LONGSHORE DRIFT RATES AND DIRECTIONS ALONG THE CARMEL COAST

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ABSTRACT

Both the direction and rate of the net longshore transport along the Carmel coast is noted to be variable and disputed between different studies. It was found that the dominant wave direction approaching the coast is very close to that of the beach normal, which means that small changes of wave directions, and the wave-induced currents, result in reversals in the direction of longshore sand transport, leading to a low net drift. During the literature review limited to no estimates were found on gross drift rates, year-to-year or seasonal variations in longshore drift or estimates for the distribution of the drift across a beach profile. This study sought to expand on the current knowledge by providing estimates of these parameters of drift rates. Analysis of the monthly variation of the potential longshore drift indicated a seasonal variation in rates and directions. A lower drift rate with a southwards bias in direction occurred during the summer whilst a higher drift rate with a northwards bias in direction occurred during the winter. Furthermore, variations of drift rates and directions were found with distance across the beach profile. The upper section of the beach profile showed a net southward sediment transport, whilst the lower section of the beach profile showed a net northwards sediment transport.

Keywords: Seasonal variation in drift; cross-shore distribution of drift; coastal processes

1 REVIEW OF EXISTING TRANSPORT RATE ESTIMATES

Carmel (Figure 1) is located at the northern end of the 650 km long Nile littoral cell which extends from Alexandria, Egypt to Akko, Israel (Inman and Jenkins, 1984). The primary source of sediment for the south-eastern Mediterranean coast is the Nile River. Since construction of the Aswan dams (in 1902 and 1964), the Nile flow regime and the Nile’s sediment transport has undergone a dramatic change. This river no longer brings fresh sand to the coast, and erosion of the Nile delta now constitutes the source of sediment for the Nile littoral cell (Carmel et al., 1985). Haifa Bay (north-east of Carmel) is a sediment sink for Nile littoral sands (Goldsmith and Golik, 1980; Zviely, 2006).

Shoshany et al. (1996) summarises the regional transport described in a number of studies, concluding that in general the sediment from the Nile Delta travels eastwards and then northwards up the coast of Israel. However, this paper states that within the littoral cell in the region of Tel Aviv and Haifa, there is some disagreement to the drift direction, for example between the papers written by Carmel et al. (1985) and Emery...
and Neev (1960), (cited in Shoshany et al., 1996). The literature considered has therefore been divided into two sections determined by the direction that they suggest the longshore transport is travelling in.

1.1 Predicted southward sediment transport

The early study by Emery and Neev (1960) proposed that, on the basis of directional relationship between the waves and the coast, the net transport of sediments between Haifa and Tel Aviv was southward. This proposed pattern of sand transport leaves open the question of the northern sand source. It was therefore suggested by Emery and Neev (1960) that in addition to the longshore drift of sand in the surf zone by wave-induced longshore currents there is an additional mechanism that drives the sand - the general northerly Mediterranean current that drives sand beyond the surf zone northward. The hypothesis was that longshore sediment transport was carried out by two mechanisms. The first is in the surf zone, where wave-induced longshore currents drive sand from Rafah northwards and from Haifa southwards with a convergence in the central part of the coast. The second mechanism takes place in deeper water beyond the breaker zone, on the inner continental shelf. Here, sand is driven northward along the entire shelf of Israel by the general northerly flowing Mediterranean current. A study of the bedforms by Golik (2002) indicated northward sediment transport on the inner continental shelf.

Shoshany et al. (1996) goes on to support this by saying that in the northern part of the Israeli coast, beach accretion against the north side of a groyne in Haifa and a tombolo behind a detached breakwater in Haifa exhibits asymmetry facing northward, which indicates a net sand transport southward. However, it is not clear when the photographs showing this beach accretion were taken and at any rate these photos are only snapshots of the beach position in time and may not indicate the overall net sand transport. Analysis of changes in beach plan shape at Carmel using Google Earth images (Figure 2) show times when the beach has accreted against the south side of the groyne (indicating northwards drift) and times when the beach has accreted against the north side of the groyne (indicating southwards drift). For example, the December 2010 shoreline shows a wider beach against the southern side of the groyne, indicating a northwards drift at this time, whereas the March 2016 shoreline shows a wider beach against the northern side of the groyne, indicating southwards drift at this time and location. Slight asymmetry of the tombolo behind the breakwater also indicates variations in the drift direction. However, the overall differences are subtle, indicating that the net drift direction is variable.

![Figure 2. Aerial images showing different shoreline positions](image)

Golik (2002) examined beach accretion and erosion next to coastal structures in Israel. This study revealed that north of Netanya accretion occurs on the northern side of the structures and erosion on their southern side, thus indicating a southwards drift at this location (northern section of the Israeli coast). To the south of Herzliyya
beach, accretion occurs on the south of coastal structures and erosion north of the structures, thus indicating a northward transport in the surf zone at this location (southern part of the Israeli coast). Somewhere between Herzliyya and Netanya is a convergence point which could shift in spatial location according to changes in the wave climate. However, if this convergence point existed then a large build-up of sand would be seen at this location; analysis of satellite images from Google Earth does not show beach accretion in this area. This lack of accretion was explained by Emery and Neve (1960) and further advocated by Golik (2002).

1.2 Predicted northward sediment transport

Carmel et al. (1985) used results of three years of directional wave measurements at Haifa to determine wave-energy-flux distributions and estimate wave-induced longshore sediment transport. The wave-energy-flux distributions revealed a moderately high-energy coast with a bimodal annual cycle. They estimated a maximum northward transport of 75,000 (± 14,000) m³/month in mid-winter and a southward transport of 26,000 (± 5,000) m³/month in the summer. The net annual transport is northward and computed at 110,000 (± 100,000) m³/year.

Coastal area modelling was undertaken (Chesher and Hatarsi, 2000) to assess the long-term impact of a proposed marina at Haifa. The impact assessment assumed an abundant supply of sediment (i.e. worst-case scenario) and found that deposition is predicted to occur to the west of the marina and potential erosion to the east indicating that the proposed marina could interrupt a net northward longshore sediment transport.

Studies (Golik, 2002) of the distribution of heavy minerals found on the seabed in Hadera as well as the orientation of bedforms beyond the surf zone indicate that there is sand moving northward. An analysis of the distribution of sand grain size on the beach and inner continental shelf found that the mean sand grain size of the deeper water population did not show any dependence with distance along the coast but in shallow water the sand size decreased from the south to Herzliyya. On the beaches north of Herzliyya, sand was similar in size to that of the deep water samples which could indicate some cross-shore transport of sediment. Golik (2002) concludes that the above-described phenomena concur with the hypothesis proposed by Emery and Neve (1960).

Perlin and Kit (1999) compared estimates of sediment transport rates (obtained by employing an analytic expression based on the CERC formula) with results of numerical simulations using LITPACK. According to their estimates, changes in net drift rates along the Israeli coast occur over a relatively short length of coastline due to changes in shoreline orientation. They state that the average net longshore sediment transport along the southern part of the Israeli coast decreases from 450,000 m³/year at Ashkelon to 200,000 m³/year at Ashdod (assumed to be northward although not explicitly stated). The average net longshore sediment transport then diminishes to 60,000–70,000 m³/year, thought to be northward, at the Carmel coast (cited in Klein et al., 2007). Zviely (2006) in a PhD thesis concludes that the large amounts of sand available for transport along the northern Carmel coast, as well as their similarity to the Haifa Bay area sands, confirms the hypothesis that the Haifa Bay area sands originated from the northern Carmel coast. This suggests that fine-grained sand is transported northward from the northern Carmel coast and then eastward around the Carmel headland towards the southern part of Haifa Bay. Zviely (2006) and Zviely et al. (2007) estimate the average amount of sand transported per year to the Haifa Bay area (from the northern Carmel coast) is approximately 80,000–90,000 m³/year (northward). This estimate was based on Perlin and Kit’s (1999) analysis (i.e. using the offshore CERC formula given in Koutitas (1988)) and on long-term sets of directional wave data collected between 1994 and 2004 at the offshore wave buoy at Haifa. The new estimate yielded an average net longshore drift rate of sand to the north of 72,000 m³/year (northward), thinking to be northward, at the Carmel coast (cited in Klein et al., 2007). Zviely (2006) also estimates gross sediment transport to be around 300,000 m³/year. No wave modelling was undertaken to transform the offshore measured waves at Haifa to nearshore locations.

Zviely et al. (2007) state it is well-known that longshore currents (and the sand transported by them) are active in both directions, subject to the wave climate (wave direction) along the south-eastern Mediterranean coast.

Klein et al. (2007) used fluorescent sand tracers to study sediment movement along the central Mediterranean coast of Israel in the vicinity of Herzliyya Marina (approximately 40 km north of Ashdod). Coloured sand was deposited (by divers) at six points in November 2001 and sampled three times during the winter. It was found that tagged sand particles (at all depths sampled) were transported up to 5 km north alongshore over a period of 36 days. Cross-shore sediment transport carried sand from a depth of 15 m to 8 m but no coloured sand from shallow water (2–4 m) was found deeper than 8 m.

1.3 Summary of literature

Drift rates along the Carmel coast are lower than along the southern Israeli coast due to the orientation of the shoreline in relation to the direction of wave approach. However, it can still be seen that it is a dynamic area with substantial amounts of sediment transport. Both the direction and rate of the net longshore transport along
the Carmel coast has been summarised in Table 1 and it is noted to be variable and disputed between different studies. Because the dominant wave direction approaching the coast is very close to that of the beach normal, a low net drift prevails, and in addition, small changes in wave direction can give rise to reversals in the direction of longshore sand transport. The studies that have quantified sediment transport rates (described earlier in this section) have estimated net northward drift rates of around 60,000–110,000 m³/yr (as shown in Table 1).

<table>
<thead>
<tr>
<th>Source</th>
<th>Net Rate (m³/yr)</th>
<th>Net Direction</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emery and Neev (1960) (cited in Golik, 2002)</td>
<td>Not specified</td>
<td>South</td>
<td>Between Haifa and Tel Aviv</td>
</tr>
<tr>
<td>Shoshany et al. (1996)</td>
<td>Not specified</td>
<td>South</td>
<td>At Haifa</td>
</tr>
<tr>
<td>Golik 2002</td>
<td>Not specified</td>
<td>South</td>
<td>North of Netanya</td>
</tr>
<tr>
<td>Not specified</td>
<td>South</td>
<td>North</td>
<td>South of Herzliyya</td>
</tr>
<tr>
<td>Carmel et al., (1985)</td>
<td>110,000 (± 100,000)</td>
<td>North</td>
<td>Between Haifa and Tel Aviv</td>
</tr>
<tr>
<td>Zviely (2006) - PhD Zviely et al., (2007)</td>
<td>80,000–90,000</td>
<td>North</td>
<td>Carmel to Haifa Bay</td>
</tr>
<tr>
<td>Chesher and Hatarsi, 2000</td>
<td>Not specified</td>
<td>North</td>
<td>Haifa</td>
</tr>
<tr>
<td>Perlin and Kit (1999) (cited in Klein et al., 2007)</td>
<td>450,000</td>
<td>Unspecified (but thought to be north)</td>
<td>Ashkelon</td>
</tr>
<tr>
<td></td>
<td>200,000</td>
<td></td>
<td>Ashdod</td>
</tr>
<tr>
<td></td>
<td>60,000–70,000</td>
<td></td>
<td>Carmel Coast</td>
</tr>
</tbody>
</table>

### 2 QUANTIFICATION OF LONGSHORE DRIFT

Several studies have been undertaken to estimate the volume and direction of the long term sediment transport (i.e. the net longshore drift) along the Israeli coastline. Net longshore drift is the difference between the amount of southward drift and the amount of northward drift that occurs during a specified period, whereas Gross longshore drift is the amount of both the southward and northward drift during a specific period. During the literature review no estimates were found on year-to-year or seasonal variations in longshore drift, or estimates for the distribution of the drift across a beach profile. This study seeks to address this and provide estimates of these parameters of drift rates. Measured offshore wave conditions, for a period of 18 years sampled at 3-hour intervals, were transformed to a nearshore point located on the -10 m ILSD contour using the SWAN model (Figure 3). Due to refraction, the spread of wave directions narrowed compared to the offshore waves with over half the records having a direction between 279°N and 290°N.

Seasonal variations of wave heights and direction also occur. For the summers months, see Figure 4a, it can be seen that a similar proportion of waves come from the directions West (W) and West-North-West (WNW) (approximately 45 % and 40 % of waves respectively). Combined, this forms the majority of waves experienced in the summer season, which can be seen to have significant wave heights up to 2.0 m. The winter months in Figure 4b show a similar proportion of about 45 % of waves from the West, but these are shown to be much larger, with significant wave heights reaching up to 6.0 m. Waves are also found to be larger from the WNW sector during winter, reaching 3.0 m significant wave heights; although only approximately 20 % of the waves during this season approach from this sector.
To summarise, a more even spread of smaller waves can be found in summer months between W and WNW, compared to the winter where the waves are larger and dominated by waves approaching from a Westerly direction.

2.1 Annual net longshore drift rates

The potential longshore drift produced by the wave climate at the nearshore wave point (Figure 3) was calculated using a model based on the CERC formula and a median grain diameter of 0.15 mm, which is in
agreement with Zviely (2007). The potential drift rate is the rate that would occur on an open beach covered with ample beach sediment.

For a shore normal beach orientation of 277° (which is the case at Carmel), and using the 18 year time-series, the model predicted a potential average annual gross drift rate of 190,000 m³/yr with a net drift of 7,000 m³/yr northward. The high gross drift rate compared to the low net drift rate indicates that the drift direction is variable and reversals in direction are likely to occur.

From experience of many coastlines around the world, there is often a substantial variation in the drift rate from year to year (and often month to month). Therefore, annual variations of the drift rate has been considered. Figure 5 shows that for nine of the 18 years of time-series data, net drift is predicted to be in a northward direction whilst for the other nine years it is in a southward direction. This would support the fact that different research studies undertaken in different years might have conflicting results, in terms of estimating drift rates and even the net drift direction.

During the 18 years of time-series wave data, the annual potential net drift rates in a northward direction were calculated to range between 4,300 and 98,800 m³/yr whilst net drift rates in a southward direction range between 1,400 and 46,100 m³/yr. Over the whole 18 years, the mean net drift is around 7,000 m³/yr northward and has a standard deviation of the annual drift rate of around 40,000 m³/yr.

Sediment transport calculations can be extremely sensitive to the shoreline orientation, so the model was re-run for the full 18 year period with variations in shoreline orientation of ±2° (i.e. 275° and 279°) as a sensitivity run. This is also equivalent to assuming a consistent error in the wave approach directions of ±2°, and this is perhaps not unreasonable given the inaccuracies in measuring wave directions, together with any inaccuracies resulting from the modelling of wave transformation from deep water into shallow water.

Table 2 compares the drift rates for each of these ±2° sensitivity runs to the 277° run. Changing the shoreline orientation has little influence on the gross drift rates.

Re-running the model with a shore normal of 275° results in a net southward drift of 51,000 m³/yr, whilst running the model with a shore normal of 279° results in a northward drift of 65,000 m³/yr. This indicates that 277° is the orientation at which there is very little net drift occurring i.e. small changes in shoreline orientation (or the angle of wave approach) results in larger net drift rates.

Table 2. Sensitivity to shoreline orientation

<table>
<thead>
<tr>
<th>Shore normal</th>
<th>Mean net drift</th>
<th>Gross drift</th>
</tr>
</thead>
<tbody>
<tr>
<td>275°</td>
<td>51,000 m³/yr southward</td>
<td>191,000 m³/yr</td>
</tr>
<tr>
<td>277°</td>
<td>7,000 m³/yr northward</td>
<td>190,000 m³/yr</td>
</tr>
<tr>
<td>279°</td>
<td>65,000 m³/yr northward</td>
<td>201,000 m³/yr</td>
</tr>
</tbody>
</table>
2.2 Seasonal variation of longshore drift

Figure 6 shows that around 78 per cent of the gross drift occurs between November and April indicating that seasonal variations in the wave climate also affect the drift rates. This result is unsurprising given that larger waves occur during the winter months (Figure 4).

Figure 7 shows the monthly distribution of the net drift rates. This supports what is shown in Figure 6, that largest drift rates were found during the winter months of December – March. Although there were variations of the direction of drift during the winter months, it was found to be dominated by a transport of sediment northwards.

The seasonal distribution of the potential longshore drift shown in Figure 7 is supported by the seasonal wave data (Figure 4). Large winter waves are shown to be dominated from a Westerly direction, which when considering a beach orientation of 277 ° can be considered to approach from the southern side of the beach profile. This direction of wave approach would be expected to induce a northerly direction of drift, as is seen from November to March in Figure 7. The smaller waves found during the summer months, with approach directions slightly rotated to the north as seen in Figure 4. This again is supported in Figure 7, where the smaller, more northerly wave approaches are found to induce net drift mostly in a southerly direction and with lower rates than found in winter. Overall this monthly analysis of the drift rates indicates a lower drift rate with a southwards bias during the summer and a higher drift rate with a northwards bias in the winter.
2.3 Cross-shore distribution of longshore drift

Another model was used to determine how the longshore drift is distributed across the beach and seabed profile. The most recent cross-shore profile was used in the model, out to a distance of nearly 800 m offshore, so as to end at a depth of about 10 m to coincide with the nearshore waves.

The cross-shore distribution of the net annual longshore drift rate using the entire 18 year record is shown in Figure 8. The representative cross-shore profile is also shown on this figure and the beach/seabed profile is shown as if viewing it from the South, i.e. with the deeper water to the left of the figure. Figure 8 also illustrates the southward and northward components of the longshore drift. A positive value (above the horizontal axis) indicates a northwards drift and a negative value (below that axis) indicates a southwards drift.

Variations of longshore sediment transport drift rates can be found with distance across the beach profile. This can be seen in Figure 8, where it is shown that the profile shape (i.e. water depth) has a dramatic influence on the drift rates found at different points along the profile.
The direction of net drift along the profile (Figure 8) can be divided into two sections, the upper beach above -3 m ILSD contour (i.e. about 0–200 m chainage) and the lower beach below 3 m ILSD (i.e. about 200–800 m chainage). For the upper beach a net southerly drift rate is predicted, suggesting that it is dominated by the proportion of smaller waves that occur in the summer months, which approach from a more northerly direction (Figure 4). The smaller heights of these waves enable them to travel into shallower water depths, further up the beach profile, before breaking and causing transport of the sand. When approaching from north of the profile, it would be expected that they would induce a southerly transport of beach sand. Conversely the larger waves occurring in the winter months have a more westerly component and therefore approach from south of the beach profile and would induce northerly transport of beach sand. These larger waves will also break further offshore in deeper water and therefore result in a net northerly drift rate in the lower beach (below -3 m ILSD contour).

This information on the distribution of the drift across the profile is useful when designing structures to maintain a beach. Structures built seaward of the -3 m ILSD contour are likely to intercept more of the northerly drift rate than shorter structures. A short groyne for example will perhaps show a southwards bias in the drift rate (as noted by Golik, 2002).

3 CONCLUSIONS

i. A review of existing studies revealed that net drift rates along the Carmel coast are lower than along the southern Israeli coast due to the orientation of the shoreline in relation to the direction of wave approach. However, it can still be seen that it is a dynamic area with substantial amounts of sediment transport. Both the direction and rate of the net longshore transport along the Carmel coast is noted to be variable and disputed between different studies.

ii. Because the dominant wave direction approaching the coast is very close to that of the beach normal, small changes of wave directions, and the wave-induced currents, will result in reversals in the direction of longshore sand transport, leading to a low net drift. The studies that have quantified sediment transport rates have estimated net northward drift rates of around 60,000–110,000 m³/yr. During the literature review no estimates were found on gross drift rates, year-to-year or seasonal variations in longshore drift or estimates for the distribution of the drift across a beach profile. This study sought to expand on the current knowledge by providing estimates of these parameters of drift rates.

Figure 8. Cross-shore distribution of the longshore drift
iii. Overall the wave climate is very dynamic with the largest significant wave height predicted to be 5.6 m. Seasonal variations of wave heights and directions have also been identified to help understand the changes in wave characteristics experienced through an average year. It was found that a more even spread of smaller waves between W and WNW can be found in summer months, compared to the winter where the waves are larger and dominated by waves approaching from a Westerly direction.

iv. Using an 18 year time-series of 3-hourly wave conditions, a potential average annual gross drift rate of 190,000 m³/yr with a net drift of 7,000 m³/yr northward was calculated for a shore orientation of 277°. The high gross drift rate compared to the low net drift rate indicates that the drift direction is variable and reversals in direction are likely to occur. This would support the fact that different research studies undertaken in different years might have conflicting results, in terms of estimating drift rates and even the net drift direction. Furthermore a sensitivity test to a small change (±2°) in beach orientation (or indeed wave direction) results in around a ± 50,000 m³/yr change in drift, which in turn could lead to drift reversals.

v. An analysis of the monthly variation of the potential longshore drift indicated a seasonal variation in drift rates and directions. A lower drift rate with a southwards bias in direction occurred during the summer whilst a higher drift rate with a northwards bias in direction occurred during the winter.

vi. The distribution of the potential net longshore drift across the beach and nearshore seabed profile provided more insight into the longshore drift and coastal processes. Variations of longshore sediment transport drift rates and directions were found with distance across the beach profile. The upper section of the beach (above -3 m ILSD) showed a net southward sediment transport, whilst the lower section of the beach profile (below -3 m ILSD) showed a net northwards sediment transport. This differential in longshore drift direction across the profile can be attributed to the variations in the wave climate. The smaller heights of waves in the summer enable them to travel into shallower water depths, further up the beach profile, before breaking and causing transport of the sand. When approaching from north of the profile, it would be expected that they would induce a southerly transport. However, the larger waves will tend to break further offshore and approach from south of the profile, which will induce a net northerly transport.

vii. Overall, the longshore sediment transport in this area is complex with both the rates and direction varying significantly on a month to month basis. The overall annual average net drift, for the 18 year period, is approximately 7,000 m³/year northwards and has a standard deviation of the annual drift rate of 40,000 m³/year. Given the large standard deviation in the annual drift rates, it can be argued that the long-term net drift rate is close to zero but with large annual and seasonal variations.

4 REFERENCES