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# Sediment Transport along the Coast of Israel: Examination of Fluorescent Sand Tracers

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**ABSTRACT**

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The method of labeled natural sand particles was used to study sediment transport along the central Mediterranean coast of Israel. Six portions of 300 kg each were tagged with various fluorescent colors, and distributed at six different locations in the vicinity of the Herzliya Marina. The tagged sand was scattered at the end of autumn, and sampled three times during the winter. Sampling was interrupted in mid-January because of unexpected dredging at the marina canal entrance.

The samples were analyzed at the Yigal Allon Kinneret Limnological Laboratory. The wave climate during that time was analyzed using wave data from Ashdod (40 km south). Wave directions measured in Ashdod were corrected to make them applicable to the Herzliya coast, in accordance with suggested directional shift values.

Seven wave storms with significant wave heights of over 2.5 m were observed. Two of them clearly indicate a dominant direction from the southwest and two others from the northwest. However, the time durations and the relative angles between the wave directions and the orthogonal to the coast of the storms propagating from the southwest are essentially larger than those arriving from the northwest.

The following results were noted: (i) The drift of tagged sand particles correlated to longshore sediment transport at all depths was in a northern direction throughout the field experiment. The longest distance of transport was 5 km over a period of 36 days. (ii) "Onshore" sediment transport was present; sand from 15 m depth was found at 8 m depth. (iii) The cross-shore sediment transport carried sand to a depth of 8 m, but no colored sand from shallow water (2–4 m) was found deeper than 8 m. (iv) Although sedimentation at the marina entrance during the experiment was high, only small amounts of tagged sand were found at the entrance. (v) Findings of tagged sand showed the main area of sedimentation to be along the marina's main breakwater.

**ADDITIONAL INDEX WORDS:** *Longshore sediment transport, tagged sand particles, Israel.*

## INTRODUCTION

The primary source of sediment to the southeastern Mediterranean coast is the Nile River. The Nile flow regime and the Nile's sediment transport has undergone a dramatic change in the last century because of the small (1902) and the big (1964) dams at Aswan. The Nile's quartz sand has been transported from the Nile outlets to the Israeli coast by consistent west-to-east and southwest-to-northeast longshore currents, generated by westerly approaching waves. INMAN *et al.* (1976) estimated the wave-induced longshore sediment transport (LST) rate at the Damietta eastern promontory of the Nile Delta to be eastward at about 860,000 $m^3/y$. This amount decreases toward the east to about 500,000 $m^3/y$ along the outer Bardawil lagoon sandbar in northern Sinai (Egypt).

The LST along the southeast Mediterranean coast was studied by ALMAGOR (2000), SHARAF EL DIN and MAHAR (1989), STANLEY (1989), and many others. The LST along the coast of Israel was studied by CARMEL, INMAN, and GOLIK (1991, 1994). The LST along the coast of Israel was studied by EMERY and NEEV (1963), GOLDSMITH and GOLIK (1980), CARMEL *et al.* (1985) and PERLIN and KIT (1999). The last three derived theoretical estimates of LST on the basis of wave measurement data that were used to calculate the potential carrying capacity of the resulting longshore currents. No direct previous LST measurements exist of the actual sand transport along the Sinai and the Israeli coast.

According to an updated estimate presented by PERLIN and KIT (1999), the average net LST along the southern part of the Israeli coast decreases from 450,000 $m^3/y$ of sand in Ashkelon to 200,000 $m^3/y$ of sand in Ashdod (Figure 1). This dramatic reduction within only 40 km is due to a significant change in coastal orientation, from azimuth = 34° in Ashkelon to azimuth = 25° in Ashdod. Further north (40 km) along the Tel-Aviv coast (azimuth = 21°), the rate of the average net LST decreases to 100,000 $m^3/y$. It diminishes to 60,000–70,000 $m^3/y$ at the Carmel coast (azimuth = 4°) just before reaching Haifa Bay, the northern end of the Nile lit-

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Figure 1. Study area.

toral cell. The question is whether the decrease in the Nile sediment contribution to the southeastern Mediterranean coasts has already affected the coasts of Israel or whether the erosion of the Nile Delta sand storage replaces the Nile sediment. Any attempt to answer that question has to rely on field observation along the Israeli coast.

The average net LST at the Herzliya coast (azimuth = 17°) was calculated by Perlin and Kit (1999) and it is slightly less than 100,000 $m^3/y$ to the north. Estimates from other research, shown in Table 1, vary dramatically, mainly because they do not incorporate necessary wave directional corrections, and therefore cannot be considered reliable.

The morphological impact of the Herzliya Marina (built in 1990–1992) on the coastal morphology of the adjacent area was studied by Zviely (2000), Zviely, Klein, and Rosen (2000), and Klein and Zviely (2001). Since 1995, dredging of around 20,000–30,000 $m^3/y$ has been done because of sedimentation at the marina entrance. Since sedimentation occurs mainly during January–April, dredging is done at the end of April, and the dredged sand is deposited some 2.5 km north of the marina, 500–1000 m from the coastline at a water depth of 6–7 m.

Table 1. *Different estimates of average net longshore sediments transport of the Herzliya coast.*

| Researchers | Model | Net transport $m^3/y \times 10^3$ |
|---|---|---|
| Baird & Associates Ltd. and Research Planning Inc. 1996 | COSMOS Ashdod wave data 1958–94 | 600 to the north |
| Baird & Associates Ltd. and Research Planning Inc. 1996 | COSMOS Ashdod wave data 4/1993–3/1995 | 400 to the south |
| Toms and van Holland 1999 | Delft3/D/2DH | 30 to the north |
| Perlin and Kit 1999 | DHI/LITPACK | 100 to the north |

The use of fluorescent tracers has been used for many years to determine sediment movement. Sediment dynamics are an important feature in the study of longshore transport (Ciavola *et al.* 1998; Michel and Howa, 1999; Tonk and Masselink, 2005). In the Nile littoral cell the fluorescent tracer method was used by Badr and Lotfy (1999) in their work along the delta coast. They sampled the sea floor within a very short time (60 minutes) and short distance (150 m) from the point and time of injection. The method of preparing labeled sediment particles was discussed by Shteinman *et al.* (1997). Shteinman *et al.* describe the method and the modifications they made to prepare tracer particles in different colors and with specified lifetimes. They applied the method in the entrance of the Jordan River to Lake Kinneret, freshwater condition, and the sampling period was 12 days (March 18, 1994 through March 29, 1994).

The aim of this study is to determine in a descriptive manner using colored particles the movement of sand around the marina area and the nearby coast, and enable assessment of the process of sand transport and sand accumulation at the marina entrance. The study tests the validity of the fluorescent tracers method to describe the coast environment and over a long, for example several-month, period of time. The results of this experiment may provide a field indication of the sediment transport process along the Israeli coast.

## METHODOLOGY

An amount of 1.8 tons of sand were dredged north of the marina. The sand was analyzed and found to have an average grain size of 190 μm, which coincided with the findings by Baird & Associates Ltd. and Research Planning Inc. (1996) and Rosen (1998) of 160–230 μm, with an average of 190 μm. The labeling of sand was done by Shteinman and his team at the Yigal Allon Kinneret Limnological Laboratory, Israel. Six different colors were used, in quantities of 300 kg each. The colored glue was intended to last for 8 months. We planned to disperse the tagged sand in Novem-

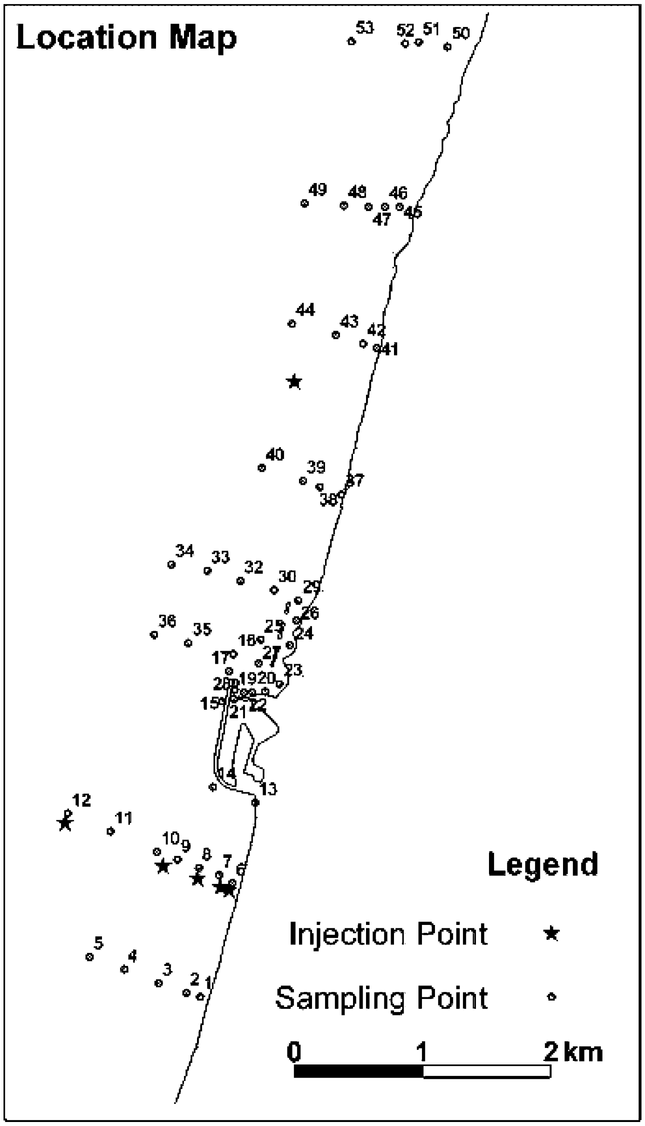


Figure 2. Location of sand particle sampling and injection points.

ber, before the winter storms, and to draw the last sediment samples after the dredging, which was planned for the spring.

In the present work, directional wave data for this study period were measured at Ashdod, 40 km south of Herzliya Marina. The measurements were made by the Coastal and Marine Engineering Research Institute (CAMERI) on behalf of the Israeli Port and Railway Authority. A Datawell Waverider buoy is deployed at a depth of 24 m to acquire 30-minute directional records of surface elevation and directional spectral information. Generally, these records were acquired once every 3 hours, but during severe storm events, attempts were made to collect data each hour. The wave data were converted from Ashdod to the Herzliya coast by using the height and wave angle corrections for generation of wave climate at particular locations along the Israeli coast (PERLIN and KIT, 1999).

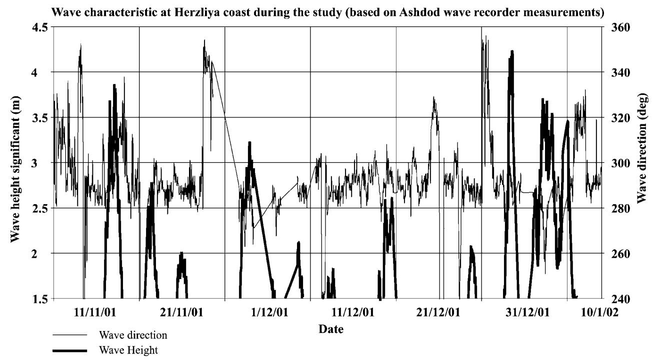


Figure 3. Wave characteristics at Herzliya coast during the study.

The colored sand was deposited on November 11, 2001. The bags with colored sand were loaded on the sea bottom by divers to eliminate dispersion of sand during sinking.

The locations of the six distributing points were measured with a global positioning system device on the boat. Five of the distributing points were along a perpendicular line to the coast at different depths: 2 m (blue), 4 m (yellow), 6 m (green), 8 m (red), and 15 m (orange). The last point (pink) was at the location where the dredged sand is being deposited some 2.5 km north of the marina, 500–1000 m from the coastline at a water depth of 6–7 m (Figure 2).

In planning the outset of the experiment, it was determined that sampling would take place once per month, or after a wave storm. Sampling was done by divers, who collected the sand from the upper 10 cm in plastic bags holding about 1.5 kg each. On the boat, 500 g from each sample were put into plastic containers. The samples in the plastic containers were dried at the Kinneret Limnological Laboratory; 200 g of dry sand were used for spectral analysis.

On November 20, 2001, 9 days after depositing the sand, the first sampling took place; 24 samples were collected. The second sampling took place on December 17, 2001, 36 days after the deposit; 49 samples were collected. The third sampling was on January 13, 2002, 62 days after the deposit; 53 samples were collected. Because of unexpected dredging at the marina canal entrance, this was the last sampling.

## RESULTS

### Wave Climate

The wave climate for the time of the experiment is given in Figure 3. In the course of the experiment, seven wave storms occurred in which the significant wave height (Hs) was over 2.5 m, and three storms occurred with Hs over 3.5 m. During the first 9 days, a storm from the north with waves from azimuth 300°–310° occurred. Since the normal to shore wave front at Herzliya measures 287°, this storm produced a southward longshore current.

### Current Measurements

Nile littoral cell longshore currents along the Israeli coast can be classified according to the primary forces that gener-

Table 2. *Location and number of colored sand particles found in the samples.*

| | | Blue | | | Yellow | | | Green | | | Red | | | Orange | | | Pink | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SP | SD | A | B | C | A | B | C | A | B | C | A | B | C | A | B | C | A | B | C |
| 2 | 2.0 | 14 | | | 2 | | | | | | | | | | | | | | |
| 3 | 5.0 | | | | | | | 5 | | | | | | | | | | | |
| 7 | 2.0 | 47 | 3 | | 14 | 10 | 2 | | | | | | | | | | | | |
| 8 | 4.0 | | | 4 | | | 5 | | 18 | 4 | | 5 | 2 | | | | | | |
| 9 | 6.0 | | 6 | 3 | | 18 | 8 | | 6 | 3 | | 11 | 3 | | | | | | |
| 10 | 8.0 | | | | | 2 | | 29 | 9 | 2 | 86 | 3 | | 135 | | | | | |
| 11 | 10.0 | | | | | | | | | | | 8 | | | 2 | 11 | | | |
| 12 | 14.2 | | | | | | | | | | | | | 82 | | | | | |
| 13 | 0.0 | 9 | 35 | 56 | 2 | 11 | 14 | | 2 | | | 2 | 8 | | | | | | |
| 14 | 4.2 | 12 | 38 | 45 | 7 | 19 | 22 | | 63 | 27 | | 48 | 16 | | | | | | |
| 15 | 6.2 | | 12 | | | 6 | 3 | | 7 | | | 21 | 9 | | | | | | |
| 16 | 5.5 | | 19 | 38 | 16 | 6 | 9 | 2 | 16 | 19 | 3 | 29 | 11 | | | | | | |
| 17 | 4.5 | | | 2 | | | 5 | | | | | 2 | 5 | | | | | | |
| 18 | 4.3 | | 5 | 8 | | 10 | 18 | | | 3 | | 2 | 9 | | | | | | |
| 19 | 3.8 | | 2 | 6 | | 3 | 9 | | | 2 | | 2 | 15 | | | | | | |
| 20 | 1.7 | | 2 | 7 | | 6 | 9 | | | | | 5 | 7 | | | | | | |
| 23 | 1.2 | | 11 | 4 | | 2 | 11 | | 4 | 2 | | 6 | 8 | | | | | | |
| 24 | 0.0 | | | | | | | | | | 2 | | | | | | | | |
| 25 | 2.5 | | 26 | 9 | | 11 | 4 | | 3 | 2 | | 44 | 2 | | | | | | |
| 26 | 6.0 | | 8 | 14 | | 3 | 11 | | 2 | 9 | | 3 | 9 | | | | | | |
| 27 | 9.0 | | | | | | | | | | | | | | | 4 | | | |
| 32 | 1.4 | 3 | | | 18 | 4 | | 3 | | | 5 | 8 | | | | | 27 | | 2 |
| 33 | 4.0 | 2 | | | 22 | | | 3 | | | 3 | 6 | | | | 1 | 9 | | |
| 36 | 0.0 | | | | | | | | | | | | | | | | 14 | | |
| 37 | 1.5 | | | | | | | | | | | | | | | | | 11 | 14 |
| 38 | 2.5 | | | | | | | | | | | | | | | | | 4 | |
| 41 | 0.0 | | | | | | | | | | | | | | | | 9 | | |
| 42 | 2.1 | | | | | | | | | | | | | | | | 63 | 18 | |
| 43 | 4.2 | | | | | | | | | | | 8 | | | | | 3 | | |
| 45 | 2.0 | | | | | | | | | | | 3 | | | | | | 4 | 2 |
| 50 | 3.5 | | | | | | | | | | | | | | | | | | 2 |
| 53 | 6.0 | | | | | | | | | | | | | | | | | | 2 |

SD = number of sampling point, SD = water depth (m) at sampling point.
A = November 20, 2001; B = December 17, 2001; C = January 13, 2002.

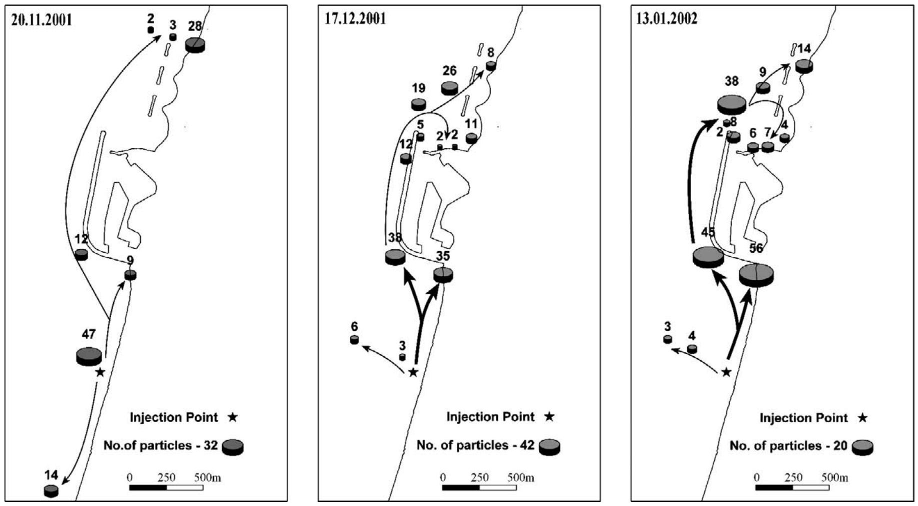


Figure 4. Location and number of colored sand particles in the blue experiment.

ate them, waves and local winds (Kit and Sladkevich, 2001). Wave-induced currents occur primarily in shallow depths, between the coastline and 5 m (up to 10 m during heavy storms). Wind-induced currents occur at depths beyond the breaker zone, generally from 5 to 30 m. Flow data were measured by current meter, at a depth of 24 m (in the wind-induced current zone), about 1 km south of Ashdod harbor (Figure 1). The measurements were carried out by Israel Oceanographic and Limnological Research for the Israel Ports Authority. Therefore, the data from Ashdod can be applied to the study of the 8- and 15-m colored sand deposits made in Herzliya in water depths beyond the breaker zone.

During the first stage, from November 11, 2001 to November 20, 2001, a slow northward current of up to 10 cm/s was recorded. On November 17, 2001 a northward current of 25 cm/s was recorded. On November 19, 2001 a southward current of 25 cm/s was recorded, the only event of flow to the south during the entire period. During the second stage from November 21, 2001 to December 17, 2001 a very slow flow northward was recorded. Flow in the third stage, from December 18, 2001 to January 13, 2002, was also northward, with maximum up to 60 cm/s. During the third stage at January 7, 2002 a fast flow of 100 cm/s to the north was recorded.

## Colored Sand

The number of sand particles found in a sample is given as the number for 200 g of sampled sand (1 g = 10,000 particles). The result of the tagged sand found is given in Table 2 (A, sample of November 20, 2001; B, sample of December 17, 2001; C, sample of January 13, 2002). Sampling points are marked on Figure 3; only points where colored sand was found are marked on Figures 3–8, with the number of particles found. The results for each color were mapped. A disk-shaped symbol describes the number of tagged sand particles of each color found; the relative size of the pie diameter is proportional to the number of tagged sand particles found in each color.

### Blue Sand Experiment (Loaded at 2-m Depth, Figure 4)

In the sample of November 20, 2001, blue sand particles were found in 7 of 24 sampling points. Fourteen sand particles were found about 1 km south of the depositing point in a water depth of 2 m. The northernmost point where blue sand particles were found was about 850 m north of the marina or almost 2 km north of the depositing point. No blue particles were found at depths of more than 4 m. In the second sample, taken on December 17, 2001, blue sand particles were found in 12 of 49 sampling points. No blue sand particles were found south of the depositing point. The northernmost point where blue sand particles were found was about 430 m north of the marina. No blue particles were found in depths of more than 6 m. High numbers of blue particles were found in all of the sampling points along the marina's main breakwater. In the third sample taken on January 13, 2002, blue particles were found in 12 of 53 sampling points. These results were almost identical to the results of the second sample.

### Yellow Sand Experiment (Loaded at 4 m Depth, Figure 5)

In the sample of November 20, 2001, yellow particles were found in 8 of 24 samples. The pattern was identical to that found in the blue experiment. In the second sample of December 17, 2001, yellow particles were found in 12 of 49 sampling points. The results are similar to that of the blue color, but the yellow color was found 850 m north of the marina. Along the depositing line, yellow particles were found at a depth of 8 m. In the third sample, yellow particles were found in 14 of 53 samples. The results were almost identical to the results

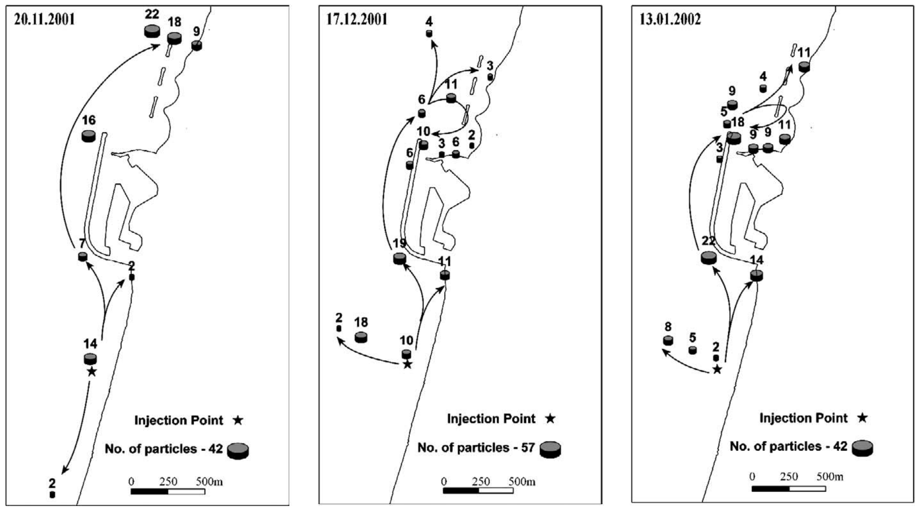


Figure 5. Location and number of colored sand particles in the yellow experiment.

of the second sample, but the northernmost point was 430 m north of the marina. No yellow particles were found at depths of more then 6 m.

### Green Sand Experiment (Loaded at 6 m Depth, Figure 6)

In the sample of November 20, 2001, green particles were found in 6 of 24 samples The pattern was similar to that found in the blue and yellow experiments, but green particles were not found along the main breakwater. In the second sample, green particles were found in 10 of 49 samples. Green particles were found 430 m north of the marina. No green particles were found in depths of more than 6 m, and very few were found in shallow water (less then 2 m). In the third sample, green particles were found in 10 of 53 samples. The results were almost identical to those of the second sample.

### Red Sand Experiment (Loaded at 8 m Depth, Figure 7)

In the sample of November 20, 2001, red particles were found in 6 of 24 samples. No red particles were found south of the depositing point. The northernmost point where red sand particles were found was about 850 m north of the marina. Few red particles were found along the main breakwater. In the second sample, red particles were found in 19 of 49 samples. Red particles were found 4 km north of the marina. A high number of red particles was found along the

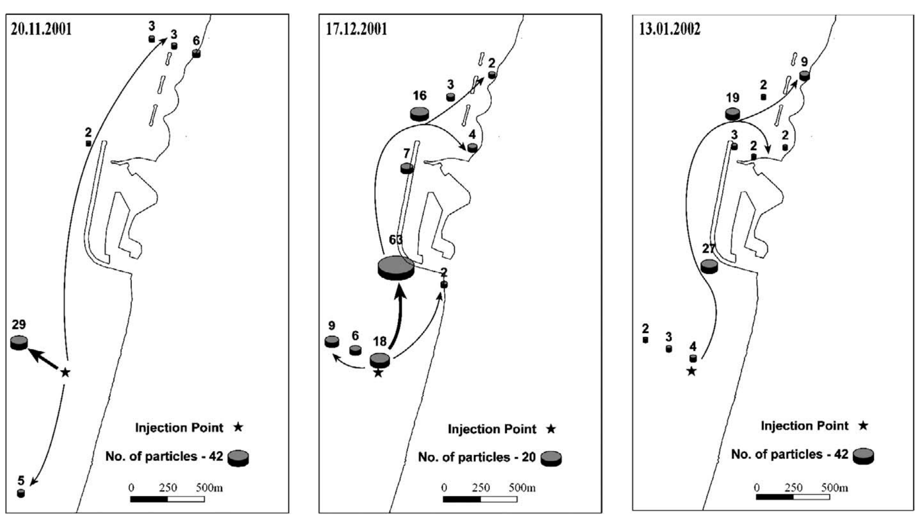


Figure 6. Location and number of colored sand particles in the green experiment.

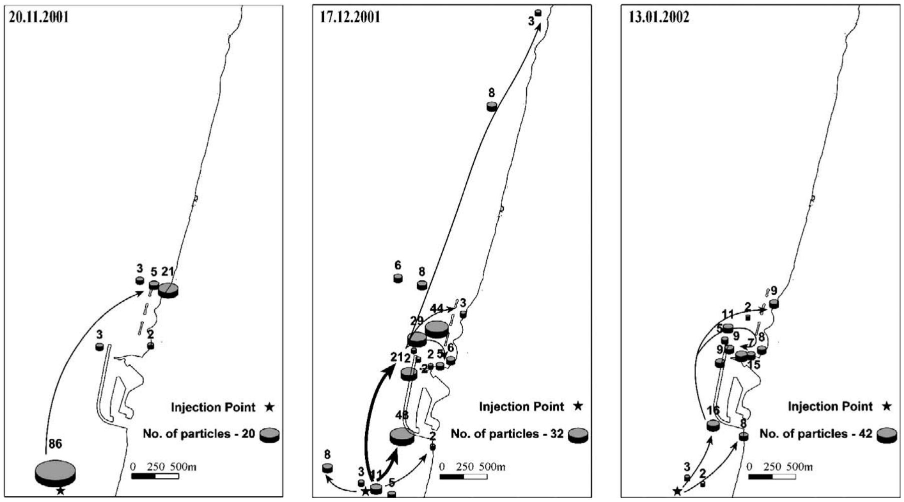


Figure 7. Location and number of colored sand particles in the red experiment.

main breakwater. In the third sample, red particles were found in 14 of 53 samples.

### Orange Sand Experiment (Loaded at 15 m Depth, Figure 8)

In the sample of November 20, 2001, orange particles were found in 2 of 24 samples, the first at the depositing point and the second along the depositing line at a depth of 7.7 m, indicating sand transport toward the coast in water depths of 8–15 m. In the second sample, orange particles were found in 1 of 49 samples along the depositing line at a depth of 10 m. In the third sample, orange particles were found in 3 of 53 samples. The northernmost point where orange sand particles were found was about 850 m north to the marina, in a depth of 4 m.

### Pink Sand Experiment (Loaded at 6 m Depth, 2.5 km North of the Marina, Figure 9)

In the sample of November 11, 2001, pink particles were found in 7 of 24 samples. Pink grains were found 500 m north and 1500 m south of the depositing point. In the second sample, pink particles were found in 4 of 49 samples, 600 m south of the depositing point and 1.6 km to the north. All four points were in water depths of 1.5–2.5 m. In the third sample, pink particles were found in 5 of 53 samples. The results were similar to the results of the second sample.

## DISCUSSION

The application of the colored fluorescent tracers in the study of coastal sediment transport by longshore current is

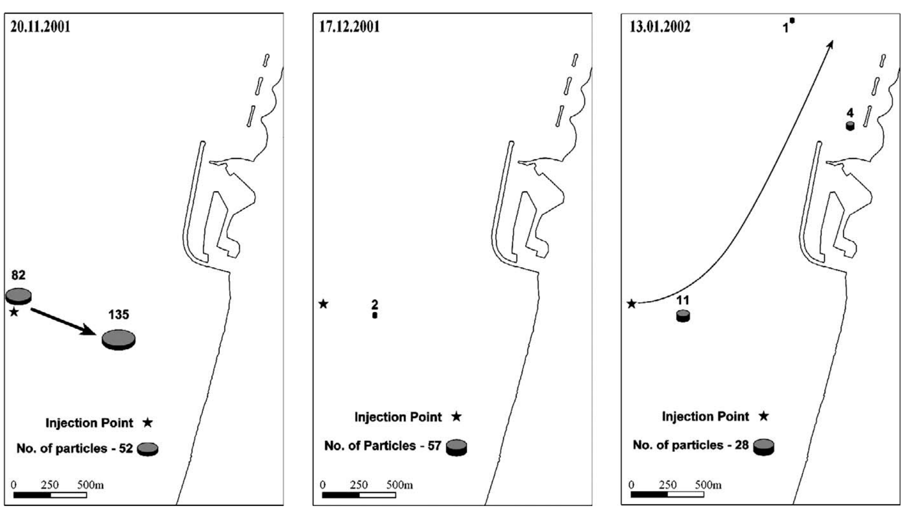


Figure 8. Location and number of colored sand particles in the pink experiment.

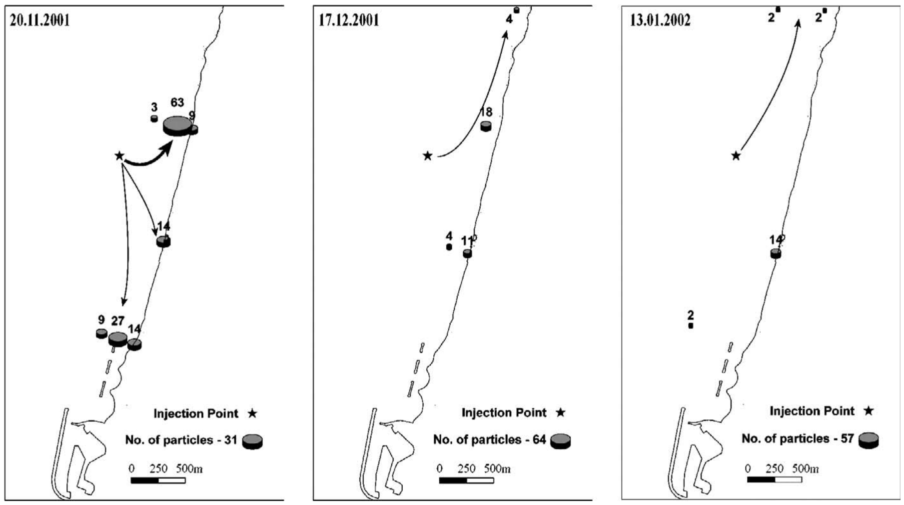


Figure 9. Location and number of colored sand particles in the orange experiment.

exemplified in this study. Each one of the different colors is an experiment of its own, but we ran the six experiments at the same time using the same field and lab plan. The method of using different colors of sediment is easy to run and gives detailed results. The ability to determine the lifetime of the fluorescent particles is a significant advantage of the method.

The results of the three series of sequential sampling, and the six colors, permitted us to compare field observations to evaluation of numerical models.

The sediment transport at the marina area has been evaluated using a particle tracking numerical model (BAIRD & ASSOCIATES COASTAL ENGINEERS LTD., 1998). The particle tracking model was described by DIMOU and ADAMS (1993)

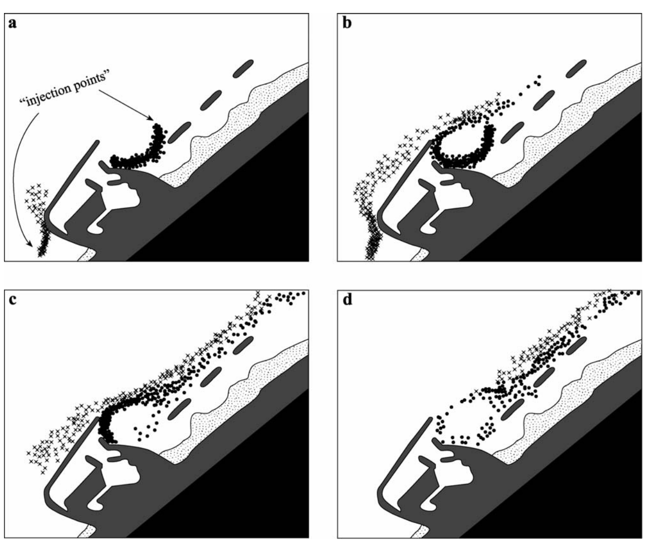


Figure 10. Sediment pathway during southwest storm in the particle tracking model (reworked from: Baird & Associates Coastal Engineers Ltd., 1998).

and was used to define the sediment pathways. The model provides a description of the sediment movement along the coast in the vicinity of the marina. Data from the wave-induced model was used as input to the particle tracking model, to assess the sediment transport pathways. Colored sand was injected into the flow at two points, north and south of the marina (two icons in Figure 10). The movement of the particles was solved through advection–dispersion techniques, meaning the particles were transported by the current and dispersed according to a random walk component. The particles were tracked continuously through time. Figure 10 (modified from BAIRD & ASSOCIATES COASTAL ENGINEERS LTD., 1998) shows the sediment pathway during a southwest storm. Sediment is transported from south of the marina in a northerly direction. The sediment bypasses the marina, but part of the sediment circulates in a clockwise eddy at the marina entrance. The limitation of the particle tracking model used is that the particles are neutrally buoyant and therefore no settling of particles is allowed for and hence prediction of accumulation area is impossible.

The findings of the blue sand, yellow sand, and green sand experiments (Figures 4–6) , in which the injection points are close to the injection point of the model, resembles the result of the particle tracking model. The predicted bypass and the clockwise eddy at the marina entrance were observed. The predicted circulation pattern was verified by the scatter of the colored particles and by field observation (A. ZINDER, personal communication) of movement of sand from the east along the exterior side of the lee breakwater, accumulating in the marina entrance. In addition, offshore and onshore transport was demonstrated. The main areas of accumulation in the blue sand, yellow sand, and green sand experiments are along the marina's main breakwater and up to a distance of 850 m north of the marina. Part of the labeled particles was found at depth of 0 m, on the coastline, a location that was not predicted by the particle tracking model.

## CONCLUSIONS

1. Northward sediment transport of sand in all water depths was demonstrated throughout the experiment.

2. Onshore sediment transport from the deeper sea was demonstrated; sand that was deposited at a depth of 15 m was found at 8 m after 8 days.

3. Offshore sediment transport was demonstrated by colored sand dispersed at a depth of 2 m and found at 6 m, and by colored sand dispersed at a depth of 4 and 6 m and found at 8 m. No colored sand from the breaker zone was observed in deeper sea.

4. Tagged sand was transported up to 5 km to the north within 36 days. The (red) sand that was loaded in water depths of 8 m (and therefore not affected by the marina) was transported the longest distance.

5. In spite of the rapid sedimentation at the marina entrance during the experiment, the number of colored particles found was low.

6. The main area of sand accumulation was along the marina's main breakwater.

7. In retrospect, the selection of five distributing points along a perpendicular line only 400 m south of the marina's main breakwater did not anticipate the possibility of the eddy formation to the south of the tip of the main breakwater caused by separation of southern current generated by northwest storms. The backward current in the northern direction produced by this vortex (that disturbs the southern longshore current) can explain the very low quantity of colored sand particles found 1450 m south of the marina, in spite of relatively strong storms occurring from the northwest direction.

## ACKNOWLEDGMENTS

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