Archaeological, geomorphological and cartographical evidence of the sea level rise in the southern Levantine Basin in the 19th and 20th centuries

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ABSTRACT

Sea level variability affected by sea water mass is strongly associated with global, regional and local climate. In this context, the eastern Mediterranean Sea has been intensively investigated in recent decades because of its sensitivity to climatic and environmental variables. The sea level in Israel during the Crusader period (12th-13th centuries CE) was found to be −0.5 ± 0.2 m relative to the present mean sea level (MSL). The difference between the Crusader sea level and the present-day MSL raises some questions which bring us to the aim of this study: estimating the timeline of the changes in sea level elevation in the eastern Mediterranean over the last two centuries. Archaeological evidence from areas of low tidal range, such as the Mediterranean Sea, can provide significant information on sea level changes for times when instrumental measurements were not yet available (e.g., before 1955 in Israel). The method employed in this study integrates two dimensions: The vertical—estimating the changes in sea levels relative to the present MSL, based on archaeological evidence; and the horizontal—determining the coastline changes, based on coastal architectural and geomorphological structures appearing in historical maps. Both the structural and the cartographic evidence for sea level changes date to the 19th Century, and indicate a rise of 0.36 m over the last two centuries.

Findings attesting to horizontal changes, indicate a gradual migration of the coastline landward, to the east since 1863 and a rapid change in the coastal geomorphology at the beginning of the 20th century. The sea level increase from the 19th century might be, in part, a consequence of regional trends and, in part, a result of a gap between method accuracy (archaeology and modern measurements). Nevertheless, the drastic change in the geomorphology of the coastline may indicate an extreme meteorological event, such as a storm at sea, accompanied by a local rise of sea level, but further research is required to verify this.

1. Introduction

Sea level variability that is a result of changes in sea water mass is strongly associated with global, regional and local climate (Jevrejeva et al., 2006; Milne et al., 2009; Church and White, 2011; Alley et al., 2005; Douglas, 2000; Fairbanks, 1989). In this context, the Mediterranean Sea has been intensively investigated in recent decades since it is sensitive to climatic and environmental variables (Tsimplis and Baker, 2000; Tsimplis and Josey, 2001; Klein et al., 2004; Vigo et al., 2005).

Sea level measurements reflect a vertical movement of sea water in relation to the adjacent land, which can be influenced by both vertical land movements and variability in ocean volume and density (Lambeck and Purcell, 2005; Peltier, 2004).

The majority of coastlines in the eastern Mediterranean have been identified as tectonically and isostatically unstable in the last two millennia (Lambeck et al., 2011; Antonioli et al., 2007; Ferranti et al., 2006; Pirazzoli, 2005; Anzidei et al., 2010; Morhange et al., 2006). This makes it complicated to monitor and assess the land's movements in order to associate sea level variability with climate changes. In the
1970's, these difficulties were discussed regarding the tectonic and neotectonic stability of the Mediterranean coastline of Israel. Discourse on determining stability or instability became intense and focused in the 1990s on the coastline of Caesarea (Neev et al., 1973; Mart and Neev, 1973; Mart and dardening became related to the tectonic stability of the Mediterranean coastline of Israel. Discourse on determining stability or instability became intense and focused in the 1990s on the coastline of Caesarea (Neev et al., 1973; Mart and Perecman, 1996). However, recent studies show that for at least the last two millennia land movements along the Israeli Mediterranean coastline have been negligible (Schattner et al., 2010; Gvirtzman et al., 2008; Sneh, 2000; Sivan et al., 2001, 2004; Toker et al., 2012). It is for this reason that the Israeli coastline, located on the southeastern edge of the Mediterranean Basin (Fig. 1) reflects sea level and climate variability, with land movement being a minimal factor (Sivan et al., 2001, 2004; Anzidei et al., 2010; Toker et al., 2012). Moreover, although nine earthquakes have been documented off the eastern Mediterranean coastline since 1837 none of them impacted the Israeli coastline (Salamon et al., 2007, 2010). Furthermore, two tsunami waves were documented in the Levant one in 1759 as a result of earthquakes in Lebanon, and the second off the Israeli coastline in 1856 (Zohar, 2017). Neither of these tsunami events have been shown to have altered the Israeli coastline. In addition, the standard continuance sea level measurements of the office of Survey of Israel examined this issue by monitoring the displacements of the tide-gauges using satellite observations and concluded that the effect of land movements on sea level measurements has been negligible (Rokhlin, 2014).

Previous studies found that sea level does not rise uniformly around the globe (Church and Wight, 2011). For instance, sea levels in the eastern Mediterranean change differently from the global oceanic ones, and even the Mediterranean's basins differ in their sea levels one from another (Tsimpis et al., 2006; Vigo et al., 2005). Scholars relate these findings to the Eastern Mediterranean Transient (EMT) and to other environmental and meteorological factors.

It is these negligible land movements and the sensitivity to climatic changes that make the Israeli Mediterranean coastline a significant location for the research of sea levels and climate changes.

Sea level measurements taken in Israel continuously since 1958 show that the mean sea level (MSL) is 0.055 m above the Israel Geodetic Datum (Shirman, 2004; Toker et al., 2012). Based on this data, according to Auriemma and Solinas’ (2009) method, the present MSL along the Israeli coastline is calculated as 0.06 m (Toker et al., 2012). Estimates of past MSL rely largely on archaeological indicators along the Israeli coastline (Flemming, 1969; Sneh and Klein, 1985; Nir and Eldar, 1986; Sneh, 2000; Sivan et al., 2001, 2004; Galli and Nir, 2007; Galli and Nir, 1993; Nir, 1997; Toker et al., 2012). Archaeological evidence from areas of low tidal range, such as the Mediterranean Sea, can provide significant information on sea level changes; namely, coastal structures that were constructed with deliberate relation to the sea can be used as indicators of the sea level at the time of their construction (Lambeck et al., 2004). Archaeological evidence of past sea level (SL) dating as far back as ~6900 BCE (~8850 BP) (Gilli and Nir, 1993) is scattered along the Israeli coastline. There are two methods of determining changes in sea level using archaeological evidence (Vunsh et al., 2017). The first based on direct evidence provided by man-made structures along the coastline, which were originally directly related to sea level at the time they were constructed and functioning (e.g. sea fortress foundations and drainage outlets) (Auriemma and Solinas, 2009; Toker et al., 2012). The second indirect evidence involves intermediate factors, between man-made structures and sea level. For instance, the coastal wells required water table levels which lean and adjust to sea-level (Sivan et al., 2004; Marcus, 1991; Nir and Eldar, 1986).

Our study focuses on direct findings, which provide evidence for sea levels over the last 200 years when the land adjacent to the sea has been relatively stable. Frequent changes of ruling powers during this period have enabled dating the archaeological SL evidence to relatively short time ranges of around a century each. The two exceptions are evidence from the Mamluk period (1291–1517), which was not sea oriented and left little archaeological SL evidence, and from the days of the Ottoman Empire, which ruled in the Holy Land for 400 years, often making it difficult to date its remains to a specific time within this span. The paucity of coastal evidence from these two adjacent periods forms a gap in SL measurements between the end of the Crusader period (1291) and employment of modern measurements in Israel (1958). The exceptions are two wells in Jaffa and Acre dating to ca.1700 (Toker et al., 2012; Vunsh et al., 2017).

The sea level in Israel during the Crusader period was found to be ~0.5 ± 0.20 m relative to the present MSL (Toker et al., 2012). A study of the Crusader period MSL in Malta produced similar results (Furlani et al., 2013). The significant difference between the Crusader and the present-day MSL raises two questions: how was this 0.5 ± 0.20 m gap closed and when did this change take place?

The aim of this study is therefore to determine the course of the changes in MSL in the eastern Mediterranean Sea during the last two centuries, as reflected in archaeological evidence scattered along the Israeli coastline, and the timeframe of these changes.

2. Methodology

The methodology of this study is based on an examination of two dimensions of change. The first is vertical: an evaluation of MSL changes over the last two centuries. The second is horizontal: an evaluation of the changes to the coastline location. In this study, evidence of the vertical change was used to evaluate sea level fluctuations and evidence pertaining to horizontal shifts was used to determine the date of the MSL change over the last two centuries.
2.1. Estimation of the vertical change in sea level

Archaeological indicators: The estimation of sea levels in this study was based on coastal structures (drains incorporated into jetties, ramparts and wooden piles used as foundations for sea walls), which can provide significant information concerning sea levels at the time of their construction because of their doubtless relation to the sea (Lambeck et al., 2004; Auriemma and Solinas, 2009; Toker et al., 2012; Vunsh et al., 2017). Based on Lambeck et al. (2004) and on Auriemma and Solinas (2009). This study employs the following method to estimate the past MSL based on archaeological evidence:

1. Identifying the coastal structure and determining its original function.
2. Understanding the structure’s relative position to the past MSL, including seasonal sea level elevations and the tidal changes at the time of construction, and finding the element in each structure that can serve as an indicator (marker) of the past MSL.
4. Calculating the past MSL according to the following equations:

When the marker represents upper-bound sea level:

\[
\text{Past MSL} = \text{marker height} - \text{amplitude} + \text{interval}
\]

When the marker represents lower-bound sea level:

\[
\text{Past MSL} = \text{marker height} + \text{amplitude} + \text{interval}
\]

The marker height is the height of the indicator relative to Israel Geodetic Datum. The amplitude is one half of the spring tide variability (0.2 m) (Goldsmith and Gibbs, 1986). Amplitude = (spring tide variability + seasonal variability)/2 = (0.2 + 0.4)/2 = 0.3 m. Therefore, the amplitude along the Israeli coast is 0.3 m. The interval is the difference between the Israel Geodetic Datum and the long-term MSL (60 years) in Israel. According to Shirman (2004) and Toker et al. (2012) the interval is 0.06 m (Fig. 2). According to Vunsh et al. (2017), after reducing the tidal effect, by averaging long term data, measurement of past MSL based on wells has an uncertainty of ±0.10 m. We have adopted this method for our estimation of MSL uncertainty. The uncertainty of each vertical evidence was fixed according to archaeological dating methods.

2.2. Estimation of the horizontal change of the coastline

An estimation of the horizontal change of the coastline can also indicate that there was a change in sea level elevations (Galili and Nir, 1993). In this study, these estimations were based on an analysis of historical maps in a two-step process: (1) reviewing the maps and identifying changes of coastline position in these maps in relation to the present-day terrain (Shtienberg et al., 2014) and (2) using archaeological remains as an additional indicator to measure the distance from the coastline (Fig. 2).

hewn stones on top of the embankment of the sea wall in Acre were constructed from headers—a building method known for withstanding intensive wave energy (Schaaffer et al., 2014). The construction of headers as protection against wave energy supports the assumption that the past MSL was as high as the top of the embankment. Due to the above and the correction (see section 2.1, the MSL in 1840 was −0.36 ± 0.10 m (−0.3 ± [−0.06]) relative to the present MSL (Fig. 6).

3.2. Evidence of horizontal changes

Coastline migration can be deduced by comparing historical maps demonstrating a change of distance between coastal structures and the coastline. This enables us to estimate the horizontal change of the latter; however, maps of the Levant lacked precision until the end of the 18th century, mainly because they were based on rare, sporadic and inaccurate measurements (Goren, 2002). It was only in the 19th century that a change occurred in cartographic methods, which were based on relatively reliable and accurate measurements. For the first time, the process of mapping the Holy Land was carried out by geographers and archaeologists for research and military intelligence goals (Goren, 2002). The first topographic maps of Palestine based on measurements were prepared by Colonel Pierre Jacotin, a French army surveyor, during Napoleon’s campaign in 1799. These were followed by maps made by 19th century European researchers. Cartography in Palestine was fully developed by the British Mandate that followed the First World War (1921–1948); detailed and accurate maps were made based on a trigonometric survey that was carried out across the entire country (Gavish, 2004).

In order to evaluate the horizontal change of the Israeli coastline position over the last 200 years, we surveyed some of these historical maps. In this study, we compare the distance between the coastline and the same structures that appear in these maps as markers of coastline position. The outline and location of some archaeological remains appear differently on different maps, reflecting horizontal change. In this paper we demonstrate these changes by examining two case studies: Caesarea and Jaffa. It is notable that texts accompanying the maps, which were also consulted for this study, are often more reliable than the maps themselves (Biger, 1996).

3.2.1. Evidence of coastline changes in Caesarea

Eight maps prepared between 1799 and 1932 show the position of the coastline relative to the intersection between the Roman high-level aqueduct and the Byzantine wall (erroneously identified as a Roman wall in some of the maps) This intersection point was selected as a reference for presenting the chronology of the coastline’s horizontal changes during the last 200 years as they were recorded (Fig. 7):

1. Jacotin Map of Caesarea (Jacotin, 1810) (Fig. 7a). This map shows the high-level aqueduct still intact, running parallel to the coastline until it intersects with the Byzantine city wall in the northern part of the shore of Caesarea. The city wall is inaccurately marked on the map as the “enceinte qui renferme des ruines” (“City wall which contains ruins”), and in later maps erroneously assigned as being from the Roman period (Vann, 1992). Although this map is based on field measurements, its accuracy is not satisfactory, and it is therefore presented here only as evidence of the existence of an intact aqueduct and not as an indication of its distance from the coastline.

2. Mansell’s Map of Caesarea (after Mansell, 1862) (Fig. 7b): Prepared by Commander Arthur Lukis Mansell for the British navy, presents in high resolution four sites along the Israeli coastline, including Jaffa and the bay of Caesarea. The high-level aqueduct of Caesarea is presented in full, intersecting with the Byzantine wall, 65 m east of the coastline.

3. Guérin map of Caesarea (after Guérin, 1870) (Fig. 7c): The high-level aqueduct appears here, but the map is very schematic and roughly

Fig. 3. (A) Sea gate to Jaffa; two drainage outlets can be seen from the sea (1895–1905); (B, C) photos and (D) schematic chart of the drain channels in the Ottoman jetty (2016).
1. **Wooden-post foundation (tolpi method):** An 80m segment of the southern sea wall was constructed using the tolpi method (Fig. 4). Wooden posts were inserted into the seabed and a horizontal wooden frame was fixed to their upper sections with iron nails. The first stone layer of the wall, consisting of large, ashlar stone blocks, was placed over the wooden frame (Schaffer et al., 2014). This section of the sea wall was designed by the engineer Declarretto from Italy (Dichter, 2000), who brought the post-and-frame foundation system that was used in Venice to Acre (Goy, 2006). The upper wooden frame was found intact with no signs of rot (Fig. 5B). Since wood rots when exposed to air and water alternatively, the elevation of the upper wooden frame was −0.84 m relative to the Israel Geodetic Datum. According to the calculation (see section 2.1), the lower boundary of the MSL in 1841 was 0.6 ± 0.1 m (−0.84 + 0.3 + [−0.06]) (Fig. 5B).

2. **Central embankment foundation.**

3. **Summary of the findings**

4. **PEF map of Caesarea (after Wilson and Conder, 1890)** (Fig. 7d): The high-level aqueduct is intact and intersected by the Byzantine wall 12.5 m east of the coastline. It is described as follows: “After passing through this ridge, which is of soft stones easily tunnelled, the aqueduct turns due south, and runs along the shore for rather more than a mile, its cross being marked by a ridge of loose sand blown over it and entirely hiding it. Near the north-west corner of the Roman enceinte of Caesarea it is, however, visible, and was here also examined” (Conder and Kitchener, 1881 Vol. II: 23).

5. **Von Müllinen’s Map of the Carmel (after von Müllinen, 1907)** (Fig. 7e): This map of the Carmel, which includes Caesarea, was attached to von Müllinen’s 1908 *Beiträge zur Kenntnis des Carmels*. The high-level aqueduct seems intact, reaching the Byzantine city wall, 6.5 m east to the coastline. The connection of the aqueduct to the city wall is described in the book as follows: “The aqueduct re-emerges west of the sandstone (kurkar) ridge, covered today with piles of sand in certain places, and continuing south, along the coastline, to Caesarea” (von Müllinen, 1908: 363).

6. **Caesarea map of the Antiquities District (Survey of Palestine, 1921)** (Fig. 7f): This is a schematic map prepared by a team of archaeologists that were working at the site. A photo of this map that is available at the Israel Antiquities Authority’s Scientific Archive did not retain the map’s original dimensions and can therefore not be consulted for matters of scale. Nevertheless, the map shows both aqueducts intact and intersected by the Byzantine city wall east of the coastline.

7. **Cadastral Map of Caesarea (Survey of Palestine, 1925a)** (Fig. 7g): This is the first map that describes Caesarea without presenting the high aqueduct that used to run parallel to the coastline and its intersection point with the Byzantine wall, since the aqueduct had been ruined by the sea by the time of the map’s preparation. The new bay that appears north of the city still exists.

8. **Topographical Map of Caesarea (Survey of Palestine, 1932)** (Fig. 7h): This map was prepared on the basis of a triangulation network and the above mentioned cadastral map (Fig. 7g). It is similar in its description to the 1925 map.

Calculating the changing distance between the coastline and the intersection between the aqueduct and the Byzantine city wall reveals the horizontal change of the shoreline during the last 200 years. According to the graph presented in Fig. 8, it appears that, during this period, the shoreline migrated 65 m eastward. Additionally, these maps prove that the destruction of the high aqueduct occurred between 1921 and 1925.

### 3.2.2. Evidence of coastline changes in Jaffa

Four maps from 1865 to 1929 reveal the horizontal changes in the position of the Jaffa coastline:

1. **Jaffa Map (Mansell, 1862)** (Fig. 9a): In this map, prepared by Commander Arthur Lukis Mansell for the British navy, a sandbank appears on the coastline of Jaffa, south of the city wall.

2. **Plan of Jaffa (Survey of Egypt, 1918)** (Fig. 9b): This map was drafted during the First World War and issued as part of a pocket guidebook. The shores north and south of Jaffa are wide and the sandbank can be identified.

3. **City map of Jaffa (Survey of Palestine, 1925b)** (Fig. 9c): Despite the massive development of the harbor, the southern shore remained wide and the sandbank can still be identified.

4. **Topo-cadastral map of Jaffa (Survey of Palestine, 1929)** (Fig. 9d): This is the latest map that describes the coastline before the construction of the port under the British Mandate. The shores are narrower than they were in previous maps and the sandbank has disappeared.

Photos from 1917 indicate a seasonal change in the accumulated sand on the above mentioned beach with the sandbank, which Haddad (2013) believes represents changes that occurred in other years as well. Though it is possible that this might also be the case in the 1929 maps, it is less likely that a seasonal change would have been incorporated into a map. The decision to relocate the coastline in the 1929 map therefore more likely indicates a permanent change that occurred when the sandbank had been washed away by the sea or flooded.

### 3.3. Summary of the findings

Finds attesting to the vertical changes (Table 1) indicate that during the 19th century the lower boundary of the MSL was −0.6 m relative to the present MSL, whereas the upper boundary was −0.2 m relative to the present MSL. Archaeological sea level evidence leans on the past average sea level elevation as indicated by the artificial embankment, which shows that the MSL was −0.36 m in 1840. The findings pertaining to horizontal changes indicate a gradual migration of the
coastline eastward, toward the land, since 1863 and a rapid change in the coastal geomorphology in the beginning of the 20th century (see Table 2).

Fig. 10 displays the sea level estimation between 1750 and 1900 deduced from previous and current research and Israel Geodetic Datum, based on the Survey of Palestine under the British Mandate and on the measurements taken along the Israeli Mediterranean coastline in the Survey of Israel in 1921–1995 (Toker et al., 2019). In addition, estimated sea levels from wells in Acre and Jaffa based on Vunsh et al. (2017) were added on this graph, in order to strengthen our findings.

4. Discussion

There is a gap in the archaeological evidence of sea level elevations along the Israeli coastline over the last 700 years between the end of the Crusader period (1291) and 1958 when analogical measurements were first employed in Israel (Shirman, 2004). Since 1291 sea level in Israel has risen by 0.50 ± 0.20 m (Toker et al., 2012). A similar rise of sea level during that time frame was found in Malta (Furlani et al., 2013). Consequently, the aims of this study were to determine the timetable of the changes in the sea level elevation of the Levantine Basin during the last 200 years as demonstrated by the Israeli coastline. Based on archaeological and geomorphological evidence from Acre, Caesarea and Jaffa and on sea level measurements from Gaza taken by the British Survey of Palestine during 1921–1922, this study suggests that over the
last two centuries sea level elevation rose by 0.36 m.

So far, no study has addressed this issue. However, previous studies have dealt with some of the evidence presented in this study, yet they employed different approaches to examining the evidence and came to different conclusions. For example, the cause and time of the destruction of the high-level aqueduct in Caesarea are disputed (Nir, 1981; Reifenberg, 1950–1951; Karni, 1982; Olamy and Peleg, 1977; Peleg, 1989; Porath and Siegelmann, 2002; Negev, 1964; Shtienberg et al., 2014). The aqueduct which is now partially in ruin has served as an indicator of coastal changes in several studies (Galili et al., 2011; Shtienberg et al., 2014). Our study claims that the high-level aqueduct was destroyed at the beginning of the 20th century due to sea level rise. However, there are studies that argue that the cause of its destruction was anthropogenic interference in the coastal environment, while others assign this change to environmental factors other than a rise in sea level. Some of these claimed that this happened after the construction of the pier of Herod’s harbor in the 1st century BCE, which created a new bay (Nir, 1981). Nir (1981) suggested that the high-level aqueduct was supported by a sea-wall which prevented the erosion of sand along the north beach. This sand erosion could be expected as the result of massive building in the sea (Herod harbor), south of the high level aqueduct by Herod. According to Nir (1981) during the Early Islamic conquest in the 7th century the supporting sea-wall fell into ruin, leaving the north shore of Caesarea, without defense from erosion. Thus according to Nir (1981) erosion of the coast caused the destruction of the high-level aqueduct. Others have asserted that the high level aqueduct fell into ruin due to an earth quake (Galili et al., 2011) or natural erosion (Reifenberg, 1950–1951; Karni, 1982). But archaeological research of the water channels on top of the high-level aqueduct revealed that the highest of these three water channels was built in the Crusader period (1101–1291) (Olamy and Peleg, 1977; Peleg, 1989). Hence the high-level aqueduct would have to have been destroyed after the Crusader period in Caesarea, during the Mameluk conquest in the 13th century (Negev, 1964; Olamy and Peleg, 1977; Peleg, 1989). However, the high-level aqueduct of Caesarea appears in all the topographic maps of the second half of the 19th century and the beginning of the 20th century, contradicting all proposals of an earlier demise. Moreover, the high-level aqueduct was witnessed and described by Guérin (1870), by Conder and Kitchner (1881) and by von Müllinen (1908).

The coastline shift in Caesarea between 1863 and 1927 was presented by Shitienberg et al. (2014), who claimed that it had eroded by 10–65 m. Shitienberg et al. (2014) related this erosion to natural processes, which were amplified by quarrying of beach sand and of coastal kurkar for building the Bosnian colony in 1878, while the high-level aqueduct was damaged by scavenging material for re-use. According to Zviely and Klein (2002), the stabilization of coastal geomorphological processes due to anthropogenic interference takes only a short period of time (5–8 years), and since the colony was built in 1878, while von Müllinen’s map (1907) shows an intact aqueduct, it is doubtful that the Bosnian colony interfered with the coastal geomorphology.

The last appearance of the high-level aqueduct of Caesarea as an intact feature is in a map dating to 1921 (Survey of Palestine, 1921). The map of Survey of Palestine (1925a) shows only a bay indenting the coast. It seems that the aqueduct was destroyed between these years. Since coastal structures are sensitive to sea level amplitude and the tides in the Mediterranean are generally small (Androulidakis et al., 2015), damage to coastal structures is more likely to be associated with extreme meteorological events that cause the sea level to rise (Pugh and Woodworth, 2014). Hence, a high sea level elevation combined with an extreme high sea level event might bring about a geomorphological change to the coastline. A report in Doar Hayom a newspaper published in Hebrew in the 1920s, offers evidence for extreme winter events. On February 5, 1924 it was reported that extreme weather caused inland flooding and broke a bridge over the Yarkon River, north of Tel Aviv. This weather event fits the time of the geomorphological change that was identified in this study and it may have been what damaged and destroyed the high-level aqueduct of Caesarea (Fig. 11).

Additionally, the fact that coastline shifts occurred in Jaffa during the same period, when the British authority banned building projects along the coastline until 1932 (Gilior, 2016), strengthens the assumption that the changes might have happened on a regional scale rather than being local-anthropogenic ones in Caesarea alone (Zviely et al., 2007). This is more likely to have been related to a larger-scale phenomenon like sea level rise.

Therefore, it seems likely that horizontal changes of the coastline observed in historical maps of Caesarea and Jaffa were a result of an extreme high sea event, which triggered geomorphological processes. These processes of extreme weather events accompanied by sea level rise might have created the coastline erosion between 1921 and 1929.

The conclusions of this study are based on direct and indirect evidence: the direct evidence is based on the unequivocal relation of coastal structures to changing sea levels. Wells constitute indirect
evidence as their function relies on the water table, which is affected by the level of the adjacent sea water (Vunsh et al., 2017). According to Fig. 10, the sea levels that are reflected by the wells presented in the research of Vunsh et al. (2017) are in line with the upper boundary established via the direct evidence in the current study, and therefore reinforce our findings.

Table 1
Findings attesting to vertical changes.

<table>
<thead>
<tr>
<th>SL Evidence (m)</th>
<th>Site</th>
<th>Evidence</th>
<th>Method</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>−0.36</td>
<td>Acre</td>
<td>Artificial embankment</td>
<td>Archaeological indicator</td>
<td>1830</td>
</tr>
<tr>
<td>−0.6</td>
<td>Acre</td>
<td>Wooden-post foundation</td>
<td>Archaeological indicator</td>
<td>1830</td>
</tr>
<tr>
<td>−0.2</td>
<td>Jaffa</td>
<td>Drainage outlets</td>
<td>Archaeological indicator</td>
<td>1888</td>
</tr>
</tbody>
</table>

Table 2
Findings attesting to horizontal changes.

<table>
<thead>
<tr>
<th>Distance of aqueduct from coastline (m)</th>
<th>Reference</th>
<th>Site</th>
<th>Method</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>Mansell’s map (Mansell, 1862)</td>
<td>Caesarea</td>
<td>Map analysis</td>
<td>1863</td>
</tr>
<tr>
<td>12.5</td>
<td>PEF map (Wilson and Conder, 1890)</td>
<td>Caesarea</td>
<td>Map analysis</td>
<td>1878</td>
</tr>
<tr>
<td>6.5</td>
<td>von Mülinen’s map (von Mülinen, 1907)</td>
<td>Caesarea</td>
<td>Map analysis</td>
<td>1907</td>
</tr>
<tr>
<td>0</td>
<td>Cadastral map (Survey of Palestine, 1925a)</td>
<td>Caesarea</td>
<td>Map analysis</td>
<td>1925</td>
</tr>
<tr>
<td>0</td>
<td>Topographical map (Survey of Palestine, 1932)</td>
<td>Caesarea</td>
<td>Map analysis</td>
<td>1932</td>
</tr>
</tbody>
</table>

Fig. 10. The sea level over the last 250 years, deduced from previous and current observations along the Israeli Mediterranean coastline.

Fig. 11. A weather report from Doar Hayom daily newspaper; February 5, 1924 (Hebrew).

research of Vunsh et al. (2017) are in line with the upper boundary established via the direct evidence in the current study, and therefore reinforce our findings.

In order to explain the 0.36 m rise in sea level elevation during the
last 200 years it is necessary to distinguish between variability and long-term trends of rising sea levels. Sea level variability is affected by local and regional meteorological factors (such as storm surges) and modes of climate variability (such as the North Atlantic Oscillation), as well as anthropogenic effects (such as the construction of the Aswan Dam). Long-term trends are brought about by global climate factors (Church and Wight, 2011). Fig. 12 shows sea level elevations between 1760 and 2017. The elevations from 1760 to 1900 are based on archaeological evidence; elevations between 1921 and 1929 are derived from mechanical sea level measurement; and since 1955 they are determined by continuous tide gauge measurements. The analysis of sea level elevations since mechanical tide gauge measurements were available (1921) shows a variability of ± 0.17 m. Based on archaeologically analyzed evidence, this study shows that between the years 1760 and 1900 the sea level along the Israeli coastline was 0.36 below the present MSL with an uncertainty of ± 0.26 (based on the lower boundarydeduced from the wooden piles) and +0.16 m (based on the upper boundary deduced from drainage outlets). The range of values for sea levels is larger than could be explained by periodical changes caused by local and regional meteorological factors that have been measured on the Israeli coastline throughout the 20th century. A similar sea level change was not identified in the long-term measurements in Marseille (representing the western Mediterranean Basin); hence, the data gap between the 19th century and 1920s is probably a consequence of the discrepancy between the accuracy afforded by archaeological data and that of instrumental measurements. Nevertheless, drainage outlets were found to be a reliable indicator for ancient sea levels (Toker et al., 2012). It can therefore be stated that between 1888—when the drainage outlet was built—and the 1920s, when the sea level was first measured, the latter rose by at least 0.2 m (Toker et al., 2019).

A comparison of the trend of rising sea levels according to the findings in this study to global and Mediterranean trends of rising sea level for the last few centuries shows the following: the rises in Israeli sea level is 2.7 mm/year which is slightly higher than the entire Mediterranean trend which is 2.4 mm/year (Bonaduce et al., 2016), and slightly lower than the global trend, 3.2 mm/year (Quarty et al., 2017). Hence it can be concluded that the sea level rise along the Israeli coastline may have been caused by global climatic factors that were more pronounced in the eastern Mediterranean Basin relative to the entire Mediterranean Sea. As for the coastline migration found in Caesarea and Jaffa, the presumed extreme weather event, and the relationship to the rise in sea level elevation might suggest a more complex explanation; however, further research is required on this point.

5. Conclusion

This study found an elevation in sea level and a narrowing of the coastal strip along the Israeli coastline over the last two centuries. Evidence of a rapid rise of sea level was obtained using two sources: structural archaeological remains and historical maps. Both sources point to the same years when changes in sea level occurred. The sea level rise determined for the 19th century may be in part a consequence of regional trends and in part the result of a gap between the accuracy provided by the different data sets (archaeological remains vs. modern measurements). It is also important to point out that the notable change in the geomorphology of the coastline may indicate an extreme meteorological event, such as a storm surge, which resulted in a local rise of sea level. Further research is required to verify this.

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Further reading