Anthropogenic changes in waterways produce "drought-like" layers in shelf sediments

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A primary component of the global sediment cycle is the delivery of sediment from rivers to the sea, an input that fluctuates in magnitude and frequency owing to changes in precipitation. Some of these fluctuations can be recognized in the sedimentary record on the continental shelf and used to reconstruct past climatic conditions. However, recent damming and waterway diversions have affected the volume, location, and arrival intervals of alluvial deposits to the sea. Yet, the reflection of these anthropogenic endeavors on the sedimentological record and how they relate to climatic shifts is not well understood. In this study, we examined the inner continental shelf sediments in the northern Gulf of Aqaba-Eilat and the Israeli coast of the Mediterranean Sea to determine how they were impacted by 20th century anthropogenic alterations of incoming rivers. In the Gulf of Aqaba-Eilat, a drought-like upper sediment layer appeared where floods are no longer reaching the sea because of river channel diversion. This Horizon contained microplastics, timing it to after the foundation of the city of Eilat. These markers are disassociated from recorded rainfall and flood events and were not replicated where floods continued to reach the sea. In the Mediterranean, the observed drought-like changes in the sediment corresponded with the damming of the Nile. Our results show that in both cases, anthropogenically reduced load of fine alluvial (mostly flood) particles and continued winnowing caused sediments to coarsen and become more sorted with higher concentrations of larger foraminifera tests. These sedimentological markings resemble those reported for prolonged droughts, but can be differentiated by discrepancies to recent climatic records. Considering the alterations of waterways worldwide, this sedimentological mismatch may constitute a new proxy of the Anthropocene and highlights the way that human activities are altering the sediment cycle.

Keywords: Rechanneling rivers, Sedimentary record, Paleoclimate, Microplastics, Anthropocene, Floods

1. Introduction

1.1. General background

Marine sedimentary deposits can document short and long-term environmental cycles or events associated with climate. Changes in precipitation affect river runoff into the sea, including eroded sediment loads from land surfaces (Syvitski et al., 2003). This alluvium commonly contains a high proportion of fine-grained sediments (<63 μm), and their deposition and preservation on the inner continental shelf have been used to reconstruct climatic conditions (Wheatcroft and Borgeld, 2000; Sommerfield et al., 2002; Moreno et al., 2012; Zhou et al., 2021). The processes involved are complex, including sedimentation rates, biological activity, sediment composition, and hydrographic conditions (Wheatcroft and Borgeld, 2000). Generally, higher concentrations of finer-grain-sized sediments are associated with periods of higher precipitation, while lower concentrations of fines (e.g., relatively coarser sequences) are linked to lower precipitation (Nesje et al., 2001; Abrantes et al., 2005; Greenbaum et al., 2006; Kalman et al., 2020). However, similar to changes in climate, changes in land use such as river channeling, damming, and coastal development may also alter the appearance of the sediment. Intensified urbanization and utilization of coastal zones has greatly increased in recent decades, a trend that is expected to continue into the future (Neumann et al., 2015). Resolving and differentiating between naturally and anthropogenically driven sedimentological processes, or their combined effects, is key to interpreting depositional records and understanding the global sediment cycle.

Human intervention of river discharge varies in orders of magnitude from small channels to major world rivers. Worldwide, as estimated 50% of rivers contain dams, and 90% will by 2030 (Van Cappellen and Maavara, 2016). When adding related efforts such as rechanneling and
river “training” linked to construction on flood plains and other flood controls, estimates of impacted rivers worldwide is even higher (Meybeck, 2003). While evidence for human altering of waterways is over 7000 years old, it has greatly intensified in the past 90 years (Van Cappellen and Maavara, 2016), both as a result of the scale of technological capabilities and increases in human population size. Many examples worldwide demonstrate how these activities result in environmental change (Holdren and Ehrlich, 1974; Walker and Thoms, 1993).

Recently, more attention has been brought to the worldwide presence of anthropogenically produced markers in the stratigraphic record (Waters et al., 2016). Markers of the newly minted “Anthropocene” epoch (Crutzen, 2006) include fly ash (Rose, 2015), fallout of anthropogenic radionuclides (Aarkrog, 2003), new, manufactured materials such as aluminum products (Zalasiewicz, 2013), as well as plastics and broken-down plastic pieces (macro and microplastics; Derraik, 2002). In addition to these markers, the Anthropocene is also marked by landscape alterations and morphological changes that can have a significant effect on the hydrological cycle (Barnett et al., 2008). Margariti et al. (2019), for instance, analyzed streamflow characteristics of six individual catchments across Europe and found an association between drought recovery and amount of anthropogenic alterations. Because of these associations, natural environmental conditions cannot be regarded independently of anthropogenic activities.

Terrestrial discharge from rivers identified in marine sediment cores has been used to infer past trends in climate (e.g., Lamy et al., 1999; Cronin et al., 2003); however, where landscape and drainage have been altered artificially, the interpretation of these records and the inference to background environmental conditions requires added caution. Syvitski (2003) concluded that monitoring the discharge from an anthropogenically altered river for the “return-interval concept for floods and droughts, for instance, becomes meaningless.” Therefore, there is a need to be able to characterize the sedimentological fingerprints related to human effects on the hydrological system versus natural processes.

Anthropogenic activity is layered upon natural, climate-related shifts in river flows. The aim of this study was to identify and explain sedimentological fingerprints from recent (1950s to the present) anthropogenic damming and rechanneling of rivers and compare them to background climatic influences to determine if and where they can be distinguished. The study targeted two sites, one in the northern Gulf of Aqaba-Eilat (GAE, Red Sea) and the other in the southeastern Mediterranean Sea (Figure 1).
The Red Sea site was selected because of well-defined and recorded artificial changes in the rivers leading to the Gulf, and recently published data regarding an association between the sedimentary record and changing climatic conditions (Kalman et al., 2020). The Mediterranean Sea site was selected as a comparative test case because of the presence of a major anthropogenic interruption in river flow in the 1960s (Aswan Dam) that greatly diminished sediment discharge to the southeastern Mediterranean Sea (Shalash, 1982). The use of these two sites, which are fundamentally different in scale (several orders of magnitude) and river type (small ephemeral versus large perennial), was intended to pinpoint which processes or characteristics would have the most broad and global application.

1.2. Study area

1.2.1. Red Sea, Eilat

Eilat, Israel, is a newly established (1951) coastal city with a well-documented history of altering the coastal landscape to accommodate development (Figure 2). The city’s surroundings are hyperarid (< 27 mm rain per year; Kalman et al., 2020) with episodic flash flooding through otherwise dry riverbeds during sporadic, localized rain events (Dayan et al., 2001). Depending on distances and volume of rain, some of the flashfloods enter the sea. Floods reaching the GAE carry sediments eroded from surrounding geological formations and settled dust (Boyko et al., 2019). These flashfloods are the main source of sediments within the GAE, settling first on the 2-km-wide shelf. The shelf is biologically active. Several studies describe mixing of the surface layer by benthic organisms (Black et al., 2012; Mathalon et al., 2019), while other studies recognize considerable local resuspension by fish (Yahel et al., 2002; Mathalon et al., 2019). Transport by resuspension is often associated with strong waves and fast currents; however, wave heights at this study site are < 1 m (Reidenbach et al., 2006), having little effect more than a few meters below the sea surface (Katz et al., 2015), and bottom currents (3.7 ± 2.5 cm s⁻¹) are generally slow (Mathalon et al., 2019). Northerly winds dominate (90%) the northernmost Red Sea, and rare storms occur only during strong southerly winds.

During Eilat’s development, canals were built to protect buildings, harbors, marinas and other structures from flashflood damage. Aerial photos (Figure 3) demonstrate that prior to this work, the incoming floods could enter from many channels across the shore, but much was concentrated towards the center of the northern shoreline near the current Jordanian-Israeli border. Over time, drainage channels were expanded, shifted and merged, concentrating the runoff by the late 1960s into the Kinnet Canal, a single outlet located east of the hotel district (Figures 1 and 3). This canal is in the same area where much of the natural discharge occurred prior to development; after its construction it became the sole conduit of flood material arriving from the north.

1.2.2. Eastern Mediterranean Sea, offshore Israel

The majority of sediments found along the eastern Mediterranean shallow shelf originated from the Nile River and were then delivered via longshore transport (Carmel et al., 1985; Zviely et al., 2007, and references therein). The Nile has been the major supplier of freshwater and suspended sediments to the eastern Mediterranean over the past 11 million years (Woodward et al., 2008).

The High Aswan Dam (1964) was built in order to better control the Nile’s water supply for drinking, fisheries, irrigation, electricity, and flood damage (Monsef et al., 2015). After its construction the maximum water discharge was reduced by 75% (Zeid, 1989), while the volume of suspended sediments discharged to the sea was reduced by 98% (Shalash, 1982). The great majority of the alluvium is now trapped in upper lake reservoirs (the largest being Lake Nasser) where the sediment composition is quite heterogeneous, mainly silty clay and clayey silt (Farhat and Salem, 2015). The influence of decreased sediment discharge is of great interest with regard to sediment supply and impacts along the eastern Mediterranean.
2. Methods

2.1. Geographic records of development

For a time series of the development of the Red Sea research area, historical aerial photos of the northernmost part of the Gulf of Aqaba-Eilat were obtained from the Survey of Israel (2018). The Ottoman Period (1912) map was found and photographed in the University of Haifa maps and media archives. The information regarding the development of Eilat and its drainage system were provided by the Eilat City Museum and the Arava Drainage Authority. The well documented construction and timing of the High Aswan Dam did not require additional validation for the study (Abu-Zeid and El-Shibini, 1997).

2.2. Collection of sediment cores

Sediment cores were collected from the offshore shallow marine shelf of the Red Sea northern GAE and from the eastern Mediterranean shelf (Figure 1). Samples were analyzed for granulometry, element composition, micropaleontology, microplastics, and assessed for age using radiocarbon dating.

2.2.1. Red Sea collections

Six push cores (two 70-cm and four 20-cm long; Table 1) were collected by divers off the northern beach of Eilat (Figure 1). The eastern core (NBE) was collected at 10-m water depth approximately 220 m offshore the Kinnet outlet in January 2016. The western core (NBW) was collected in front of the north beach hotel district, about 180 m offshore at 13-m water depth in July 2016. The other 4 shorter cores were collected along an E–W transect in May 2015. The push cores were made of transparent plastic with 45-mm inner diameter. Each core was sliced into 1-cm sections that were weighed wet, dried at 60°C and weighed again before further analysis.

2.2.2. Mediterranean Sea collections

One of the Mediterranean sediment cores (EMT13-C6) was collected from 33-m depth offshore of Jaffa in 2013 using a diver-operated pneumatic hammer (described in Goodman-Tchernov et al., 2016). The aluminum core with 80-mm inner diameter penetrated to 2-m depth and the upper 25 cm were analyzed for purposes of this study.

Figure 3. Time sequence of urban development in the Eilat region over the past century. Red dots mark the outlet point of the modern Kinnet Canal. (A) 1912 oil-painted topographic map of the northern Gulf of Aqaba-Eilat (GAE). (B) Aerial photo from 1945 of the northern GAE and the alluvial fan, before Eilat was established. (C) 1956 aerial photograph of the developing city with the primary structures on the hillside, the airport on the edge of the braided channel alluvial fan, and agriculture fields on the alluvial fan. (D) 1968 extensive expansion of modern construction in the alluvial plain. (E) 1978 aerial photograph showing the artificially reinforced Kinnet Canal. (F) 2021 current view of Eilat. DOI: https://doi.org/10.1525/elementa.2021.00039.f3
addition, 3 box core samples were collected from the Bat Galim Research Vessel and subsampled with push cores (transparent plastic with 45-mm inner diameter) in 2017 (T3-60) and 2019 (T6-40, T11-40). Similar to the Red Sea cores, the sediments in these cores were sectioned at 1-cm resolution for further analysis.

2.3. Lab analysis

2.3.1. Granulometry

Sediments in both the Red Sea and Mediterranean Sea cores were analyzed for grain size distribution in centimeter intervals after being treated with 35% H₂O₂ to digest organic matter. In all but the 3 short cores from the Mediterranean Sea, grain size (< 2000 μm) distribution was measured using a Beckman Counter LS 13 320 Laser Diffraction Particle Size Analyzer (Goodman-Tchernov et al., 2009). In the remaining 3 cores, grain size distribution was measured by Laser Diffraction using Malvern’s MasterSizer 3000 following the PT4SD pretreatment procedure described in Jaijel et al. (2021).

2.3.2. Porosity

Porosity profiles for the Red Sea sediment cores were calculated from the water loss during drying in each of the core sections (1 cm), assuming particle density of 2.65 g cm⁻³.

2.3.3. Microplastics

Microplastics were used to correlate our findings with recent human activity (Waters et al., 2016). This analysis was performed on samples from the Red Sea in combined 3-cm batches in order to achieve the required volume of sediment (approximately 28 g dry sediment). The microplastics in the samples were separated by flotation technique (density separation) following Thompson et al. (2004) with some minor modifications. Analytical NaCl was used in order to create a saturated (26 wt%), approximately 1.2 kg L⁻¹ dense brine solution; in addition, after introducing the solution and shaking, the samples were sonicated for 3 minutes in order to remove adhered materials from the surface (Ashton et al., 2010). After separation, samples were filtered using a vacuum pump and 1-μm pore diameter glass fiber filters. The filters were then dried and analyzed under a binocular microscope, and any microplastics were enumerated and described. An unused filter was left exposed during the analysis and used as an environmental control to determine background microplastic contamination within the laboratory.

2.3.4. Radiocarbon dating

Radiocarbon analysis was used to date pre-modern phases in the northern GAE sediment cores. From the longer northwestern (NBW) core at 59 cm, larger benthic foraminifera (species independent) with the least visually apparent damage and diagenesis were isolated, cleaned with a sonicator and weak (0.1 M HCl) acid for a few seconds, and then dried for direct accelerator mass spectrometry (AMS) analysis. In total, 166 individual foraminifer were picked, treated with acid, and dried and weighed (0.0161 g). The ¹⁴C measurement was completed at Direct AMS laboratories in Washington, USA, where AMS was used to measure ¹⁴C isotope concentration in the sample. The prepared sample went through a series of physical and chemical protocols to transfer the carbon content of the sample first to CO₂ then to graphite where the measurements of carbon isotopes were performed by AMS. During the measurement, a beam of carbon ions is produced, the beam is accelerated, focused and split into 12, 13 and for our purpose 14 atomic mass units into the cathodes of the AMS. Each cathode is sampled multiple times, allowing for a statistical evaluation of numerous data points of a single sample. Direct AMS raw data were transferred into their proprietary analysis software, where calculations were performed and then transferred to us. The final calibration was performed using Calib Rev 7.10 software applying MARINE13 calibration (Stuiver and Reimer, 1993; Reimer et al., 2013). The foraminifer tests (83 individuals that weighed 0.0167 g after acid treatment and sonication) picked at 5 cm from the other long (NBE) core were measured and calibrated the same way as the NBW core, and its calibrated radiocarbon data was first published and then obtained from Kalman et al. (2020).

### Table 1. Sediment cores collected and used in this study. DOI: https://doi.org/10.1525/elementa.2021.00039.t1

| Core ID | Location     | Year | Core Length (cm, Analyzed) | Depth (m) | LAT   | LONG   |
|---------|--------------|------|---------------------------|-----------|-------|--------|
| NBW     | Red Sea      | 2016 | 70 (70)                   | 13.0      | 29.5469 | 34.9616 |
| NBE     | Red Sea      | 2016 | 70 (70)                   | 10.0      | 29.5431 | 34.9696 |
| 1600W   | Red Sea      | 2015 | 20 (20)                   | 12.6      | 29.5477 | 34.9571 |
| 1000W   | Red Sea      | 2015 | 20 (20)                   | 13.0      | 29.5460 | 34.9626 |
| 550W    | Red Sea      | 2015 | 20 (20)                   | 13.1      | 29.5443 | 34.9665 |
| 500E    | Red Sea      | 2015 | 20 (20)                   | 13.8      | 29.5420 | 34.9739 |
| T3-60   | Mediterranean Sea | 2017 | 11 (11)                  | 61.0      | 32.7541 | 34.8737 |
| T6-40   | Mediterranean Sea | 2019 | 18 (18)                  | 40.0      | 32.4031 | 34.8224 |
| T11-40  | Mediterranean Sea | 2019 | 15 (15)                  | 40.0      | 31.9124 | 34.6168 |
| EMT13C6 | Mediterranean Sea | 2013 | 200 (25)                 | 33.0      | 32.0567 | 34.7474 |
Although in marine environments, radiocarbon samples are susceptible to yield anomalies up to several thousands of years from their real age (Alves et al., 2018), the regional marine reservoir correction (ΔR) values for the northern GAE are 58 ± 35 yr and –30 ± 30 yr (calculated in CALIB v8.20 based on data presented in Felis et al., 2004), on fossil Porites coral colonies in Aqaba, about 9 km distance from this study location). These radiocarbon ΔR values rather extinguish each other, or increase uncertainty; we present our radiocarbon date results without an additional ΔR marine reservoir correction, and only the standard marine calibration.

2.3.5. Major elements in the sediment

Normalizing elements, such as creating elemental ratios can help to separate common alluvial materials from each other and focus on the actual decreases or increases of specific elements of interest. For example, Si/Al ratios can be linked to mineralogy (e.g., quartz to aluminosilicate ratios) and grain size (e.g., clastic sands to clay ratios; Singer, 1984; Lopez et al., 2006; Katz et al., 2015). Ca in the marine environment is commonly related to increased biological activity (more CaCO3 shells in the sediment). However, alluvial sediment can also include high concentrations of Ca if flood water erodes and transports carbonaceous sediments (e.g., limestone deposits). In this case, additional chemical analysis is required for differentiation. Major elements (Si, Fe and Al) were measured in the sediment at 1-cm resolution in the GAE cores NBE and NBW using energy dispersive x-ray fluorescence (ED-XRF; SPEC-TRO-SCOUT). Two grams of oven-dried (60°C) sediment were ground and homogenized to a powder with mortar and pestle and analyzed in a vacuum chamber to enhance the precision of the XRF readings. Measurements were calibrated with 3–8 certified sediment standards as described in Zirks at al. (2021).

2.3.6. Micropaleontology

Using the grain size and XRF results, foraminifera samples were selected from sections of the cores that represented the major sequences. Three subsamples were taken from NBW (Red Sea, NBW 7–9, 52–54, 61–63 cm) and 3 were selected from NBE (Red Sea, NBE 16–18, 46–48, 61–63 cm). Each aliquot (1.25 ml) was sieved using a 125-μm wet sieve for Red Sea samples and 250-μm then 125-μm for Mediterranean Sea samples. The sieved samples were dried then quantified for a range of foraminiferal characteristics: total abundance, diversity, size ratio (LBFs > 500 μm, following Goodman Tchernov et al., 2016). All samples were split, with each split analyzed in its entirety until a minimum of 300 individuals was achieved. When the full aliquot (1.25 ml) contained less than 300 individuals, that value was accepted. The 4 Mediterranean cores (EMT13-C6, T3-60, T6-40, T11-40) were analyzed for abundance (> 125 μm) per ml at 1-cm resolution.

3. Results

3.1. Eilat geospatial evolution

In 1945, the town of Eilat did not yet exist (British Royal Air Force photo, Figure 3B). At this time, and at least until 1956, the area was dominated by a heavily branched alluvial fan and sabkha, with multiple runoff channels along the northern coast. When flowing, runoff in these channels reached the sea in many locations with a primary discharge towards the center of the northern coast (Figure 3B and C). The Eilat Airport (1949) was the first project that altered natural runoff pathways from land to sea. Eilat residential neighborhoods followed in the 1950s. Buildings and homes were placed on the more stable areas between natural runoff pathways. These pathways were initially unpaved throughways which were replaced over time by paved roads. The city expanded quickly due to growth in sea trade, copper mining and tourism. The photographs from 1956 and 1968 (Figure 3C and D) demonstrate this active development and show how drainage channels were diverted towards the easternmost waterpath, today called the Kinnet Canal, which is very well defined in the 1978 aerial photograph (Figure 3D).

In the 1980s and 1990s construction of massive hotel complexes filled the drainage area that was once marked only by agricultural fields. To accommodate this development, the existing canals were further broadened, reinforced (some with cement), and regulated. Since then, while development, run-off diversion and regulation efforts have continued, the basic layout of the discharge into this major canal has remained the same (Figure 3E).

3.2. Red Sea sediments

All the Red Sea sediment cores were generally characterized by fine sand that contains fine shell fragments and smaller (approximately 0.5 cm) bivalves and gastropods. The sediments were of a mixed mineralogical composition, mostly siliciclastic with terrestrial and biogenic calcium carbonates. At the time of collection, we did not see color changes owing to bioturbation, likely owing to the very low organic carbon content (< 1%) and hence small differences in redox conditions.

3.2.1. Short cores

Results from the short (20-cm) cores from the GAE (Figure 4) provide characterization of sediment size distribution of the northern Red Sea shallow shelf for the recent period.

The Ocean Data View contour plots (Figure 4) show a visual representation of sediment sorting. Core 1600W, the westernmost core (1600W = 1600 m from the Kinnet Channel outlet), had the highest degree of sorting relative to the remaining cores in the sequence. Sediments closer to the canal, both east and west, were more poorly sorted (550W and 500E). Cores 1600W and 1000W were characterized by more stable and constant values of concentrations of fine particles, while the cores closest to the outlet (550W and 500E) contained more fluctuations. Porosity values decreased downcore in all of the cores, and were generally lower in the cores closest to the Kinnet Canal (550W and 500E). With regard to depth in core, microplastics were present down to the bottommost samples of the western cores (1600W and 1000W), but no deeper than 9 cm in the easternmost cores (550W and 500E).
3.2.2. North Beach West (NBW) long core

Based on grain size distribution, 3 horizons are distinguishable in the core (Figure 5), Horizon I from 70 to 59 cm, Horizon II from 59 to approximately 28 cm, and Horizon III from approximately 28 cm to the modern seafloor.

The bottommost horizon (I) had low fine concentrations (23–33%) relative to the other horizons, with mean grain size varied between 130 and 192 μm, with larger standard deviations (SD: 134–246 μm) relative to other parts of the core. Variations in the elemental ratios of Fe/Si (μ = 0.129, σ = 0.007) and Al/Si (μ = 0.226, σ = 0.006) in Horizon I are more confined, with lower SD between these values than other horizons. A representative section (61–63 cm) of this horizon had high foraminiferal abundance (1597 individuals/ml), in which 276 foraminifera tests were larger than 500 μm (large benthic foraminifera: LBF). The proportion of foraminifera species associated with a seagrass and/or hard substrate (S/H) type environment was 86.5%.

There was a transition to overlying Horizon II. Above Horizon I, from 58 cm to approximately 28 cm, there are higher fine concentrations (30–55%), lower mean grain size (70–146 μm) with lower SD between the grain size range (60–177 μm). An increase in elemental ratios (Fe/Si μ = 0.145, σ = 0.011; Al/Si μ = 0.242, σ = 0.010) was observed between 50 and 59 cm, and despite a distinct decrease at 50 cm, the values of the ratios between 40 and 50 cm were still higher (Fe/Si μ = 0.136, σ = 0.005; Al/Si μ = 0.233, σ = 0.006) than in Horizon I below. A well-marked decrease (349 fewer individuals/ml, 36 fewer LBF per mil and 3.2% less S/H) in foraminifera distribution was measured in section 52–54 cm.

In contrast, the transition to the uppermost Horizon III was more gradual, occurring at around 38–26 cm. The top section (Horizon III) from approximately 28 cm to the modern seafloor had higher mean grain size (156–339 μm), lower fines (18–30%), and higher overall SD (129–448 μm). Chemically, the elemental ratios (Fe/Si μ = 0.053, σ = 0.065; Al/Si μ = 0.096, σ = 0.113) were the lowest in the uppermost section. Foraminiferal abundances in Horizon III were the highest. For example, there were 477 more individuals/ml, and 108 more LBF/ml relative to Horizon I, and 3.8% more S/H species relative to mid-Horizon II.

Microplastics were present (1 microplastic identified per sample of approximately 27 g, or 230 individuals/kg) to a depth of 42 cm, and were of garish green color with both flat and 3D structures.

3.2.3. North Beach East (NBE) long core

Based on grain size distribution, three horizons are distinguishable in core NBE (Figure 5), Horizon I from 70 to 51 cm, Horizon II from 51 to 11 cm, and Horizon III from 11 cm to the modern seafloor. Bottommost Horizon I had low fine concentrations (10–17%) with mean grain size variations between 246 and 366 μm, and large SD (273–441 μm). Elemental ratios of Fe/Si (μ = 0.099, σ = 0.007) and Al/Si (μ = 0.214, σ = 0.007) had low and stable variations relative to the
overlying horizons. A representative section (61–63 cm) of Horizon I had 976 individuals/ml, 266 LBF/ml and 92.5% associated with seagrass and/or hard substrate (S/H).

The transition to overlying Horizon II was fairly distinct. The first section from 50 to approximately 11 cm included more fine concentrations relative to the bottommost horizon (12–29%), slightly lower overall mean grain size (177–378 μm) and high variations of SD (140–468 μm). In the middle section the average elemental concentrations increased slightly, with higher variations of the fluctuations present (Fe/Si μ = 0.101, σ = 0.011; Al/Si μ = 0.218, σ = 0.013). There was no notable change in the total number of foraminifera (992 individuals/ml), but the number of LBF (234 individuals/ml) and S/H (85.8%) decreased relative to Horizon I.

The transition to uppermost Horizon III occurred at 10 cm and contained a dramatic lowering of mean grain size before reaching minimum at the surface (from 212 to 43 μm), occurring in tandem with an increase in the fines proportion (from 10 to 77%). Elemental ratios had 3-fold SD and concentrations were higher (Fe/Si μ = 0.119, σ = 0.034; Al/Si μ = 0.228, σ = 0.031) relative to mid-Horizon II. Foraminiferal abundances were the lowest amongst all the sections (876 individuals in which only 225 are LBF/ml) and S/H foraminifera (92.2%) showed no remarkable change relative to Horizon I.

No microplastics were found in any of the NBE samples.

3.2.4. Radiocarbon dating

The distinct contact between Horizons I and II in both of the long Red Sea cores (at 59 cm in NBW and 51 cm in NBE) were selected for AMS 14C age analysis (Figure 5). The estimated (calibrated) ages for the transitions were 1484 ± 47 AD and 1383 ± 58 AD, respectively (NBE data from Kalman et al., 2020; Table 2).

3.2.5. Microplastics

Microplastics of garish green and light blue color, with both flat and 3D structures, were found in all cores except NBE, located in front of the canal. In all but 2 samples wherein plastics were found, the number of individual microplastics per sample (about 25–30 g vertical section) was 1. In the other 2 samples (1600W 16–18 cm and 1000W 10–12 cm), we found 2 microplastics per sample. For this reason, the microplastics results are presented in Figures 4 and 5 simply as “presence/absence.”

3.2.6. Eilat core results summary

The 4 short cores (Figure 4) are characterized by decreased sediment sorting occurring from east to west with distance from the Kinnet Canal outlet. Microplastics also decreased from the west (in front of Hotel area) to east (closer to Kinnet Canal). Horizon I (bottoms of cores) in both NBW and NBE (Figure 5) are characterized by lower grain size sorting values, absence of microplastics, and higher relative abundances and larger sized...
foraminifera than other horizons. Horizon I terminates in both cores at approximately 1400 AD (Medieval Warm Period–Little Ice Age transition). Elemental ratios in Horizon II shifted in both cores with regard to Fe/Si and Al/Si at this core depth. Horizon II in both cores exhibited higher grain size sorting values and higher concentrations of fines relative to Horizon I, which then changed as it approached upper Horizon III. Foraminiferal abundances and sizes in Horizon II were smaller than those of Horizon I in both cores. Microplastics were present rarely in NBW Horizon II and absent in NBE Horizon II; Horizon III varied significantly between NBW and NBE.

NBE exhibited elevated fine grain size proportions overall and much higher concentrations of fines in the uppermost layers, as well as higher Fe/Si and Al/Si values, with no microplastics. In contrast, NBW had lower fine grain sediment abundance coupled with higher foraminiferal abundance and size, as well as greater presence of microplastics (Figure 5).

### 3.3. Mediterranean Sea sediments

All of the Mediterranean cores became coarser towards the top (Figure 6). The textural differences between the bottom and the top layers of the cores were either transitional (T series) or occurred sharply, sometimes even visible to the naked eye (EMT13-C6). Relative to the bottommost samples measured in each core, the reduction of fines at the surface was 63% (T3-60), 83% (T6-40), 45% (T11-40) and 91% (EMT13-C6). Foraminiferal abundances (> 125 μm) were considerably higher (6 times in T6-40, 7 times in T3-60, 4 times in EMT13-C6 and 16 times in T11-40) at the top of the cores relative to deeper in the cores.

### 4. Discussion

#### 4.1. Natural versus anthropogenic sedimentological imprints in the Gulf of Aqaba–Eilat

Our analysis shows that the bottoms of the western sediment core (NBW, from in front of the Eilat hotels area) and the eastern core (NBE, from in front of the Kinnet Canal outlet) in the northern Red Sea show similar trends, though not similar values, in the fines (≤ 63 μm) fraction and the Fe/Si, Al/Si ratios (Figure 5). In both, the deepest part is relatively poor in fines with a sharp rise in their concentrations at depths of approximately 53 and 58 cm, respectively. The generally corresponding profiles of Al/Si and Fe/Si ratios in these sections are likely related to changes in the ratios of clay minerals to quartz, the first being more abundant in fines and the second, in sand-size particles. Considering uncertainties relating to biological mixing, the radiocarbon ages in the cores (1383 ± 58 AD in NBE and 1484 ± 47 AD in NBW) are close to each other. Recently, Kalman et al. (2020) suggested that this visible shift occurred at the end of the Medieval Warm Period (MWP), concluding that it was a relatively dry (drought) period in the GAE and the start of a more humid period thereafter. This shift occurred hundreds of years before there was anthropogenic river rechanneling in this area. During this climate anomaly there were fewer floods and longer intermissions between sequential flood events (Kalman et al., 2020).

Winnowing, the preferential transport by currents of fine particles that are slower to settle following resuspension (whether physical or biological), continues during these droughts (Katz et al., 2015; Kalman et al., 2020). Owing to mixing by bioturbating organisms, sediments in the uppermost layers, until they are ultimately buried, are exposed to surface processes that winnow fine particles and transport them from the shallow shelf to the deeper basin. This exposure is why the entire mixed layer will show signs of coarsening associated with “anthropogenic drought” relatively soon (years) after its initiation.

Although winnowing also removes fines in humid periods, these rainier periods have shorter intervals between flood deposition events and, therefore, more fines are retained in the record. Consequently, Kalman et al. (2020) proposed that relative depletion of fines in the sedimentary record can serve as a proxy for prolonged drought periods. Contrary to the lowermost intervals of the 2 cores, the trends in grain size in the uppermost part of the cores (Horizon III) are very different from one another. In NBE, the larger fine fraction is fairly constant from the post MWP anomaly shift to 12-cm depth. At 12-cm depth there is a 2-cm layer of coarser sediments that was attributed to a recent (1995–2012) drought period (Kalman et al., 2020). The top approximately 10 cm of NBE (Figure 5) contains a much higher concentration of fines compared to the rest of the core. This upper layer probably relates to the recent deposition of fine, flood sediment beginning in 2012, a period with an exceptionally high frequency of flood events (8), the latest occurring about 2 months before core NBE was collected.
The approximately 50-cm long, Horizon II of NBE relates to a more humid period (in relative terms) for this hyperarid area that persisted between the MWP anomaly and the present.

In NBW, concentrations of fines also increase above the MWP anomaly shift (at about 58-cm depth). However, contrary to NBE, the fines decrease gradually between core depths of approximately 30 and 18 cm, and then stabilize.

Figure 6. Regional map with locations of the Mediterranean sediment cores collected in this study. The common features of the physical appearance (core picture, grain size) and micropaleontological properties of all 4 cores indicate a general coarsening and sharp increase in foraminiferal abundances in the top layers along the eastern Mediterranean coast. The arrows mark the dominant direction of eastern Mediterranean circulation (after Bergamasco and Malanotte-Rizzoli, 2010). Bathymetry map was downloaded from the website of the Geological Survey of Israel (2020b). DOI: https://doi.org/10.1525/elementa.2021.00039.f6

(Kalman et al., 2020). The approximately 50-cm long, Horizon II of NBE relates to a more humid period (in relative terms) for this hyperarid area that persisted between the MWP anomaly and the present.
at their lowest values towards the surface (Figure 5). The upper part of NBW thus has a grain size signature resembling that of prolonged droughts, such as are seen in the bottom of the two cores (Horizons I). This coarsening at NBW cannot be related to changes in precipitation because the equivalent Horizon III in the neighboring core to the east (NBE) shows that floods occurred in the north beach, which is also known from direct observations (Kalman et al., 2020). Given that the earlier phases (Horizons I and II) are represented in both locations (cores NBE, NBW), and recent years have experienced floods, we conclude that the “drought-like” signal in NBW Horizon III is the product of anthropogenically reduced discharge of flood sediments in that area.

In this case of reduced discharge, the cause is the channelization of runoff to the Kinnet, evident in the time series of aerial photographs (Figure 3). Prior to the establishment of Eilat (Figure 3B), there was a sabkha to the north of the GAE shoreline with many braided channels of ephemeral rivers that reached the sea all along the north beach. This photo suggests that up until then fine flood sediments could directly reach the area where the NBW core was collected (Figure 2). However, water runoff regulation, beginning in the 1950s, diverted these channels to the east to accommodate major construction projects (hotels and marina areas) (Figure 3D).

The regulation of the Kinnet Canal (formerly unnamed), in its current route, took place in the late 1970s (Figure 3E). Thus, owing to anthropogenic activity, direct discharge of flood sediments to the area of the NBW core has been mostly or entirely halted in the last six decades. In contrast, the NBE core was collected from an area that has always received flood runoff, and continues to do so today (Figure 3B). Because only small amounts of fine flood sediments can now arrive to the western area via longshore currents, the anthropogenic deprivation of fines and continuous natural, uninterrupted winnowing produced a drought-like, coarse uppermost layer in core NBW. No such coarse layer is present in the NBE core, because its location was near the mouth of the canal where flood runoff occurs today as well as in the past. The particle size distribution among the short cores (Figure 4), also demonstrates the decrease in fines that occurs from east to west with increasing distance from the Kinnet Canal outlet. Natural winnowing of the seabed without flood sediment resupply leads to higher sorting values as the finer fraction of the sediments is removed.

From the ages of the dated foraminifera collected in these cores, mean sedimentation rates of 0.75 and 1.10 mm yr⁻¹ were calculated for NBE and NBW, respectively. These rates suggest that a maximum of 8 cm of sediment accumulated on the shelf in the study site area since the establishment of Eilat (around 1950), assuming that the sedimentation rate has been constant. The gradual depletion of fines, down to a depth of approximately 36 cm in NBW (Figure 5) is therefore attributed to deep biological mixing rather than the new arrival of coarser sediments. This unusually deep mixing is corroborated by a reported mixing depth of 18–34 cm (Edelman-Furstenberg et al., 2020, using ²¹⁰Pb profiles) very close to this study area. Moreover, their ²¹⁰Pb profiles contain a few high activity data points downcore, resembling signals ordinarily linked with recent sediments. They suggested bioturbation from burrowing organisms as the source of these anomalous measurements. This conclusion is reinforced by the presence of microplastics in NBW reaching similar depths downcore (Figure 5). Given that microplastics would not have been introduced prior to the 1950s, their presence constrains the period over which this downcore mixing and dwindling of fines towards the surface occurred. The mixing depth, which is much larger than the average 10 cm reported from most marine areas (Boudreau, 1998), may be related to mound-building organisms (Mathalon et al., 2019) that are common in this area. Similarly, the shallower mixing depths detected by the downward loss of fines in cores closer to the Kinnet Canal correspond with the shallower presence of microplastics there (maximum depth of 8 cm; Figure 4). This also agrees with the shallower mixing depths in front of the Kinnet outlet detected by Edelman-Furstenberg et al. (2020), who suggested that higher sediment loads delivered during floods had possibly suppressed burrowing activity. Overall, there were more microplastics towards the west, corresponding to the more developed and touristic areas, with the arrival of microplastics coming directly from the coastline (trash blownwind into the sea by the dominant northern winds).

In all cores, the abundance of large benthic foraminifer followed the same trend as grain size: cores with coarser layers also had relatively higher abundances of LBF. The input of flood sediments to the shelf can influence foraminiferal abundance both physically and ecologically. Physically, the introduction of foraminifera-barren, terrestrially originated flood sediments reduces (“dilutes”) the overall proportion (abundance) of foraminifers per volume of bulk sediment. Alternatively, when floods are absent, winnowing of fines may result in an increase in the concentration of coarse sediments, including the foraminifers within those size ranges. Ecologically, turbidity and burial from incoming floods can reduce light availability, which can suppress the photosynthesizing capabilities of symbiont-bearing foraminifera (Uthicke et al., 2008, 2017), retard the growth or eradicate seagrass habitats and their epiphytic species (Winters et al., 2016), and alter overall food availability. In the absence of floods, foraminifera population and generational succession may occur without or with less interruption. The seagrass habitat and the tendency towards a coarser substrate may further raise the overall number of foraminifera associated with those conditions. Thus, whether due to physical or ecological mechanisms, or as an outcome of both, more flood sediments are expected to be associated with lower benthic foraminiferal abundances, and less flood sediments with higher foraminiferal abundances. On a spatial scale, this expectation corresponds with the observed difference between foraminiferal abundance in the cores, which is 1.5- to 2-fold greater in NBW where inputs of flood sediments are low, compared to NBE where they are high (Figure 5). Per core, there are also upsection changes in foraminiferal abundance that can imply temporal shifts in flood sediment inputs. This
pattern is seen in the high abundance at the bottom of the core, synchronous with the MWP anomaly drought, even higher abundance at the top of the core in the modern, post-settlement mixed layers in Horizon III, and the lowest values in the middle part of the core during the relatively more humid (flood-prone) period (Horizon II). Corresponding changes in the ratio of foraminifera that are epiphytic (or prefer hard substrate) in NBW (Figure 5) suggest that reduction in flood sediment inputs may have also benefited the growth of seagrass meadows in that area (Winters et al., 2016). In contrast, at NBE where anthropogenic regulation of the river channels did not reduce the input of flood sediments, the timing of changes in foraminiferal abundance is different. As can be expected, no foraminifers were observed in the fresh (about 2-month-old) flood layer in Horizon III near the surface, a relatively small abundance occurred at the upper part of the humid period in Horizon II with slightly higher abundances at the bottom of the humid layer in Horizon II and during the MWP anomaly in Horizon I. There is some resemblance in Horizon II in the bottom layers of both cores, suggesting that at a depth of 45–48 cm in NBE these layers are partially mixed. This conclusion can be supported by the difference in the location of the shift between the layers in the grain size and the Fe/Si and Al/Si ratio profiles (Figure 5). Hence, here too, the changes in the abundance of foraminifera tests reflects the frequency and overall input of flood sediments to the shelf. The abundance of large benthic foraminifers and ratio of epiphytic plus hard substrate dwelling foraminifera in this area did not show much variation over time.

Thus, in this research of the shallow continental shelf of the GAE, we showed the resemblance between the sedimentological features associated with natural droughts and those associated with sediment deprivation owing to anthropogenic alteration of river channels. The evidence for the association includes both the depletion of fines and increase in the concentration of foraminifera tests in horizons associated with natural drought (Horizons I in both NBE and NBW), as well as the co-presence in the uppermost horizons of a drought (Horizon III in NBW) and flood layer (Horizon III in NBE). Because this flood layer (Horizon III in NBE) is associated with recent documented floods, the findings in the western area (NBE) cannot be linked to regional climatic conditions, but rather to anthropogenic interference in sediment discharge. The anthropogenic alteration of the river channels that changed the offshore distribution of incoming flood sediments, significantly changing substrate patterns, is illustrated in Figure 7.

4.2. Altered sedimentological appearances along the eastern Mediterranean Sea

Are the basic processes observed from a somewhat provincial study site on the outskirts of the Negev Desert more widely applicable? To test the larger relevance of this study, we shifted from our observations of the sedimentological impacts from the diversion of the small, ephemeral rivers that surround the head of the Gulf of Aqaba-Eilat to one of the largest examples of sediment retention, the High Aswan Dam on the Nile River, Egypt, erected in 1964.

A thorough and detailed study by Almogi-Labin et al. (2009) reported sharp grain size coarsening on the upper portions of a transect of box cores collected at 40-m depth from the Israeli shelf. This shift corresponded to the timing of construction of the High Aswan Dam, based on excess $^{210}$Pb dating. During this same time period, instrumentally recorded rainfall and flood records at Khartoum, Sudan (Walsh et al., 1994), as well as records from stations throughout the Nile Basin (Mokria et al., 2017), show no major changes in precipitation relative to the centuries before construction of the High Aswan Dam.

Cores EMT13-C6, T3-60, T6-40, and T11-40 from the EMS were collected (Figure 1) along more than 100 km of what was once a main pathway for long-shore transported and discharged Nile sediments (Schattner et al.,...
Figure 8. Regional map with the locations and dated grain size variations of the Mediterranean sediment cores. The cores represent grain size variations and general coarsening along the eastern Mediterranean coast. The age models of the additional short cores were calculated from $^{210}$Pb measurements (adapted from Almogi-Labin et al., 2009). The arrows mark the dominant direction of eastern Mediterranean circulation (after Bergamasco and Malanotte-Rizzoli, 2010). Bathymetry map was downloaded from the website of the Geological Survey of Israel (2020b). DOI: https://doi.org/10.1525/elementa.2021.00039.f8
2015). As with the NBW core from Eilat, the upper part of these cores (approximately 11 cm) displays considerable coarsening and higher abundance of foraminifera tests, particularly of larger individuals, compared to the underlying sediment horizons (Figure 6). These findings also agree with the measurements of Almogi-Labin et al. (2009; Figure 8). A recent foraminifera study by Avnaim-Katav et al. (2020), comparing dead and live community assemblages from this area, found a recent shift in community assemblages, suggesting that the changes in the substrate have had environmental and ecological consequences.

4.3. Comparison of GAE and EM

The Mediterranean site differs fundamentally from the Gulf of Aqaba-Eilat site in its size, as well as the magnitude, character, chemistry, and mineralogy of riverine sediment source, and other attributes. Nonetheless, our results suggest that in response to the disruption and reduction of incoming sediments from river outflow in both areas, a similar set of processes led to a similar trend in certain sediment characteristics. We argue that the coarsening upper layers represent a change in the balance between deposition of alluvial sediments and their removal. This "change" must be linked to some shift in recent decades, in a way that would impact the seafloor broadly. Considering this commonality, we propose that, when out of sync with climatic variation or other natural effects, an observed scarcity of fines and increase in large benthic foraminifera in continental shelf surface sediments, offshore of waterways, can indicate human divergence or damming of these rivers, rather than drought or drought alone.

While large benthic foraminifera add CaCO₃ to the sediment, enrichment of carbonate values in the bulk sediment is not a good proxy for the process we describe. In some cases (e.g., GAE, see Supplementary Materials), the winnowed fine particles may also be carbonaceous, thus muting the carbonate signal related to increased numbers of large benthic foraminifera.

Other human activities such as dredging by trawlers (Jones, 1992; Thrush and Dayton, 2002) may also affect the recent sedimentary record. Bottom trawling creates physical disturbances to sediments that change the quality of the substrate (Tillin et al., 2006). Mengual et al. (2016) analyzed the influence of trawling on sediment resuspension on the continental shelf of the Bay of Biscay and found an upward coarsening trend in the first 5 cm of the cores from an intensively trawled zone. On the other hand, in the absence of advective transport by currents, results of continual resuspension can lead to the accumulation of fine sediments in the uppermost layers affected by trawling (Trimmer et al., 2005; Queirós et al., 2006). However, at least with regard to the Eilat site, no trawling has been allowed or carried out for decades. While the influence of trawling on the Mediterranean sediments cannot be entirely negated as a factor in the coarsening observed, the lateral continuity between sample sites along the coast and by depth suggests a less localized causal mechanism.

Considering the broader global picture, a reduction of 1.4 billion tons of sediment per year is expected in the flux of terrestrial sediment through rivers to the coastal ocean due to damming (Sivitski et al., 2005), which according to our conclusions will cause similar consequences as above. Reductions have already occurred in geographically distant locations. For example, following the construction of a series of dams on the Yangtze tributaries, sediment discharge to the East China Sea gradually reduced from 511 Mt yr⁻¹ in the late 1960s to 145 Mt yr⁻¹ in 2003–2012 (Yang et al., 2018a). This change was followed by a significant coarsening of surface sediment (at 5–20 m water depth) offshore (Yang et al., 2018b). Another example is in the northern Gulf of California, near the mouth of the Colorado River where damming since the 1930s (e.g., Pitt, 2001; All, 2006) has led to the almost total elimination of water and sediment discharge into the delta region. These post-dam sediments contain decreased fine fraction (Shumilin et al., 2002) and altered chemical composition (Carriquiry and Sánchez, 1999). Similar coarsening is seen offshore of altered and dammed rivers in the Gulf of Mexico, Rio Grande (Rodriguez et al., 2001), and in sediments of Monterey Bay (Carlin et al., 2019). In Carlin et al. (2019), coastal erosion in the absence of sediment delivery from rivers is evoked as a major causal mechanism for this coarsening. The coarsening that we have described in the GAE occurred without the presence of coastal erosion, suggesting that coastal erosion is not a necessary component of the process.

5. Conclusions

Our results suggest that the sedimentary outcome from natural droughts that is observed offshore of rivers in marine inner shelf systems is fundamentally similar to the sedimentary fingerprint observed as a result of reduced discharge owing to the anthropogenic alterations of rivers. However, because anthropogenic activity occurs in tandem with natural fluctuations in water and sediment delivery, its differentiation and identification are best accomplished by recognizing disagreement between the sedimentary fingerprint and documented climatic conditions. Given the worldwide proliferation of dammed or otherwise altered rivers, we expect to find these sedimentological markers (i.e., increased grain size coarsening, larger sized and higher abundance of foraminifera) offshore from discharge points of altered rivers on a global scale. As such, this pattern can be considered one of the features characterizing the Anthropocene epoch. Importantly, this must be considered when comparing modern sedimentological records with older ones for purposes of interpreting or identifying impacts of recent climate change; for example, mislabeling an anthropogenically “drought-like” for a precipitation-linked, climatic drought. Anthropogenically altered sediment is also significant because grain size is a fundamental aspect of substrate environmental conditions. The ecology of living benthic communities, flora and fauna, are dependent and linked to these landscapes, and are altered when these conditions change (e.g., Avnaim-Katav et al., 2020). Given the widespread phenomena of anthropogenic river alterations, we
presume that there is a global “anthropogenic drought” coarsening effect, which is expected to escalate in coming decades given known development plans and predicted population growth (Neumann et al., 2015). The future consequences from this escalation are complex and undoubtedly planet-altering.

Finally, projected global aridification models (Sherwood and Fu, 2014) predict increased droughts worldwide in the next century. This increase, combined with the off-shore “drought-like” anthropogenically altered sediments, would presumably result in an even further coarsening of marine sediments, bringing with it related ecological and environmental changes. This anthropogenic drought effect should be added to the many other anthropogenic influences that have impacted and are directly impacting the marine seafloor substrate, including eutrophication, marine and coastal structures and infrastructure, aquaculture, soil erosion, dredging, and paving (Thrush and Dayton, 2002; Dearing and Jones, 2003; Bulleri and Chapman, 2010; Steffen et al., 2016; Tomašových and Kidwell, 2017; Baud et al., 2021).

**Data accessibility statement**

Raw sedimentological data were generated at the University of Haifa, Haifa; the Israel Limnological and Oceanographic Institute, Haifa; and the Interuniversity Institute for Marine Sciences, Eilat, Israel. The data that support the findings of this study are available in Supplementary Materials. Eastern and southeastern Mediterranean bathymetric maps used in support of study figures were downloaded from the following websites: https://www.gov.il/en/departments/general/east-mediterranean-coast-bathymetric-map; https://www.gov.il/en/departments/general/mediterranean-coast-bathymetric-map.

**Supplemental files**

The supplemental files for this article can be found as follows:

Supplementary Data. Xlsx

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**Competing interests**

There are no competing interests to declare.

**Author contributions**

Substantial contributions to conception and design: AK, BGT, TK.

Acquisition of data: AK, AM, BGT, TK.

Analysis and interpretation of data: AK, CE, BGT, TK.

Drafting the article or revising it critically for important intellectual content: AK, BGT, PH, CE, AM, TK.

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