Modelling of Dredged Material Disposal:

Mersin Bay Case Study

Ehsan Sadighrad[(1)], Süleyman Tuğrul[(2)] and Barış Salihoğlu[(3)]

Institute of Marine Sciences, Middle East Technical University, 33731, Erdemli, Turkey.
Tel: +90-324-521 34 34 Fax: +90-324-521- 23 27

[(1)] ***ehsan@ims.metu.edu.tr***
[(2)] ***tugrul@ims.metu.edu.tr***
[(3)] ***baris@ims.metu.edu.tr***

Abstract

Management of disposal of solid materials dredged from harbours, shipping channels and coastal environments for different purposes is essential for sustainable land/marine ecosystems, keeping economic values and human quality of life along coastal areas. Therefore, comprehensive and detailed investigations of geo-chemical properties of organic/inorganic pollutants in dredged materials and principal physical and bio-geo-chemical properties of the selected disposal sites are commonly a prerequisite for any planned dredging activity. These appropriate control measures should be taken to avoid or reduce unwanted impacts of dredged materials at dumping sites and to meet specific environmental objectives. This study focuses on major physical factors/processes (under different current velocity, stratification, barge volume/speed and direction during dumping) that govern the amount of dredged solid materials (sediment in different sizes) that go into suspension and the parameters which affect the short term spreading of sediments dumped into the upper layer (4-10 m depth range) of disposal areas. The STFATE model developed in the USA for this purpose is widely applied by environmental scientists in other seas. We have also adapted this multi-layer model to simulate spreading of sediments (composed of sand, silt, and clay) at disposal point (depth: 50m and 150m) on NE Mediterranean shelf. This model simulates short-term spreading of disposed materials which is divided into three phases; the convective phase which is the time from disposal to the bottom impact, the dynamic collapse which describes how the material spreads at the bottom after impact and the passive diffusion phase which is a long term process and not included in our study. The model results indicate critical roles of ship speed/direction under different current and sediment compositions during the short-period (2-3 hours) from dumping until sedimentation on the bottom. According to the model results, sandy particles sink much faster and reach the bottom in about 5 minutes whilst smaller fractions of sediments spreads over an area of about 7400 m^2 (in 10 m depth below surface) and then dispersed on the bottom of disposal site in 60-120 minutes under changing factors such as current and barge velocities at the time of disposal, and sediment composition. These factors also determine the thickness of disposed materials on the bottom, varying between 25 cm to 2 m depending on barge volume and other physical factors in each disposal. Model results also imply that dumping of non-toxic dredged materials mainly influence bio-optical properties of merely upper layer waters and benthic fauna of disposal site selected on the shelf having low biomass and fisheries.

Introduction

Dredging and disposal of dredged material can lead to a temporary decrease in water transparency, increased concentrations of suspended matter, and increased rates of sedimentation. In the case of contaminated sediment or sediments with high contents of organic matter, dredging and re-suspension may also affect water quality (e.g. Filho et al., 2004), leading to an increase in nutrients concentrations and reduced dissolved oxygen in the water column. Physical removal of substratum and associated plants and animals from the seabed, and burial due to subsequent deposition of material are the most likely direct effects of dredging and reclamation projects. New habitats may also be created as a result of the operation, either directly in the dredged area or by introduction of new habitats on the slopes of a reclaimed area (e.g. hard substratum in the form of breakwaters and revetments) (Erftemeijer, et al.,2006).

The degree of adverse environmental impacts caused by dredging and disposal depends on the quantity, frequency and duration of dredging, methodology of dredging and disposal, physical dimensions and water depth of the dredging location, grain-size composition, density and degree of contamination of the dredged material, background water quality (especially suspended matter and turbidity), seasonal variations in weather conditions (especially wind and waves), and proximity/distance of ecologically sensitive or economically important areas or species relative to the location of the dredging or disposal site (Pennekamp et al., 1996).

Magnitude of the impact and recovery depends on the thickness, area and configuration of the disposed layer that buries the benthos, frequency and timing of the dredging operation, the material characteristics of the discharged material (such as organic enrichment, pollutants and sediment grain-size), but also on the characteristics of the receiving habitat (such as sediment characteristics, water depth and hydrodynamic regime) and the community composition and lifehistory and mobility of the species at the disposal site (Wal et al., 2011).

Simulation of discrete discharges of dredged material from barges and hopper dredges in open water enables us to study the convective descent and dynamic collapse of the dredged material, and monitor sediment particle and contaminant concentration in the water column after dumping. Examination of different scenarios produced from model simulations allows us to assess short term impacts of dumping materials at disposal site having different ecological properties before dredging and disposal processes of sediments in coastal/open waters.

Material and Methods

The ADDAMS (Automated Dredging and Disposal Alternatives Modelling System) modules relevant to the ocean disposal of sediments dredged from marinas and small boat harbours are STFATE, LTFATE, and MDFATE. STFATE describes the short term fate of sediments placed in a single dump (Morris, 2000). STFATE was developed to provide water column contaminant and suspended sediment concentrations for environmental purposes. Short-term Fate of Dredged Material Disposed in Open Water (STFATE) predicts sediment deposition and water quality effects from a single placement of dredged material. Regardless of the disposal method, the behaviour of the disposal material can be separated into three phases: convective descent, during which the disposal cloud or discharge jet falls under the influence of gravity; dynamic collapse, occurring when the descending cloud or jet either impacts the bottom or arrives at a level of neutral buoyancy where descent is retarded and horizontal spreading dominates; and passive transport-dispersion, commencing when the material transport and spreading are determined more by ambient currents and turbulence than by the dynamics of the disposal operation (Johnson and Fong, 1995). When the material is disposed it starts sinking towards the bottom. If the moisture content of the disposed sediments is high and the density is much higher than the density of ambient water, the dredged material will sink as a density current. The current will contain a range of particle sizes, from really fine clay particles up to big clumps or aggregates (Raymond, 1986). Continuing its way toward bottom, some of the material is lost to the surrounding water due to turbulent shear forces, and carried away by water currents (Brandsma and Divoky, 1976).

In STFATE the disposal is assumed to be instantaneous and the sinking mass is described as hemispheric shape cloud which maintains its identity by the formation of a vortex ring structure (Fig. 1). Due to high density of sediment cloud and the initial momentum (from the disposal) the hemispheres will sink towards the bottom in the convective descent phase. Cloud volume increases as ambient water entrains in the plume. Some of fine particles are stripped from the sinking plume to ambient water and stay in the upper parts of water column, consequently, particle concentration of the cloud decreases (Johnson and Fong, 1995). Dynamic collapse occurs either at the stratification boundary or the cloud continues to collapse at the sea floor. As sediment cloud sinks toward bottom its mass increases while its particle concentration decreases and its horizontal velocity reaches the velocity of ambient water and its vorticity approaches zero. By collapsing at the bottom cloud’s shape changes from hemisphere to semi-ellipsoid and after colliding with the sea floor dredged materials continue to spread radially until the settlement of particles in consequence of energy loss. The collapse phase terminates when the rate of spreading becomes less than an estimated rate of spreading due to turbulent diffusion (Johnson, 1990). It is assumed that sea floor is horizontal and sediment cloud maintains its symmetrical shape. Also it is assumed that pressure is hydrostatic and the pressure at the cloud boundary is identical to the pressure of the ambient water. The STFATE model assumes that particles settle on the bottom and no re-suspension is assumed for short term modelling of sedimentation processes (Johnson, 1990).

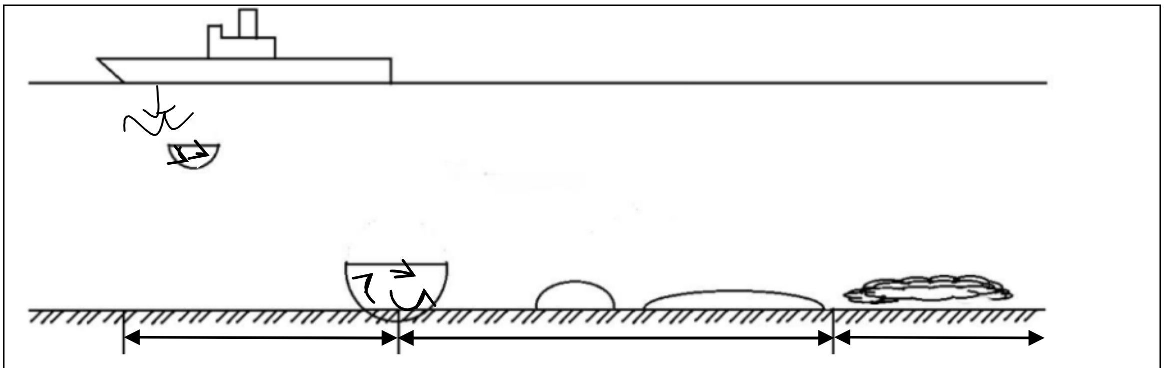


Fig. 1: The three phases of dredged material disposal. The disposed material is modelled as sinking hemispheres with the curved arrows showing the effect of the vortex ring (Brandsma and Divoky, 1976, Palermo et al. 1998).

The area considered for the disposal of sediments shown in Fig. 2 (the trapezoid) includes an area of 1.77 km^2 (0.75 km x 2.35 km) with varying depth between 40 to 50 m, while in simulations deeper depths (150 m) are examined to study the behaviour of sediment particles. In Mersin Bay at the disposal area currents are in northwest direction (NW currents) with a velocity of 15 to 30 cm/s. The disposal area is divided into rectangular grids (30.5 m in x-direction and 61.0 m in y-direction). A two point velocity profile is considered to simulate the vertically decreasing current velocity and its influence on concentration and distribution pattern of sediment particles. Low and high volume barge cases are simulated separately to analyse the impact of sediment volume on particles concentration. In order to determine the optimum barge velocity and direction relative to the currents at the time of disposal 16 directions are examined; the northward barge movement is considered in simulations (Fig. 3). Disposal material is composed of sand, silt, and clay fractions. List of parameters and their values used in simulations are given in table 1.

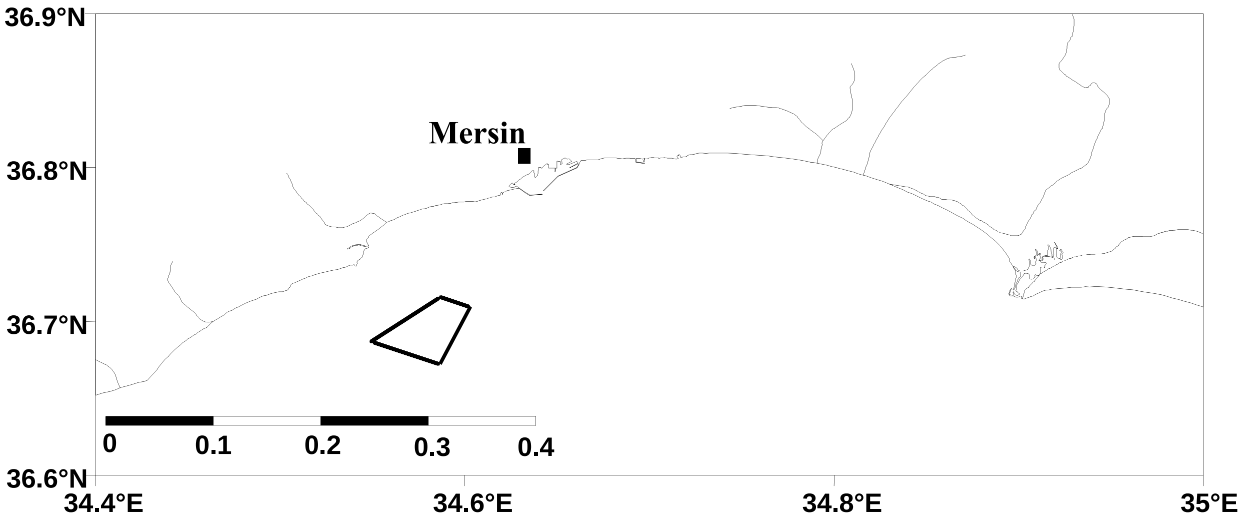


Fig. 2: Mersin bay map. Trapezoid is the disposal area.

Table 1: Specification of disposal area and parameters used for the simulation

<table>
<tr><th colspan="2">Disposal area specification</th><th colspan="2">Current velocity</th><th colspan="2">Barge Specifications</th></tr>
<tr><td rowspan="2">Number of grid points
In x- and y-direction</td><td>64</td><td>Velocity in upper layer</td><td>35 cm/s
60 cm/s</td><td>Barge volume</td><td>500m^3
8000m^3</td></tr>
<tr><td>84</td><td>Velocity in second layer</td><td>20 cm/s
25 cm/s</td><td>Barge velocity</td><td>0.1 to 1.0 mile/h</td></tr>
<tr><td>Grid length</td><td>30.5 m</td><td colspan="2">Sediment composition</td><td rowspan="2">Barge length</td><td rowspan="2">76.5 m
48 m</td></tr>
<tr><td>Grid width</td><td>61 m</td><td>Sand particles</td><td>20%</td></tr>
<tr><td>Water depth at disposal area</td><td>50m
150 m</td><td>Silt particles</td><td>30%</td><td>Barge width</td><td>14 m
9 m</td></tr>
<tr><td>Simulation duration</td><td>2500s
7500 s</td><td>Clay particles</td><td>50%</td><td>Pre-disposal draft</td><td>9 m
4 m</td></tr>
<tr><td>Time step</td><td>300 s</td><td rowspan="2">Current direction</td><td rowspan="2">Northwest</td><td>Post-disposal draft</td><td>4 m
2 m</td></tr>
<tr><td colspan="2"></td><td>Dumping duration</td><td>600 s</td></tr>
<tr><td colspan="4"></td><td>Barge movement direction</td><td>Northward</td></tr>
</table>

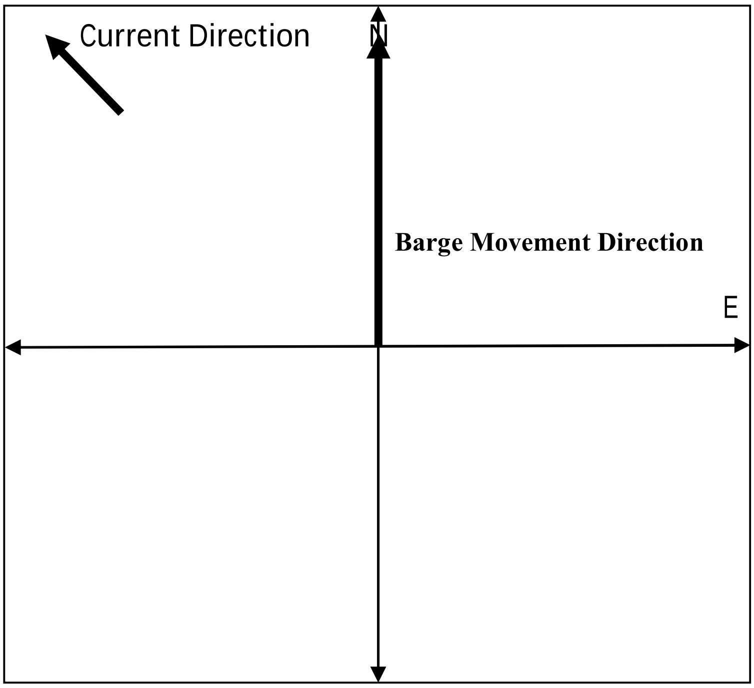
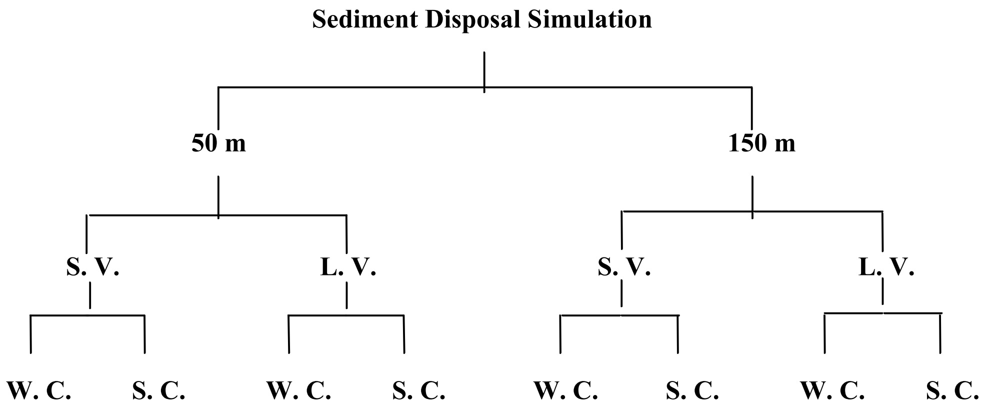


Fig.3: Northward barge movement relative to northwest current.

Results of simulations for different barge movement directions and northwest current indicate that while barge moves in any direction other than N, NW, and NNW, sediments are displaced out of dumping area and the accumulation of sediments occur in disposal point. Comparison of simulation results for N, NW, and NNW barge direction at the time of disposal shows that sedimentation in bottom comprises the lowest thickness when barge direction is northward.

Results

Analysis for the study of sediment particles concentration after disposal is conducted for two different depths, 50 and 150 m. For each depth, small and large volume sediments is considered, where each is influenced by weak and strong currents. While testing impact of weak or strong currents different barge velocities varying from 0.1 to 1.0 mile/h (0.04 – 0.44 m/s) are examined to determine the proper barge velocity at the time of disposal (Fig. 4). Determination of proper barge velocity for the disposal leads to the least sediment particles distribution in water column and hence, distribution of contaminants. A two layer velocity profile in water column is considered in which current velocity in the upper 30 m is higher than the bottom layer. For weak conditions it is assumed that the northwest currents flow with a velocity of 30 and 20 cm/s in upper and bottom layer, respectively. To simulate particles concentration for strong current case velocity of northwest currents is considered 60 and 25 cm/s in upper and bottom layer, respectively. The simulation duration for 50 m depth scenario is 2500 s and for 150 m depth case is 7500 s. It is assumed that the time duration for evacuation of sediments is 10 minutes. According to the samples during dredging process in Mersin Bay, sediments are composed of 20% sand, 30% silt, and 50% clay particles, and this composition is included in simulations. Difference in currents intensity (weak and strong) can be interpreted as two different goals, one from the aspect of seasonal changes (stratification), and the second change in weather condition.



S. V.: Small Volume Barge

L. V.: Large Volume Barge

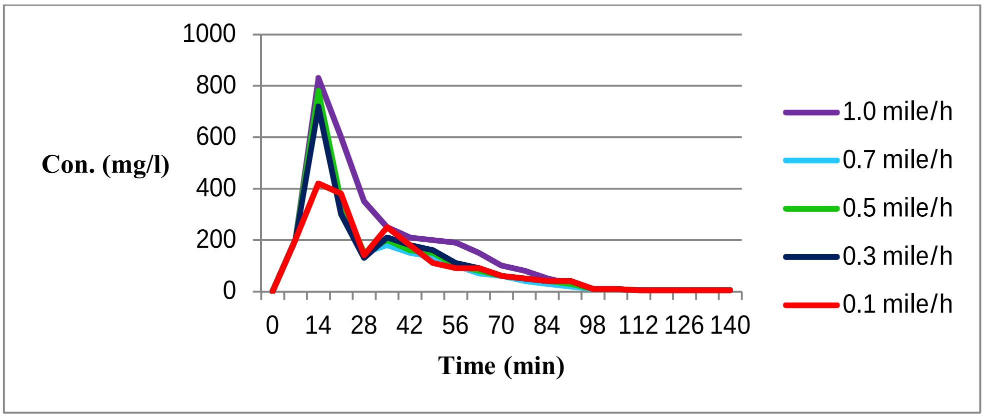
W. C.: Weak Currents

S. C.: Strong Currents

Fig. 4: Schematic diagram of simulation process.

The goal is to reach minimum turbidity in water column and minimum thickness of deposited sediment on seabed. Examining different barge velocities allows the determination of appropriate barge velocity in both weak and strong current cases. Fig. 5 and 6 show the simulation results for the weak and strong currents influence on sediment concentration in 10 m (left) and 150 m (right), respectively. In both cases for different barge velocities in bottom layer –below upper layer- concentration doesn't change (for all sediment particles), while in upper layer different velocities show different concentrations. Lower concentration of the sediment particles in water column indicates minimum turbidity and hence, minimum changes in ecosystem of water column in disposal area. Simulations show that the optimum barge velocity for disposal of sediments is 0.1 mile/h (0.04 m/s). While for 50 m depth clay particles concentration is minimum when barge velocity is 0.1 and 1.0 mile/h (0.04 and 0.44 m/s) (Fig. 7).

Simulation results show that in upper layer sediment particles which leave sediment cloud are carried in current direction toward northwest and as time passes concentration of particles decreases which is due to spreading and sinking of particles in several steps in water column. While the part of sediment that sinks to deeper depth or bottom does not deflect and sedimentation occurs approximately in disposal site which contains the highest amount of sediment concentration. Duration of sedimentation for sediment cloud depends on total depth of disposal site which is 5 minutes for 50 m depth and 15 minutes for 150 m depth.



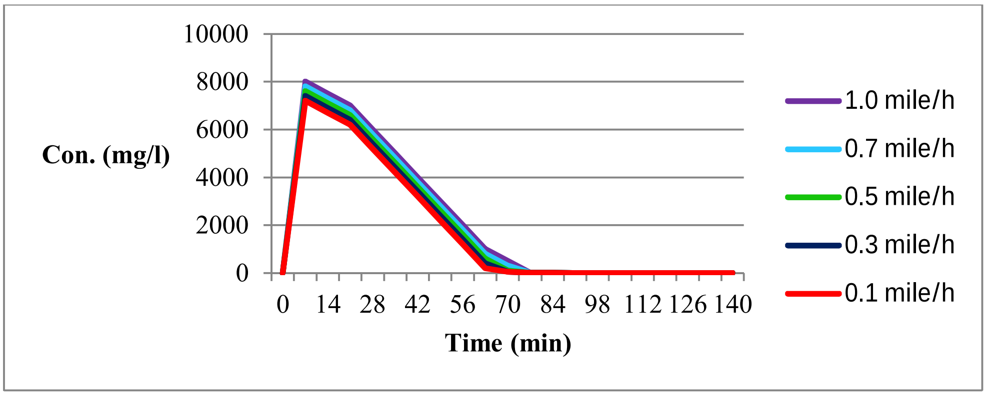
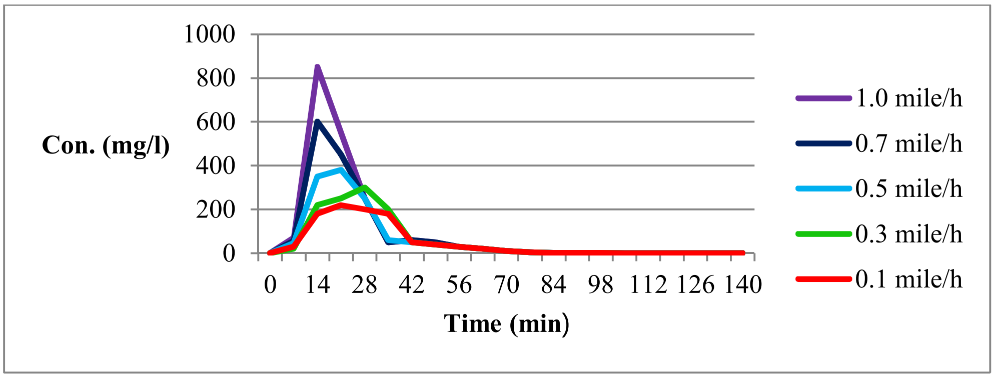


Fig 5: Clay particles concentration in 10 (upper) and 150 m (lower) depth for weak current case and large volume sediment disposal.

Discussion and conclusion

Both dredging and disposal of dredged material is an environmental concern throughout the world. Benthic macro-fauna is often used as an indicator for the ecological impact of such disturbances, partly because the macro-benthos integrates the changes in environmental conditions (e.g. Gray, 1974). In many cases, effects of disposal on the benthic community are near-field and short term although prolonged effects on macro-faunal biomass and composition have been reported.

Dredging and dumping operations cause local and temporal re-suspension of sediments, in turn causing increased turbidity (K. Essink, 1999). Increased turbidity impairs functioning of organisms such as phytoplankton, micro-phytobenthos, and etc. which is a negative effect of dredging and dumping. These negative effects can be reduced by choosing the proper dumping which results in reduced disposal thickness that does not exceed 0.2 – 0.3 m (i.e. K. Essink, 1999). With respect to the simulation results the cases which result in less turbidity and high dilution, and thinner deposition determines barge velocity and dredging period. Since the deposition layer thickness is an important factor for ecosystem changes, in Mersin Bay case in which high amount of sediments is dredged and dumped in disposal site it is believed that from both ecological and economical aspect of view large volume sediment dumping is advantageous.



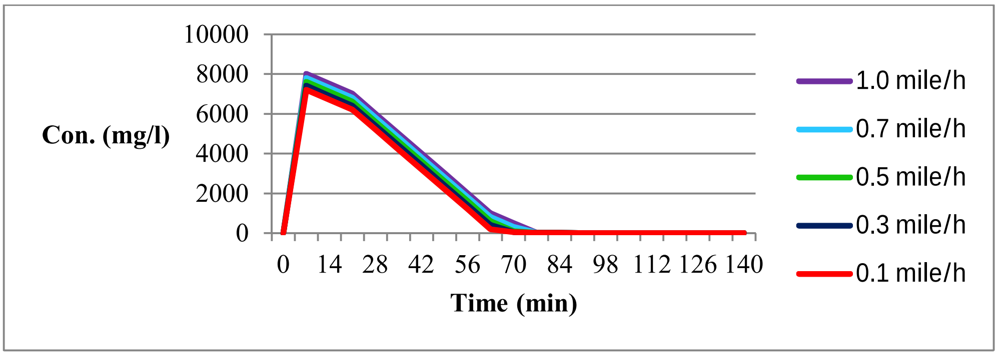


Fig 6: Clay particles concentration in 10 m (upper) and 150 m (lower) depth for intense current case and large volume sediment disposal.

Disposal process is performed by two different high and low volume barges. In the first five months low volume barge (500 m^3) with a 4 m pre-disposal draft is used. In the second stage high volume barge (6000 m^3) with a 9 m pre-disposal draft disposes sediment. Duration of sediment dumping in the determined grid points is approximately 2 and 10 minutes for low and high volume barge, respectively. Because of weak currents in the disposal area (10–30 cm/s) sediment particles distribution in water column and in bottom are not affected by the currents. Main parameters are barge velocity at the time of dumping and sediment composition. For higher volume of sand in sediment composition barge velocity should increase which leads to lower sediment thickness on seabed. Because of higher sand particles specific density in comparison with silt and clay particles, sand particles sink faster than the other particles. Consequently, in 10 m a small part of sediment concentration is sand. The major part of sand particles sink into bottom and spreads on sea bed. Small particle sediment (<0.63 micron) sinks slowly. Ship velocity is considered 0.1–1.0 mile/h (0.04 m/s to 0.44 m/s) and the duration of dumping is 8–10 minutes. In the upper layer (10 m) small particles sediments (silt and clay) concentration is distributed dependent on barge and current velocity. It takes 30 to 60 minutes for the values of particulate matter to change into natural values in seawater. Small sediment particles concentration in water column is dependent on barge and current velocity. If the velocity of barge is closer to the current velocity, sedimentation in bottom will be homogeneous. The thickness of small particle sediment is 15–25 cm, which the impact of sedimentation on seabed will compress sediment layer that results in a thinner thickness.

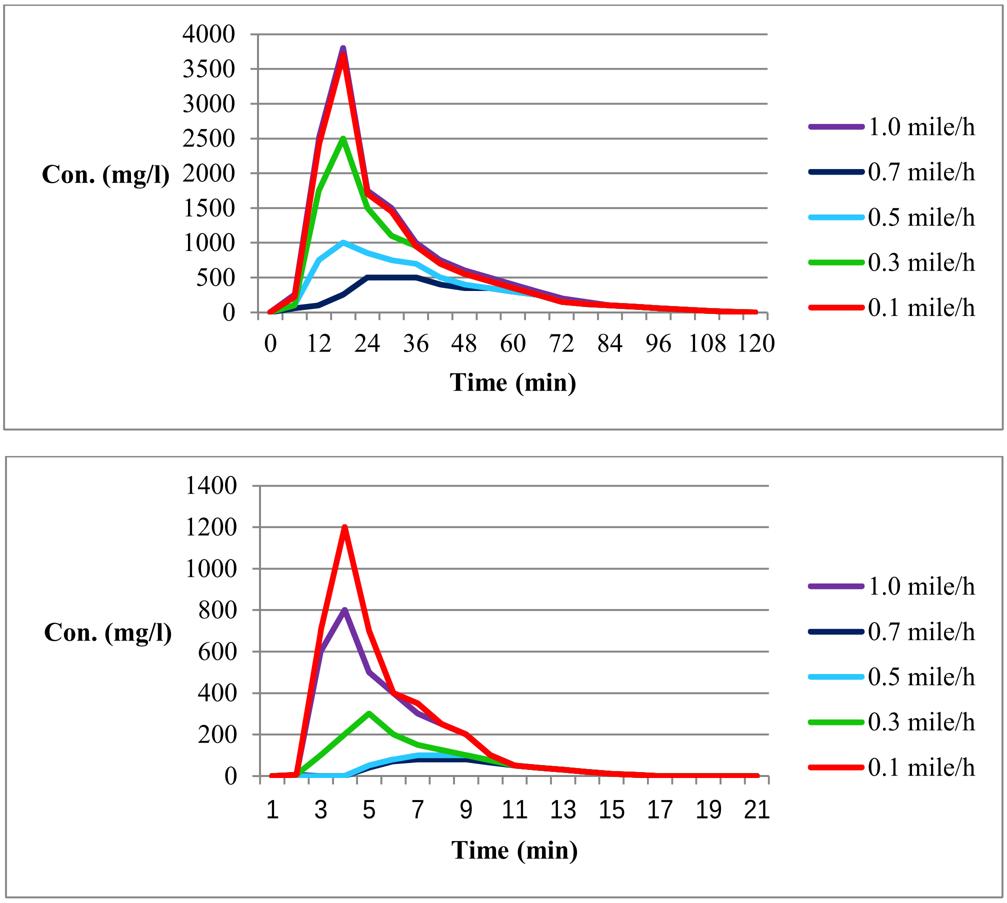


Fig. 7: Clay particles concentrations in 10 m depth (50 m total depth) weak current upper) and strong current (lower).

The thickness of settled sediment in bottom after dumping about 4.1 x 10^6 m^3 sediment will be about 1.5 m. Model results for the high volume barge dumping show that under 10 cm/s current influence, particles concentration in water column is 200 mg/l and the turbidity of the upper layer (10 m depth) lasts for 20 minutes and then water reaches its previous state. Due to different sinking rates in seawater, silt and clay particles float in water column. Measurements of silt concentration in water column show that silt particles concentration is 500-3000 mg/l (sediment dumping by large volume barge); concentration reaches 1000 mg/l, in 140-150 m distance from disposal pint. Clay concentration is measured 3000 mg/l, 65-90 m far from the disposal point and decreases to 1000 mg/l in a distance of 115-135 m from the disposal point.

Model results show that seasonal changes do not influence sediment concentration in water column; the time required to empty the barge, current and barge velocities influence particles concentration and sediment distribution. Increases of water content of sediments, behavioural change of deposition, partially change of settling property, and its distribution to a wider area is predicted.

Acknowledgment

This study was supported by TUBİTAK (Project No: 111G 152).

References

Brandsma, M.G.and Divoky, D.J. (1976), "Development of models for prediction of short term fate of dredged material discharged in the estuarine environment", U.S. Army Engineer Waterways Experiment Station. Dredged Material Research Program, Contract Report D-76-5.

Erftemeijer, Paul L.A., Robin Lewis III and Roy R. (2006),"Environmental impacts of dredging on seagrasses: A review", Marine Pollution Bulletin 52, 1553–1572.

Essink, K. (1999), "Ecological effect of dumping of dredged sediments; options for management", J. Coastal Conservation, 5, 69-80.

Filho, G.M.A., Creed, J.C., Andrade, L.R. and Pfeiffer, W.C. (2004), "Metal accumulation by Halodulewrightii populations", J. Aquatic Botany 80, 241–251.

Gray, J.S.(1974), "Animal–sediment relationships", Oceanography and Marine Biology:An Annual Review 12, 223–261.

Johnson, B.H. (1990),"User's guide for models of dredged material disposal in open water", U.S. Army Engineer Waterways Experiment Station. Dredging Operations Technical Support Program, Technical Report D-90-5.

Johnson, B.H., and Fong, M.T. (1995), "Development and verification of numerical models for predicting the initial fate of dredged material disposed in open water", Technical Report DRP-93-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Morris, P. H. (2000), **"**Progress report on research into ocean and land disposal of sediments dredged from marinas and small boat harbors", CRC for Sustainable Tourism.

Palermo, M., Randall, R. and Johnson, B.H. (1998),"Evaluation of Dredged Material Proposed for Discharge in Waters of the U.S. –Inland Testing Manual, Appendix C Evaluation of Mixing", Environmental Protection Agency and Department of the Army.

Pennekamp, J.G.S., Epskamp, R.J.C., Rosenbrand, W.F., Mullie, A., Wessel, G.L., Arts, T., Deibel and I.K. (1996),"Turbidity caused by dredging: viewed in perspective", Terra et Aqua 64, 10–17.

Raymond, L. (1986), "Fate of dredged material during open-water disposal, environmental Effects of Dredging Technical Notes, U.S. Army Engineer Waterways Experiment Station", Technical Report EEDP-01-2.

Wal, D., Forster, R. M., Rossi, F., Hummel, H., Roose, T.Y.F. and Herman, P.M.J. (2011), "Ecological evaluation of an experimental beneficial use scheme for dredged sediment disposal in shallow tidal waters", Marine Pollution Bulletin 62, 99–108.

Keywords

Ecosystem, Dredging impacts, Sediment management, Sediment transport, Dredging and disposal, STFATE.