CHAPTER 213

The Spreading of Dredging Spoils During Construction of the Denmark-Sweden Link

Ida Brøker[1], John Johnsen[1], Morten Lintrup[1], Anders Jensen[1], and Jacob Steen Møller[1]

Abstract

An overview of the model complex, including a combined Lagrangian and Eulerian approach to simulation of sediment transport, developed to study spreading of dredging spoils in connection with off-shore earth works necessary for construction of the Denmark-Sweden Link is provided; - together with in-depth descriptions of two particular work topics: (a) Model representation of flow friction to allow application of an inherently depth-integrated model system to a partially stratified environment, and (b) overall design of the model complex to make it fit as a versatile tool at several stages of this large project.

Introduction (Location and Scope)

In connection with the planned Link between the Danish capital Copenhagen and Malmoe in Sweden along the Drogden Sill, see Figure 1, dredging of clay and chalk is necessary for flow compensation as well as for direct construction purposes since it is required that the net water and salinity exchange through the Sound must not be affected. The dredging results in release of substantial amounts of fine material within an area, which is both environmentally perceptive and hydraulically complicated since the sill in combination with an approximately 25 PSU longitudinal salinity difference between Kattegat to the north and the Baltic to the south induces a mobile and variable mixing front over a fairly stable salinity interface normally extending southwards only to Drogden Sill.

The model setup and calibration have been supported by laboratory and field experiments. The model complex is verified by comparison with data from test dredgings totalling 64,000 m^3 of moraine clay and chalk, of which 8,200 m^3 were spilled. During these tests spill percentages and variability for different types

---

[1]Danish Hydraulic Institute, Agern Allé 5, DK-2970 Hørsholm, Denmark.

of operations were specifically evaluated. The actual dredgings are expected to approach 7 mill. m^3 after early planning had indicated dredging requirements to be twice that amount.

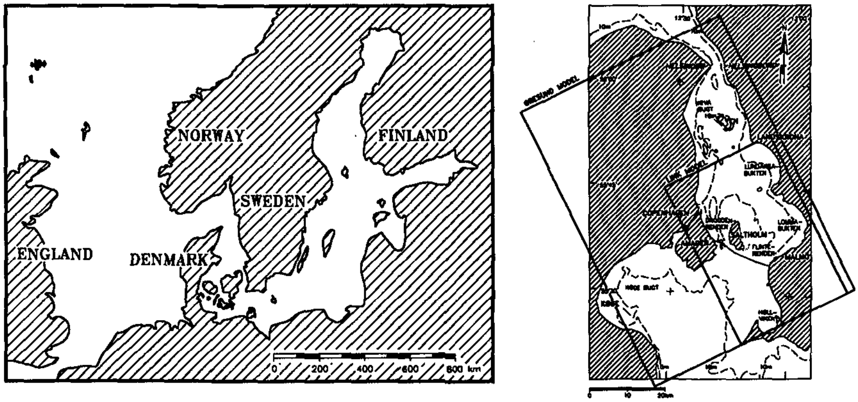

Figure 1. Location Map (left) and Model Areas (right).
The large area indicates extent of main model. The small area corresponds to a fine resolution model used in calibration/ verification of material specific parameters.

The scope of the present study was to establish a numerical model complex for simulating the spreading of fines, notably determining shading effects associated with dredging plumes and the eventual fate of spilled material. This should be done so as to facilitate subsequent planning of actual dredging operations as well as to prepare a tool useful in the implementation of an actual dredging spill control strategy.

Administrative objectives as well as legal requirements for dredging operations primarily focus on instantaneous spill rates, specified by area and season. These limitations have been derived from maximum acceptable concentrations by inverse interpretation of results obtained with the model complex described in this paper. An effective dredging period of almost 4 years is anticipated.

Overall, an upper limit to the average spill rate of 5% (implying a total spill of up to 350,000 m^3) will be imposed. A dredging control strategy should aim at monitoring during the entire operation that actual spill rates allow compliance with this target. Since economical dredging practice dictates operating with a variable spill rate, this implies comparison of measured spill to an *a priori* planned and contractually agreed spill budget.

Background, Physical Processes and Model Complex Overview

The seabottom material along the planned link consists of hard chalk (limestone), partly overlaid by moraine clay. Construction works include dredging operations for a submerged tunnel along half the crossing length, foundation of bridge piers (approx. tot. 4.5 mill. m^3) and compensation dredging to maintain the present water and salinity exchange through the Sound (approx. 2.3 mill. m^3).

The spreading of fine particulates from dredging spoils is a function of currents, wave action and sediment properties. Immediately after the release spreading takes the form of narrow plumes which can be observed far away from the source due to generally appreciable current speeds. Parts of the material settles and deposits on the bottom where a consolidation process takes place.

The settling velocity - which is one of the most important parameters - depends on the material in question, salinity, temperature and biological activity due to flocculation. However, preliminary simulation results indicated application of straight values of 0.00018 m/s (moraine clay) and 0.00021 m/s (chalk/limestone) to be satisfactory in this case.

If bed shear stresses are increased above a critical value, resuspension takes place. This resuspension is a function of the degree of consolidation, see Mehta et al. (1989), whose formulation has generally been followed in the modelling.

All relevant processes are represented in a comprehensive setup of numerical models, comprising (H=Horizontal):

- 2-D(H) hydrodynamic model
- 2-D(H) discrete spectral wind wave model
- Particle model (random walk (x,y,z)-tracer technique) for the initial spreading around the source
- 2-D(H) advection-dispersion model for spreading in the far field

Furthermore, these models have been linked to an associated ecological model, describing growth and distribution of benthic vegetation notably eelgrass, *Zostera marina*. The ecological model is also an integrated part of the EIA (Environmental Impact Assessment) and anticipated dredging control procedures, and it is reported elsewhere, Bach et al. (1991).

The source/sink term in the advection-dispersion model represents the link between transporting agents and in-the-bottom processes. A multi-layer representation of shear strength of the bed and consolidation in the bed are included.

The study concept has been to apply nested far-field and near-field models (two, with resolutions of 500 m and 100 m, termed ØRESUND and LINK modelling areas, respectively, see Figure 1) and to couple wave, current and sediment models as shown in Figure 2. Sediment models must be run separately for both moraine clay and chalk, and result fields added, as needed.

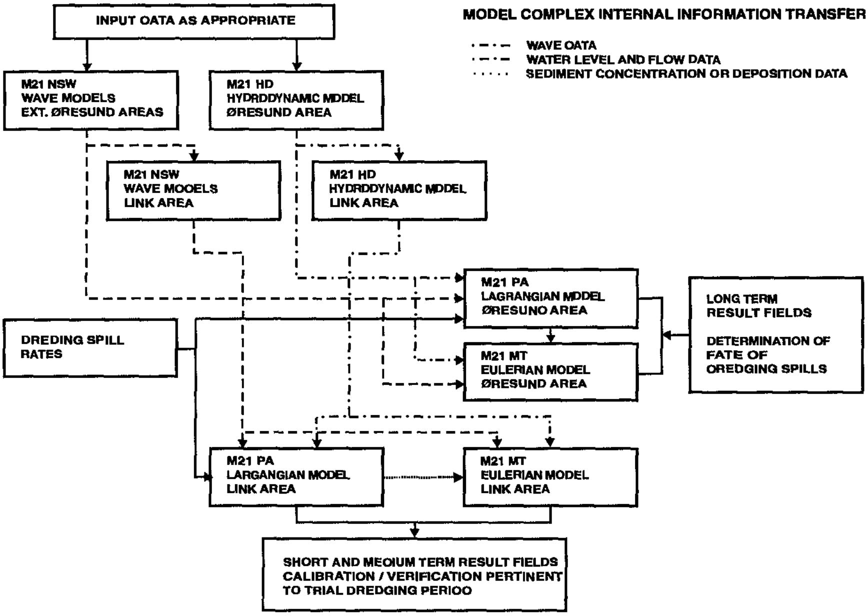

Figure 2. Sediment Spreading Model Complex. Overview emphasizing internal structure and input/output of data on transport/deposition rates.

The two nested models have to some extent served different objectives. The finer model has been sufficiently detailed to allow model calibration and verification to test data from field experiments covering a three months period with respect to material specific parameters; - whereas the coarser model has proved useful for repeated, several-year-long simulations covering a larger area in support of operations planning.

Two coupled sediment models have been applied; the first having a Lagrangian modelling approach. In addition to savings in execution time and computer storage, two main advantages are achieved over traditional, direct Eulerian modelling:

Numerical dispersion due to "poor" resolution is avoided even though a relatively coarse grid is maintained for the current, ie. model concentrations of suspended matter reach realistic high values very close to the source. This is important for subsequent modelling of eelgrass growth.

Most dredging spoils are released near the surface, ie. the areal spread and time lag before it is justified to assume a standard vertical concentration profile is considerable. This adaptation takes place within the Lagrangian model.

After a certain period the sediment is then transferred to an advection-dispersion model comprising a more refined description of bed consolidation and resuspension effects. The transfer period is basically a matter of technical judgment and compromise; here values in the range 3-6 hours have been found to work satisfactorily.

The *sediment transport module* needs input of settling velocity of flocs depending on degree of flocculation, whereas the *bottom process module* needs input of critical bed shear stresses for erosion and deposition for description of reentrainment and erosion and parameters for description of the consolidation process. Parameters in the sediment transport and bottom process modules are derived from laboratory and field experiments.

In-situ settling experiments using an Owen settling tube to determine settling rates were carried out. In the laboratory the resuspension as a function of shear stress and degree of consolidation were investigated in an annular flume. Consolidation rates were studied in the annular flume and in settling tubes.

Flow conditions in the laboratory are stationary and the biological activities are minimized. Those experiments have therefore been supplemented with field experiments where a test area (20 x 10 x 0.25 m^3) was constructed in the Sound close to the Link alignment. The test area was covered by chalk similar to the finest fractions (<63μ) of dredging spoils. All experiments and the sediment model calibration process including actual selections of parameters are described in detail in Johnsen et al. (1994).

The wave climate in Øresund has been demonstrated to be effectively fetch-limited and dominated by locally generated waves. As a result, conditions are generally mild with waves in the range H_s=0.2 to 0.6 m. This has justified a simplified wave modelling approach based on a number (36) of stationary simulated wave fields (12 wind directions times wind speeds 5, 10, and 15 m/s), from between which instantaneous wave fields as input to sediment models were interpolated using measured wind conditions.

The flow is modelled dynamically with bathymetry, bed resistance, eddy viscosity, wind and boundary water levels as the main defining input. The latter are derived from four water level stations - two each north and south of the Sound;

two lying on the Danish and two on the Swedish side. An entire year of registered currents at two stations were available for verification of the flow model. A detailed description of the bed resistance input is provided in the following section.

In Figure 3 is shown an example comparison of plumes observed, respectively simulated on basis of the combined wave, current and sediment models.

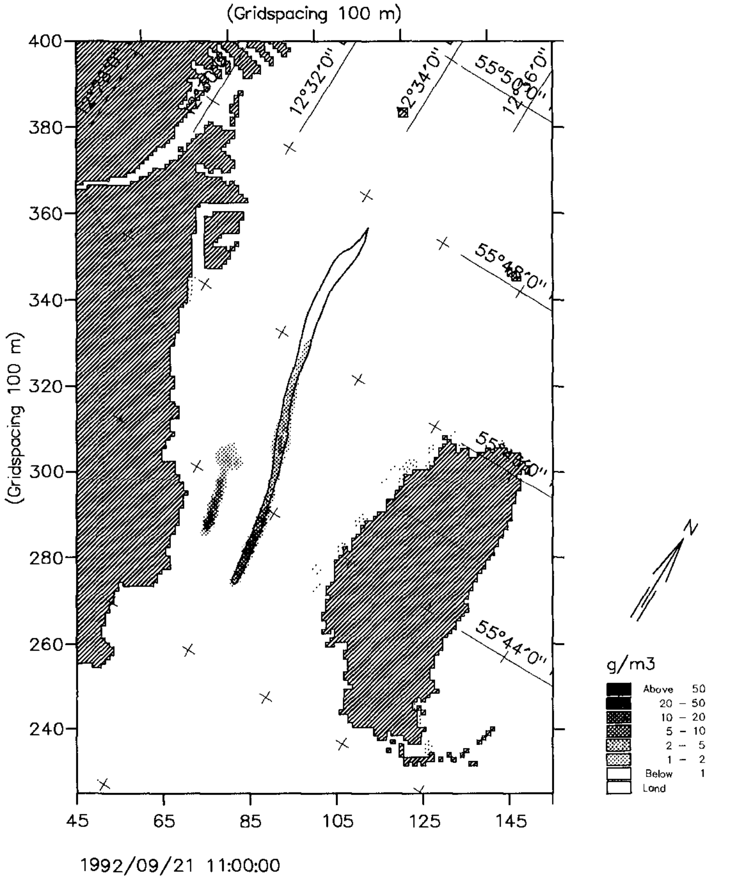

Figure 3. Comparison of Observed and Simulated Plumes for Model Verification (example)

The verified model has been run for a full year, Sept. '92 - Aug. '93, to simulate the fate of spoils from the test dredgings. That same year has then been designated as design period for subsequent EIA-studies.

With respect to spoils from test dredgings it appears that final deposition areas are mainly along the Danish coastline, and there is only a minor difference between spreading of moraine clay and chalk because settling characteristics are very similar and both types of spoil consolidate relatively quickly after deposition. It is estimated that 90% of moraine clay and 80% of chalk spoils are deposited within the Sound, the majority less than 20 km from the spill site.

Model Representation of Flow Friction

In order to use the DHI MIKE 21 hydraulical modelling system - which assumes a "homogenous" (one-layered) current regime - to simulate the normally stratified environment in the Sound north of Drogden sill, a correction procedure has been developed and applied to the flow friction; expressed in the model in terms of a Chezy no., *C*, which is reciprocally defined in relation to current velocities.

For homogenous flow a logarithmic velocity profile is assumed. When the water column is stratified, the velocity profile will be contorted and for identical head losses result in a higher water discharge. In other words, stratification may be seen as a lubricant for the current. The principal differences between homogenous and stratified (two-layered) current regimes may be visualized as in Figure 4.

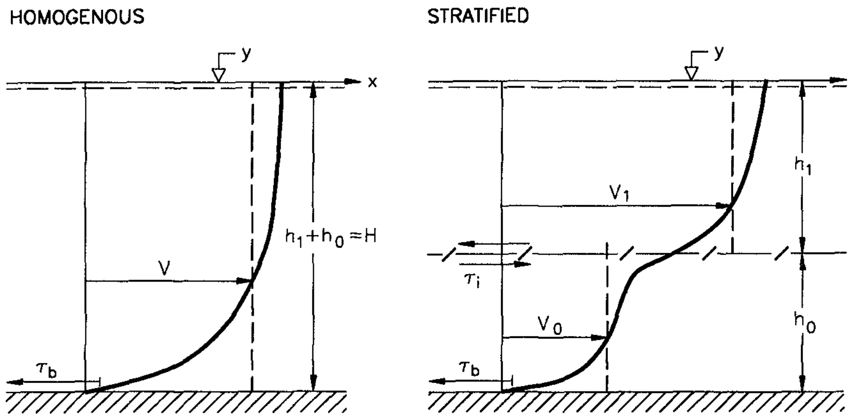

Figure 4. Definition sketch for homogenous (left) and two-layered (right) current regimes

The reduced energy loss caused by the stratification can be incorporated in a homogenous one-layer calculation by introducing an *equivalent (reduced) bottom friction.* This is done on the assumption that the current is dominated by barotropic effects, ie. pressure gradients caused by water level differences are (much) more significant than those caused by density gradients in the flow momentum equation. Then, the momentum equations may be written as:

$$gh_1 I = \frac{\tau_i}{\rho_R}$$

$$gh_0 I = \frac{\tau_b}{\rho_R} - \frac{\tau_i}{\rho_R}$$

where g (9.81 m/s^2) is gravity, h (m) is the thickness of a layer (index 1 is for the upper layer, and 0 for the lower), I is the energy gradient, τ (N/m^2) is the friction (index b is for the bottom, and i for the interface), and ρ_R (1010 kg/m^3) is a reference density. Shear stresses are determined by

$$\frac{\tau_i}{\rho_R} = (1-c)\frac{f_i}{2}\frac{1}{4}(V_1-V_0)^2 + c\frac{f_b}{2}V_1^2$$

$$\frac{\tau_b}{\rho_R} = (1-c)\frac{f_b}{2}V_0^2 + c\frac{f_b}{2}V_1^2$$

where f is the friction factor, and V (m/s) is the mean velocity in a layer. The factor c has been introduced to the equations in order to transfer bottom shear stress directly to the surface layer when bottom layer thickness, $h_0=H-h_1$, decreases to a value comparable to the equivalent bottom roughness, k:

$$c = \frac{h_1}{H}\exp\frac{-(H-h_1)}{\alpha k}$$

The equivalent bottom roughness is typically 0.3 m in the Sound. The h_0/k aspect ratio, α, has been roughly estimated as $\alpha=2$. It is noted that the equations lead to the traditional one-layer formulation when the thickness of either of the two layers approaches zero.

Dividing the momentum equations, an equation regarding the ratio of the upper and lower layer velocities, V_1/V_0, is obtained: The ratio shows a higher velocity in the upper layer than in the lower as shown in Figure 4 and measured in Øresund. In the velocity ratio equation, the ratio between the friction factors, f_i/f_b, is present. This ratio is evaluated to be 1/3.

Adding the momentum equations it is seen that the total pressure is balanced by the bottom friction, which in the considered case is a function of both the lower and upper layer veloctity (the right side of next equation). To model the two layer system as a one-layer system we need to relate the bottom friction to the depth mean velocity by defining an equivalent bottom friction factor (f_e):

$$\frac{f_e}{2} \cdot \left(\frac{h_0 V_0 + h_1 V_1}{h_0 + h_1}\right)^2 = \frac{f_b}{2}\left((1-c)\, V_0^2 + c V_1^2\right)$$

Thus, by applying the equivalent bottom friction factor in the flow simulations the correct depth mean velocity is obtained.

The relation between a friction factor and its corresponding Chezy no, C, is taken as:

$$C = \left(\frac{2g}{f}\right)^{1/2} \Leftrightarrow \frac{f}{2} = \frac{g}{C^2}$$

Following calibration of the model a constant "homogenous" reference Chezy no., C_b of 35 $m^{1/2}/s$ has been used, corresponding to f_b=0.016. By applying an equivalent Chezy no. C_{eq} instead of C_b for calculations north of Drogden Sill the lubricating effect of stratification on current has been accounted for in the modelling. In Figure 5 is seen how the equivalent Chezy no. (corresponding to a reference Chezy no. of 35 $m^{1/2}/s$) varies with the position of the interface for different total water depths. The importance of the stratification as a lubricant is evident from the figure.

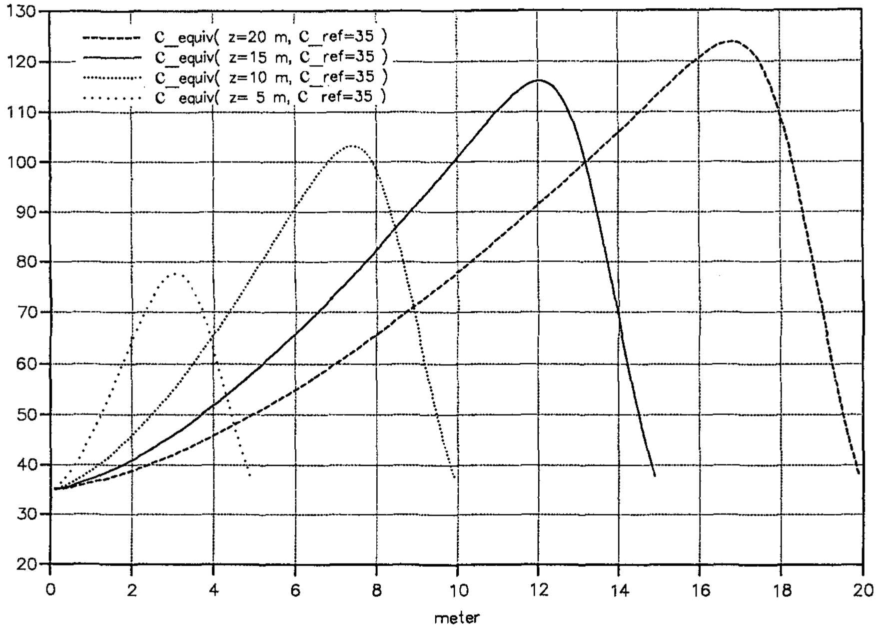

Figure 5. Equivalent Chezy no. as a function of interface depth for total depths 5, 10, 15, and 20 m.

Model Complex Applications with Example Results

In this section it is demonstrated how the developed model complex has been and continues to be a useful tool in several, at least three, cases (a)-(c), stages of the project planning and execution.

Particularly, it is noted how the modelling complex may provide results with a statistical character since it is comprehensive, yet operationally manageable for extensive and/or repetitive calculations. Thus the complex is especially likely to be useful in connection with criteria, objectives, requirements etc. that are cast in statistical terms.

Additionally, it is noted that results may be obtained by inverse as well as direct interpretation of results.

(a) A number of relatively short simulations were made corresponding to four typical key dredging and deposition activities, two different dredging (spill) intensities, and two types of hydrographic conditions, summer calm and autumn variable (incl. storm) conditions.

Results from these simulations were compared to conservatively estimated empirical tolerances with respect to bathing water quality, eider and swan forage (1), mussel beds (2), mussel larvae settling (3), and herring migration (4). Tolerances were expressed as concentration maximum exceedance time (1), max. weekly sedimentation (2), sedimentation rate max. exceedance time (3), and max. concentration (4), - all concerning specific areas and seasons. From the comparison a number of restrictions on dredging activities expressed as maximum spill rates (kg/s) were identified, and in some cases it was demonstrated that conflicts were unlikely to occur.

In Figure 6 is shown an example result field of calculated 6 g/m^3 concentration percentage excecdance time pertaining to herring migration tolerance.

(b) Based on experiences from (a) above a complete realistic dredging scenario was worked out for EIA purposes assuming that two backhoe dredgers and one cutter suction dredger will be employed. This preliminary scenario consists of 26 individual dredging (and deposition) activities and spans the period October '95 to April '99. Scenario resolution is daily production rates.

By recursive application of the design year period EIA background simulations for the entire dredging operation could be made. The associated ecological (eelgrass) module was similarly applied.

The model complex has been further refined for this application to include movable sources along piece-wise linear transects in the sediment modules.

As an example and to illustrate the areal impact of the entire operation is shown in Figure 7 the calculated distribution of net accumulation after four years. It is noted that expected maximum accumulation is just over 5000 g/m^2.

Presently, EIA is an ongoing process actively in support of project planning and development rather than just a passive instrument for legal acceptance.

(c) It is anticipated that the model complex will be applied also at later stages in connection with implementation of control procedures for actual dredging operations, but the exact role(s) and extent of its use remains to be defined.

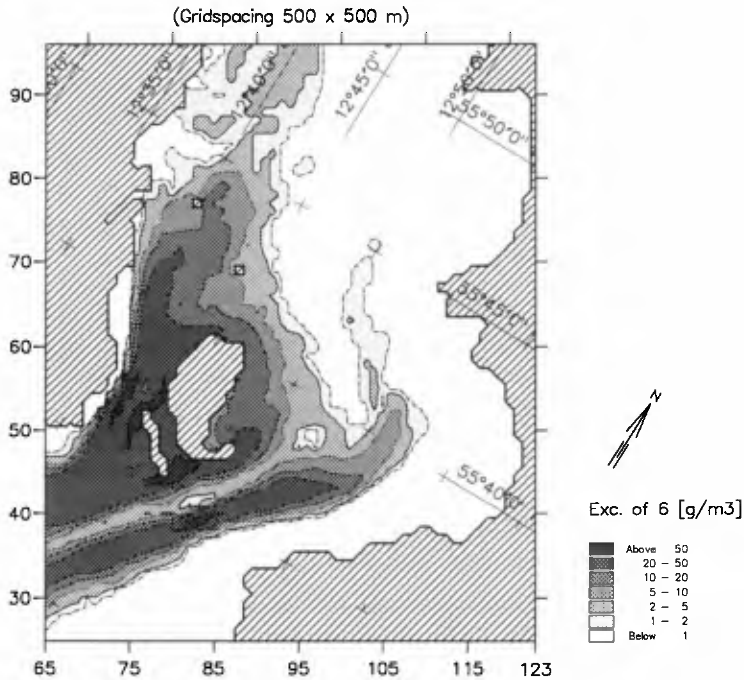

Figure 6. Example results pertaining to Migration of Herring. Depth averaged concentration of 6 g/m^3, Percentage Exceedance Time.

Conclusion

A general and figurative outline of the entire complex developed for modelling of spreading of dredging spoils during construction of the Denmark-Sweden Link, - mainly composed of already existing individual modules, - but with some customizations to fit special requirements and make it a versatile tool in connection with several project stages, - has been given.

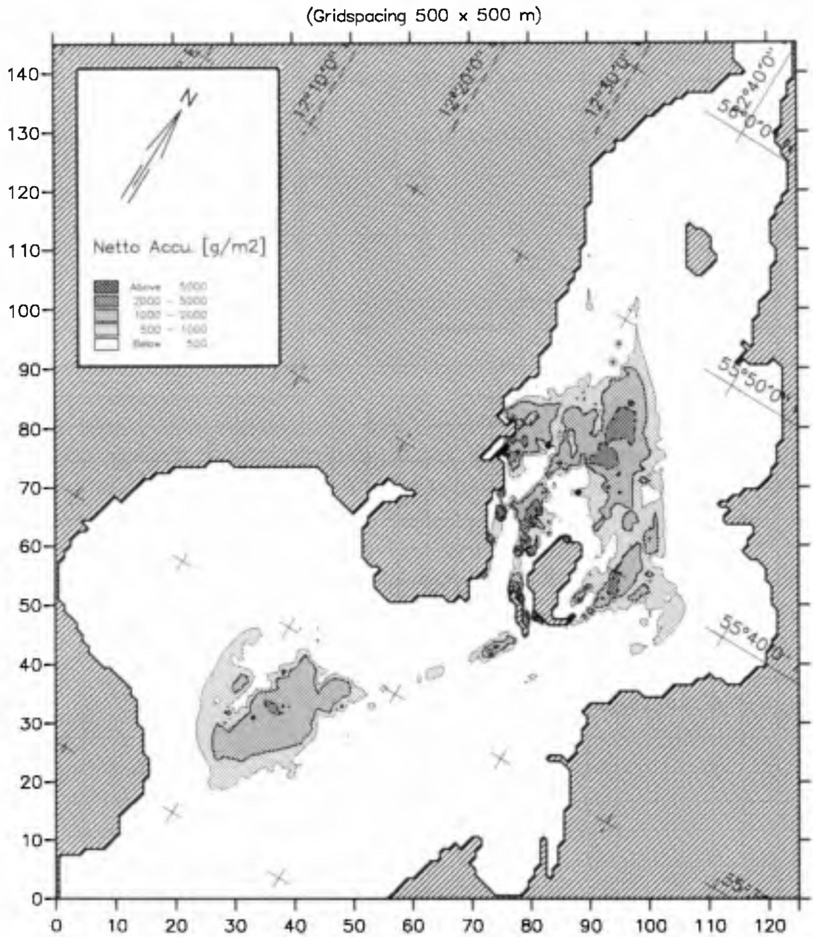

Figure 7. Calculated Net Accumulation from Entire Dredging Operation, 951001-990930.

The main innovation is the use of a relatively fast and practical Lagrangian (random walk particle tracer) sediment model to describe spreading very close to the source, rather than an Eulerian (2-D advection-dispersion) model, which becomes very unwieldy when a high resolution is required.

It has been demonstrated how - given the right circumstances - a depth-integrated hydraulic model system may be adapted for application to a stratified environment by the introduction of an equivalent (reduced) bottom friction calculation.

Furthermore it has been demonstrated how overall design of the model complex is made to fit requirements for EIA-purposes as well as anticipated procedures for control of dredging spill compliance with strict administrative and legal requirements.

More generally, the model complex allows generation and presentation of results in a statistical form. Thus, whenever biological criteria, administrative objectives, legal requirements, etc. are cast in statistical terms the complex is likely to be a useful tool.

Acknowledgments

The Sound model complex was implemented under contract to the Øresundsconsortium. The cohesive sediment models were developed as part of the G8 Coastal Morphodynamics programme (contract no. MAS2-CT-92-0027).

References

Bach, H., E.K. Rasmussen & H.H. Riber (1991). Use of an Ecological Model in Assessing the Impact from Sediment Spill on Benthic Vegetation. Proceedings of the 12'th Baltic Marine Biologists Symposium held in Helsinore, Denmark, 25-30 August.

Johnsen, John, A. C. Ellegaard, and A. Jensen, (1994). Calibration data for modelling of spreading of fines from dredging operations during construction of the Øresund Link. Australian Journal of Marine & Freshwater Research.

Mehta, A.J., Hayer, E.J., Parker W.R., Krone R.B., and Teeter, A.M., (1989). Cohesive Sediment Transport, I: Process Description. J. Hydraul. Eng., Vol. 115, No. 8, pp. 1076-1093.

Møller, Jacob Steen, I. Brøker, and R. Warren, (1994 A). Engineering design for minimum impact on ecology. Proceedings for COEI/CWR Joint International Symposium on 'Ecology and Engineering'. Malaysia.

Møller, Jacob Steen, I. Brøker, and J. Krogsgaard Jensen, (1994 B). The environmental aspects of the Denmark-Sweden Link. Proc. 1st International Symposium in Habitat Hydraulics in Trondheim, Norway. August 18-20, 1994.