northern boundary. Although this variation is relatively small, the ~3° change over a distance of only ~16 km is

morphodynamically significant because it influences wave incidence angles and, consequently, the magnitude and direction of LST along the coast.



Figure 4. Coarse sandy beach and beachrock north of Ashdod Port, photographed on 5 May 2025.

From a sedimentological perspective, the Ashdod coast and its adjacent inner shelf, extending from the shore to ~30 m water depth and up to ~3 km offshore, form part of the Nile littoral cell [11,12].

Field studies of sediment characteristics along the Ashdod coast [40–44] reveal that beaches in the southern domain and the seabed to ~30 m water depth are predominantly composed of fine-grained quartz sand. The median grain size (D_{50}) ranges from 180 to 220 μm between the shoreline and ~5 m water depth, decreasing to 140–170 μm between ~6 and ~10 m water depth, and to 100–150 μm beyond ~10 m water depth. Near the outer part of the port's MBW, D_{50} remains 160–200 μm even in deeper water.

The northern domain exhibits greater heterogeneity in grain size, with a mixture of fine quartz sand, coarse carbonate sand, and shell fragments (Figure 4). Beyond ~12 m water depth, D_{50} typically ranges from 110 to 140 μm , similar to that observed south of the port.

The active nearshore zone is predominantly sandy and is dominated by fine quartz sand, although greater textural heterogeneity occurs north of the port. The measured volumetric changes can therefore be interpreted primarily as sand redistribution rather than as changes associated with major differences in sediment composition.

2.2. Development of Ashdod Port

Ashdod Port was constructed between 1961 and 1964 along a straight, open-shelf sandy shoreline exposed to energetic wave conditions and began operation in 1965.

Prior to construction of the port, the first major coastal engineering structure within the study area was the Eshkol Power Station cooling-water basin, constructed between 1955 and 1957 approximately 1 km north of the future Ashdod Port. The original cooling basin was protected by a 390 m main breakwater and a 140 m secondary breakwater. The cooling basin was enlarged during 1974–1975, increasing the lengths of the main and secondary breakwaters to approximately 640 m and 300 m, respectively. Ashdod Port occupies a 1.6 km section of coastline, located approximately 200 m north of the Lachish River outlet and about 1 km south of the Eshkol Power Station cooling-water basin (Figure 5).

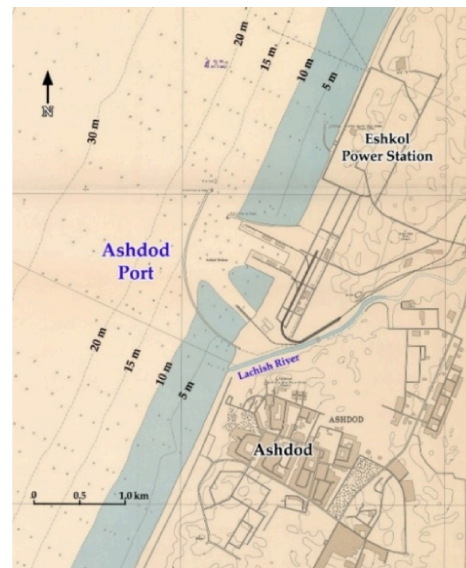


Figure 5. Ashdod Port and adjacent coasts on the 1965 nautical chart, published by the Survey of Israel (SOI) shortly after the port began operation, showing the original configuration of Ashdod Port and the adjacent Eshkol Power Station cooling-water basin before major sand accumulation and subsequent port expansions. Part of Ashdod Port Nautical Chart No. 2 (1965) [45]. Public domain, reproduced without restriction.

The port's MBW was originally 2.2 km long, extending to a water depth of ~15 m [19,20,25]. Between 1995 and 1997, Ashdod Marina was constructed about 2.5 km south of the MBW (Figure 6). Its LBW extends ~400 m offshore to ~6 m water depth. Between 2001 and 2005, the first major expansion (the “Yovel Port” Project) extended the MBW by 1.15 km to ~21 m water depth and included construction of the Eitan Terminal immediately south of the Eshkol cooling-water basin, initiating the northward expansion of the port complex (Figure 6) [22].



Figure 6. Ashdod Port in 2009, four years after completion of its first expansion, with Ashdod Marina located south of the port (constructed during 1995–1997). The enlarged Eshkol Power Station cooling-water basin is visible within the northern part of the expanded port area. Background image: Google Earth, 24 May 2009. © Google, Maxar Technologies. Used under fair use for research and illustrative purposes.

Between 2015 and 2021, the second expansion (the “South Port” Project) further lengthened the MBW by 600 m to a total length of 3.95 km, with its head reaching ~25 m water depth (Figure 7) [23]. These expansions progressively enclosed the Eshkol cooling-water basin within the port complex, where it remains between the Eitan Terminal and South Port.



Figure 7. Ashdod Port in 2022, one year after completion of its second expansion. The Eshkol Power Station cooling-water basin is enclosed within the expanded port area between the Eitan Terminal and South Port while continuing to function as the cooling-water facility of the adjacent power station. Background image: Copernicus Sentinel-2 L2A, acquired on 20 May 2022. Credit: European Union, contains modified Copernicus Sentinel data 2022, processed with Sentinel Hub.

2.3. Wave Climate and Hydrodynamic Regime

The southeastern Mediterranean coast of Israel is characterized by a wave-dominated microtidal environment, where wave forcing constitutes the primary driver of coastal morphodynamics and LST [13,16,21,36,45–49]. The regional wave climate exhibits strong seasonal variability, with relatively calm summer conditions and energetic winter storm activity associated mainly with cyclonic systems over the eastern Mediterranean [13,17,50–54].

Wave monitoring along the Israeli coast began at Ashdod in 1957 with visual observations of wave conditions [19,20,50,55]. Instrumental measurements of wave height and period were introduced in the late 1970s, followed by directional measurements during the 1980s [55]. Continuous directional spectral wave measurements have been collected offshore Ashdod since April 1992 using Datawell directional Waverider buoys deployed at ~24 m water depth (New Israeli Grid: 166997 E, 642614 N), approximately 3 km north-northeast of the present-day Ashdod Port main breakwater head, by the Israeli Coastal and Marine Engineering Research Institute (CAMERI) on behalf of the Israel Ports Company (IPC) [17,21,36,49,51–54]. A second directional Waverider buoy has operated offshore Haifa since November 1993 [16,17,21,49,54]. These datasets constitute the principal long-term observational basis for evaluating offshore wave conditions, wave approach direction, hydrodynamic forcing, and LST along the Israeli coast.

The Israeli Mediterranean wave climate is strongly seasonal. Summer conditions (April–October) are generally characterized by relatively low-energy seas, with significant wave heights (H_s) $< \sim 2$ m, whereas winter conditions (November–March) include frequent storm-wave events with H_s commonly reaching ~ 4 – 5 m (Figure 8) [18,21,36,49,50,52–54]. Analysis of Ashdod buoy data for the period 1992–2015 indicates that $H_s \leq 1.5$ m occurred in approximately 86.8% of observations, whereas wave heights exceeding 3 m represented less than 2% of the total record [49]. Storm events are most frequent between December and February and are typically generated hundreds of kilometers offshore over the eastern Mediterranean Basin [11,13,46,51].

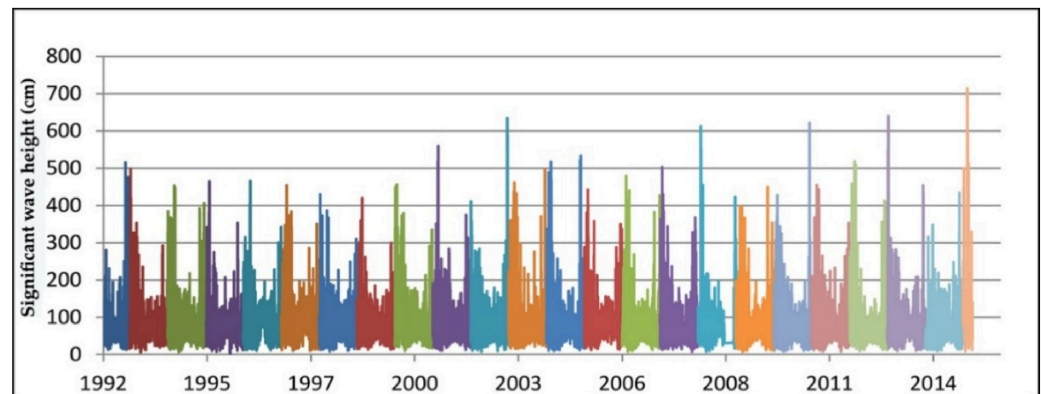


Figure 8. Continuous time series of significant wave height (H_s , cm) measured by the CAMERI directional Waverider buoy moored at ~ 24 m water depth north of Ashdod Port, from 1 April 1992 to 31 March 2015. Each wave year, defined from April 1 to March 31 of the following year, is shown in a different color. Short gaps in the record correspond mainly to instrument maintenance or temporary malfunction. Wave data were kindly provided by CAMERI.

Although infrequent, extreme storm events exert a dominant influence on long-term sand transport and nearshore morphodynamics. Weibull-based extreme-wave analysis for Ashdod indicates H_s values of approximately 6.54 m, 7.07 m, 7.76 m, and 8.28 m for 10-, 20-, 50-, and 100-year return periods, respectively [52]. Four storm events with $H_s > 7$ m were recorded offshore Haifa between 2001 and 2015 [37,55,56]. These high-energy events strongly influence closure depth, sand transport rates, seabed reworking, and beach-profile adjustment along the Israeli coast.

Wave approach along the Ashdod coast is dominated by WNW directions, commonly between 290° and 295° relative to north [49,52–54]. However, extreme storm waves may arrive from a broader directional sector ranging approximately from 255° to 315° [53,54] (Figure 9). Given the gradual change in shoreline azimuth along the study area ($\sim 26^\circ$ in the south to $\sim 23^\circ$ in the north), these directional variations significantly influence local wave-incidence angles and, consequently, the magnitude and spatial variability of LST along the coast.

The dominant offshore wave approach relative to the local shoreline orientation produces highly oblique wave incidence along substantial parts of the Israeli coast, thereby enhancing longshore current generation and sand transport rates [13,16,19,21,36,46,48,49]. These processes are particularly important along the Ashdod coast, where relatively small shoreline orientation variations may significantly influence alongshore gradients in LST.

Wave-induced longshore currents, generated by breaking waves within the littoral zone, constitute the dominant mechanism driving LST in shallow nearshore environments [11,13,15,16,21,36,48,49,55]. These currents typically dominate in water depths up to ~ 5 m and may extend beyond ~ 10 m during energetic storm conditions. However, beyond

the breaker zone, the influence of wave breaking on LST rapidly decreases, and alongshore sand transport becomes increasingly controlled by wind-induced shelf currents operating across the inner continental shelf [56,57].

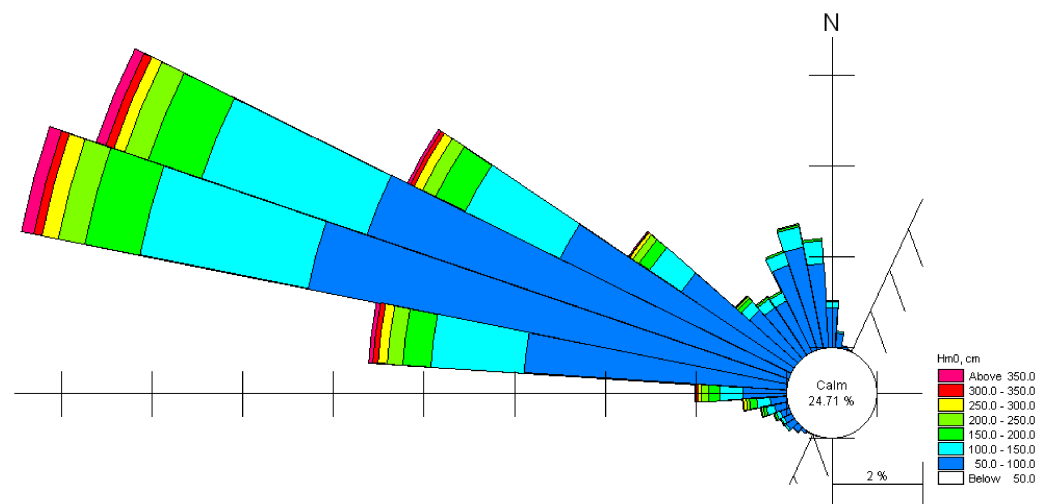


Figure 9. Rose diagram showing the annual directional distribution of significant wave height (H_{m0} , cm) measured north of Ashdod Port by CAMERI between 1 April 1992 and 31 March 2011 [53]. This figure is adapted from environmental impact assessment documents submitted to the Israeli Ministry of Environmental Protection and available as part of the public environmental record.

Although wave- and wind-induced longshore currents act in both directions along the Israeli coast [48], the net long-term LST across the entire inner continental shelf (0–30 m water depth) is consistently directed northward toward Haifa Bay, which constitutes the terminal depositional sink of the Nile littoral cell [13–18,21,40,46–49].

The Israeli Mediterranean coast is characterized by a microtidal regime, with a tidal range of approximately 0.15 m during neap tides and up to ~0.4 m during spring tides [42,48,52,53]. Winter storms may additionally generate storm surges reaching ~0.7 m above predicted tidal levels [49,58], thereby enhancing wave run-up, nearshore water levels, and sand redistribution.

2.4. Longshore Sand Transport Estimates

Between the construction of Ashdod Port and the late 1980s, numerous studies estimated LST south of Ashdod Port using visual observations, simplified wave-climate assumptions, and empirical transport formulations (references in [19,20,55]). However, the available wave datasets were very limited and suffered from substantial uncertainty in wave-direction data, thereby reducing the reliability of these early assessments.

Following the initiation of continuous directional wave measurements offshore Ashdod and Haifa during the 1990s, additional evaluations of LST along the Ashdod coast were carried out using both empirical formulations and numerical LST models [19–21,59–63] (Table 1; Figure 10).

Although all investigations identified a dominant net northward LST regime, reported transport rates varied substantially due to differences in wave datasets, transport formulations, shoreline orientation assumptions, and numerical-model parameterization.

Table 1. Selected published estimates of potential wave-induced LST rates in the vicinity of Ashdod Port, as reported by various studies since the 1990s. All net LST rates are directed northward.

Study and Location	LST Formula or Model (Approach)	Wave Data	Time Period	LST Rates (m ³ /yr)
Delft Hydraulics (1994) [59] South of Ashdod Port	Bijker Formula (semi-empirical)	Wave model hindcast data, and wave measurements from Ashdod	n/d	North 420,000 South 240,000 Net 180,000 Gross 660,000
Golik et al. (1996) [19,20] South of Ashdod Port	Bijker Formula (semi-empirical)	Ashdod directional wave-rider buoy	1 April 1992–31 March 1995	Net 180,000
	LCHF Formula (semi-empirical)			Net ~170,000
	CERC Formula (semi-empirical)			CERC 1: Net 720,000 CERC 2: Net ~650,000
	Bijker Formula With currents (semi-empirical)			Net 350,000 Gross 570,000
HR Wallingford (1996) [60] 5.0 km south of Ashdod Port	BEACHPLAN Model (1D one-line)	UKMO wave model hindcast data	1987–1995	Net 196,000
	PISCES Model (2D coastal-area)		1992–1995	Net 153,000
			1992–1995	Net 114,000 (1.5 km south of the Port)
HR Wallingford (1999) [61] Between the Marina and Ashdod Port	COSMOS Model (1D cross-shore/profile-based)	Ashdod directional wave-rider buoy	May 1997–May 1998	North 186,000 South 115,000 Net 70,000 Gross 301,000 (Grain Size 0.2 mm)
Perlin and Kit (1999) [21] South of Ashdod Marina	Modified CERC Formula (semi-empirical)	Ashdod and Haifa directional wave-rider buoys	1 April 1994–31 March 1997	North 250,000 South 050,000 Net 200,000 Gross 300,000
	LITDRIFT Module (1D profile-based)			
Sladkevich et al. (2016) [62] 5.5 km south of Ashdod Port	LITDRIFT Module (1D profile-based)	Ashdod and Haifa directional wave-rider buoys	1 April 1992–31 March 2014	North 222,000 South 123,000 Net 98,000 Gross 346,000
	GenCade Model (1D one-line)			North 235,000 South 136,000 Net 98,000 Gross 371,000

A review of these studies reveals substantial quantitative discrepancies among published LST estimates for the Ashdod coast since the initiation of continuous directional wave monitoring offshore Ashdod and Haifa. These discrepancies primarily reflect differences in wave datasets, transport formulations, shoreline-orientation assumptions, study periods, locations, and numerical-model parameterization. Moreover, most previous assessments focused primarily on wave-induced transport within the shallow littoral zone and did not explicitly account for wind-induced sediment transport operating across the inner continental shelf. Consequently, long-term volumetric analyses based on repeated bathymetric–topographic surveys provide an independent empirical basis for constraining sand redistribution adjacent to the expanding port system.

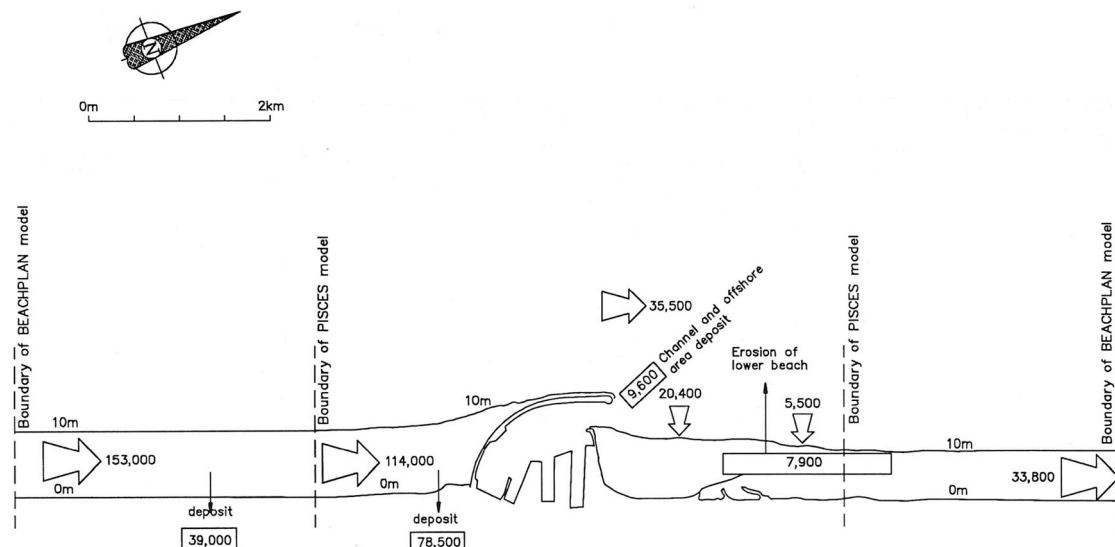


Figure 10. Average annual LST rates, bypassing rates, and onshore sand transport (m^3/yr) along the Ashdod coast prior to the first major offshore expansion of the Ashdod Port MBW, as calculated using the BEACHPLAN and PISCES models by HR Wallingford (1996) (Figure 54 in [60]). Adapted from environmental impact assessment documents submitted to the Israeli Ministry of Environmental Protection and available as part of the public environmental record.

2.5. Morphodynamic Response to Ashdod Port

The construction of Ashdod Port along a straight sandy shoreline exposed to energetic storm-wave conditions substantially disrupted the natural LST regime, producing pronounced morphodynamic asymmetry along the adjacent coast. The port's MBW progressively intercepted the dominant northward LST, resulting in extensive sand accumulation south of the port and a sediment deficit and erosion within the northern nearshore zone.

By the early 1990s, beaches south of the port's MBW had widened by up to ~100 m, with the depositional influence gradually decreasing southward over a distance of approximately 2.5 km [19,20].

A prominent sandbar developed adjacent to the MBW and along the southern beaches, accumulating approximately $4.5 \times 10^6 \text{ m}^3$ of sand by 1995, including $\sim 2.2 \times 10^6 \text{ m}^3$ between 1985 and 1995 alone [19].

In contrast, the northern nearshore zone experienced progressive seabed erosion extending locally to water depths of ~10 m, whereas shoreline retreat remained relatively limited because historical beach sand quarrying had already substantially reduced the active littoral sand reservoir and exposed extensive beachrock prior to construction of Ashdod Port (Figure 4). Beach widening north of the port extended only ~300 m beyond the LBW before reaching a relatively stable configuration [19,20].

Since the mid-1990s, systematic high-resolution bathymetric–topographic monitoring programs have been conducted by the Israel Ports Authority (IPA) and later by the IPC [63]. These surveys supported both the planning of the offshore port expansions and continuous monitoring of shoreline and seabed evolution adjacent to the MBW.

However, despite the extensive datasets collected during the last three decades, most previous monitoring studies and engineering reports, primarily prepared by CAMERI [28–33,62], focused mainly on short- to medium-term shoreline and bathymetric variability associated with individual monitoring periods or engineering interventions.

Consequently, long-term morphodynamic evolution and cumulative sediment redistribution adjacent to Ashdod Port have not previously been systematically quantified within an integrated multi-decadal sediment-budget framework.

2.6. Sand Bypass and Sediment-Management Interventions

Prior to the first major offshore expansion of the MBW, HR Wallingford conducted sedimentological and morphodynamic assessments to evaluate the potential impacts of the planned port extension on regional LST [60,61]. Based on these studies, several mitigation measures were proposed to the Ports Development Administration (currently the Israel Ports Company, IPC) in cooperation with the Ministry of Environmental Protection (MoEP) [59]. The primary objective was to reduce seabed and beach erosion north of the port by mechanically bypassing sand accumulated south of the MBW and transferring it to downdrift coastal sectors.

A central component of this strategy involved dredging approximately 180,000 m³/yr of sand from a designated borrow area located between Ashdod Marina and Ashdod Port and depositing it north of the port (Figure 11) [61].

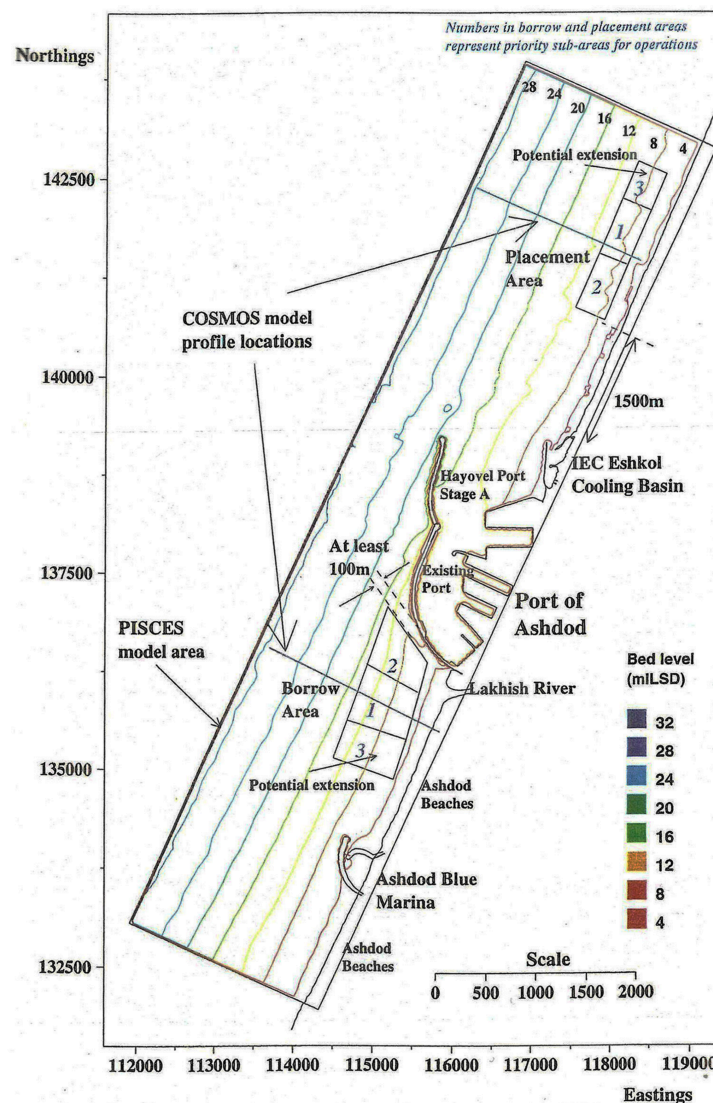


Figure 11. Conceptual sand borrow area south of Ashdod Port and placement area north of the port, as proposed by HR Wallingford (1999) (Figure 8 in [61]), prior to the first major offshore expansion of the MBW. The PISCES model domain and COSMOS profile location shown in the original source are also indicated. Coordinates are shown in the Old Israeli Grid.

HR Wallingford further recommended continuous monitoring of the borrow and placement areas and adaptive adjustment of bypass volumes according to observed morphodynamic response [61].

Based on these recommendations, large-scale sand bypass operations began in late 2000, with approximately 180,000 m³ dredged annually from water depths of 6–10 m south of the port and deposited north of the port at comparable water depths [28–30] (Figure 11: Placement Area).

Between 2000 and 2003, approximately 720,000 m³ of sand were bypassed during four consecutive operations, each accompanied by detailed morphodynamic monitoring programs [29,30]. These operations were intended to compensate for the interruption of northward LST by Ashdod Port by dredging sand from the southern (updrift) side and bypassing it to the northern (downdrift) side of the port.

In summer 2001, substantial narrowing of the bathing beaches south of the port was reported by Ashdod Municipality. Subsequent CAMERI investigations documented shoreline retreat reaching up to ~30 m opposite the borrow area and ~10 m along adjacent coastal sectors [28]. The retreat was attributed to a combination of borrow-area dredging and the exceptionally energetic February 2001 storm event [22,28].

Additional bypass and nourishment operations were conducted during 2011, 2013, 2016, 2019, 2021, 2022, and 2025 [22,23,31–34]. Unlike the earlier offshore dumping operations, later projects increasingly involved shallow-water rainbowing and direct beach nourishment north of the port and at additional erosion-prone sites along the Israeli coast. The 2011 operation north of Ashdod Port marked the first use of bypassed sand for direct beach nourishment in this area. During 2021, 2022, and 2025, the Mediterranean Coastal Cliffs Preservation Government Company (MCCP) transported sand dredged south of Ashdod Port for nourishment projects in Bat Yam (2021), Ashkelon and Netanya (2022), and Netanya (2025). The dates, dredging and placement areas, placement methods, and sand volumes associated with these operations are presented in Section 4.2, where they are related directly to the DEM-derived volumetric changes.

Since 2011, beach nourishment has become the primary national strategy for mitigating coastal erosion along the Israeli Mediterranean coast (Figure 12) [22,23,64]. Between 2011 and 2023, approximately 2.5×10^6 m³ of sand were used for nourishment projects along the coasts of Ashkelon, Ashdod, Bat Yam, Netanya, and southern Haifa Bay [27,35,62]. Of particular relevance to the present study, approximately 1.5×10^6 m³ of sand were dredged south of Ashdod Port between 2000 and 2025 for bypassing and nourishment operations. Most of the sand dredged during the earlier operations was transferred north of the port, whereas part of the sand dredged during later operations was transported to nourishment sites elsewhere along the Israeli Mediterranean coast.



Figure 12. Nourishment rainbowing operation via discharge pipe, north of Ashdod Port, May–August 2011. Photograph courtesy of EDT Marine Construction (Figure 2 in [22]). Used with permission.

3. Methodology

This study is based on an integrated dataset covering the period 1957–2025, combining bathymetric–topographic data and orthorectified aerial photographs. The bathymetric–topographic datasets constitute the principal quantitative framework of the study and include repeated elevation measurements acquired across the coastal zone and adjacent inner shelf domains south and north of Ashdod Port, extending from the backshore (+5 m relative to the Israel Land Survey Datum; ILSD) to approximately 20 m water depth, depending on survey period and spatial coverage. These datasets provide the primary quantitative basis for assessing seabed evolution, shoreline migration, sand redistribution, and volumetric sand-budget changes adjacent to the port. Because the dataset spans nearly seven decades, the original surveys differ in measurement technology, spatial sampling density, positioning accuracy, and data format. These differences, and the procedures used to harmonize and quality-control the datasets for quantitative comparison, are described in the following subsections.

Shoreline evolution was evaluated primarily using the elevation-derived 0 m ILSD contour extracted from repeated bathymetric–topographic elevation datasets rather than instantaneous waterline positions identified on aerial photographs. Because the objective of the present study is to reconstruct long-term morphodynamic evolution rather than instantaneous shoreline position, the elevation-derived 0 m contour was adopted as the principal shoreline indicator. This contour provides a consistent elevation-based morphodynamic reference while reducing uncertainty associated with wave run-up, sea-state conditions, and interpretation of the wet/dry boundary in aerial imagery. The microtidal regime of the southeastern Mediterranean further minimizes the influence of tidal water-level fluctuations on long-term shoreline reconstruction.

Orthorectified aerial photographs were therefore used primarily as supplementary datasets to support qualitative interpretation of shoreline configuration and morphodynamic evolution. Together, these datasets establish a consistent spatial and temporal framework for evaluating long-term morphodynamic evolution and multi-decadal sand redistribution adjacent to Ashdod Port, with primary emphasis on volumetric changes derived from bathymetric–topographic elevation datasets.

3.1. Evolution of Hydrographic and Geodetic Survey Methods

Systematic bathymetric–topographic surveys along the Ashdod coast have been conducted since 1957, immediately prior to the construction of Ashdod Port [19,20].

The earliest campaigns (1957–1970), including the 1957, 1959, 1965, and 1969–1970 surveys, were performed along shore-normal transects extending up to 2–3 km offshore, typically reaching depths of 15–20 m. Navigation control relied on visual alignment between fixed onshore markers, sextant fixes, or shore-based triangulation, while water depths were measured using mechanical analog single-beam echo sounders (SBES) that produced paper roll profiles. The shallow-water zone inaccessible to the survey vessel, including the beach and approximately the first 1.5 m of water depth, was surveyed separately using contemporary land-based geodetic methods at discrete measurement points.

Horizontal positioning accuracy varied according to the positioning method and survey configuration, whereas the vertical accuracy of the early SBES measurements was approximately ± 0.2 – 0.5 m (Table 2). For SBES surveys conducted during 1957–1979, the shore-normal survey lines were generally spaced approximately 50–100 m apart.

During the 1970s and 1980s, electronic navigation systems such as Decca Trisponder (± 5 – 10 m) and Miniranger (± 2 – 5 m) were introduced, improving survey control and line repeatability [19]. SBES remained the standard depth-measurement system, and cross-shore profiles continued across the coastal zone and adjacent inner shelf domain to ~ 20 m water

depth. From 1980 through 2004, the shore-normal SBES survey lines were generally spaced approximately 50 m apart. From 2005 onward, this spacing was reduced to approximately 25 m, thereby increasing the spatial density of the bathymetric observations. These spacings refer specifically to the shore-normal SBES survey lines and not to the spatial density of land-based topographic measurements or subsequent multibeam echo-sounder (MBES) coverage. Shore-parallel control lines were also included in the SBES survey configuration.

Table 2. Principal bathymetric–topographic survey campaigns used in the quantitative volumetric analysis within the study area between 1957 and 2025, including the responsible institutions, survey methodologies, positional accuracy, and calculated optimal computational DEM grid spacing used to generate the interpolated surfaces for morphodynamic and volumetric analyses.

Survey Year (Month)	Surveying Body	Survey Position & Elevation Measurements Methodology	Survey Position & Elevation Accuracy (m)	Automatically Calculated DEM Grid Spacing: Width/Height (m) *
1957	IPA	Visual Range Alignment & Analog SBES	Horizontal: ±2–5 Vertical: ±0.2–0.5	7.496/13.725
1965				44.273/41.414
1969–1970				9.041/13.914
1975 (Oct–Dec)		Decca Trisponder & Analog SBES	Horizontal: ±5–10 Vertical: ±0.2–0.5	14.780/32.666
1985 (Jun–Jul)		Miniranger & Analog SBES	Horizontal: ±2–5 Vertical: ±0.2–0.5	9.333/17.281
1995 (May–Jun)	IOLR	DGPS & SBES	Horizontal: ±1 Vertical: ±0.1–0.3	3.946/6.223
2005 (Nov)–2006 (Feb)	OCEANA			4.429/2.619
2007 (Apr–Aug)				1.910/3.350
2010 (Jul–Oct)	EDT	DGPS & SBES + MBES	Horizontal: ±1 Vertical: ±0.1–0.3	1.763/2.261
2012 (May)			Horizontal: ±1 Vertical: ±0.05–0.15	1.174/2.336
2015 (Oct)–2016 (Apr)	EDT	RTK & SBES + MBES	Horizontal: ±0.02–0.05 Vertical: ±0.02–0.05	1.990/1.568
2017 (Oct)–2018 (Jan)	LIA			1.099/1.020
2021 (Oct–Nov)				0.988/0.988
2024 (Apr–Oct)				1.000/1.000
2025 (Apr–Oct) (Marine) 6 Feb. 2026 (Airborne)	LIA + Northern Arrow	SBES + MBES + Topo bathymetric Airborne Lidar		1.000/1.000

* The calculated optimal DEM grid spacing represents the uniform computational grid used to generate each integrated bathymetric–topographic surface. It does not represent the spacing or spatial resolution of the original measurements. Original sampling density varied across each survey according to water depth and acquisition method, including discrete land-based measurements, shore-normal SBES lines, and, from 2009 onward, dense MBES coverage generally seaward of ~5 m water depth.

By the mid-1990s, the integration of Differential GPS (DGPS) with digital SBES significantly improved positioning and depth precision, achieving accuracies of ± 1 m horizontally and ± 0.1 –0.3 m vertically (Table 2). Coverage typically extended from the backshore to ~20 m water depth and combined land-based measurements of the beach and very shallow-water zone with vessel-based hydrographic measurements offshore.

The first bathymetric map in the Ashdod monitoring series incorporating MBES data dates from 2009, providing swath mapping and full seabed coverage generally beyond ~5 m water depth.

Since 2013, MBES combined with RTK GNSS and motion-reference units has achieved vertical precision of $\pm 0.02\text{--}0.05$ m (centimeter-level) (Table 2), providing dense, near-continuous seabed coverage in the MBES-surveyed zone, generally seaward of ~ 5 m water depth, while the shallower zone continued to be surveyed using land-based geodetic measurements and SBES where vessel access permitted. These integrated survey methods characterize the recent coastal hydrographic surveys used in the present study. The resulting survey products therefore integrate measurements acquired using different techniques and spatial sampling densities across the cross-shore profile.

These technological developments resulted in progressive improvements in hydrographic positioning, bathymetric resolution, and vertical accuracy over time. However, the spatial density of the original measurements was not uniform within individual surveys and varied according to water depth and survey method. Accordingly, the nominal grid spacing of the interpolated digital elevation models (DEMs) should not be interpreted as the original measurement spacing or as uniform spatial resolution of the source observations. The influence of these differences on the robustness of the volumetric comparisons is evaluated separately through the quality-control, uncertainty, and grid-resolution sensitivity analyses described below.

All bathymetric and topographic datasets were therefore critically evaluated prior to integration to identify inconsistencies associated with georeferencing, vertical datum conversion, interpolation artifacts, shoreline matching, and localized survey anomalies. Historical analog bathymetric charts and fair sheets were scanned, digitized, and georeferenced prior to interpolation and morphodynamic analysis. All datasets were subsequently transformed into a unified horizontal and vertical reference framework based on the ITM coordinate system, referenced to the GRS 80 ellipsoid, and the ILSD.

The 1965 dataset required separate consideration because, unlike the original fair sheets available for the other early surveys, the original survey fair sheet was not available for this study. The available 1965 source consisted of a bathymetric chart containing individual depth soundings together with 5 m bathymetric contours. These data were digitized and used jointly to reconstruct the 1965 bathymetric surface. Because this reconstructed bathymetric surface provides the earliest post-construction representation of the seabed adjacent to the newly completed Ashdod Port breakwater system, its consistency was additionally evaluated against the 1957 and 1959 pre-construction datasets. The resulting spatial pattern of seabed change was morphologically coherent with the expected early adjustment following port construction; this comparison was used as a consistency check rather than as an independent quantitative validation of survey accuracy.

3.2. Bathymetric and Topographic Data Sources

The bathymetric–topographic elevation datasets analyzed in this study were obtained from systematic hydrographic and geodetic survey records spanning 1957–2025 conducted by governmental institutions, including the Israel Ports Authority (IPA), Israel Oceanographic and Limnological Research (IOLR), and the Israel Ports Company/Israel Ports Development & Assets Company Ltd. (IPC), as well as by private hydrographic survey companies, including OCEANA Marine Research Ltd., EDT Marine Construction, LIA Surveying & Engineering Services Ltd., and Northern Arrow Mapping & Engineering Ltd. (Table 2). These surveys provide repeated measurements extending from the backshore ($+5$ m relative to the ILSD) to ~ 20 m water depth, forming the primary quantitative basis for evaluating long-term seabed evolution, shoreline migration, and sand redistribution adjacent to Ashdod Port. As described in Section 3.1, the original spatial sampling density varied with survey method and water depth, whereas the interpolated surfaces used for volumetric comparison were generated on uniform computational grids.

Several bathymetric–topographic survey campaigns were conducted over periods spanning two calendar years (Table 2). For consistency throughout the Results section and all subsequent analyses, each survey campaign is designated by the calendar year in which field acquisition commenced. Accordingly, the 1969–1970, 2005–2006, 2015–2016, and 2017–2018 survey campaigns are hereafter referred to as the 1969, 2005, 2015, and 2017 surveys, respectively. Time intervals (Δ years) between successive surveys were calculated using these reference years. The same convention was applied to all long-term survey comparisons.

The first dataset consists of digitized historical bathymetric surveys conducted in 1957, 1959, 1969–1970, 1975, 1980, 1983, and 1985, together with the 1965 post-construction nautical chart of Ashdod Port (Figure 5). These historical datasets correspond to the bathymetric–topographic maps documented and analyzed by Golik et al. (1996) [19,20]. Digital files derived from the original analog maps were kindly provided by Mr. Arik Golan of IOLR, who participated in the original study, including the volumetric-change analysis. The historical bathymetric surveys were originally compiled as analog Fair Sheets prepared by the Israel Ports Authority (IPA), and later digitized by IOLR into XYZ files referenced to the Israeli Cassini–Soldner (ICS) coordinate system and vertically to the ILSD, using the Modified Clarke 1880 ellipsoid. These fair sheets preserve the original hydrographic survey information and differ from the 1965 dataset described below, for which the original fair sheet was not available.

Because the 1965 post-construction nautical chart represents the earliest bathymetric–topographic dataset documenting coastal adjustment immediately following completion of the original port, the chart [43] was scanned, georeferenced to the same coordinate system and vertical datum, and converted into digital vector data for subsequent analysis. The available chart contains both individual depth soundings and bathymetric contours at 5 m vertical intervals; both types of information were digitized and incorporated into the reconstruction of the 1965 bathymetric surface. Because the original fair sheet was unavailable, this dataset was treated separately during quality control. Its morphological consistency was evaluated against the 1957 and 1959 pre-construction surfaces, as described in Section 3.1.

The second dataset comprises high-resolution digital bathymetric–topographic surveys collected between 1995 and 2025 for the IPA and later for the IPC. These surveys encompass most of the study area, extending approximately 6 km south and 6.3 km north of Ashdod Port. Most datasets cover the cross-shore zone from the backshore (+5 m relative to the ILSD) to the ~20 m isobath, thereby encompassing the coastal zone and adjacent inner-shelf domain analyzed in this study. Within individual surveys, the final digital surface may integrate land-based topographic measurements, SBES observations, and, from 2009 onward, MBES observations. Consequently, the spatial density of the source measurements varies across the cross-shore profile even where the final DEM is represented by a uniform grid.

Since 2023, recurrent GPS reception and positioning disruptions, together with operational restrictions for security reasons, have constrained the ability to conduct complete conventional hydrographic surveys throughout the study area, particularly north of Ashdod Port. Consequently, the 2021 survey represents the most recent dataset providing complete coverage of the study area using the conventional hydrographic survey configuration. During the 2025 campaign, high-resolution MBES data acquired by LIA Surveying & Engineering Services Ltd. provided seabed coverage generally from ~5 m water depth seaward, but complete coverage of the required study area could not be obtained. To supplement the missing coastal and shallow-water coverage, high-resolution airborne topo-bathymetric LiDAR data acquired by Northern Arrow Mapping & Engineering Ltd.

on 6 February 2026 were incorporated. The LiDAR survey extended from the backshore to approximately 15 m water depth and overlapped with the MBES coverage. The two datasets were spatially integrated to provide the most complete bathymetric–topographic representation available for the 2025 survey campaign. For consistency with the survey-year convention adopted throughout the study, this integrated surface is referred to as the 2025 dataset, reflecting the year in which the principal marine survey campaign commenced.

The ~20 m depth limit was adopted because: (1) the MBW head was constructed at ~15 m depth within the active transport zone; (2) published closure-depth estimates for the Israeli Mediterranean coast are generally shallower than ~10 m, although seabed adjustment may extend farther offshore during major storm events; and (3) the ~20 m isobath provides a consistent seaward boundary for comparison among surveys with different offshore coverage. Although most surveys extend seaward to ~30 m water depth, restricting the volumetric analysis to ~20 m also avoids artifacts associated with differences in offshore survey coverage.

Where survey coverage permitted, relatively stable offshore areas were used as reference areas for quality control and vertical harmonization. Candidate reference areas were identified from DEM-difference maps in sectors sufficiently distant from the principal zones of port-induced accretion and erosion and generally at water depths where profile adjustment is expected to be limited. Their final selection was based on spatially coherent low-magnitude elevation differences rather than on a fixed depth range, as described below.

Until 2009, surveys were referenced to the ICS and the former ILSD. Since 2009, all data have been referenced to the ITM projection and the updated ILSD based on the GRS-80 ellipsoid. All shoreline and elevation data were transformed into this unified horizontal and vertical reference framework, ensuring spatial and temporal consistency across the multi-decadal dataset. For historical datasets, transformation to a common reference framework was followed by additional quality-control procedures to identify and, where justified, correct systematic vertical offsets before DEM differencing and volumetric analysis.

The spatial coverage of the bathymetric–topographic data varies between survey years, and additional survey campaigns were available beyond those selected for the quantitative analyses presented in Table 2. During the first study period (1957–1995), the otherwise valid 1959, 1980, and 1983 surveys were not included in the quantitative volumetric analysis because their spatial coverage was insufficient for consistent comparison across the required southern and northern study areas. The 1959 survey was nevertheless used as an independent control for assessing the consistency and vertical calibration of the 1957 and 1965 datasets.

For the second study period (1995–2025), datasets providing the greatest spatial coverage were selected, with a minimum interval of approximately two years between consecutive surveys. The 2024 and 2025 surveys were additionally used as independent controls against the 2021 dataset for the southern study area. Table 2 therefore presents the principal datasets selected for the quantitative volumetric analysis rather than a complete inventory of all available surveys.

The resulting bathymetric–topographic database provides a coherent spatio-temporal framework for the quantitative reconstruction of long-term seabed evolution, shoreline migration, and sand redistribution adjacent to Ashdod Port throughout the 1957–2025 study period.

3.3. Shoreline Data Sources

Shoreline evolution was evaluated primarily using elevation-derived 0 m contours extracted from the bathymetric–topographic datasets presented in Table 2. Digital orthophotos (2005–2025) and analog aerial photographs (1976–2000) supplied by the Survey of Israel (SOI) were used to visually corroborate the elevation-derived shoreline reconstruction,

provide an independent qualitative check on the extracted shoreline positions, and support the interpretation of long-term morphodynamic evolution (Table 3).

Table 3. Selected aerial photographs and digital orthophotos used for supplementary corroboration and interpretation of shoreline evolution along the coasts south and north of Ashdod Port (1976–2025), including acquisition date, data source, image type, spatial resolution, and estimated horizontal accuracy.

Date (DD MM YYYY)	Data Source	Image Type	Spatial Resolution (m)	Estimated Horizontal Accuracy (m)
6 November 1976	Survey of Israel	Analog aerial photograph	0.30	±5–7
19 September 1982				±5–7
1 September 1990				±4–6
11 February 2000				±2–3
30 March 2005	Ofek Aerial Photography Ltd.	Digital Orthophoto	1.00	±1–2
3 September 2009			0.50	<±1
16 July 2014			0.25	~±0.5–1.0
20 November 2022	Northern Arrow Mapping & Engineering Ltd.		0.10	~±0.2–0.5
15 June 2025			0.10	~±0.2–0.5

The imagery also provided an independent visual reference for assessing major shoreline changes identified from the elevation-derived shoreline reconstruction, particularly during periods characterized by substantial beach widening, shoreline retreat, or anthropogenic modification.

All photographs were georeferenced to the ITM coordinate system to ensure compatibility with the bathymetric–topographic datasets. Images were processed in Global Mapper using stable GCPs identified from permanent artificial structures and natural features unaffected by shoreline change.

Because the Ashdod coastal sector has undergone extensive infrastructural development since the 1950s, georeferencing was performed sequentially from the most recent to the oldest imagery using previously rectified orthophotos as intermediate reference layers. GCPs were measured from the 2025 digital orthophoto, which has a spatial resolution of 0.10 m and an estimated horizontal accuracy of approximately ±0.2–0.5 m.

Each aerial photograph was rectified in Global Mapper using an affine transformation based on GCPs. The estimated horizontal accuracies of the resulting georeferenced imagery are presented in Table 3 and should not be interpreted as uncertainty estimates for the elevation-derived 0 m shoreline positions.

The aerial-image processing workflow generally followed the methodology of Zviely et al. (2009) [18]. Only photographs acquired during relatively calm-sea conditions and characterized by clearly distinguishable shoreline positions were retained. Spatial coverage is not uniform throughout the study period, particularly in the early aerial photographs covering the northern part of the study area.

Consequently, aerial photographs and digital orthophotos were not used as the primary source for quantitative shoreline reconstruction. Instead, they served as supplementary visual references for corroborating the elevation-derived shoreline positions, assessing long-term shoreline evolution, and interpreting morphodynamic changes identified from the bathymetric–topographic analyses. The procedure used to extract the 0 m ILSD contour from the interpolated elevation surfaces, together with its associated uncertainty and the method used to quantify shoreline displacement, is described separately below.

3.4. Study Area Segments

To evaluate seabed-volume changes, sand redistribution, and shoreline evolution, the analysis domains were subdivided into alongshore morphodynamic segments across the coastal zone and adjacent inner-shelf domain south and north of Ashdod Port (Figure 13).

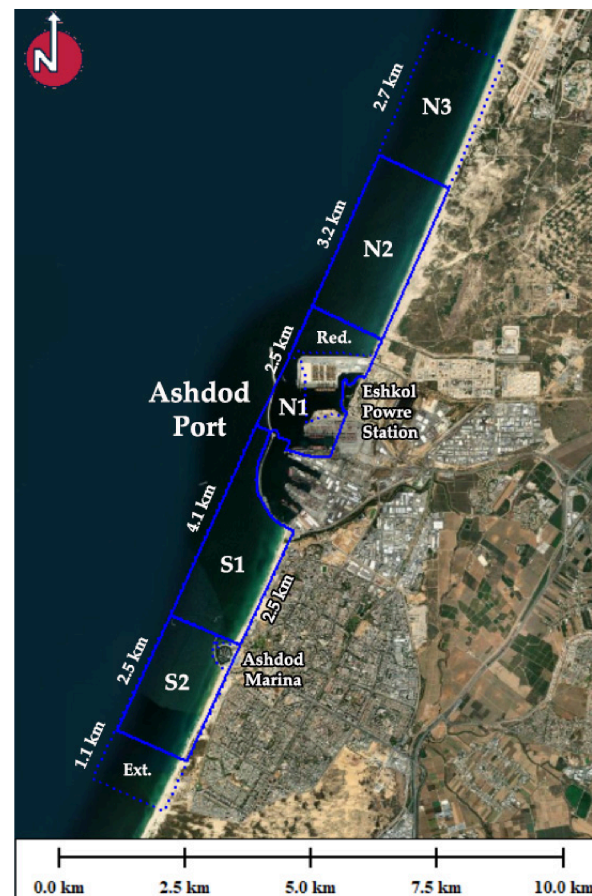


Figure 13. Segments S1–S2 and N1–N2 represent the core comparison areas used in both study periods (1965–1995 and 1995–2025). During the second study period (1995–2025), S2 was extended southward and is designated S2 Ext.; N1 was progressively reduced as a result of port expansion and is designated N1 Red.; and N3 was added north of N2 to extend the downdrift analysis domain. The segment boundaries define the spatial domains used for the volumetric analyses; dotted boundaries indicate areas added or modified during the second study period, including S2 Ext. and N3. Background image: Maxar (Vivid) satellite imagery, acquired on 18 September 2023. © Maxar Technologies. Used with permission.

All segments were bounded landward by a straight backshore baseline at elevations up to +5 m ILSD and seaward by a straight offshore baseline located approximately along the ~20 m water-depth contour. The same cross-shore landward and seaward limits were applied to each segment wherever spatial coverage permitted, thereby maintaining a common cross-shore analysis domain for multi-decadal volumetric comparisons.

The segmentation scheme was designed to accommodate the progressive expansion of Ashdod Port and the changing geometry of the adjacent coastal system while maintaining clearly defined spatial units for quantitative comparison between successive survey periods. Segment boundaries were selected to represent morphodynamically distinct coastal sectors and to allow independent evaluation of sand accumulation, erosion, shoreline migration, and sand redistribution within the southern (updrift) and northern (downdrift) analysis domains.

Compared with previous studies [19,20], which considered only two principal coastal sectors, the present study adopts a refined segmentation reflecting the substantially larger spatial extent of the analyzed domain and the progressive modifications associated with port expansion (Figure 13).

The first study period (1965–1995), extending from the first post-construction bathymetric map of Ashdod Port to the beginning of construction of Ashdod Marina, was subdivided into two southern and two northern segments. South of the port, S1 extended ~2.5 km from the root of the MBW southward, while S2 covered the following ~2.5 km farther south. Together, these two southern segments represented ~5.0 km alongshore. The corresponding analysis areas were 4.557 km² for S1 and 3.820 km² for S2. North of the port, N1 extended ~2.5 km immediately north of the LBW, and N2 spanned an additional ~3.2 km farther north, giving a combined northern length of ~5.7 km. The corresponding analysis areas were 3.933 km² for N1 and 4.987 km² for N2.

The second study period (1995–2025), extending from the beginning of construction of Ashdod Marina through subsequent port expansions, was subdivided into two southern and three northern segments. South of the port, the configuration of S1 remained essentially unchanged, extending ~2.5 km from the MBW root to the head of the Marina's MBW. Its analysis area increased slightly from 4.557 km² in 1995 to 4.598 km² from the 2000 survey onward because the entrance to Ashdod Marina was incorporated into the analysis domain. S2 was extended by ~1.1 km to a total length of ~3.6 km, designated as S2 Ext., with the marina basin excluded from the analysis domain. The area of S2 Ext. was 5.201 km².

North of the port, N1 was renamed N1 Red. because its extent was progressively reduced by successive stages of port expansion. The original N1 domain had an area of 3.933 km² in 1995. By the 2000 survey, excavation and construction associated with the first major port expansion had reduced the available N1 analysis domain to 2.310 km²; this reduced domain is designated N1 Red. A further reduction associated with the South Port expansion decreased the N1 Red. analysis area to 1.042 km² from 2015 onward. Following completion of the South Port (Figure 7), only ~360 m of shoreline remained north of the South Port's secondary breakwater. N2 retained its ~3.2 km length and its 4.987 km² analysis area, while a new northernmost segment, N3, was added, extending ~2.7 km farther north and covering 4.087 km². After completion of the South Port, the combined alongshore length of the three northern segments was ~6.3 km.

For integrated volumetric assessment, Total South was calculated as the sum of the net volumetric changes in the constituent southern segments (S1 and S2, or S1 and S2 Ext. where applicable), whereas Total North was calculated as the sum of the corresponding northern segments (N1 and N2, or N1 Red., N2, and N3 where applicable). Integrated totals were reported only when volumetric data were available for all constituent segments included in the corresponding analysis domain.

The same segment framework was also used to spatially assign documented dredging and sand-placement operations to the volumetric analysis. Dredged and placed sand volumes were assigned to the corresponding segments according to the documented locations of the operations. These assignments provide the spatial basis for relating the intervention records to the DEM-derived volumetric changes, as described in Section 3.5 and presented in Section 4.2.

Because the geometries of some analysis segments changed during the study period, a strict common-area principle was applied to all volumetric comparisons. For every pair of surveys, irrespective of the time interval between them, the volume difference was calculated exclusively within the spatial domain common to both datasets. Any area absent from, or excluded from, either survey was also excluded from the other survey before DEM differencing. This procedure was applied consistently to both successive and

long-term comparisons. Consequently, all pairwise volume changes represent elevation differences calculated over identical spatial domains, thereby preventing differences in segment area or survey coverage between the compared datasets from directly biasing the calculated volume change. The same procedure was applied to the long-term comparisons referenced to the 1965 nautical chart. Although the 1965 dataset produced the coarsest automatically determined DEM grid among the datasets used in this study, the sensitivity assessment demonstrated that the resulting multi-decadal volumetric estimates are robust to differences in DEM grid resolution. Accordingly, the 1965 dataset was retained as the reference dataset for evaluating long-term morphological change over the 60-year period.

3.5. Elevation Analysis Methods

Morphological changes across the coastal zone and adjacent inner shelf were quantified using differential elevation and volumetric analyses of selected bathymetric–topographic datasets derived from digitized historical charts and modern hydrographic surveys.

All datasets were reprojected to the ITM coordinate system and interpolated into continuous digital elevation models (DEMs) using the “Create Elevation Grid from 3D Vector Data” function in Global Mapper.

Elevation grids were generated in Global Mapper v24.1 using the software’s default Triangulated Irregular Network (TIN) gridding algorithm. No alternative interpolation algorithm or grid-cell dimensions were manually prescribed for the DEMs used in the primary analysis. For each dataset, the “Automatically Determine Optimal Grid Spacing” option was applied, resulting in dataset-specific X- and Y-grid spacing values (Table 2). The resulting grid spacing does not represent the original measurement spacing or imply uniform source-data resolution across the survey area. Rather, each DEM integrates the available measurements from the different survey methods described in Sections 3.1 and 3.2, whose spatial density varies with water depth and acquisition technique.

The same automatic TIN-based gridding procedure was applied consistently to all datasets throughout the multi-decadal analysis. The sensitivity of the calculated volumes to DEM grid spacing was additionally evaluated for the 1965–1995 comparison, which incorporates the coarsest automatically generated grid in the dataset and therefore provides a conservative test of grid-resolution sensitivity. The 1965 source data were regridded using manually specified cell dimensions of 30 m × 30 m and 60 m × 60 m, bracketing the automatically determined 44.273 m × 41.414 m grid used in the primary analysis. All other processing parameters, the 1995 DEM, vertical correction, segment boundaries, and common-area procedure were held unchanged.

Before DEM differencing, the interpolated surfaces were subjected to spatial and vertical quality control. Where survey coverage permitted, candidate offshore reference areas were identified from preliminary DEM-difference maps in sectors sufficiently distant from the principal zones of port-induced accretion and erosion and generally at water depths where profile adjustment was expected to be limited. Reference-area selection was based on spatially coherent, low-magnitude elevation differences rather than on a predetermined depth interval. Difference maps displayed at 0.25 m elevation intervals were used for this quality-control screening because the finer visualization scale facilitated the identification of low-magnitude spatial patterns. This 0.25 m interval was used solely as a visualization aid and was not applied as an elevation-change threshold in the quantitative analysis.

For each candidate reference area, the mean elevation difference (mean Δz) between the compared DEMs was calculated. A spatially uniform residual difference was interpreted as a systematic vertical bias when it was consistent with the broader spatial pattern of the DEM comparison and could not be attributed to coherent morphodynamic change. Systematic vertical offsets identified primarily in historical datasets were corrected by ap-

plying a uniform vertical adjustment to the corresponding elevation surface relative to these morphologically stable reference areas before volumetric comparison. A uniform vertical correction was applied only where the observed elevation difference was interpreted as a spatially systematic bias. Spatially coherent patterns of erosion or accumulation were interpreted as morphodynamic signals and were therefore retained rather than removed through vertical correction. No elevation-change threshold was applied to remove or suppress small Δz values after vertical harmonization; all elevation differences within the common analysis domain were retained in the volumetric calculations. Datasets exhibiting substantial or spatially inconsistent vertical inconsistencies that could not be reliably resolved were excluded from the quantitative analysis.

DEMs from selected survey years were compared by subtracting the earlier elevation surface from the later surface, thereby generating differential DEMs representing spatial patterns of erosion and sand accumulation. Comparisons included both successive survey intervals and selected longer-term intervals used to quantify cumulative morphodynamic change. For the long-term synthesis, the 1965 DEM was additionally used as a common reference surface for comparisons with subsequent surveys through 2025, providing a consistent baseline for evaluating cumulative morphological change over periods of 30–60 years. For every DEM pair, the analysis was restricted to the spatial domain common to both datasets, following the common-area principle described in Section 3.4. These differential DEMs were visualized using color maps, cross-sections, and three-dimensional perspectives to facilitate the interpretation of long-term morphodynamic evolution throughout the study area. For presentation of the regional DEM-difference maps, a 0.50 m color interval was used to emphasize the dominant spatial patterns of multi-decadal seabed change and reduce visual emphasis on small-scale variability. As noted above, this display interval does not constitute a quantitative threshold; the underlying continuous Δz values were retained for all volumetric calculations.

Sand-volume changes were calculated by integrating vertical elevation differences between the compared DEMs over each predefined coastal segment using the “Measure Volume Between Surfaces” function in Global Mapper. For each DEM pair, volume integration was restricted to the common spatial area of the two compared surfaces, as described in Section 3.4. This procedure provided quantitative estimates of erosion and accumulation volumes for each survey interval and formed the basis for reconstructing long-term sand budgets.

The analysis domain extended from the backshore baseline (+5 m ILSD) to the ~20 m water-depth contour, encompassing the coastal zone and adjacent inner-shelf domain analyzed in this study.

Documented dredging, sand bypassing, and beach nourishment operations were considered when interpreting the volumetric analyses. The DEM-derived volume changes represent the net measured morphological change between surveys and therefore include the combined effects of natural sand redistribution and any anthropogenic sand removal or placement occurring within the analysis domain during the corresponding interval.

To distinguish the measured morphological change from the direct volumetric contribution of documented human interventions, dredged and placed sand volumes were assigned to the relevant analysis segments and DEM-comparison intervals according to their documented locations and operation dates in relation to the actual survey periods of the corresponding DEMs. Sand removed from an analysis segment was added to the corresponding DEM-derived volume change, whereas sand placed within a segment was subtracted. Sand dredged from an analysis segment was treated as removal from that segment irrespective of its subsequent destination; where the dredged sand was placed within another analysis segment, the corresponding placement volume was also accounted

for in that receiving segment. Sand transported to nourishment sites outside the study area therefore contributed only to the removal adjustment. The resulting adjusted values separate the documented direct volumetric contribution of dredging and placement from the net DEM-derived morphological change. The intervention records, their spatial assignment to the analysis segments, and their application to the corresponding DEM-comparison intervals are presented in Section 4.2.

Port basins, navigation channels, and designated offshore disposal areas were excluded from the volumetric calculations because these areas are directly affected by engineering activities rather than natural morphodynamic processes.

Uncertainty in the DEM-derived elevation and volumetric changes reflects the combined effects of survey positioning and elevation accuracy, spatial sampling density, interpolation, grid resolution, and spatial coverage. Rather than assigning generalized percentage uncertainties to historical and modern surveys, residual vertical uncertainty after harmonization was evaluated empirically from the distribution of elevation differences within the selected morphologically stable reference areas. For each reference-area comparison, the mean Δz was used to evaluate residual vertical bias, while the standard deviation (SD) characterized the spatial dispersion of the elevation differences.

The root-mean-square elevation difference (RMSE) was calculated as

$$\text{RMSE} = \sqrt{[(\text{mean } \Delta z)^2 + \text{SD}^2]}$$

The reference-area analyses yielded mean residual elevation differences generally within several centimeters of zero after harmonization. For example, in the southern offshore reference area, mean Δz was -0.028 m for 1965–1995, $+0.012$ m for 1995–2025, and -0.016 m for the full 1965–2025 interval, with corresponding RMSE values of approximately 0.165, 0.144, and 0.132 m, respectively. For the higher-resolution 2015–2021 comparison, the corresponding RMSE decreased to approximately 0.079 m. These values provide empirical measures of residual DEM-difference variability and demonstrate the progressive improvement in survey consistency among the more recent datasets.

To evaluate the potential influence of residual vertical uncertainty on the calculated sand-volume changes, the reference-area RMSE was propagated conservatively over the corresponding common analysis area. For a segment of area A, a conservative volumetric uncertainty bound was estimated as:

$$\text{UV} = \text{RMSE} \times A$$

where UV is the potential volumetric uncertainty (m^3), RMSE is the empirical residual elevation uncertainty (m) derived from the corresponding reference area, and A is the common comparison area (m^2). This formulation represents a conservative uncertainty bound because it assumes that the residual vertical uncertainty acts coherently over the entire analysis area; it is therefore not interpreted as a statistical confidence interval. The resulting uncertainty bounds were used to evaluate whether the magnitude and direction of the observed volumetric changes were robust relative to the residual DEM uncertainty. These uncertainty bounds quantify uncertainty in the DEM-derived volumetric changes and should not be interpreted as demonstrating sediment-budget closure, because sediment fluxes across the open boundaries of the analysis domains were not directly measured.

Grid-resolution sensitivity was assessed independently using the 1965–1995 comparison described above. Relative to the automatically determined 1965 grid (44.273×41.414 m), regriding the same source data at 30×30 m and 60×60 m changed the calculated net accumulation in S1 by only $+0.22\%$ and -0.14% , respectively, and the net erosion in N2 by $+0.37\%$ and -0.28% , respectively. These two segments contain the dominant volumetric

signals for the 1965–1995 period ($\sim +4.5 \times 10^6 \text{ m}^3$ in S1 and $\sim -4.4 \times 10^6 \text{ m}^3$ in N2). The direction of net change was preserved in all four analyzed segments (S1, S2, N1, and N2) across all three grid resolutions. Larger relative percentage differences in the near-balanced S2 and N1 segments reflect their small net volumes and were therefore evaluated together with absolute volume differences and mean Δz rather than percentage change alone.

3.6. Shoreline Analysis Methods

Quantitative shoreline-change analyses were based on elevation-derived 0 m contours extracted from the bathymetric–topographic datasets. This approach was adopted because the objective of the present study was to reconstruct long-term morphodynamic shoreline evolution rather than instantaneous shoreline position. Shoreline positions interpreted from digital orthophotos and orthorectified aerial photographs were used as independent datasets for visual corroboration of the elevation-derived shoreline reconstruction, assessment of shoreline continuity, and interpretation of long-term morphodynamic evolution. Where temporally proximate aerial imagery was available, waterlines mapped from the orthorectified imagery were compared with the elevation-derived shorelines as an independent consistency check. The two shoreline indicators showed comparable spatial patterns and long-term trends, providing an independent consistency check on the elevation-derived reconstruction.

For each survey, the bathymetric–topographic elevation data were interpolated to generate continuous digital elevation models (DEMs), from which the 0 m contour was extracted. All shoreline datasets were referenced to the ITM coordinate system and the Israel Land Survey Datum (ILSD), ensuring spatial consistency throughout the multi-decadal analysis. Thus, the same elevation-based shoreline indicator and extraction procedure were applied consistently to all survey years, irrespective of the original survey method or data density.

Shoreline change was quantified using the Mean Width (MW) method, applied independently to each predefined analysis segment (Figure 13). Within each segment, a polygon was delineated between the shoreline (0 m ILSD contour) and a fixed straight landward baseline. The polygon was closed by fixed northern and southern segment boundaries, which coincided with the roots of the Ashdod Port MBW and the Ashdod Marina LBW where applicable.

For each survey, the area of the polygon enclosed by the shoreline (0 m ILSD contour), the fixed landward baseline, and the fixed northern and southern segment boundaries was measured in Global Mapper (Figure 14). The Mean Width (MW) was calculated by dividing the polygon area by the fixed length of the landward baseline (L_s), thereby representing the average shoreline position relative to a constant geometric reference. The northern and southern segment boundaries served solely to delimit and close the polygon and were not included in the baseline length used to calculate MW. Because the reference boundaries remain unchanged throughout the analysis, the calculated MW values depend solely on changes in shoreline position between successive surveys. For each survey, MW was calculated as:

$$MW = A/L_s$$

Temporal shoreline migration was quantified as:

$$\Delta MW = MW_2 - MW_1 = \frac{L_s}{A_2} - A_1$$

where A_1 and A_2 are the polygon areas (m^2) of the reference and comparison shoreline surveys, respectively, and L_s is the fixed length (m) of the landward baseline defining the corre-

sponding coastal segment. Positive ΔMW values indicate shoreline progradation (seaward migration), whereas negative ΔMW values indicate shoreline retreat (landward migration).



Figure 14. Geometric definition of the variables used in the Mean Width (MW) shoreline analysis for Segment S1. The example is shown on a satellite image overlaid with the elevation-derived 0 m ILSD contour for 2025 (red). Segment S1 extends from the root of the Ashdod Marina LBW northward to the root of the Ashdod Port MBW. The analysis polygon is enclosed by the shoreline (0 m ILSD contour), a fixed straight landward baseline (L_s), and fixed northern and southern segment boundaries (blue). The polygon area (A) is used to calculate the Mean Width (MW) by dividing A by the fixed baseline length (L_s). Background image: Maxar (Vivid) satellite imagery, acquired on 18 September 2023. © Maxar Technologies. Used with permission.

The MW method provides a robust measure of long-term shoreline change by quantifying the average shoreline position over entire coastal segments rather than along individual transects, thereby reducing the influence of localized shoreline irregularities.

Conceptually, MW represents the alongshore spatial integral of the distance between the fixed baseline and the shoreline, normalized by the baseline length. If denotes the local cross-shore distance from the baseline to the shoreline along the segment, MW can therefore be expressed as:

$$MW = \frac{1}{L_s} \int_0^{L_s} w(x) dx$$

Accordingly, the MW approach is equivalent to averaging shoreline position over a continuous set of cross-shore transects distributed along the entire segment, rather than sampling shoreline displacement at a finite number of discrete transects. This spatial integration is particularly appropriate for the present study because the objective is to quantify segment-scale shoreline evolution over coastal reaches several kilometers long and to compare these changes with integrated volumetric seabed changes over the corresponding domains. Conventional discrete-transect methods remain advantageous where localized shoreline responses at specific sites or individual coastal structures are the primary focus; however, such localized variability is not the principal metric examined here. In the present

analysis, shoreline change is therefore treated as a complementary two-dimensional morphodynamic indicator to the primary three-dimensional volumetric assessment of sand redistribution across the analysis domain.

Compared with the previous comprehensive shoreline assessment of the Ashdod coast by Golik et al. [19,20], which reconstructed shoreline evolution from grouped historical aerial photographs, the present study quantifies shoreline migration using discrete elevation-derived 0 m shoreline positions integrated with the corresponding volumetric analyses.

The accuracy of shoreline-change estimates depends primarily on the quality of the bathymetric–topographic surveys, survey accuracy, foreshore slope, and interpolation accuracy. Elevation measurements across the beach and very shallow-water zone (0–1.5 m water depth) were obtained using geodetic surveying methods rather than vessel-mounted echo sounders. Except for 1965, for which the shoreline was shown on the historical nautical chart, the quantitative shoreline positions were extracted as interpolated 0 m ILSD contours from the same elevation grids used in the morphodynamic analysis. Their positional accuracy therefore reflects the horizontal and vertical accuracy and spatial density of the source survey data, together with the interpolation used to generate each DEM. The survey-specific positioning accuracies reported in Table 2 provide the general accuracy framework for the source measurements, while the DEM quality-control and grid-resolution sensitivity analyses described in Section 3.5 provide additional assessment of the resulting elevation surfaces. The elevation-derived 0 m ILSD contour is a fixed datum-based shoreline indicator and does not represent the instantaneous wet/dry boundary visible in aerial imagery, which varies with water level, wave conditions, and run-up. Accordingly, the image-derived wet/dry boundaries were not used to determine the absolute positional accuracy of the 0 m contours. Instead, selected high-resolution digital orthophotos acquired at dates close to the corresponding surveys were used as an independent check of the spatial consistency and long-term trends shown by the elevation-derived shorelines.

The multi-year to decadal comparison intervals and segment-averaged MW approach were intended to emphasize persistent shoreline trends over short-term fluctuations associated with individual storm events or seasonal beach variability.

4. Results

Bathymetric–topographic and shoreline datasets spanning 1957–2025 provide a long-term record extending over nearly seven decades, including six decades of port-induced morphodynamic evolution adjacent to Ashdod Port, and form the basis for quantifying long-term changes in nearshore morphology, sand redistribution, and shoreline position. The analyses distinguish two spatial domains: a southern (updrift, depositional) nearshore area and a northern (downdrift, erosional) nearshore area, together with two chronological phases: Phase I (1965–1995), extending from port construction to the establishment of Ashdod Marina, and Phase II (1995–2025), encompassing marina construction and the subsequent offshore expansion of Ashdod Port. Results are presented separately for (1) seabed morphological and volumetric evolution and (2) shoreline evolution within the predefined analysis segments (Figure 13).

4.1. Seabed Morphological and Volumetric Changes 1965–1995

Between 1965 and 1995, Ashdod Port induced a pronounced morphodynamic asymmetry characterized by extensive sand accumulation south of the MBW and widespread seabed erosion north of the port. Differential elevation maps (Figure 15) and volumetric analyses (Table 4) quantify the magnitude and spatial evolution of this sand redistribution during the first three decades following port construction.

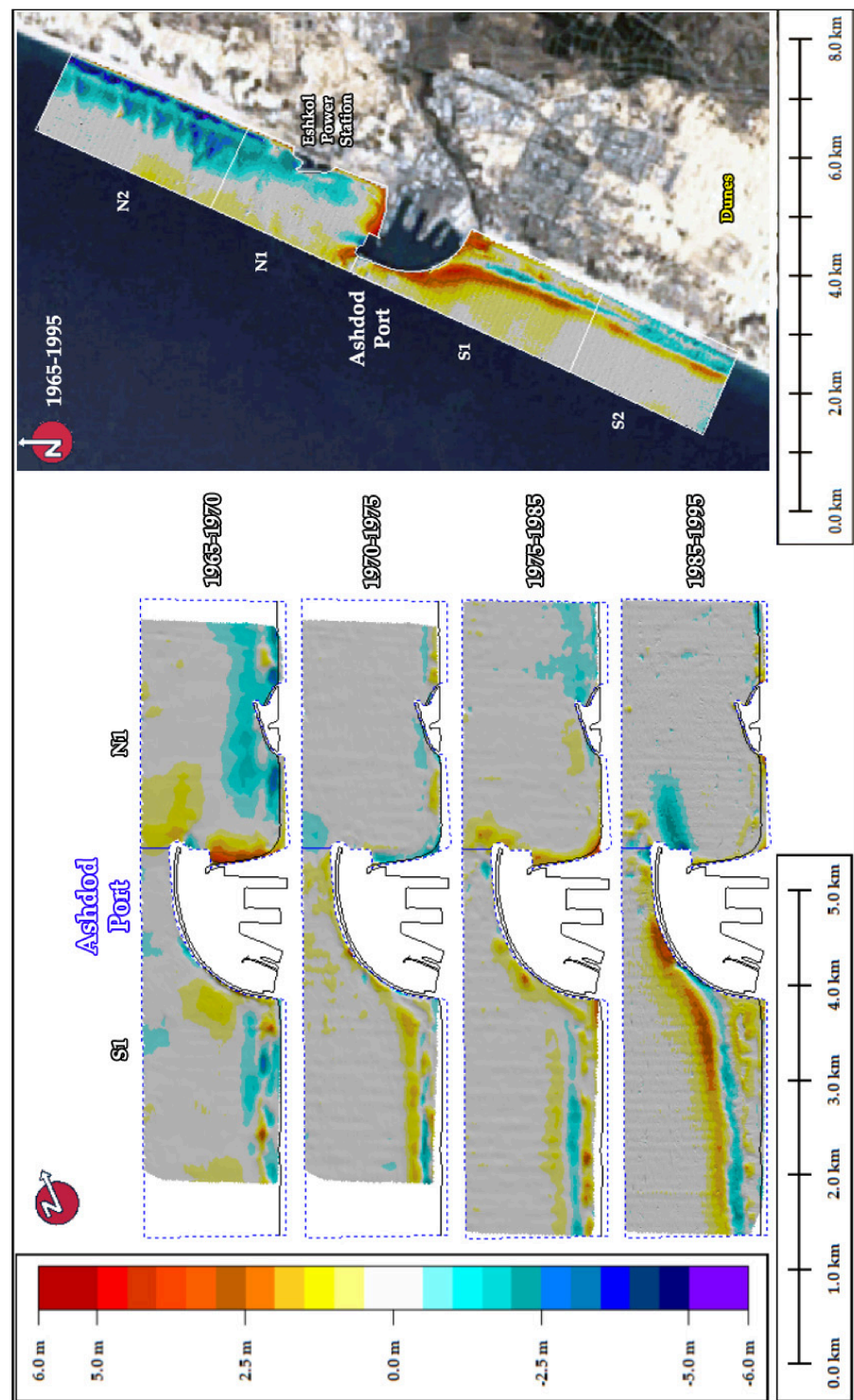


Figure 15. Differential elevation maps illustrating seabed morphological changes within the study area during the periods 1965–1969, 1969–1975, 1975–1985, 1985–1995, and over the full period 1965–1995. Segments S1–S2 (southern nearshore area) and N1–N2 (northern nearshore area) define the spatial domains used for quantitative bathymetric and volumetric analyses. Dashed lines indicate the boundaries between the coastal segments. Background image: © Google Earth, satellite imagery acquired 31 December 1984. Source: <https://earth.google.com> (accessed on 25 June 2025).

Table 4. Net seabed volumetric changes during Phase I (1965–1995) for the predefined southern (S1–S2) and northern (N1–N2) coastal segments. Total South and Total North represent integrated DEM-derived volumetric changes across the complete southern and northern analysis domains, respectively, and are reported only where complete spatial coverage of all constituent segments was available. Positive values indicate net sand accumulation, whereas negative values indicate net sand erosion.

Comparison Period	Δ Years	S1 ΔV (10^3 m^3)	S2 ΔV (10^3 m^3)	Total South ΔV (10^3 m^3)	N1 ΔV (10^3 m^3)	N2 ΔV (10^3 m^3)	Total North ΔV (10^3 m^3)
1965–1969	4	325 *	N/D	—	−61	N/D	—
1965–1975	10	1334	N/D	—	−397	−873 *	—
1965–1985	20	2513	N/D	—	−104	N/D	—
1965–1995	30	4497	11	4508	−128	−4424	−4552 †
1969–1995	26	3704 *	N/D	—	205	N/D	—
1975–1995	20	2951	N/D	—	175	−604 *	—
1985–1995	10	1964	N/D	—	−40	N/D	—

Abbreviations: N/D = data not available; — = integrated total not calculated because complete spatial coverage of all constituent segments was unavailable. * Partial spatial coverage of the corresponding segment. † DEM-derived Total North volume change. During 1985–1995, approximately $354 \times 10^3 \text{ m}^3$ of sand were dredged from Segment N1 and disposed offshore outside the study area. After accounting for this dredging, the adjusted northern sand balance for 1965–1995 was approximately $-4198 \times 10^3 \text{ m}^3$.

4.1.1. Southern Nearshore Segments S1–S2

A large depositional sand body progressively developed immediately adjacent to the seaward side of the MBW during the study period. This feature subsequently extended southward along the MBW while simultaneously prograding seaward and alongshore within Segment S1 (Figure 15).

Differential elevation maps for the four survey intervals (1965–1969, 1969–1975, 1975–1985, and 1985–1995), together with the 1965–1995 elevation-difference map, consistently document the progressive growth of this depositional feature, whereas only minor seabed changes occurred within Segment S2. These patterns delineate the spatial extent of the depositional zone that developed immediately south of the MBW.

Among the four survey intervals, the period 1985–1995 exhibited the highest accumulation rate within Segment S1 (Table 4). Over the 30-year study period, Segment S1 accumulated $4.50 \times 10^6 \text{ m}^3$ of sand, corresponding to a mean annual accumulation rate of $150 \times 10^3 \text{ m}^3/\text{yr}$. Nearly 44% of this total volume ($1.98 \times 10^6 \text{ m}^3$) accumulated during the final decade (1985–1995), when the mean annual accumulation rate increased to $196 \times 10^3 \text{ m}^3/\text{yr}$. Across the complete southern analysis domain (S1 + S2), the net volumetric increase between 1965 and 1995 was $4.51 \times 10^6 \text{ m}^3$, corresponding to a mean annual rate of $150 \times 10^3 \text{ m}^3/\text{yr}$ (Table 4).

4.1.2. Northern Nearshore Segments N1–N2

Between 1965 and 1995, the northern nearshore area experienced progressive and spatially variable seabed erosion. The greatest sand loss occurred within Segment N2, located approximately 2.5–5.8 km north of the port's LBW (Figure 15).

Between 1965 and 1995, Segment N2 lost $4.42 \times 10^6 \text{ m}^3$ of sand, closely matching the $4.50 \times 10^6 \text{ m}^3$ accumulated within Segment S1 (Table 4). The mean annual erosion rate ($147 \times 10^3 \text{ m}^3/\text{yr}$) was nearly identical in magnitude and opposite in sign to the mean annual accumulation rate ($150 \times 10^3 \text{ m}^3/\text{yr}$) observed within Segment S1. Across the complete northern analysis domain (N1 + N2), the DEM-derived volume loss between 1965 and 1995 reached $4.55 \times 10^6 \text{ m}^3$, corresponding to a mean annual rate of $-152 \times 10^3 \text{ m}^3/\text{yr}$.

During 1985–1995, however, $0.354 \times 10^6 \text{ m}^3$ of sand was dredged from N1 and disposed of offshore outside the study area. After accounting for this dredging, the adjusted northern sand balance for 1965–1995 was approximately $-4.20 \times 10^6 \text{ m}^3$, corresponding to a mean annual rate of $-140 \times 10^3 \text{ m}^3/\text{yr}$.

Erosion within Segment N2 extended across a broad cross-shore zone. The principal zone of sand loss occurred between the backshore and approximately 5 m water depth, with additional localized erosion between 6 and 10 m water depth. Beyond 10 m, erosion became progressively more localized and was largely confined to the southern part of the segment.

Segment N1 exhibited a more spatially variable morphodynamic response than Segment N2. Although localized erosion characterized much of the study period, the magnitude of seabed change remained considerably smaller than that observed within Segment N2.

Integrated Total South and Total North values were calculated only for comparisons with complete spatial coverage of all constituent segments. During Phase I, complete coverage of both domains was available for the 1965–1995 comparison. Over this 30-year period, Total South accumulated $4.51 \times 10^6 \text{ m}^3$ of sand, corresponding to a mean annual accumulation rate of $150 \times 10^3 \text{ m}^3/\text{yr}$. The DEM-derived volume change in Total North was $-4.55 \times 10^6 \text{ m}^3$. During 1985–1995, however, $0.354 \times 10^6 \text{ m}^3$ of sand were dredged from N1 and disposed offshore outside the study area. Accounting for this dredging gives an adjusted northern sand balance of approximately $-4.20 \times 10^6 \text{ m}^3$, equivalent to $-140 \times 10^3 \text{ m}^3/\text{yr}$ over 1965–1995.

The northern nearshore area was characterized by persistent seabed erosion dominated by Segment N2, whereas morphodynamic adjustment immediately adjacent to the port (Segment N1) remained comparatively limited. The results show that the principal downdrift morphodynamic response to construction of Ashdod Port extended several kilometers beyond the immediate vicinity of the breakwaters.

Segment S2 exhibited negligible net volumetric change over the complete 1965–1995 comparison ($+11 \times 10^3 \text{ m}^3$), in marked contrast to the substantial accumulation recorded in Segment S1 ($+4.50 \times 10^6 \text{ m}^3$).

4.2. Seabed Morphological and Volumetric Changes 1995–2025

Between 1995 and 2025, the nearshore area adjacent to Ashdod Port underwent continued morphodynamic evolution characterized by persistent sand accumulation south of the MBW and persistent seabed erosion north of the port. Differential elevation maps (Figures 16 and 17) illustrate the progressive evolution of the study area throughout Phase II.

Interpretation of the DEM-derived volumetric changes during Phase II requires consideration of the documented sand dredging, bypassing, and placement operations. During Phase II, sand was repeatedly dredged from the southern nearshore area and either bypassed to the northern side of the port or transported to nourishment sites outside the study area. Sand dredged from the port approach channel, inner basin, and dock areas was also periodically placed north of the port. Table 5 summarizes the documented dredging, bypassing, and placement operations relevant to the volumetric analysis.

For the sand-balance calculations presented in Tables 6–8, the DEM-derived volumetric changes were adjusted for these documented interventions. Sand dredged from a given analysis segment was added to the measured volumetric change, whereas sand placed within a segment was subtracted. The original unadjusted DEM-derived volumetric changes are provided in Appendix A (Tables A1–A3), corresponding to Tables 6–8, respectively. This distinction allows the measured morphological change, representing

sediment-storage change within the analysis domain, to be separated from the sand balance after accounting for documented sediment-management operations.

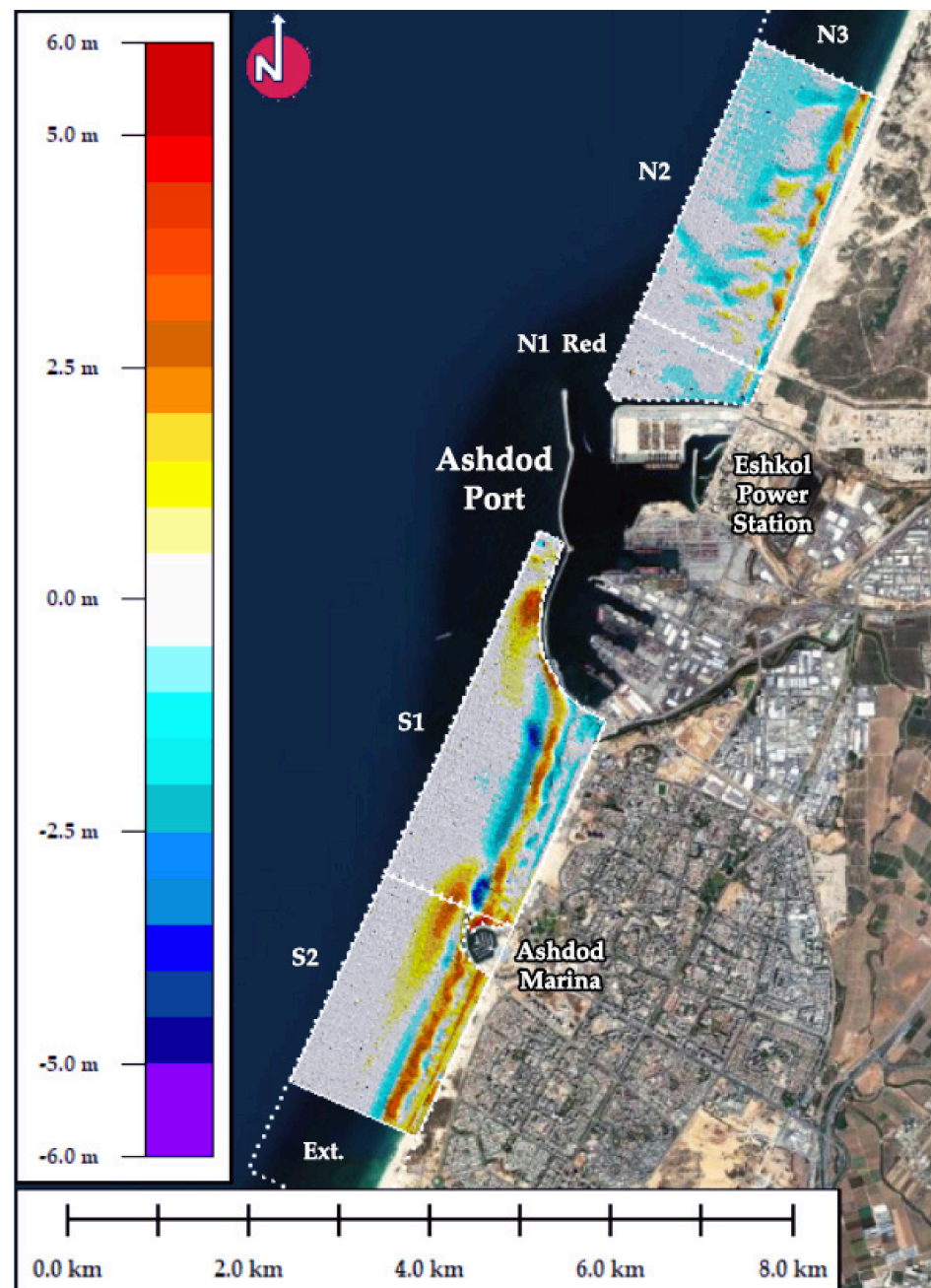


Figure 16. Cumulative differential elevation map showing seabed morphological changes within the expanded study area during Phase II (1995–2021). Segments S1 and S2 Extended (southern nearshore area) and N1 Reduced, N2, and N3 (northern nearshore area) define the coastal segments used for qualitative interpretation and quantitative volumetric analyses. Dashed lines indicate the boundaries between the coastal segments. Background image: © 2023 Maxar Technologies (Vivid Imagery), acquired on 18 September 2023. Used with permission.

The intervention records summarized in Table 5 were assigned spatially to the corresponding analysis segments and temporally to the relevant survey intervals. These records form the basis for adjusting the DEM-derived volume changes presented in Appendix A and deriving the intervention-adjusted sand balances presented in Tables 6–8.

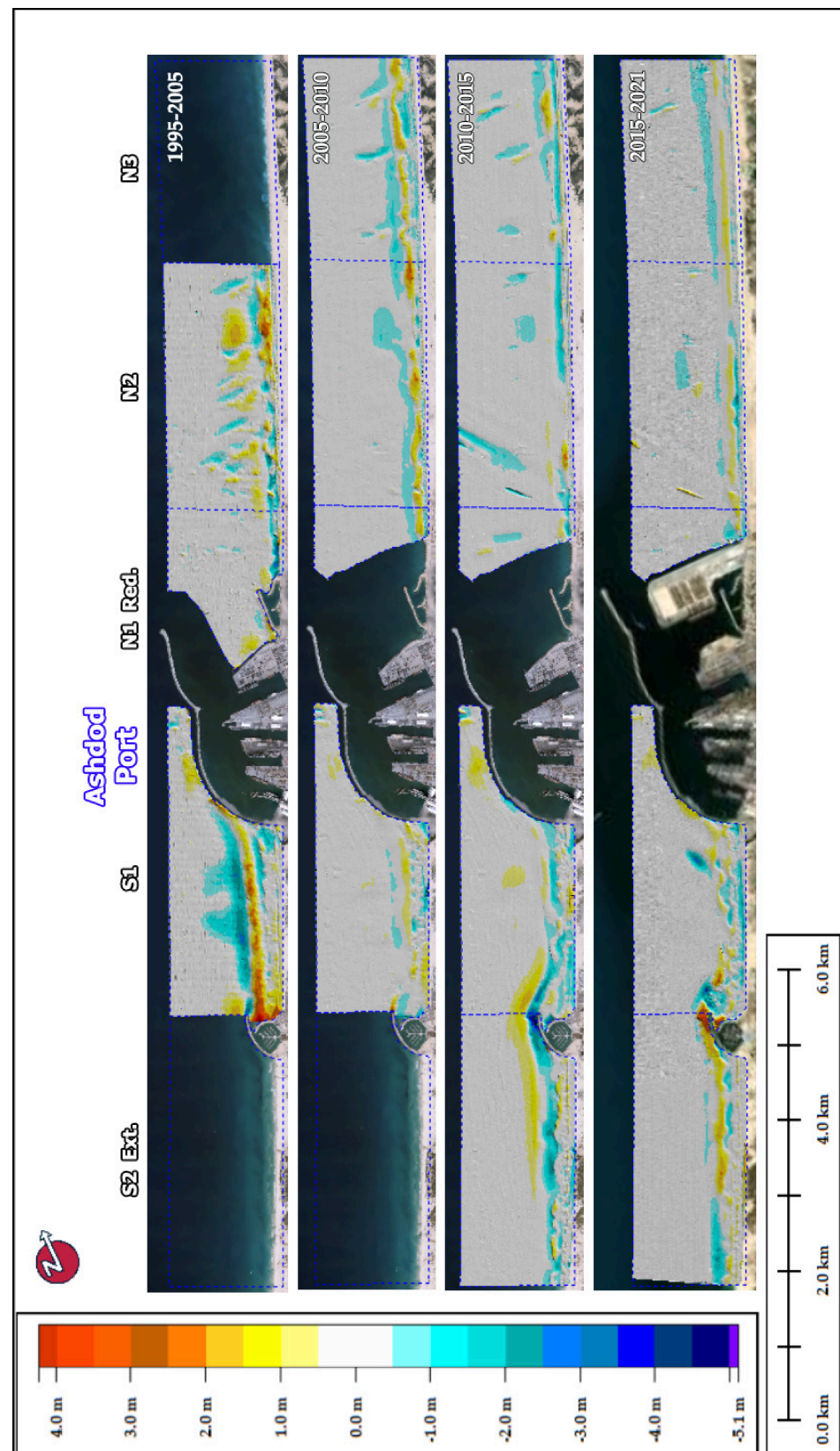


Figure 17. Differential elevation maps showing seabed morphological changes within the expanded study area during the periods 1995–2005, 2005–2010, 2010–2015, and 2015–2021. Segments S1 and S2 Extended (southern nearshore area) and N1 Reduced, N2, and N3 (northern nearshore area) define the coastal segments used for qualitative interpretation and quantitative volumetric analyses. Dashed lines indicate the boundaries between the coastal segments. Background image: © 2023 Maxar Technologies (Vivid Imagery), acquired on 18 September 2023. Used with permission.

Table 5. Documented sand dredging, bypassing, and placement operations relevant to the Phase II (1995–2025) volumetric analysis. Sand volumes are expressed in 10^3 m^3 .

Date/ Operator	Operation/ Aim	Dredging Area	Sand Dredged by Segment (10 ³ m ³)	Placement Method	Sand Placement Area/Segment and Volume (10 ³ m ³)
Nov–Dec 2000/IPC [28–30]	Sand Dredging and Bypass	6–10 m water depths between Ashdod Marina and Ashdod Port	S1: ~180	Dumping at 6–10 m water depths (Figure 11)	North of Ashdod Port/N2: ~180
Aug–Oct 2001/IPC [29,30]			S1: ~180		North of Ashdod Port/N2: ~180
Aug–Sep 2002/IPC [29,30]			S1: ~180		North of Ashdod Port/N2: ~180
Aug–Oct 2003/IPC [29,30]			S1: ~180		North of Ashdod Port/N2: ~180
May–Aug 2011/IPC [22,31,32]	Sand Dredging and Bypass for Beach Nourishment	6–10 m water depths between Ashdod Marina and Ashdod Port	S1: ~99	Rainbowing toward the coast at 0–3 m water depths (Figure 12)	North of Ashdod Port/ N2: ~314 *
Apr–May 2013/IPC [22,31,32]	Sand Dredging and Bypass		S1: ~103	Rainbowing toward the coast along the 5 m water-depth contour	North of Ashdod Port/ N2: ~61.5; N3: ~61.5 *
Jun–Jul 2016/IPC [26,35]			S1: ~97		North of Ashdod Port/ N2: ~48.5; N3: ~48.5
May–Aug 2019/IPC [23]			S1: ~203	Rainbowing toward the coast at 6–8 m water depths	North of Ashdod Port/ N2: ~101.5; N3: ~101.5
May–Aug 2021/MCCP [23]	Sand Dredging for Beach Nourishment	Offshore Ashdod Marina, 6–7 m water depths	S1: ~36	Rainbowing toward the coast	Rock Beach, Bat Yam: ~36
May–Aug 2022/MCCP			S1: ~70; S2: ~130	Pipe dis- charge/rainbowing	South Netanya Beach: ~150; North Ashkelon Beach: ~50
Sep–Oct 2025/MCCP			Adjacent to Ashdod Port MBW, 12–15 m water depths	S1: ~50	Pipe discharge
Total			S1: ~1378; S2: ~130; Total: ~1508		Within study area: N2: ~1245.5 N3: ~211.5 Total: ~1457 Outside study area: ~286

Abbreviations: — = not applicable. * The total sand placed in the northern analysis domain during the 2011 and 2013 campaigns includes sand dredged from the southern bypass area together with documented sand dredged from Ashdod Port and placed within the northern receiving domain. Approximately $215 \times 10^3 \text{ m}^3$ and $20 \times 10^3 \text{ m}^3$, respectively, were derived from port dredging. These port-dredged volumes are therefore included in the placement totals but not in the $1508 \times 10^3 \text{ m}^3$ total dredged south of Ashdod Port. Note: Of the $\sim 1508 \times 10^3 \text{ m}^3$ dredged south of Ashdod Port during 2000–2025, $\sim 1222 \times 10^3 \text{ m}^3$ were bypassed and placed within the northern analysis domain, whereas $\sim 286 \times 10^3 \text{ m}^3$ were transported to nourishment sites outside the study area. An additional $\sim 235 \times 10^3 \text{ m}^3$ dredged from within Ashdod Port was placed in the northern analysis domain, resulting in a total documented placement of $\sim 1457 \times 10^3 \text{ m}^3$.

Table 6. Intervention-adjusted sand-balance changes relative to the 1995 reference survey during Phase II (1995–2025) for the predefined southern (S1–S2) and northern (N1–N2) coastal segments. Adjusted values were calculated from the DEM-derived net volumetric changes by adding documented sand volumes dredged from each segment and subtracting documented sand volumes placed within each receiving segment, based on the operations summarized in Table 5. Total South and Total North represent the corresponding integrated adjusted sand balances. Positive values indicate net sand accumulation, whereas negative values indicate net sand deficit. Volumes are expressed in 10^3 m^3 .

Comparison Period	Δ Years	S1 Adjusted ΔV (10^3 m^3)	S2 Adjusted ΔV (10^3 m^3)	Total South Adjusted ΔV (10^3 m^3)	N1 Adjusted ΔV (10^3 m^3)	N2 Adjusted ΔV (10^3 m^3)	Total North Adjusted ΔV (10^3 m^3)
1995–2000	5	330 *	N/D	—	−19 *	−440 *	−459 *
1995–2005	10	1380	−63	1317	−190 †	−765	−955 †
1995–2007	12	1356	−89	1267	−181 †	−836	−1017 †
1995–2010	15	1043	1535	2578	43 †	−1093	−1050 †
1995–2012	17	1452	1662	3114	107 †	−1107	−1000 †
1995–2015	20	1157	1327	2484	−209 ‡	−2086.5	−2295.5 ‡
1995–2017	22	1332	1376	2708	−232 ‡	−2374	−2606 ‡
1995–2021	26	1577	1774	3351	−272 ‡	−2737.5	−3009.5 ‡
1995–2024	29	1852	1817	3669	N/D	N/D	—
1995–2025	30	1892	1852	3744	N/D	N/D	—

Abbreviations: N/D = data not available; — = integrated total not calculated because complete spatial coverage of all constituent segments was unavailable. * The November–December 2000 dredging and bypass operation was not applied to the 1995–2000 adjustment because the 2000 bathymetric survey extended from October 2000 to January 2001 and therefore overlapped the intervention. The 2000 operation is included in all comparisons terminating in 2005 or later. The historical survey schedule confirms this temporal overlap. † Comparison performed using the reduced extent of Segment N1 following the first northward expansion of Ashdod Port (Yovel Port Project). ‡ Comparison performed using the further reduced extent of Segment N1 following completion of the South Port expansion.

Table 7. Intervention-adjusted sand-balance changes relative to the 2010 reference survey during Phase II (2010–2025) within the expanded study area, including the southern segments S1 and S2 (Ext.) and the northern segments N1 (Red.), N2, and N3. Adjusted values were calculated from the DEM-derived net volumetric changes by adding documented sand volumes dredged from each segment and subtracting documented sand volumes placed within each receiving segment, based on the operations summarized in Table 5. Total South and Total North represent the corresponding integrated adjusted sand balances. Positive values indicate net sand accumulation, whereas negative values indicate net sand deficit. Volumes are expressed in 10^3 m^3 .

Comparison Period	Δ Years	S1 Adjusted ΔV (10^3 m^3)	S2 (Ext.) Adjusted ΔV (10^3 m^3)	Total South Adjusted ΔV (10^3 m^3)	N1 (Red.) Adjusted ΔV (10^3 m^3)	N2 Adjusted ΔV (10^3 m^3)	N3 Adjusted ΔV (10^3 m^3)	Total North Adjusted ΔV (10^3 m^3)
2010–2012	2	411	61	472	63	−24	18	57
2010–2015	5	192	−351	−159	−83 ‡	−1005.5	−707.5	−1796 ‡
2010–2017	7	211	−208	3	−106 ‡	−1287	−956	−2349 ‡
2010–2021	11	542	18	560	−139 ‡	−1974.5	−1832.5	−3946 ‡
2010–2024	14	804	77	881	N/D	N/D	N/D	—
2010–2025	15	849	143	992	N/D	N/D	N/D	—

Abbreviations: N/D = data not available; — = integrated total not calculated because complete spatial coverage of all constituent segments was unavailable. ‡ Comparison performed using the reduced extent of Segment N1 (Red.) following completion of the South Port expansion.

Table 8. Intervention-adjusted long-term sand-balance changes relative to the bathymetric surface reconstructed from the 1965 nautical chart during 1965–2025 for the predefined southern (S1–S2) and northern (N1–N2) coastal domains. Adjusted values were calculated from the DEM-derived net volumetric changes by adding documented sand volumes dredged from each segment and subtracting documented sand volumes placed within each receiving segment. Phase I adjustments include the documented dredging of $354 \times 10^3 \text{ m}^3$ from N1 during 1985–1995, whereas Phase II adjustments are based on the operations summarized in Table 5. Total South and Total North represent the corresponding integrated adjusted sand balances. Positive values indicate net sand accumulation, whereas negative values indicate net sand deficit. Volumes are expressed in 10^3 m^3 .

Comparison Period	Δ Years	S1 Adjusted ΔV (10^3 m^3)	S2 Adjusted ΔV (10^3 m^3)	Total South Adjusted ΔV (10^3 m^3)	N1 Adjusted ΔV (10^3 m^3)	N2 Adjusted ΔV (10^3 m^3)	Total North Adjusted ΔV (10^3 m^3)
1965–1995	30	4497	11	4508	226	−4424	−4198
1965–2000	35	4827 *	N/D	—	207 *	−4864 *	−4657 *
1965–2005	40	5877	−52	5825	36 †	−5189	−5153 †
1965–2007	42	5853	−78	5775	45 †	−5260	−5215 †
1965–2010	45	5540	1546	7086	269 †	−5517	−5248 †
1965–2012	47	5949	1673	7622	333 †	−5531	−5198 †
1965–2015	50	5654	1338	6992	17 ‡	−6510.5	−6493.5 ‡
1965–2017	52	5829	1387	7216	−6 ‡	−6798	−6804 ‡
1965–2021	56	6074	1785	7859	−46 ‡	−7161.5	−7207.5 ‡
1965–2024	59	6349	1828	8177	N/D	N/D	—
1965–2025	60	6389	1863	8252	N/D	N/D	—

Abbreviations: N/D = data not available; — = integrated total not calculated because complete spatial coverage of all constituent segments was unavailable. * The November–December 2000 dredging and bypass operation was not applied to the 1965–2000 adjustment because it overlapped the 2000 bathymetric survey. The operation is included in all comparisons terminating in 2005 or later. † Comparison incorporates the reduced extent of Segment N1 following the first northward expansion of Ashdod Port (Yovel Port Project). ‡ Comparison incorporates the further reduced extent of Segment N1 following completion of the South Port expansion. Note: All comparisons terminating in 1995 or later incorporate the documented removal of approximately $354 \times 10^3 \text{ m}^3$ of sand from Segment N1 during 1985–1995. This material was disposed of offshore outside the study area and was therefore added back to the DEM-derived N1 volume change when calculating the intervention-adjusted sand balance.

4.2.1. Southern Nearshore Segments S1–S2

Differential elevation maps (Figures 16 and 17) document continued growth of the depositional system south of the MBW throughout Phase II. In addition to the depositional sand body that developed adjacent to the MBW during Phase I, a second major depositional feature evolved following construction of the Ashdod Marina MBW. This depositional system progressively expanded southward toward the marina, while continued accumulation occurred adjacent to the port MBW. Compared with Phase I, deposition during Phase II became distributed between the area adjacent to the port MBW and the coastal sector influenced by Ashdod Marina, reflecting the development of a broader southern depositional system.

Integrated Total South and Total North values were calculated only for comparisons with complete spatial coverage of all constituent segments. The longest Phase II comparison with complete coverage of both domains is therefore 1995–2021. Over this 26-year period, the intervention-adjusted sand balance was $+3.351 \times 10^6 \text{ m}^3$ in Total South, corresponding to a mean rate of approximately $+129 \times 10^3 \text{ m}^3/\text{yr}$, whereas Total North exhibited a deficit of $-3.010 \times 10^6 \text{ m}^3$, corresponding to approximately $-116 \times 10^3 \text{ m}^3/\text{yr}$ (Table 6).

Complete spatial coverage of the southern domain extends through 2025. Between 1995 and 2025, the intervention-adjusted positive sand balance in Total South reached $+3.744 \times 10^6 \text{ m}^3$, equivalent to a mean rate of approximately $+125 \times 10^3 \text{ m}^3/\text{yr}$. This total comprised $+1.892 \times 10^6 \text{ m}^3$ in S1 and $+1.852 \times 10^6 \text{ m}^3$ in S2.

The corresponding unadjusted DEM-derived change for Total South was $+2.236 \times 10^6 \text{ m}^3$ (Table A1). The difference of approximately $1.508 \times 10^6 \text{ m}^3$ reflects the documented sand dredged from the southern analysis domain during Phase II. Thus, the volume remaining within the southern seabed in 2025 represents only part of the total positive sand balance, because a substantial quantity of sand that entered and accumulated within this domain was subsequently removed by dredging.

Of the approximately $1.508 \times 10^6 \text{ m}^3$ dredged from the southern analysis domain during 2000–2025, approximately $1.222 \times 10^6 \text{ m}^3$ were bypassed to the northern analysis domain, whereas approximately $0.286 \times 10^6 \text{ m}^3$ were transported to nourishment sites outside the study area (Table 5).

4.2.2. Northern Nearshore Segments N1–N2

During Phase II, the northern nearshore area experienced continued and widespread seabed erosion, concentrated primarily within the active nearshore zone extending from the shoreline to approximately 10 m water depth (Figures 16 and 17).

Segment N1 exhibited comparatively limited volumetric change, although its spatial extent was progressively reduced by successive northward expansions of Ashdod Port. In contrast, N2 remained the principal erosional segment within the original northern analysis domain.

For 1995–2021, the unadjusted DEM-derived volumetric change in N2 was $-1.492 \times 10^6 \text{ m}^3$ (Table A1). After accounting for approximately $1.246 \times 10^6 \text{ m}^3$ of documented sand placement within N2, the intervention-adjusted deficit increased to $-2.738 \times 10^6 \text{ m}^3$ (Table 6). Across N1 and N2 together, the adjusted sand deficit reached $-3.010 \times 10^6 \text{ m}^3$ over 1995–2021.

The difference between the unadjusted DEM-derived change and the intervention-adjusted balance indicates that artificial sand placement partly compensated for the underlying northern sand deficit. Consequently, the measured seabed-volume loss alone underestimates the magnitude of the negative sand balance within the northern domain.

The Phase II results therefore show the persistence of the morphodynamic asymmetry established during Phase I, with a positive sand balance south of Ashdod Port and a negative sand balance north of the port despite repeated artificial sand placement in the downdrift domain.

4.2.3. Expanded Study Area, 2010–2025

Because construction of Ashdod Marina extended the southern study area by approximately 1 km and successive northward expansions of Ashdod Port reduced N1 while enabling the incorporation of the additional downdrift Segment N3, volumetric changes within the expanded study area were evaluated separately using the 2010 survey as the reference surface (Table 7). The corresponding unadjusted DEM-derived values are provided in Table A2.

Within the expanded southern domain, the intervention-adjusted balance varied substantially during 2010–2021, reflecting both morphological change and the timing of dredging operations. Relative to 2010, Total South showed a positive balance of $+472 \times 10^3 \text{ m}^3$ by 2012, a negative balance of $-159 \times 10^3 \text{ m}^3$ by 2015, an approximately neutral balance ($+3 \times 10^3 \text{ m}^3$) by 2017, and a renewed positive balance of $+560 \times 10^3 \text{ m}^3$ by 2021 (Table 7). By 2025, the intervention-adjusted positive balance had increased to $+992 \times 10^3 \text{ m}^3$, comprising $+849 \times 10^3 \text{ m}^3$ in S1 and $+143 \times 10^3 \text{ m}^3$ in S2 (Ext.).

The corresponding unadjusted DEM-derived change for Total South during 2010–2025 was only $+204 \times 10^3 \text{ m}^3$ (Table A2). The substantially larger intervention-adjusted balance again reflects the removal of sand by dredging from the southern nearshore domain during this period.

North of the port, the expanded analysis demonstrates that the negative sand balance extended beyond N2 into N3. During 2010–2021, the unadjusted DEM-derived changes were $-1.449 \times 10^6 \text{ m}^3$ in N2 and $-1.621 \times 10^6 \text{ m}^3$ in N3 (Table A2). After accounting for documented sand placement, the corresponding intervention-adjusted deficits were $-1.975 \times 10^6 \text{ m}^3$ and $-1.833 \times 10^6 \text{ m}^3$, respectively (Table 7).

Across the complete expanded northern domain [N1 (Red.) + N2 + N3], the intervention-adjusted deficit reached $-3.946 \times 10^6 \text{ m}^3$ between 2010 and 2021, equivalent to a mean rate of approximately $-359 \times 10^3 \text{ m}^3/\text{yr}$. This spatial pattern demonstrates that the negative sand balance was not confined to the coastal sector immediately adjacent to the port but extended several kilometers farther north through N2 and N3.

Bathymetric–topographic surveys were not available north of Ashdod Port in 2024 and 2025; consequently, corresponding volumetric balances for N1 (Red.), N2, N3, and Total North could not be calculated for those years.

4.2.4. Long-Term Volumetric Changes Relative to 1965

To integrate Phase I and Phase II within a common multi-decadal framework, long-term intervention-adjusted sand balances were calculated relative to the bathymetric surface reconstructed from the 1965 post-construction nautical chart (Table 8).

The corresponding unadjusted DEM-derived volumetric changes are provided in Table A3. In addition to the Phase II interventions summarized in Table 5, these calculations account for the approximately $354 \times 10^3 \text{ m}^3$ dredged from N1 during 1985–1995 and disposed offshore outside the analyzed coastal domain.

The long-term results demonstrate the persistence and magnitude of the contrasting sand balances on the two sides of Ashdod Port. During 1965–1995, the southern domain accumulated $+4.508 \times 10^6 \text{ m}^3$, whereas the intervention-adjusted northern balance was $-4.198 \times 10^6 \text{ m}^3$.

By 2021, the longest interval for which complete spatial coverage of the predefined southern (S1–S2) and northern (N1–N2) domains is available, the intervention-adjusted sand balance had reached $+7.859 \times 10^6 \text{ m}^3$ in Total South and $-7.208 \times 10^6 \text{ m}^3$ in Total North. Over the 56-year period from 1965 to 2021, these values correspond to mean rates of approximately $+140 \times 10^3 \text{ m}^3/\text{yr}$ and $-129 \times 10^3 \text{ m}^3/\text{yr}$, respectively.

Complete coverage of the southern domain extends through 2025. Over the full 60-year period from 1965 to 2025, the intervention-adjusted positive sand balance south of Ashdod Port reached $+8.252 \times 10^6 \text{ m}^3$, corresponding to a long-term mean rate of approximately $+138 \times 10^3 \text{ m}^3/\text{yr}$. The corresponding unadjusted DEM-derived accumulation was $+6.744 \times 10^6 \text{ m}^3$ (Table A3). The difference of $1.508 \times 10^6 \text{ m}^3$ corresponds to the documented sand removed from the southern analysis domain during Phase II.

The long-term volumetric record therefore distinguishes between the morphological change preserved in the successive DEMs and the broader sand balance obtained after accounting for documented sediment-management interventions. This distinction is particularly important south of the port, where repeated dredging removed part of the accumulated sand, and north of the port, where artificial placement partly compensated for the persistent sand deficit.

4.3. Shoreline Changes 1957–1995

Shoreline evolution during Phase I was quantified using the Mean Width (MW) method applied to the elevation-derived 0 m ILSD shoreline positions extracted from the bathymetric–topographic datasets, thereby providing a consistent quantitative measure of shoreline migration for each predefined coastal segment.

Shoreline response varied considerably among the predefined coastal segments, as quantified by the MW analysis (Table 9) and illustrated by the elevation-derived shoreline positions shown in Figure 18.

Table 9. Elevation-derived shoreline changes during Phase I (1965–1995), quantified using the Mean Width (MW) method. Shoreline positions correspond to the 0 m ILSD contour extracted from bathymetric–topographic elevation datasets. Shoreline changes are presented for successive survey comparisons. Positive values indicate seaward shoreline migration, whereas negative values indicate landward migration.

Comp. Period	Δ Years	S2 Δ MW (m)	S1 Δ MW (m)	N1 Δ MW (m)	N2 Δ MW (m)	S2 Mean Annual Migration (m/yr)	S1 Mean Annual Migration (m/yr)	N1 Mean Annual Migration (m/yr)	N2 Mean Annual Migration (m/yr)
1957–1965	8		−3.5	−34.5 *			−0.44	−4.32 *	
1965–1985	20	N/D	37.6	25.8	N/D	N/D	1.88	1.29	N/D
1985–1995	10		14.8	31.6 *			1.48	3.16 *	
1965–1995	30	−35.7	52.4	43.7	−8.6	−1.20	1.75	1.50	−0.30

Note: N/D = data not available; * indicates partial spatial coverage of the corresponding segment.

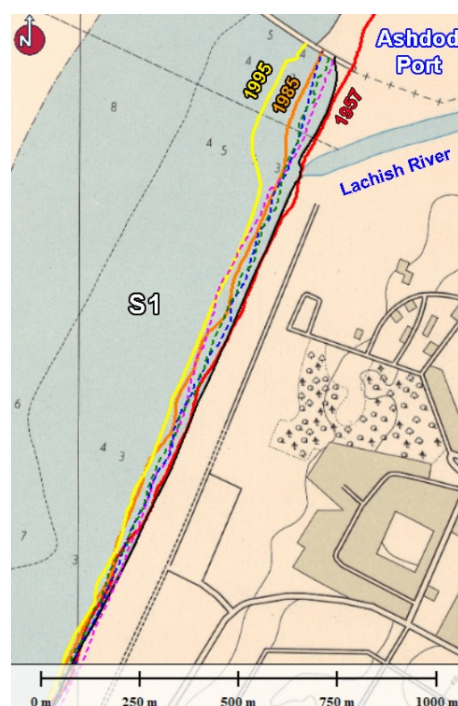


Figure 18. Elevation-derived 0 m ILSD shoreline positions for 1957 (red), 1985 (orange), and 1995 (yellow) superimposed on the 1965 nautical chart, whose original 0 m ILSD contour (black) represents the 1965 shoreline. Shoreline positions interpreted from historical aerial photographs 1976 (pink), 1982 (blue), and 1990 (green); dashed lines; Table 3) are included as an independent qualitative dataset to corroborate long-term shoreline evolution. Although these positions do not correspond to elevation-derived 0 m ILSD shorelines, they independently corroborate the long-term shoreline progradation south of Ashdod Port indicated by the elevation-derived shoreline reconstruction and the corresponding volumetric sand accumulation during Phase I.

South of Ashdod Port, Segment S1 exhibited the largest shoreline progradation throughout Phase I. Between 1965 and 1995, the shoreline advanced by 52.4 m, corresponding to a mean annual progradation rate of 1.75 m/yr. Most of this shoreline advance occurred during 1965–1985 (37.6 m), followed by a further 14.8 m during 1985–1995. In contrast, Segment S2 retreated by 35.7 m during the same period, corresponding to a mean annual shoreline retreat

rate of 1.2 m/yr. No comparison was possible for Segment S2 during 1957–1965 because the pre-construction bathymetric survey did not extend sufficiently far south.

Figure 18 illustrates the progressive shoreline evolution within Segment S1. Successive elevation-derived shoreline positions document continued shoreline progradation throughout Phase I. The greatest shoreline advance occurred immediately south of the Ashdod Port MBW, where the separation between the 1957 and 1995 shoreline positions exceeded 130 m. Shoreline advance decreased progressively with increasing distance from the port. At approximately 1.5 km south of the MBW, the separation between the earliest and latest shoreline positions decreased to less than 30 m. With the exception of the immediate vicinity of the Lachish River mouth, where shoreline evolution followed a less systematic temporal sequence, the successive elevation-derived shoreline positions indicate consistent long-term seaward migration.

North of the port, shoreline response was spatially variable. Segment N1 exhibited a net shoreline advance of 43.7 m between 1965 and 1995, corresponding to a mean annual progradation rate of 1.5 m/yr. During the final decade (1985–1995), shoreline advance within the mapped portion of Segment N1 reached 31.6 m, corresponding to 3.16 m/yr. In contrast, Segment N2 exhibited only limited shoreline retreat throughout Phase I, amounting to 8.6 m over the 30-year period, corresponding to a mean annual retreat rate of 0.3 m/yr, despite the substantial seabed erosion documented within this segment (Section 4.1).

4.4. Shoreline Changes 1995–2025

Shoreline evolution during Phase II was quantified using the MW method applied to the elevation-derived 0 m ILSD shoreline positions extracted from the bathymetric–topographic datasets, thereby providing a consistent quantitative measure of shoreline migration for each predefined coastal segment.

Shoreline response during Phase II varied considerably among the predefined coastal segments, as quantified in Tables 10 and 11. Figure 19 illustrates the elevation-derived shoreline evolution within the southern coastal sectors during Phase II, including the area between Ashdod Port and Ashdod Marina (Segment S1) and the coast south of Ashdod Marina (Segment S2).

Table 10. Elevation-derived shoreline changes during Phase II (1995–2025), quantified using the MW method. Shoreline positions correspond to the elevation-derived 0 m ILSD contour extracted from bathymetric–topographic elevation datasets. Shoreline changes are presented relative to the 1995 elevation-derived shoreline. Positive values indicate seaward shoreline migration, whereas negative values indicate landward migration.

Comp. Period	Δ Years	S2 Δ MW (m)	S1 Δ MW (m)	N1 (Red.) Δ MW (m)	N2 Δ MW (m)	S2 Mean Annual Migration (m/yr)	S1 Mean Annual Migration (m/yr)	N1 (Red.) Mean Annual Migration (m/yr)	N2 Mean Annual Migration (m/yr)
1995–2000	5	N/D	7.2	−12.9 †	−7.4	N/D	1.43	−2.57 †	−1.49
1995–2005	10	N/D	2.0	−4.7 †	−2.2	N/D	0.20	−0.47 †	−0.22
1995–2010	15	26.7	3.4	−11.4 †	−6.3	1.78	0.22	−0.76 †	−0.42
1995–2015	20	34.4	−1.7	−2.2 ‡	−6.8	1.72	−0.09	−0.11 ‡	−0.34
1995–2021	26	42.8	−22.4	−12.1 ‡	−12.7	1.65	−0.86	−0.47 ‡	−0.49
1995–2025	30	44.2	−6.9	−5.0 ‡	−7.8	1.47	−0.23	−0.17 ‡	−0.26

Notes: N/D = data not available. † Comparison performed using the reduced extent of Segment N1 following the first northward expansion of Ashdod Port (Yovel Port Project). ‡ Comparison performed using the further reduced extent of Segment N1 following completion of the South Port expansion.

Table 11. Elevation-derived shoreline changes within the expanded study area during Phase II (2010–2025), quantified using the MW method. Shoreline positions correspond to the elevation-derived 0 m ILSD contour extracted from bathymetric–topographic elevation datasets. Positive values indicate seaward shoreline migration, whereas negative values indicate landward migration. Mean annual shoreline migration rates for the 2010–2025 comparison are reported in the accompanying text.

Comparison Period	Δ Years	S2 (Ext.) Δ MW (m)	S1 Δ MW (m)	N1 (Red.) Δ MW (m)	N2 Δ MW (m)	N3 Δ MW (m)
2010–2015	5	4.9	−4.9	0.2	−0.5	1.0
2010–2021	11	12.8	−25.8	−9.7	−6.4	−2.9
2010–2025	15	12.6	−10.3	−2.6	−1.5	−2.2

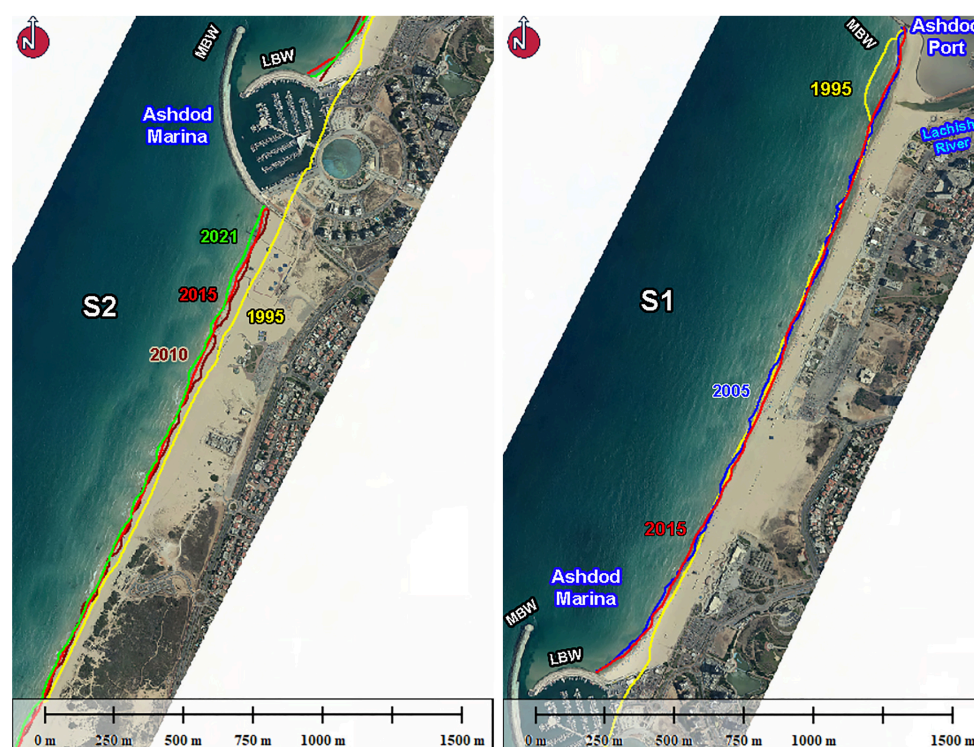


Figure 19. Elevation-derived 0 m ILSD shoreline positions superimposed on the 15 June 2025 orthophoto, illustrating shoreline evolution during Phase II. (Left) shoreline positions for 1995 (yellow), 2010 (brown), 2015 (red), and 2021 (green) south of Ashdod Marina. (Right) shoreline positions for 1995 (yellow), 2005 (blue), and 2015 (red) between Ashdod Marina and Ashdod Port.

4.4.1. Southern Nearshore Segments S1–S2

South of Ashdod Port, shoreline changes continued throughout Phase II, although their spatial distribution differed from that observed during Phase I.

Based on the original Phase II study-area configuration (Table 10), Segment S2 exhibited progressive net shoreline progradation relative to 1995, advancing by 44.2 m between 1995 and 2025, corresponding to a mean annual progradation rate of 1.47 m/yr. Shoreline advance increased from 26.7 m in 2010 to 34.4 m in 2015, 42.8 m in 2021, and 44.2 m in 2025.

In contrast, Segment S1 exhibited comparatively small net shoreline changes throughout the study period. Relative to the 1995 shoreline, the mean shoreline position was 7.2 m seaward in 2000, 2.0 m seaward in 2005, and 3.4 m seaward in 2010. It was subsequently 1.7 m landward in 2015 and 22.4 m landward in 2021, before partially recovering to a net landward displacement of 6.9 m by 2025, corresponding to a mean annual migration rate of -0.23 m/yr.

Figure 19 illustrates the temporal evolution of the elevation-derived shoreline positions within Segments S2 (left) and S1 (right) during Phase II.

4.4.2. Northern Nearshore Segments (N1–N2)

North of Ashdod Port, shoreline migration remained comparatively limited during Phase II (Table 10). Comparisons within Segment N1 were progressively restricted to reduced common analysis domains because of the successive northward expansions of Ashdod Port, whereas the geometry of Segment N2 remained unchanged.

Despite this relatively limited shoreline migration, the volumetric analyses documented substantial long-term seabed erosion. Segment N2 retreated by 8.6 m during Phase I and by 7.8 m during Phase II, whereas substantial net seabed-volume losses occurred within this segment during both phases (Sections 4.1 and 4.2).

4.4.3. Expanded Shoreline Study Area (2010–2025)

Although all shoreline datasets acquired after 1995 provide complete coverage of Segments S1 and S2, the northern shoreline geometry changed following the successive northward expansions of Ashdod Port, requiring progressive reduction in Segment N1 in the later comparisons. Because the expanded southern Segment S2 (Ext.) and the northern Segment N3 were defined only after expansion of the shoreline study area, shoreline changes within these segments were evaluated separately using the 2010 shoreline as the reference dataset (Table 11).

Between 2010 and 2025, Segment S2 (Ext.) advanced by 12.6 m, corresponding to a mean annual progradation rate of 0.84 m/yr. During the same period, Segment S1 exhibited a net shoreline retreat of 10.3 m, corresponding to a mean annual migration rate of -0.69 m/yr.

North of the port, shoreline changes remained comparatively small within all three northern segments. Between 2010 and 2025, Segment N1 (Red.) retreated by 2.6 m (-0.17 m/yr), Segment N2 by 1.5 m (-0.10 m/yr), and Segment N3 by 2.2 m (-0.15 m/yr).

The expanded shoreline analysis therefore shows a clear contrast between shoreline progradation within Segment S2 (Ext.) and the comparatively limited net shoreline changes within the remaining segments. The relatively limited shoreline migration, particularly north of Ashdod Port, contrasts with the substantial seabed volumetric changes documented within the corresponding analysis domains (Section 4.2), indicating that much of the downdrift morphodynamic response was expressed through seabed erosion rather than large-scale shoreline retreat.

4.5. Integrated Morphodynamic Evolution of the Ashdod Coastal System (1965–2025)

The integrated volumetric and shoreline analyses provide a quantitative synthesis of six decades of morphodynamic evolution following construction of Ashdod Port. By integrating the results from Phases I (1965–1995) and II (1995–2025), the long-term morphodynamic evolution of the southern and northern nearshore areas is reconstructed.

The bathymetric synthesis is based primarily on the 1965–2021 comparison because the 2021 survey represents the most recent dataset providing complete bathymetric coverage of both the southern and northern nearshore areas. The spatial pattern of bathymetric–topographic change over this 56-year period is shown in Figure 20. Complete bathymetric coverage of the southern nearshore area extends through 2025, whereas comparable coverage north of Ashdod Port was unavailable after 2021 because of security restrictions. Shoreline analyses extend through 2025 in both the southern and northern coastal sectors.

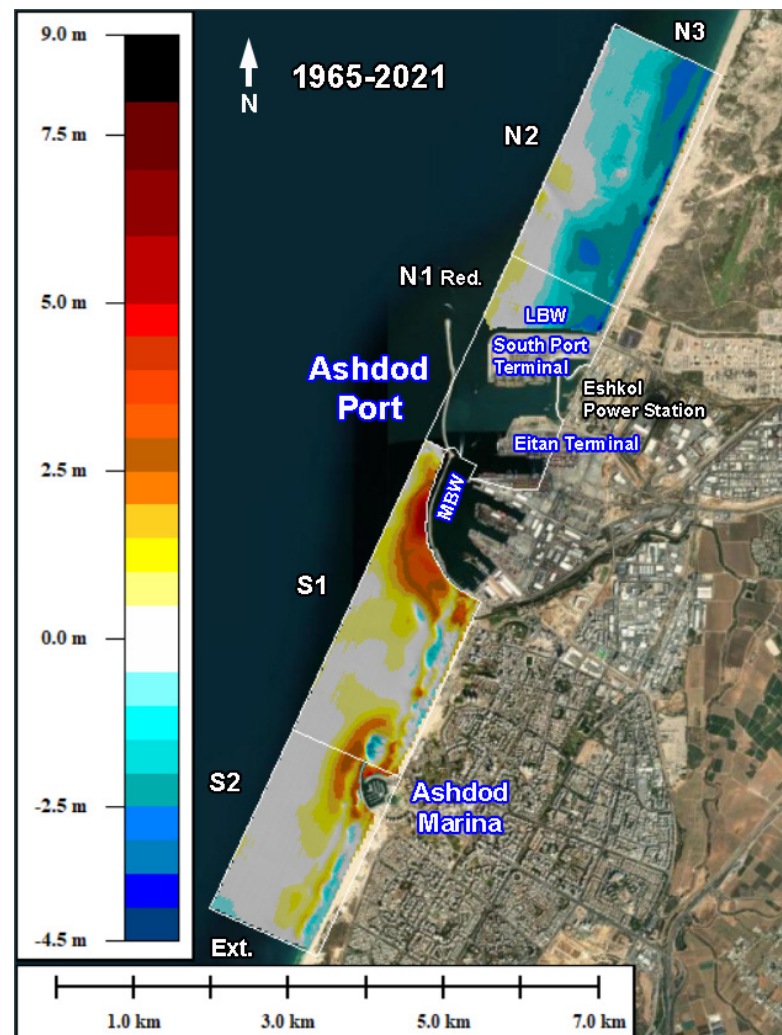


Figure 20. Net bathymetric–topographic changes between 1965 and 2021 illustrating the integrated morphodynamic evolution of the Ashdod coastal system during the 56 years following construction of Ashdod Port. Positive values indicate net seabed accretion, whereas negative values indicate net seabed erosion. The mapped changes represent the net morphological outcome over the comparison period, during which the coastal system was influenced by natural sand redistribution, construction and successive expansion of Ashdod Port, construction of Ashdod Marina, dredging, sand bypassing, beach nourishment, and maintenance dredging. The 2021 survey represents the most recent dataset providing complete bathymetric coverage of both the southern and northern nearshore areas. The boundaries of Segments S2 (Ext.) and N3 are shown to illustrate the expanded study area introduced during Phase II, although quantitative bathymetric analyses within these segments are available only for their corresponding study periods.

4.5.1. Southern Nearshore Area

The volumetric analyses indicate persistent net sand accumulation throughout the southern nearshore area during the six decades following construction of Ashdod Port (Table 8). Within the original southern analysis domain (S1 + S2), the intervention-adjusted sand balance reached $7.859 \times 10^6 \text{ m}^3$ between 1965 and 2021, corresponding to a mean annual rate of approximately $140 \times 10^3 \text{ m}^3/\text{yr}$. Complete southern coverage extends through 2025, when the intervention-adjusted sand balance relative to 1965 reached $8.252 \times 10^6 \text{ m}^3$, equivalent to a 60-year mean annual rate of approximately $138 \times 10^3 \text{ m}^3/\text{yr}$ (Table 8). The corresponding DEM-derived net morphological change was $6.744 \times 10^6 \text{ m}^3$ (Table A3); the difference of $1.508 \times 10^6 \text{ m}^3$ reflects the documented sand removals incorporated into the intervention-adjusted balance for the southern analysis domain during Phase II.

Shoreline evolution exhibited a marked temporal shift in the location of maximum shoreline progradation. During Phase I, shoreline advance was concentrated immediately south of the MBW within Segment S1, where the shoreline advanced by 52.4 m between 1965 and 1995. During Phase II, the principal shoreline response shifted southward into Segment S2 following construction of Ashdod Marina, where net shoreline progradation relative to 1995 reached 44.2 m by 2025. The long-term southern response was characterized by substantial net sand accumulation accompanied by spatially variable shoreline progradation.

4.5.2. Northern Nearshore Area

North of Ashdod Port, the volumetric analyses document persistent long-term seabed erosion and sand depletion throughout the study period (Table 8). For the longest comparison with complete coverage of the original northern analysis domain, the intervention-adjusted sand balance reached $-7.208 \times 10^6 \text{ m}^3$ between 1965 and 2021, corresponding to a mean annual rate of approximately $-129 \times 10^3 \text{ m}^3/\text{yr}$. Long-term comparison within Segment N1 was progressively constrained by the successive northward expansions of Ashdod Port, which reduced the common analysis extent available for later surveys.

The expanded study-area analysis provides a complementary measure of the more recent northern response. Between 2010 and 2021, the expanded northern domain comprising N1 (Red.), N2, and N3 had an intervention-adjusted sand balance of $-3.946 \times 10^6 \text{ m}^3$ (Table 7). This value represents a separate 2010-based spatial and temporal comparison and is therefore not additive to the 1965–2021 northern balance.

The shoreline analyses indicate that shoreline migration north of the port remained comparatively small despite substantial long-term seabed erosion. Segment N2 retreated by 8.6 m during Phase I and by 7.8 m during Phase II, whereas N3 retreated by only 2.2 m between 2010 and 2025. Thus, substantial long-term seabed-volume losses north of the port were accompanied by comparatively limited landward shoreline migration (Table 12).

Table 12. Integrated long-term intervention-adjusted sand balances and shoreline changes within the original and expanded analysis domains of the Ashdod coastal system. Sand-balance values account for documented dredging and sand-placement operations summarized in Table 5. Values are reported only for directly comparable spatial domains and reference periods. Positive values indicate net sand accumulation, whereas negative values indicate net sand deficit.

Analysis Domain	Comparison Period	Intervention-Adjusted Sand Balance ($\times 10^6 \text{ m}^3$)	Corresponding Shoreline Response
Southern original domain (S1 + S2)	1965–2021	+7.859	Long-term progradation, with the principal shoreline response shifting from S1 during Phase I to S2 during Phase II
Northern original domain	1965–2021	−7.208	Comparatively limited shoreline retreat relative to the magnitude of the negative sand balance
Southern original domain (S1 + S2)	1965–2025	+8.252	Continued net shoreline progradation, spatially variable between S1 and S2
Southern expanded domain [S1 + S2 (Ext.)]	2010–2025	+0.992	S2 (Ext.): +12.6 m; S1: −10.3 m
Northern expanded domain [N1 (Red.) + N2 + N3]	2010–2021	−3.946	Comparatively limited shoreline migration across the expanded northern domain

Note: The original and expanded analysis domains represent different spatial configurations and reference periods; their sand balances are therefore reported separately and are not additive.

4.5.3. Integrated Morphodynamic Response

The combined bathymetric–topographic, intervention-adjusted sand-balance, and shoreline analyses demonstrate a persistent regional morphodynamic asymmetry that developed following construction and successive expansion of Ashdod Port and remained evident throughout the study period. Net sand accumulation characterized the southern nearshore area, whereas persistent sand depletion dominated the northern nearshore area. Over the longest period with complete coverage of both original analysis domains (1965–2021), the intervention-adjusted sand balance reached $+7.859 \times 10^6 \text{ m}^3$ south of the port and $-7.208 \times 10^6 \text{ m}^3$ north of the port. This pronounced sand-balance asymmetry was accompanied by substantial shoreline progradation south of the port, whereas shoreline migration north of the port remained comparatively limited.

The integrated bathymetric–topographic, sand-balance, and shoreline analyses provide a quantitative reconstruction of six decades of seabed evolution, shoreline migration, and sand redistribution within the Ashdod coastal system. The contrast between substantial seabed-volume changes and comparatively limited shoreline retreat north of the port further indicates that shoreline position alone does not fully represent the magnitude of the downdrift morphodynamic response.

These results establish the quantitative framework for the process-based interpretation presented in the Discussion.

5. Discussion

The six-decade record examined in this study shows that the morphodynamic response to Ashdod Port has extended well beyond the immediate vicinity of the breakwaters and has persisted through successive stages of port development. Sand accumulation south of the port and sand loss north of it remained the dominant long-term pattern, but their spatial expression changed following construction of Ashdod Marina, the Yovel Port expansion, and the South Port expansion. During the same period, dredging, sand bypassing, and nourishment increasingly became part of the sediment budget and modified the measured distribution of sand within the study domains.

The discussion therefore focuses on three related aspects of the observed evolution: the long-term redistribution of sand south and north of the port, including the contrasting shoreline and submerged morphological responses; the relationship of this redistribution to the predominantly northward longshore sand transport along the Israeli coast; and the effects of successive port expansions and documented sand-management interventions. Particular attention is given to the implications of these changes for future bypassing, nourishment, and management of the limited coastal sand resource along the Israeli Mediterranean coast.

5.1. Spatial and Temporal Patterns of Sand Redistribution and Morphological Response

Ashdod Port was constructed in 1961–1964 along a straight, gently sloping sandy coast exposed to energetic winter wave storms and characterized by predominantly northward LST [13–17,19–21]. The 1965 nautical chart, representing the earliest available post-construction bathymetry, provides the starting point for examining the morphological response of the coastal zone and adjacent inner shelf during the following six decades. The most persistent change is the development of two contrasting morphological trends: long-term sand accumulation south of the port's MBW and erosion of the sandy seabed north of the port. These trends continued as the port was enlarged and Ashdod Marina was constructed, but their spatial distribution and rates changed with time.

The spatial framework used to describe these changes is shown in Figure 13. S1 extends ~2.5 km southward from the root of the port's MBW to Ashdod Marina, and S2 continues for a further ~2.5 km. Following construction of the marina, S2 was extended by

~1.1 km to form S2 Ext. North of the port, N1 originally extended ~2.5 km from the port's LBW, followed by N2 for a further ~3.2 km, while N3 extends another ~2.7 km northward. Successive northward expansions of the port progressively reduced N1, represented as N1 Red. in the later analyses. All segments extend across the coastal zone and adjacent inner shelf, from +5 m ILSD on land to approximately 18–20 m water depth (Figure 4).

During Phase I (1965–1995), approximately $4.50 \times 10^6 \text{ m}^3$ of sand accumulated in S1, at a mean rate of about $150 \times 10^3 \text{ m}^3/\text{yr}$, whereas S2 remained nearly balanced. This contrast is consistent with continued northward sediment transport through S2, with limited net sediment storage within the segment, while accumulation became concentrated where this transport encountered the port's MBW, in agreement with the earlier findings of Golik et al. [19,20]. North of the port, most of the sand loss occurred in N2, which lost approximately $4.42 \times 10^6 \text{ m}^3$. After accounting for documented dredging from N1, the intervention-adjusted balance of the northern domain was $-4.198 \times 10^6 \text{ m}^3$, compared with $+4.508 \times 10^6 \text{ m}^3$ south of the port. Although these values do not constitute a closed sand budget, their similar magnitude and opposite signs are consistent with large-scale redistribution of sand following interruption of the predominantly northward LST by the port.

During Phase II (1995–2025), sand continued to accumulate south of the port, but its spatial distribution changed following construction of Ashdod Marina in 1995–1997. The intervention-adjusted balance of the original southern domain was $+3.744 \times 10^6 \text{ m}^3$, or approximately $125 \times 10^3 \text{ m}^3/\text{yr}$, divided almost equally between S1 ($+1.892 \times 10^6 \text{ m}^3$) and S2 ($+1.852 \times 10^6 \text{ m}^3$). This differs from Phase I, when accumulation was concentrated almost entirely in S1. The shoreline response reflects the same shift: S2 advanced by 44.2 m during Phase II, whereas the net shoreline change in S1 was small compared with its pronounced Phase I progradation. Ashdod Marina therefore modified the distribution of sand accumulation south of the port without reversing the long-term positive balance.

The mean accumulation rate decreased from approximately $150 \times 10^3 \text{ m}^3/\text{yr}$ during Phase I to approximately $125 \times 10^3 \text{ m}^3/\text{yr}$ during Phase II. The two periods are not strictly comparable because construction of Ashdod Marina changed the geometry of the southern domain. The 2010–2025 analysis of the expanded southern domain does not indicate, however, that inclusion of S2 Ext. explains this difference. Of the $+0.992 \times 10^6 \text{ m}^3$ intervention-adjusted gain by 2025, $+0.849 \times 10^6 \text{ m}^3$ occurred in S1 and only $+0.143 \times 10^6 \text{ m}^3$ in S2 Ext. The lower Phase II accumulation rate is therefore evident in the record, but its cause remains unresolved. In particular, it cannot be used as evidence for reduced sand supply to the Israeli coast following construction of the Aswan High Dam. Large volumes of Nile-derived quartz sand stored along northern Sinai, Gaza, and southern Israel continue to provide a reservoir for northward transport within the Nile littoral cell [13–17,21].

The Lachish River provides an additional, episodic sediment source immediately south of the port. Golik et al. [19,20] considered its contribution during major winter floods. This input consists mainly of fine terrestrial material rather than the Nile-derived quartz sand that dominates the beaches and sandy seabed of the study area. The absence of substantial long-term mud accumulation within the analyzed coastal domain [39–42] suggests that much of this fine material is dispersed in suspension toward deeper water. The river therefore contributes to the local sediment budget during flood events, but does not alter the interpretation of the multi-decadal volumetric record primarily in terms of coastal sand redistribution.

North of the port, sand depletion persisted and extended farther downdrift during Phase II. In N2, the intervention-adjusted deficit reached $-2.738 \times 10^6 \text{ m}^3$ between 1995 and 2021 after accounting for artificial sand placement. Between 2010 and 2021, substantial deficits developed in both N2 ($-1.975 \times 10^6 \text{ m}^3$) and N3 ($-1.833 \times 10^6 \text{ m}^3$). The extension

of erosion into N3 indicates that depletion of the sandy seabed has progressed northward rather than remaining confined to the sector immediately downdrift of the port.

This depletion is much less apparent from shoreline change alone. Despite losing more than $4 \times 10^6 \text{ m}^3$ of sand during Phase I, N2 experienced only modest shoreline retreat. Much of the northern coast is partly rocky, with exposed beachrock and limited subaerial sand storage, and the long-term response is expressed mainly through erosion of the submerged sandy profile. The sand remaining north of the port also provides a reservoir that may continue to supply sediment to northward LST as it is progressively eroded. This offers a physical explanation for continued sand transport farther downdrift despite the strong restriction of direct sand passage around the port's MBW. The development of erosion in N3 suggests that depletion of this reservoir is progressing northward, although its future rate and extent cannot be determined from the present record.

The contrast between shoreline and volumetric change is therefore an important component of the observed morphodynamic response. South of the port, substantial sand accumulation was accompanied by pronounced shoreline progradation, whereas north of the port, large sediment losses occurred with comparatively limited shoreline retreat. The port-induced response is thus fundamentally three-dimensional, involving redistribution across the subaerial beach and submerged profile. Shoreline change alone would consequently underestimate the magnitude of the long-term sediment redistribution documented by the repeated topographic and bathymetric surveys.

For the common 1965–2021 interval, the intervention-adjusted balance was $+7.859 \times 10^6 \text{ m}^3$ south of the port and $-7.208 \times 10^6 \text{ m}^3$ north of it, corresponding to mean rates of approximately +140 and $-129 \times 10^3 \text{ m}^3/\text{yr}$, respectively. Complete southern coverage through 2025 extends the positive balance to $+8.252 \times 10^6 \text{ m}^3$, confirming that accumulation south of the port continued through the end of the study period. The six-decade record therefore documents a persistent redistribution of the coastal sand reservoir: accumulation south of the port and progressive depletion of the sandy seabed to the north, with the downdrift response extending farther north through time.

5.2. Longshore Sand Transport and Sediment Connectivity Across Ashdod Port

The long-term morphological response described above reflects the interaction between the predominantly northward sand transport regime and the progressive seaward extension of Ashdod Port. Along the Israeli coast, wave-induced longshore currents dominate sand transport within the shallow coastal zone, whereas wind-induced currents contribute to alongshore transport farther offshore across the sandy inner shelf [13–18,21,46,48,56,57]. As discussed in Section 2.3, sand transport therefore extends beyond the zone of recurrent profile adjustment defined by the morphological closure depth. This distinction is important at Ashdod, where the effects of the port cannot be evaluated solely in relation to the shallow wave-dominated littoral zone.

The progressive extension of the port's MBW substantially changed its position within this transport system. The original 2.2 km-long MBW extended to approximately 15 m water depth. The Yovel Port expansion increased its length by 1.15 km and moved the breakwater head to approximately 21 m depth, and the South Port expansion completed in 2021 extended the MBW to a total length of 3.95 km, with its head reaching approximately 25 m water depth [19,20,22,23]. In comparison, the Nile-derived sandy sediment province off Ashdod extends from the coast to approximately 30 m water depth [14–17,39–42]. The present MBW therefore crosses most of the sandy inner-shelf domain within which alongshore sand transport can occur, including depths well beyond the long-term morphological closure depth.

This geometry does not imply that sediment motion ceases seaward of the present breakwater head. Previous observations along the southern Israeli shelf have demonstrated sand transport at depths exceeding the conventional morphological closure depth, including evidence of northward sediment transport at water depths greater than 24 m [49,65]. The important implication for Ashdod is therefore not that the ~25 m breakwater head defines an absolute offshore limit to sand transport, but that successive port expansions have progressively reduced the cross-shore width available for natural sediment bypassing around the structure. Any present-day bypassing around the MBW head would therefore have to occur through the relatively narrow outer part of the sandy inner shelf, rather than through the much broader shallow-water transport zone intercepted by the structure.

The strongest evidence for the long-term effect of this interception is provided by the morphological record itself. For 1965–2021, the longest interval for which complete bathymetric coverage is available for both original study domains, the intervention-adjusted sand balance was $+7.859 \times 10^6 \text{ m}^3$ south of the port and $-7.208 \times 10^6 \text{ m}^3$ north of it, corresponding to mean rates of approximately $+140$ and $-129 \times 10^3 \text{ m}^3/\text{yr}$, respectively. The close correspondence between these separately derived values, with opposite signs, is consistent with the progressive retention of northward-moving sand south of the port together with a long-term sediment deficit along the downdrift seabed. The difference between the two rates is small relative to the volumes redistributed over 56 years and is compatible with an open coastal system in which sediment can cross the offshore and alongshore boundaries of the analysis domains and undergo cross-shore redistribution within and beyond them.

These volumetric rates should not be interpreted as a new direct estimate of LST at Ashdod. Previous estimates vary substantially according to the wave record, transport formulation, shoreline orientation, and the processes included in the calculation (Table 1). Most quantify potential wave-induced transport, whereas the observed bathymetric evolution integrates the cumulative effects of sediment transport, storage, erosion, deposition, and anthropogenic redistribution over several decades. The significance of the present results is therefore different: they provide a long-term field-based constraint on the morphological consequences of interrupting the natural sand-transport system. The persistent accumulation south of Ashdod Port, the comparable sediment deficit to its north, and the progressive extension of the MBW from approximately 15 to 25 m water depth together indicate that port development has increasingly reduced sediment connectivity between the updrift and downdrift sectors of the Ashdod coastal system.

5.3. Effects of Port Expansion and Sand-Management Interventions

Successive expansions of Ashdod Port progressively modified both the geometry of the coastal system and the spatial distribution of sediment storage around the Port. As shown in Sections 5.1 and 5.2, the long-term response is characterized by persistent accumulation south of the Port and sediment depletion to the north, while successive seaward extensions of the MBW increasingly constrained natural sediment connectivity between the updrift and downdrift sectors. During the later development stages, these structural changes were accompanied by additional modification of the southern sector following construction of Ashdod Marina in 1995–1997 and by increasingly intensive dredging, bypassing, and nourishment operations. The post-1995 morphological evolution therefore reflects the combined effects of continued port development, redistribution of sand around the marina, and direct anthropogenic sediment transfers.

The spatial development of erosion north of the port is particularly relevant to the successive port expansions. Sand depletion persisted north of the port and was subsequently documented farther downdrift, including within N3 during Phase II. This progression

is consistent with an expanding spatial influence of the port as the MBW was extended seaward, although the observed bathymetric changes cannot be attributed to breakwater length alone. The changing breakwater geometry can also modify local wave transformation and circulation near the port, providing a plausible mechanism contributing to the spatial variability of sediment redistribution. The present study, however, does not independently resolve or quantify these hydrodynamic effects.

Sand-management interventions have attempted to compensate for the interruption of the natural sediment pathway. Since 2000, approximately 1.457×10^6 m³ of sand has been artificially transferred from the southern side of Ashdod Port to locations north of it (Table 5). Monitoring of individual nourishment operations has shown that the morphological response of the receiving areas can vary substantially between survey intervals, indicating that the volume placed at a particular location cannot be assumed to remain stored there over subsequent years [31,32]. The disappearance of a nourishment body from its placement area does not necessarily imply loss from the wider coastal system, because the deposited sand may subsequently be redistributed alongshore or offshore. Nevertheless, the long-term bathymetric record shows that, despite substantial artificial sand transfer, a persistent sediment deficit remained north of the port and extended farther downdrift. The interventions implemented to date therefore redistributed significant quantities of sand across the port but did not eliminate the long-term morphodynamic asymmetry between its updrift and downdrift sides.

The marine sand resource along the Israeli Mediterranean coast is limited, strategically important, and environmentally sensitive. It consists predominantly of Nile-derived fine quartz sand distributed across a relatively narrow coastal and inner-shelf zone extending to approximately 30 m water depth [14–17,39–42,66,67]. Sand quarrying from Israel's beaches has been prohibited since 1964 [38], while marine sand extraction is subject to regulatory and environmental constraints. Against this background, the substantial volume accumulated south of Ashdod Port has potential importance for sediment management. However, the cumulative accumulation since port construction should not be regarded as an equivalent present-day reserve available for future extraction. Part has already been artificially transferred northward, part has become incorporated into the widened subaerial beach and developed coastal zone, and part is stored within the submerged depositional morphology associated with the port structures. Historical accumulation and presently available sand are therefore fundamentally different quantities.

This distinction became particularly important following construction of Ashdod Marina in 1995–1997. Before the marina was constructed, the southern study area formed a more continuous morphodynamic sector extending toward the MBW. The marina introduced an additional cross-shore barrier and altered the spatial partitioning of sediment storage south of the port. During 1995–2025, accumulation occurred both south of the marina and within the compartment between the marina and the port, while substantial volumes were simultaneously removed through dredging and bypassing. Consequently, the several million cubic meters accumulated relative to the early post-construction condition should not be interpreted as an indefinitely renewable sand reserve within the marina–Port sector.

For sediment-management purposes, approximately 1995 provides a more meaningful morphological reference condition than the early post-construction baseline for assessing the contemporary sand surplus relevant to future sediment-management considerations. This does not replace the 1965 reference used in the present study to quantify the cumulative morphodynamic impact of Ashdod Port. Rather, the two baselines serve different purposes: the earlier reference documents the long-term morphological response to Port construction, whereas the 1995 condition approximately marks the transition to the present

sediment-storage configuration associated with the marina and subsequent port expansions. Evaluating post-1995 morphological changes together with documented dredging and bypassing volumes therefore provides a more appropriate framework for assessing the remaining contemporary surplus.

The limited persistence reported for some conventional nourishment operations also suggests that alternative placement strategies may warrant investigation. Large feeder nourishments, in which a concentrated sediment volume is progressively redistributed by natural coastal processes, have been investigated internationally, most notably through the Sand Engine project in the Netherlands [68]. The present results neither establish the feasibility of such an approach at Ashdod nor identify an appropriate sediment source, placement location, or volume. They do, however, demonstrate the persistent sediment imbalance that any future strategy would need to address and, equally importantly, show why the historical accumulation south of the port should not be assumed to constitute an unlimited source for such interventions.

The 1957–2025 record shows that successive port development altered sediment connectivity, while artificial bypassing transferred substantial quantities of sand across the port without eliminating the persistent downdrift deficit. Previous bypassing, shoreline progradation, coastal development, and redistribution around the marina and port structures have also changed the amount and accessibility of the accumulated southern sand. Future sediment-management assessments should therefore distinguish between total historical accumulation and the finite contemporary sand surplus, with the post-1995 morphology providing the most relevant reference for evaluating the latter.

6. Conclusions

This study provides an integrated quantitative reconstruction of the long-term morphodynamic evolution of the Ashdod coastal system using historical and modern bathymetric–topographic records spanning 1957–2025. By combining repeated elevation datasets, volumetric sediment-budget analysis, and shoreline positions derived from the 0 m Israel Land Survey Datum (ILSD) contour, the study resolves six decades of coastal adjustment following construction and successive expansion of Ashdod Port. It thereby addresses the principal knowledge gap identified in this study: previous investigations documented individual monitoring periods, specific engineering interventions, or shoreline changes but did not integrate the full historical record within a consistent multi-decadal morphodynamic framework.

The results demonstrate a persistent morphodynamic asymmetry between the updrift and downdrift sides of the port. During Phase I (1965–1995), approximately $4.50 \times 10^6 \text{ m}^3$ of sand accumulated in S1, the coastal sector extending approximately 2.5 km southward from the port's main breakwater (MBW), while S2, the adjoining sector farther south, remained nearly balanced. North of the port, most of the sediment loss occurred in N2, the second sector north of the port, which lost approximately $4.42 \times 10^6 \text{ m}^3$. After accounting for documented dredging from N1, the sector immediately north of the port, the intervention-adjusted northern balance was $-4.198 \times 10^6 \text{ m}^3$, compared with $+4.508 \times 10^6 \text{ m}^3$ south of the port. These similar but opposite-signed changes indicate that the early response to port construction involved redistribution of sand at the scale of the coastal system rather than only local morphological adjustment adjacent to the breakwaters.

During Phase II (1995–2025), the same fundamental asymmetry persisted, but its spatial expression changed. Following construction of Ashdod Marina in 1995–1997, S1 represented the coastal sector between the southern side of the port's MBW and Ashdod Marina, while S2 extended southward from the marina. Accumulation subsequently occurred in both sectors rather than being concentrated almost entirely in S1 as during Phase

I. North of the port, sediment depletion persisted in N2 and subsequently extended into N3, the farthest downdrift sector analyzed in this study. For 2010–2021, the intervention-adjusted deficits reached approximately $-1.975 \times 10^6 \text{ m}^3$ in N2 and $-1.833 \times 10^6 \text{ m}^3$ in N3. The record therefore demonstrates that the downdrift sediment deficit progressively extended northward rather than remaining confined to the coastal sector immediately adjacent to the port.

For the common 1965–2021 interval, the intervention-adjusted sand balance reached $+7.859 \times 10^6 \text{ m}^3$ south of the port and $-7.208 \times 10^6 \text{ m}^3$ north of it, corresponding to mean rates of approximately $+140$ and $-129 \times 10^3 \text{ m}^3/\text{yr}$, respectively. These rates should not be interpreted as a new direct estimate of longshore sand transport (LST). Rather, their close correspondence provides a long-term field-based constraint on the cumulative morphological consequences of interrupting the predominantly northward sediment-transport system. The difference between the two balances is consistent with the open nature of the analyzed coastal system, in which sediment can cross the offshore and alongshore boundaries of the analysis domains and undergo cross-shore redistribution within and beyond them. Complete southern coverage through 2025 shows that the intervention-adjusted positive balance continued to increase, reaching $+8.252 \times 10^6 \text{ m}^3$.

A further major finding is the contrast between shoreline displacement and sediment-volume change. South of the port, large positive sediment balances were accompanied by pronounced shoreline progradation. North of the port, however, substantial sediment losses occurred with comparatively limited shoreline retreat. In N2, more than $4 \times 10^6 \text{ m}^3$ of sand were lost during Phase I despite only modest shoreline displacement. The partly rocky character of the northern coast, including extensive beachrock exposure and limited subaerial sand storage, provides a plausible explanation for this response, with sediment depletion expressed largely through erosion of the submerged sandy profile rather than proportional landward migration of the shoreline. The Ashdod record therefore demonstrates that shoreline change alone can substantially underestimate the magnitude of long-term morphodynamic adjustment around a major coastal structure.

The morphological effects of Ashdod Port also cannot be interpreted solely within the shallow wave-dominated littoral zone. The Nile-derived sandy sediment province off Ashdod extends to approximately 30 m water depth, while previous field observations indicate sand mobility and northward transport at depths greater than 24 m. Successive port expansions extended the MBW from approximately 15 m water depth to its present head at approximately 25 m, creating a continuous structural barrier across most of the sandy inner-shelf transport domain. Any natural northward sand transfer around the port would therefore have to occur seaward of the ~ 25 m-deep MBW head, within the relatively narrow outer part of the sandy sediment province extending toward ~ 30 m water depth. The significance of the ~ 25 m depth is not that sediment transport ceases there but that the present port geometry leaves only this outer-shelf pathway for natural sediment connectivity between the southern and northern sectors.

Anthropogenic sediment-management interventions have become an increasingly important component of this system. Since 2000, approximately $1.457 \times 10^6 \text{ m}^3$ of sand has been artificially placed within the northern analysis domain, comprising approximately $1.222 \times 10^6 \text{ m}^3$ bypassed from south of Ashdod Port and approximately $0.235 \times 10^6 \text{ m}^3$ dredged from within the port. These operations redistributed substantial quantities of sand across the port but did not eliminate the persistent downdrift sediment deficit. Monitoring of individual nourishment operations further shows that sand placed within a receiving area may subsequently be redistributed alongshore or offshore rather than remaining at the placement site. Evaluation of bypassing and nourishment effectiveness should therefore consider sediment redistribution across the wider coastal system rather than

relying solely on the persistence of the placed sediment or on shoreline response at the receiving site.

The long-term accumulation south of Ashdod Port also has important implications for sediment-resource management. The cumulative historical accumulation should not be equated with a present-day extractable sand reserve. Part of the accumulated sand has already been transferred northward through bypassing and nourishment, part has become incorporated into the widened subaerial beach and developed coastal zone, and part is stored within the submerged depositional morphology associated with the port structures. Construction of Ashdod Marina further altered the spatial partitioning of sediment storage south of the port. For contemporary sediment-management considerations, approximately 1995 therefore provides a more meaningful morphological reference condition for evaluating the subsequent sand surplus, while 1965 remains the appropriate baseline for quantifying the cumulative morphodynamic impact of port construction.

The 1957–2025 record demonstrates that the response of an engineered sandy coast can persist and spatially reorganize over many decades as coastal infrastructure expands and sediment-management interventions accumulate. The principal contribution of this study is therefore not a single transport-rate estimate but a field-based reconstruction of how a large deepwater port progressively altered sediment storage, shoreline position, submerged morphology, and sediment connectivity within an active littoral system. Long-term assessment of comparable coastal structures should integrate repeated bathymetric and topographic surveys, shoreline analysis, documented anthropogenic sediment transfers, and explicit treatment of measurement uncertainty to resolve the full three-dimensional morphodynamic response.

Funding: This research received no external funding.

Data Availability Statement: The data analyzed in this study were obtained from multiple historical and institutional sources, as described in Section 3. Some of the datasets are subject to restrictions imposed by the organizations that provided them and are therefore not publicly available. Data may be available from the corresponding author upon reasonable request, subject to permission from the respective data owners.

Acknowledgments: I would like to express my sincere gratitude to the Israel Ports Development & Assets Company Ltd. (IPC) for providing access to the extensive bathymetric and topographic datasets used in this study. I also gratefully acknowledge CAMERI—the Coastal and Marine Engineering Research Institute at Technion City, Haifa—for providing hydrographic data and technical reports, and particularly Michael Glozman, Michael Sladkevich, and Anna Levin for their long-standing professional contributions and valuable scientific support. I am indebted to the National Marine Environment Protection Unit of the Israeli Ministry of Environmental Protection for encouraging this comprehensive investigation and recognizing its national relevance. I sincerely thank Arik Golan and Dov S. Rosen of Israel Oceanographic and Limnological Research (IOLR) for providing historical bathymetric and wave data and valuable information concerning Ashdod Port. I also thank Avi Dror, Yitzhak Elhanty, and Roni Lapid for their valuable assistance with the processing, analysis, and evaluation of the historical bathymetric datasets. Finally, I wish to express my heartfelt appreciation to Eliezer Kit of Tel Aviv University for his long-standing professional guidance and scientific insight, which have contributed substantially to my understanding of coastal processes and longshore sand transport along Israel’s Mediterranean coast.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A

Table A1. Net seabed volumetric changes relative to the 1995 reference survey during Phase II (1995–2025) for the predefined southern (S1–S2) and northern (N1–N2) coastal segments. Total South and Total North represent integrated volumetric changes across the southern and northern analysis domains applicable to each survey comparison, respectively, and are reported only where data were available for all constituent segments. Positive values indicate net sand accumulation, whereas negative values indicate net sand erosion. These values represent the net DEM-derived morphological changes before adjustment for documented sand dredging and placement operations, which are presented in Table 5.

Comparison Period	Δ Years	S1 ΔV (10^3 m^3)	S2 ΔV (10^3 m^3)	Total South ΔV (10^3 m^3)	N1 ΔV (10^3 m^3)	N2 ΔV (10^3 m^3)	Total North ΔV (10^3 m^3)
1995–2000	5	330	N/D	—	−19	−440	−459
1995–2005	10	660	−63	597	−190 †	−45	−235 †
1995–2007	12	636	−89	547	−181 †	−116	−297 †
1995–2010	15	323	1535	1858	43 †	−373	−330 †
1995–2012	17	633	1662	2295	107 †	−73	34 †
1995–2015	20	235	1327	1562	−209 ‡	−991	−1200 ‡
1995–2017	22	313	1376	1689	−232 ‡	−1230	−1462 ‡
1995–2021	26	319	1774	2093	−272 ‡	−1492	−1764 ‡
1995–2024	29	524	1687	2211	N/D	N/D	—
1995–2025	30	514	1722	2236	N/D	N/D	—

Abbreviations: N/D = data not available; — = integrated total not calculated because complete spatial coverage of all constituent segments was unavailable. † Comparison performed using the reduced extent of Segment N1 following the first northward expansion of Ashdod Port (Yovel Port Project). ‡ Comparison performed using the further reduced extent of Segment N1 following completion of the South Port expansion.

Table A2. Net seabed volumetric changes relative to the 2010 reference survey within the expanded study area during 2010–2025, including the southern segments S1 and S2 (Ext.) and the northern segments N1 (Red.), N2, and N3. Total South and Total North represent integrated volumetric changes across the southern and northern analysis domains, respectively, and are reported only where data were available for all constituent segments. Positive values indicate net sand accumulation, whereas negative values indicate net sand erosion. These values represent the net DEM-derived morphological changes before adjustment for documented sand dredging and placement operations, which are presented in Table 5.

Comparison Period	Δ Years	S1 ΔV (10^3 m^3)	S2 (Ext.) ΔV (10^3 m^3)	Total South ΔV (10^3 m^3)	N1 (Red.) ΔV (10^3 m^3)	N2 ΔV (10^3 m^3)	N3 ΔV (10^3 m^3)	Total North ΔV (10^3 m^3)
2010–2012	2	312	61	373	63	290	18	371
2010–2015	5	−10	−351	−361	−83 ‡	−630	−646	−1359 ‡
2010–2017	7	−88	−208	−296	−106 ‡	−863	−846	−1815 ‡
2010–2021	11	4	18	22	−139 ‡	−1449	−1621	−3209 ‡
2010–2024	14	196	−53	143	N/D	N/D	N/D	—
2010–2025	15	191	13	204	N/D	N/D	N/D	—

Abbreviations: N/D = data not available; — = integrated total not calculated because complete spatial coverage of all constituent segments was unavailable. ‡ Comparison performed using the reduced extent of Segment N1 (Red.) following completion of the South Port expansion.

Table A3. Long-term net seabed volumetric changes relative to the bathymetric surface reconstructed from the 1965 nautical chart during 1965–2025 for the predefined southern (S1–S2) and northern (N1–N2) coastal domains. Total South and Total North represent integrated volumetric changes across the southern and northern analysis domains, respectively, and are reported only where data were available for all constituent segments. Positive values indicate net sand accumulation, whereas negative values indicate net sand erosion.

Comparison Period	Δ Years	S1 ΔV (10^3 m^3)	S2 ΔV (10^3 m^3)	Total South ΔV (10^3 m^3)	N1 ΔV (10^3 m^3)	N2 ΔV (10^3 m^3)	Total North ΔV (10^3 m^3)
1965–1995	30	4497	11	4508	−128	−4424	−4552
1965–2000	35	4827	N/D	—	−147	−4864	−5011
1965–2005	40	5157	−52	5105	−318 †	−4469	−4787 †
1965–2007	42	5133	−78	5055	−309 †	−4540	−4849 †
1965–2010	45	4820	1546	6366	−85 †	−4797	−4882 †
1965–2012	47	5130	1673	6803	−21 †	−4497	−4518 †
1965–2015	50	4732	1338	6070	−337 ‡	−5415	−5752 ‡
1965–2017	52	4810	1387	6197	−360 ‡	−5654	−6014 ‡
1965–2021	56	4816	1785	6601	−400 ‡	−5916	−6316 ‡
1965–2024	59	5021	1698	6719	N/D	N/D	—
1965–2025	60	5011	1733	6744	N/D	N/D	—

Abbreviations: N/D = data not available; — = integrated total not calculated because complete spatial coverage of all constituent segments was unavailable. † Comparison incorporates the reduced extent of Segment N1 following the first northward expansion of Ashdod Port (Yovel Port Project). ‡ Comparison incorporates the further reduced extent of Segment N1 following completion of the South Port expansion.

References

- Dean, R.G.; Dalrymple, R.A. *Coastal Processes with Engineering Applications*; Cambridge University Press: Cambridge, UK, 2004.
- Kamphuis, J.W. *Introduction to Coastal Engineering and Management*, 2nd ed.; World Scientific Publishing: Singapore, 2010; Volume 16. [CrossRef]
- Mangor, K.; Drønen, N.K.; Kærgaard, K.H.; Kristensen, S.E. *Shoreline Management Guidelines*, 4th ed.; DHI: Hørsholm, Denmark, 2017.
- Bosboom, J.; Stive, M.J.F. *Coastal Dynamics*; TU Delft Open Textbook Series; TU Delft: Delft, The Netherlands, 2021.
- Anfuso, G.; Domínguez, L.; Gracia, F.J. Short- and medium-term evolution of a coastal sector in Cádiz, SW Spain: Implications for coastal management. *J. Coast. Res.* **2006**, *22*, 1130–1142. [CrossRef]
- Anfuso, G.; Pranzini, E.; Vitale, G. An integrated approach to coastal erosion problems in southern Tuscany (Italy): Geomorphology, coastal engineering, and socio-economics. *Geomorphology* **2011**, *129*, 204–214. [CrossRef]
- Bray, M.J.; Carter, D.J.; Hooke, J.M. *Littoral Cell Definition and Budgets for Sediment Management: The South Coast of England*; National Coasts Protection Centre, University of Portsmouth: Portsmouth, UK, 1995.
- Carter, R.W.G.; Bartlett, D. Coastal stability and harbour construction: The case of Rosslare Harbour, southeast Ireland. *Ir. Geogr.* **1990**, *23*, 1–15.
- Theron, A.K. Port and estuarine structures and their impact on the adjacent coastline: A South African perspective. *S. Afr. J. Sci.* **1992**, *88*, 449–454.
- Patsch, K.; Griggs, G.B. *Development of Sand Budgets for California's Major Littoral Cells*; California Department of Boating and Waterways and San Diego State University: Sacramento, CA, USA, 2007; 110p.
- Inman, D.L.; Jenkins, S.A. The Nile littoral cell and man's impact on the coastal zone of the Southeastern Mediterranean. In *Proceedings of the 19th International Conference on Coastal Engineering, Houston, TX, USA, 3–7 September 1984*; ASCE: Reston, VA, USA, 1984; pp. 1600–1617.
- Inman, D.L. *Littoral Cells*; Schwartz, M., Ed.; Preprint from Encyclopedia of Coastal Science; The Earth Sciences Encyclopedia Online; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2003; 19p.
- Goldsmith, V.; Golik, A. Sediment transport model of the southeastern Mediterranean coast. *Mar. Geol.* **1980**, *37*, 135–147. [CrossRef]
- Nir, Y. *Recent Sediments of Haifa Bay*; Report MG/11/80; Geological Survey of Israel: Jerusalem, Israel, 1980.
- Golik, A. Pattern of sand transport along the Israeli coastline. *Isr. J. Earth Sci.* **2002**, *51*, 191–202. [CrossRef]
- Zviely, D.; Kit, E.; Klein, M. Longshore sand transport estimates along the Mediterranean coast of Israel in the Holocene. *Mar. Geol.* **2007**, *237*, 61–73. [CrossRef]

17. Zviely, D. Sedimentological Processes in Haifa Bay in Context of the Nile Littoral Cell. Ph.D. Thesis, Department of Geography and Environment Studies, University of Haifa, Haifa, Israel, 2006. (In Hebrew with English abstract).
18. Zviely, D.; Kit, E.; Rosen, B.; Galili, E.; Klein, M. Shoreline migrations and beach-nearshore sand balance over the last 200 years in Haifa Bay (SE Mediterranean). *Geo-Mar. Lett.* **2009**, *29*, 93–110. [[CrossRef](#)]
19. Golik, A.; Rosen, D.S.; Golan, A.; Shoshany, M.; DiCastro, D.; Harari, P. Chapter 339, Ashdod Port's Effect on the Shoreline, Seabed and Sediments. In *Proceedings of the 25th International Conference on Coastal Engineering*; ASCE: Reston, VA, USA, 1996; pp. 4376–4389.
20. Golik, A.; Rosen, D.S.; Golan, A.; Shoshany, M. *The Effect of Ashdod Port on the Surrounding Seabed Shoreline and Sediments*; Final Report H02/96; Israel Oceanographic & Limnological Research: Haifa, Israel, 1996.
21. Perlin, A.; Kit, E. Longshore sediment transport on the Mediterranean coast of Israel. *J. Waterw. Port Coast. Ocean Eng.* **1999**, *125*, 80–87. [[CrossRef](#)]
22. Bitan, M.; Zviely, D. Sand Beach Nourishment: Experience from the Mediterranean Coast of Israel. *J. Mar. Sci. Eng.* **2020**, *8*, 273. [[CrossRef](#)]
23. Spanier, E.; Zviely, D. Key Environmental Impacts along the Mediterranean Coast of Israel in the Last 100 Years. *J. Mar. Sci. Eng.* **2023**, *11*, 2. [[CrossRef](#)]
24. Dornhelm, R.B. *Determination of the Longshore Sand Transport Rate in the Vicinity of Ashdod Port*; Marine Geology Division, Geological Survey of Israel: Jerusalem, Israel, 1972; Unpublished report.
25. Kran, N. *Analysis of Bathymetric Data and Sedimentation Near Ashdod Harbour (1964–1971)*; Report MG/6/80; Geological Survey of Israel: Jerusalem, Israel, 1980.
26. Finkelstein, A. *Development of Ashdod Port: Research on a Sedimentological Model—Model Calibration*; Report P.M. 74/80; Coastal and Marine Engineering Research Institute (CAMERI): Haifa, Israel, 1980. (In Hebrew)
27. Vajda, M.; Mechrez, E.; Etrog, U. *Disposal of Sand from Deepening Dredging at Ashdod Port for Construction of Quay No. 9: Evaluation of Alternative Disposal Options and Assessment of the Environmental Impact of the Port*; Report P.M. 201/88; Coastal and Marine Engineering Research Institute (CAMERI): Haifa, Israel, 1988. (In Hebrew)
28. Kit, E.; Sladkevich, M.; Drimer, N. *Engineering Opinion Concerning Recent Beach Erosion in Ashdod*; P.N.557/01; CAMERI—Coastal and Marine Engineering Research Institute, Technion City: Haifa, Israel, 2001.
29. Sladkevich, M.; Levin, A.; Kit, E. *Artificial Sand Nourishment Impact on Morphological Changes Within the Ashdod Port Region. Period October 2000–March 2008*; P.N.695/09; CAMERI—Coastal and Marine Engineering Research Institute, Technion City: Haifa, Israel, 2009.
30. Levin, A.; Tokarev, D.; Sladkevich, M.; Kit, E. *Morphological Changes Within the Ashdod Port Region (2000–2010)*; P.N.732/11; CAMERI—Coastal and Marine Engineering Research Institute, Technion City: Haifa, Israel, 2011.
31. Sladkevich, M.; Levin, A.; Kit, E. *Morphological Changes Within the Ashdod Port Region (2011–2012)*; P.N.779/13; CAMERI—Coastal and Marine Engineering Research Institute, Technion City: Haifa, Israel, 2013.
32. Levin, A.; Sladkevich, M.; Kit, E. *Morphological Changes Within the Ashdod Port Region (1998–2006–2012–2013)*; P.N.811/15; CAMERI—Coastal and Marine Engineering Research Institute, Technion City: Haifa, Israel, 2015.
33. Kushnir, U.; Kit, E. *Morphological Changes Within the Ashdod Port Region (2013–2014–2015)*; P.N.838/17; CAMERI—Coastal and Marine Engineering Research Institute, Technion City: Haifa, Israel, 2017.
34. Trifonova, E.; Sladkevich, M.; Levin, A. *Morphological Changes Within the Ashdod Port Region (2015–2020)*; P.N.912/2020; CAMERI—Coastal and Marine Engineering Research Institute, Technion City: Haifa, Israel, 2021.
35. Dror, A. Morphological Changes in Israel's Mediterranean Coast. Ph.D. Thesis, Department of Geography and Environment Studies, University of Haifa, Haifa, Israel, 2017. (In Hebrew, English Abstract).
36. Brozin, J. The Effect of Extreme Wave Storms on the Mediterranean Coastal Morphology of Israel. Master's Thesis, Faculty of Marine Sciences, Ruppiner Academic Center, Michmoret, Israel, 2024.
37. Bitan, M.; Zviely, D. Lost value assessment of bathing beaches due to sea level rise: A case study of the Mediterranean coast of Israel. *J. Coast. Conserv.* **2019**, *23*, 773–783. [[CrossRef](#)]
38. Goldsmith, V.; Bowman, D.; Kiley, K. Sequential stage development of crescentic bars: Hahoterim Beach, southeastern Mediterranean. *J. Sediment. Petrol.* **1982**, *52*, 233–249. [[CrossRef](#)]
39. Bowman, D.; Goldsmith, V. Bar morphology of dissipative beaches: An empirical model. *Mar. Geol.* **1983**, *51*, 15–33. [[CrossRef](#)]
40. Minister of Housing and Development. *The Zifzif Commission Report*; Minister of Housing and Development: Jerusalem, Israel, 1964. (In Hebrew)
41. Rim, M. Sand and soil in the coastal plain of Israel. *Isr. Explor. J.* **1950**, *1*, 33–48.
42. Emery, K.O.; Neev, D. Mediterranean beaches of Israel. *Isr. Geol. Surv. Bull.* **1960**, *26*, 1–24.
43. Technion Research and Development Foundation Ltd. *Ashdod North Port Development 1996 Granulometric Investigation*; Soil and Roads Testing Laboratories, Technion City: Haifa, Israel, 1996.

44. Gartner, Y. *Sand Granulometry and Mineralogy at Vicinity of Ashdod Port*; Report H21/09; Israel Oceanographic & Limnological Research: Haifa, Israel, 2009.
45. Survey of Israel. *Ashdod Port*; Chart 2, Natural Scale 1:12,500; Ministry of Transport and Communications, Department of Shipping and Ports: Tel Aviv, Israel, 1965.
46. Carmel, Z.; Inman, D.; Golik, A. Chapter 87, Transport of Nile sand along the southeastern Mediterranean coast. In *Proceedings of the 19th International Conference on Coastal Engineering, Houston, TX, USA, 3–7 September 1984*; ASCE: Reston, VA, USA, 1984; pp. 1282–1290.
47. Rohrllich, V.; Goldsmith, V. Sediment transport along the southeast Mediterranean: A geological perspective. *Geo-Mar. Lett.* **1984**, *4*, 99–103. [\[CrossRef\]](#)
48. Zviely, D.; Kit, E. S-shape distribution of the longshore sand transport at the Mediterranean coast of Israel. In *Proceedings of the Israel Geological Society Annual Meeting, Ashkelon, Israel, 23–27 March 2012*; pp. 143–144.
49. Kit, E.; Kroszynski, U. *Marine Policy Plan for Israel: Physical Oceanography, Deep Sea and Coastal Zone Overview*; Report P.N. 800/14; CAMERI—Coastal and Marine Engineering Research Institute, Technion City: Haifa, Israel, 2014.
50. Rosen, D.S.; Kit, E. Evaluation of the Wave Characteristics at the Mediterranean Coast of Israel. *Isr. J. Earth Sci.* **1982**, *30*, 120–134.
51. Carmel, Z.; Inman, D.; Golik, A. Characteristics of storm waves off the mediterranean coast of Israel. *Coast. Eng.* **1985**, *9*, 1–19. [\[CrossRef\]](#)
52. Levin, A.; Glozman, M.; Keren, Y.; Kushnir, U.; Kit, E. *Processing of Hydrographic Data at the Ashdod Region*; P.N.736/11; CAMERI—Coastal and Marine Engineering Research Institute, Technion City: Haifa, Israel, 2012.
53. Levin, A.; Glozman, M.; Keren, Y.; Kushnir, U.; Kit, E. *Hydrographic Conditions (Winds, Currents and Waves) North Ashdod—Palmachim Area 1992–2016*; Report P.N.829/16; CAMERI—Coastal and Marine Engineering Research Institute, Technion City: Haifa, Israel, 2016.
54. Tal, D. Extreme Waves Characteristics and Their Return Period at the Vicinity of Ashdod and Haifa Ports. Master's Thesis, Department of Geography and Environment Studies, University of Haifa, Haifa, Israel, 2020. (In Hebrew, English abstract)
55. Golik, A.; Rosen, D.S. *Management of the Israeli Coastal Sand Resources*; Report H28/1999; Israel Oceanographic & Limnological Research: Haifa, Israel, 1999.
56. Kit, E.; Sladkevich, M. Structure of offshore currents on sediment Mediterranean coast of Israel. In *Proceedings of the 6th Workshop on Physical Processes in Natural Waters, Girona, Spain, 27–29 June 2001*; Casamitjana, X., Ed.; Servei de Publicacions: Barcelona, Spain, 2001; pp. 97–100.
57. Kunitsa, D.; Rosentraub, D.; Stiassnie, M. Estimates of winter currents on the Israeli continental shelf. *Coast. Eng.* **2005**, *52*, 93–102. [\[CrossRef\]](#)
58. Rosen, D.S. *Sea-Levels Climate*; IOLR Report No. H3/98; Building and Planning Department, Ports and Railways Authority (PRA): Haifa, Israel, 1998.
59. Delft Hydraulics. *Port of Gaza, Basic Engineering Study*; Final report, Part 11; Coastal Impact Study: Delft, The Netherlands, 1994.
60. HR Wallingford. *Ashdod Sedimentological Study, Final Report*; Report EX 3518; HR Wallingford Ltd.: Wallingford, UK, 1996.
61. HR Wallingford. *Hayovel Port Stage A. Coastal Nourishment with Dredged Material. Final Report*; Report EX 4025; HR Wallingford Ltd.: Wallingford, UK, 1999.
62. Sladkevich, M.; Levin, A.; Glozman, M.; Keren, Y.; Kit, E. *Manganon Project*; Interim Report No. 2, Morphological Study, Present Layout of the Ashdod Port. P.N.832/16; CAMERI—Coastal and Marine Engineering Research Institute, Technion City: Haifa, Israel, 2016.
63. Israel Ports Company Development and Assets. *National Master Plan (TAMA) 13/B/2/1/A Environmental Impact Assessment*; AdaMa Environment & Geological Sciences: Shoham, Israel, 2012. (In Hebrew)
64. Zviely, D.; Zurel, D.; Edelist, D.; Bitan, M.; Spanier, E. Does Sand Beach Nourishment Enhance the Dispersion of Non-Indigenous Species? The Case of the Common Moon Crab, *Matuta victor* (Fabricius, 1781), in the Southeastern Mediterranean. *J. Mar. Sci. Eng.* **2021**, *9*, 911. [\[CrossRef\]](#)
65. Golik, A. Indirect evidence for sediment transport on the continental shelf of Israel. *Geo-Mar. Lett.* **1993**, *13*, 159–164. [\[CrossRef\]](#)
66. Almagor, G.; Gill, D.; Perath, I. Marine sand resources offshore Israel. *Mar. Georesour. Geotechnol.* **2000**, *18*, 1–42. [\[CrossRef\]](#)
67. Zviely, D. “The Gift of the Nile”—Israel's Marine Sand Resource: Sources, Uses and Quantities. In *Maritime Strategic Evaluation for Israel 2018/19*; Chorev, S., Gonen, E., Eds.; Maritime Policy & Strategy Research Center, University of Haifa: Haifa, Israel, 2019; pp. 285–297. (In Hebrew)
68. de Schipper, M.A.; de Vries, S.; Ruessink, G.; de Zeeuw, R.C.; Rutten, J.; van Gelder-Maas, C.; Stive, M.J.F. Initial spreading of a mega feeder nourishment: Observations of the Sand Engine pilot project. *Coast. Eng.* **2016**, *111*, 23–38. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.