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Abstract

In the safety assessment of a potential repository for spent nuclear fuel, it is important to assess the consequences of a hypothetical leak of radionuclides through the seabed and into a waterborne transport phase. Radio-nuclides adsorbed to sediment particles may be transported great distances through the processes of sedimentation and resuspension. This study investigates the transport patterns of sediment particles of two different sizes, released in the Forsmark and Laxemar area. The results show that the closed waters around Forsmark to a higher degree makes the particles stay in the area close to the release points.

Sammanfattning

I arbetet med att välja en plats för slutförvar av uttjänt kärnbränsle är det av vikt att undersöka konsekvenserna av ett eventuellt diffust läckage. Radionukleider som adsorberar till sedimentpartiklar kan transporteras långa sträckor genom sedimentation och resuspension. De kan också stanna i det direkta närområdet av utsläppsplatsen, beroende på hur sedimentationsprocesserna verkar i det aktuella området.

Den här studien undersöker transportmönstren för sedimentpartiklar av två olika storlekar, lera och silt, i områdena kring Forsmark och Laxemar. Resultaten visar att batymetri och dominerande strömningsmönster kring Forsmark gör att en mycket stor andel av sedimentpartiklarna där stannar kvar i kustnära områden. De mer öppna vattnen kring Laxemar gör att den största delen av sedimentpartiklarna lämnar området.

Contents

1 Introduction

The purpose of the study is to examine how radioactive material adsorbed to sediment particles of different sizes behaves over time in a water basin. The simulations are made for the areas around Forsmark and Laxemar. The main interest is to se how large fraction of the released material that does not get transported away, but stays in shallow coastal areas that may be affected by land rise.

The study is made with a numerical 3D model that calculates sediment transport, with sedimentation and resuspension. The simulation is based on the assumption of a diffuse leakage from a number of release points in the coastal zone, specified by SKB. From these entering points the movement of sediment particles carrying radioactive material was modelled during one year. The resulting sediment pattern and statistics of transport behaviour is presented in the result section of this report.

2 Model setup and specifications

The modelling of the particle transport, sedimentation and resuspension used in the present study is made in four steps.

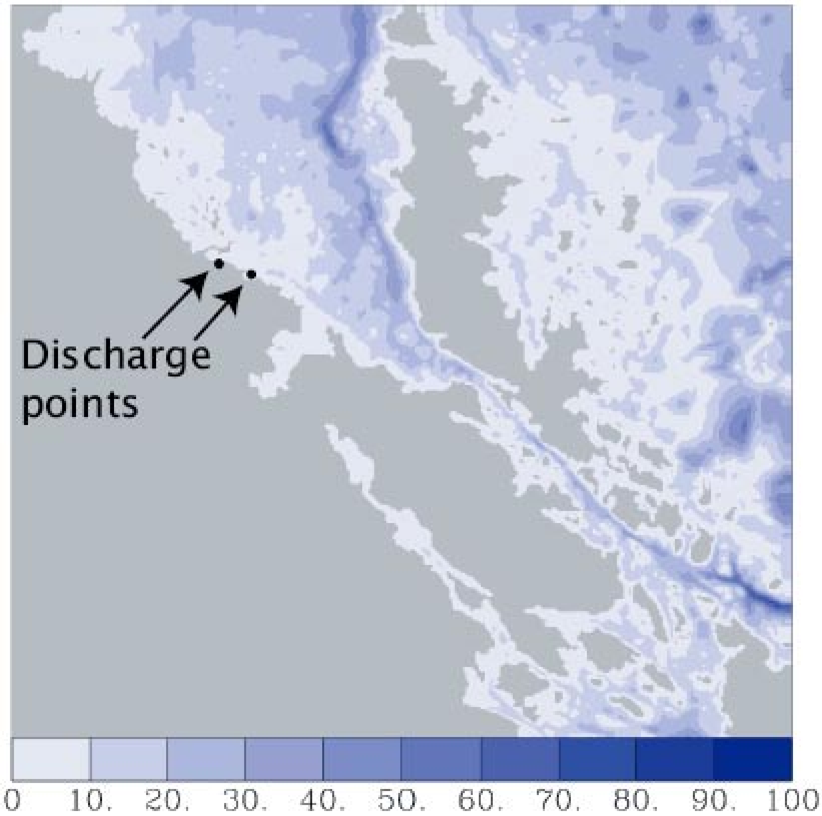
1. The general circulation model, which simulates the velocity fields.
2. The Lagrangian trajectory model, which calculates the particle trajectories as they are advected passively by the velocity fields.
3. A sedimentation model, which adds an extra vertical component to the velocity fields in order to enable the particles to fall to the sea floor.
4. A resuspension parameterisation, which will enable the particle to resuspend from the sea floor if the shear stress near the bottom of the sea exceeds a threshold value.

2.1 The general circulation model

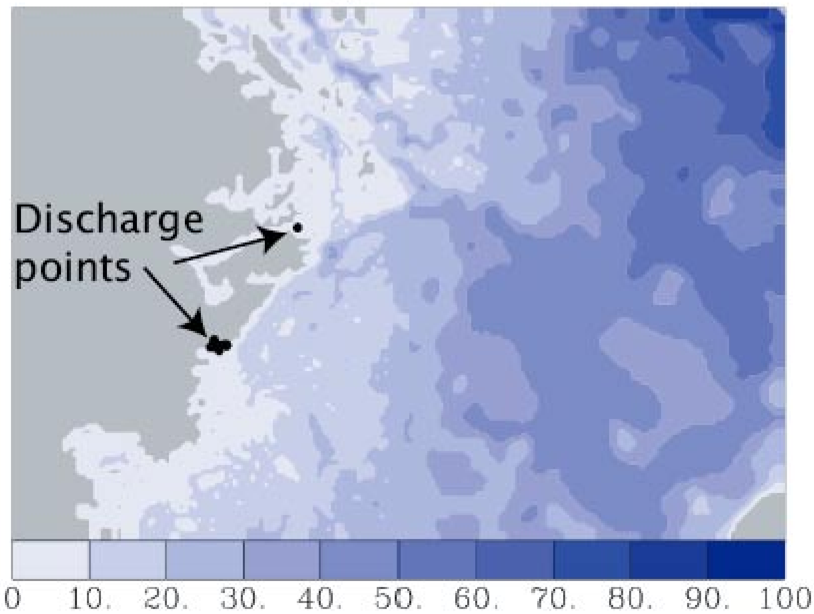
The general circulation model (GCM) used in the present study was first formulated by /Andrejev and Sokolov 1989/. It is time-dependent with a free surface and based on the basic set of the primitive hydrodynamical equations. The circulation model integrates and calculates the velocity, temperature, salinity and density fields, which will be used by the trajectory and sedimentation models. The horizontal resolution is 0.1 nautical mile or approximately 185 meters. The model is integrated forward in time with a time step of 6 minutes. The maximum depth is 60 meters and it has 18 vertical levels. The model is forced by a coarser Baltic model through open boundaries to the Baltic Sea and by meteorological and hydrological gridded data. All solid borders use the no slip condition except where there is a river discharge. The model does not include the warm water discharge from the reactor cooling systems. This makes it possible to interpret the development after the shutdown of the power plants, but limits the contingency to validate the output data. The circulation model is described by /Engqvist and Andrejev 1999/ and in detail for the Forsmark model setup, and the Laxemar model setup in /Döös and Engqvist 2007/ and /Engqvist et al. 2006/.

The Forsmark area is located in Öregrundsgrepen, which appears as a funnellike open-ended embayment with the wider end toward the north, (Figure 2-1a). The narrow southern end is also shallower with a threshold of approximately 25 m. There are notable density fluctuations over a yearly cycle mainly due to the collective discharge of all the rivers into the Bothnian Bay. Via the strait of Öregrund (Öregrundsund), a connection is made to the southern basins, forming a buffer zone to the study area. The basins of the buffer zone are connected to the Baltic by one main strait.

The Laxemar area, (Figure 2-1b), is in contrast to the Forsmark area open and with few surrounding islands. This leads to rapid water exchange with the rest of the Baltic Sea. The two grids for the two coastal areas have the same grid sizes but with different amount of grid cells. The Forsmark coastal area was resolved horizontally into 241×241 grid cells and the Laxemar into 174×121 grid cells.



(a) Forsmark



(b) Laxemar

Figure 2-1. *The model bathymetry in meters of the Forsmark and Laxemar coastal regions. The nuclei leakage or discharge positions are marked with black dots from where the trajectory particles are released.*

2.2 The trajectory model

The Lagrangian methodology used in this study is about following a point in space, and studying how the environmental variables around the point develop over time. The opposite way is the Eulerian method, where the developments of the environmental variables in a specified volume are followed.

The Lagrangian trajectories in the present study have been calculated with the trajectory model TRACMASS, which is based on /Döös 1995/ and /Blanke and Raynaud 1997/. It is presented in detail in the Appendix A. TRACMASS makes it possible to calculate Lagrangian trajectories both forwards and backwards between any sections or regions in the ocean. The Lagrangian trajectories correspond to the passive advection of particles by the velocity fields from a GCM. Using fields of temperature, density and velocity from a circulation model as input data, the advective movement of points in the fluid is calculated continuously, as they move along. This method was first applied to the Baltic by /Döös et al. 2004/ and /Jönsson et al. 2004/, where residence times were calculated for the Bay of Gdansk. These studies made use of the trajectory method's capability of keeping a record of all released water particles, which in turn makes it possible to perform statistical analysis of for instance the particles' different ages. It is hence possible to calculate the residence time R of a trajectory particle, by integrating the trajectory forward in time (See Appendix B).

Using the velocity fields from the circulation model described in the previous section, the paths of sediment particles travelling in the water basin are calculated. The trajectory particles are to mimic radio-nuclides exiting though the bottom of the sea floor. In the present study the trajectory particles all originate from the discharge points marked in Figure 2-1. These positions correspond to where radio-nuclides would exit the sea floor due to accidental leakage of radio-nuclides from a deep repository for radioactive waste, /Lindgren et al. 2001/.

There are in total 383 unevenly distributed discharge points in the Forsmark coastal region, with most of them (371) projected over 3 adjacent grid cells in the north of Figure 2-1a and 12 points are located further south in one single grid cell. In the Laxemar area there are in total 1,835 unevenly distributed discharge points. Most of them (1,815) are projected over 8 adjacent grid cells in the southern area of Figure 2-1b. The remaining 20 discharge points are located further north in one single grid cell.

2.3 Sedimentation

The concept of the sedimentation model is that suspended particulate matter is bound to follow the movements of the water. If the motion of the particles in quiescent water is known, and the paths of the water can be calculated, then the movements of the particles will be a combination of these motions.

To the vertical velocity of the water from the GCM data set, a settling velocity for the particle is added. This velocity, w_s, is calculated by Stoke law from particle density ρ_s and diameter d, and water density and viscosity, ρ_w and μ.

$$w_s = \frac{\rho_s - \rho_w}{18\mu} g d^2 \qquad \text{Equation 2-1}$$

In practice, the settling velocity of a particle has a basic relation to its size and shape. Since it is not possible to account for all different shapes a particle can have, the concept of equivalent size is used. That is the size of a quartz sphere having the same settling velocity as a less spherical natural grain /Shepard 1967/.

The particles will travel through the water mass following the motion of the water. The horizontal movements are prescribed solely by the GCM field, and the vertical movements by the vertical movement from the GCM field together with the settling velocity. If a particle reaches the lower wall of the deepest grid box in the water column, i.e. the lower boundary, it will settle. Once settled it will stay at the settling position and can only leave it by resuspension. If no resuspension occurs, the particle will remain at its position until the simulation ends.

2.4 Resuspension

Resuspension of a settled particle will take place if the shear stress at the bottom where the particle is located exceeds a threshold value. When this occurs the particle will be lifted up a short distance above the bottom. There it will catch on to the water flow field again, and continue its motion in the water body.

The shear stress at the bottom is dependent of the turbulent kinetic energy. Since this is not included in the data set from the GCM the velocities in the bottom box is used instead, using the view that the water velocities gives rise to the kinetic energy that leads to the shear stress. A threshold velocity for entrainment is taken from the relationship postulated by /Postma 1967/. It states the relation between the grain diameter in micrometers and the mean velocity 15 cm above the bottom in cm/s for silt and clay. For a water content of 100% the velocity is 10 cm/s for the whole fraction. The relationship is valid for cohesive material of 0.1 mm and smaller.

2.5 The simulation setup

Two simulations were made for both Laxemar and Forsmark; one simulation with clay particles, having a diameter of 1 μm, and one with silt particles with a diameter of 10 μm. The particles have a density of 2,620 kg/m^3, and were released at positions where a diffuse leakage of radionuclides from the ground water to the sea may occur. The release points were taken from a set of points on land and at sea specified by SKB /Lindgren et al. 2001/. No release points on land were included.

The density of the starting points decided the number of trajectories so that a fix set of particle trajectories was released per release point. The Forsmark and Laxemar simulations are comparable in number of particles trajectories per release point, but the Laxemar simulations have a total number of particle trajectories about two and a half times the number in Forsmark. Particle trajectories are released every hour during a year and then the simulation is run for another year. Each particle trajectory is hence followed for one year from its release time. The GCM data sets are one year in total so the sets are looped twice.

The density and temperature of the water is updated every hour from the GCM data set. The dynamic viscosity is taken from table values using the temperature, which is updated every hour. The variations in salinity are ignored when the settling velocity is calculated.

3 Results

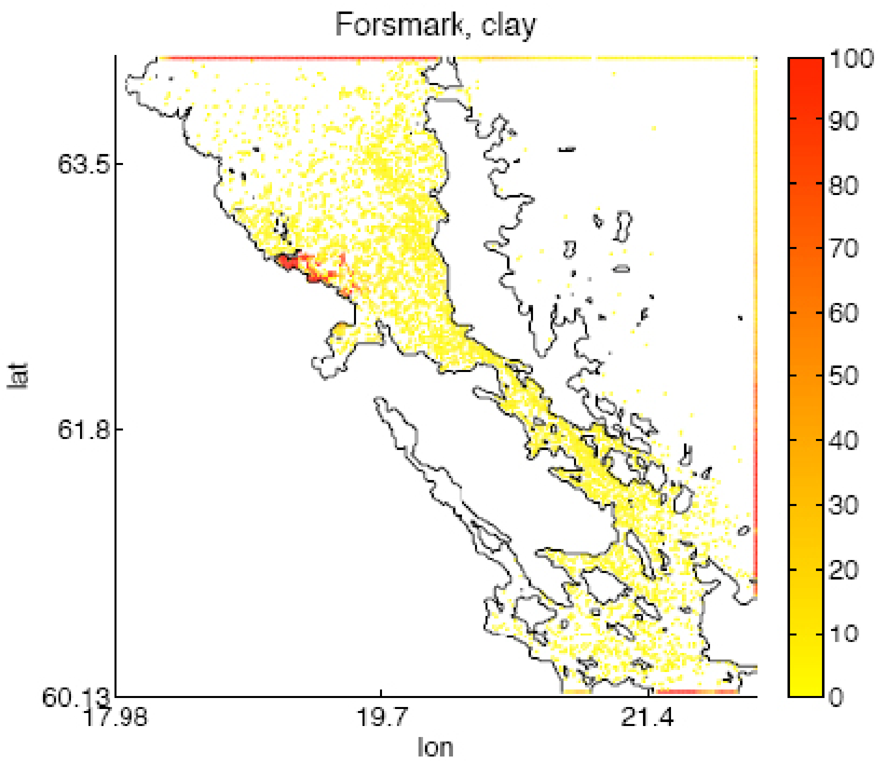
After a two-year simulation all particles have either sedimented or left the domain, except for silt in Laxemar where 0.6% of the particles still are in suspension. Longer simulations shows that the sedimentation and resuspension stops totally after little over two years. The two areas differ profoundly as to how large amount of the particles that have left the domain after the simulation. For the Laxemar area, as much as 90% of the clay particles have left the domain, and almost 70% of the silt particles. In Forsmark, only about 6% of the clay and less than 1% of the silt have left the domain.

In Forsmark, a very large fraction of the particles stays in the absolute vicinity of the release points. As much as 96% of the particles of silt in Forsmark, and 90% of the clay particles are found in the grid cells closest to the release points. The numbers for Laxemar are 30% for silt and about 6% for clay. If this is solely a consequence of higher water velocities and more open coast at the release points at Laxemar or if it is partly a result of a deficiency of the model to handle transport in narrow areas is hard to say. Comparing the absolute numbers should be done with care.

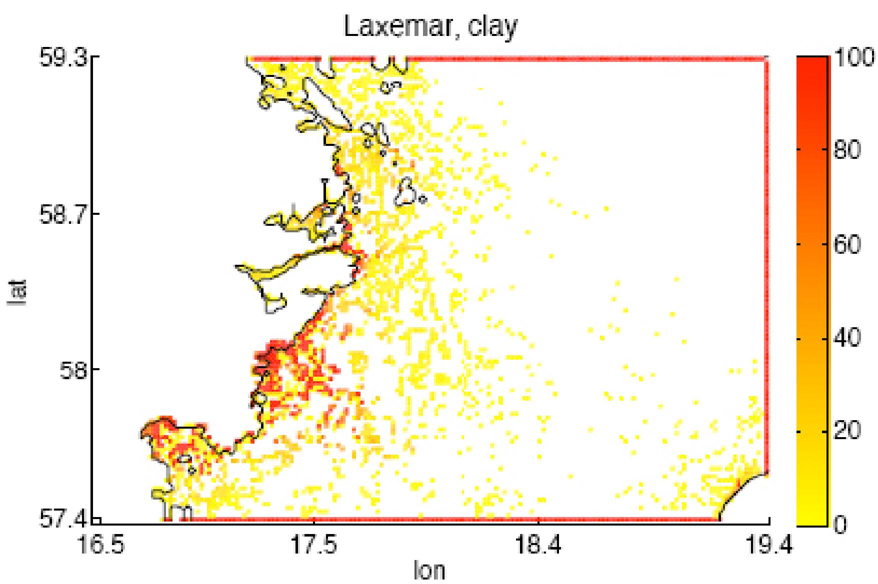
The figures show the positions of the sedimented particles in the two areas, for clay and silt particles respectively. All particles that have left the model domain during the simulation are shown as sedimented on the edge of the domain. This makes it possible to se where the particles left the domain. Both full-area figures, Figures 3-1 and 3-3, and close-ups of the area around the release points, Figures 3-2 and 3-4, are shown. To enable a colour scale to show the sediment pattern the number of particles in the grid cells closest to the release points have been set to a lower value, i.e. 100 for the full-area and 500 for the close-up. This is to make the figures from the two different areas comparable. The actual numbers of particles in these grid cells are several thousands.

In Figure 3-5 the cumulative percentage of particles sedimented as a function of depth is shown. The fact that more than 90% of the particles in the Forsmark runs stays in the grid cells around the release points makes the depths of these few cells dominate the result, but the curves looks almost the same even if these cells are excluded.

The residence times of the particles in the model domains have been calculated (See Appendix B) and are shown in Figure 3-6. It shows the average time evolution of the decay of the number of particles in the model domain, which have been released during the whole year in the discharge areas and followed until they fall to the sea floor or exit the model area. The yearly average has been constructed from all the 8,760 (24×365) clusters of particles, which were released during one year. Figure 3-6 shows that the number of trajectories in the areas decays exponentially in time. The associated e-folding time i.e. when about 63% of the particles have left the basin can be referred to as the residence time /Engqvist et al. 2006/. The residence time is an order of magnitude longer in the Forsmark region than in the Laxemar region. This can simply be explained by the presence of surrounding islands in the Forsmark region in contrast to the Laxemar region which is much more open. There is no strict residence time for the silt particles since less of a percent of them exit the Forsmark region after a year and 66% in the Laxemar region. Most of the clay is however light enough to leave the Laxemar region but not in the Forsmak region where 94% still remains in the area after one year.

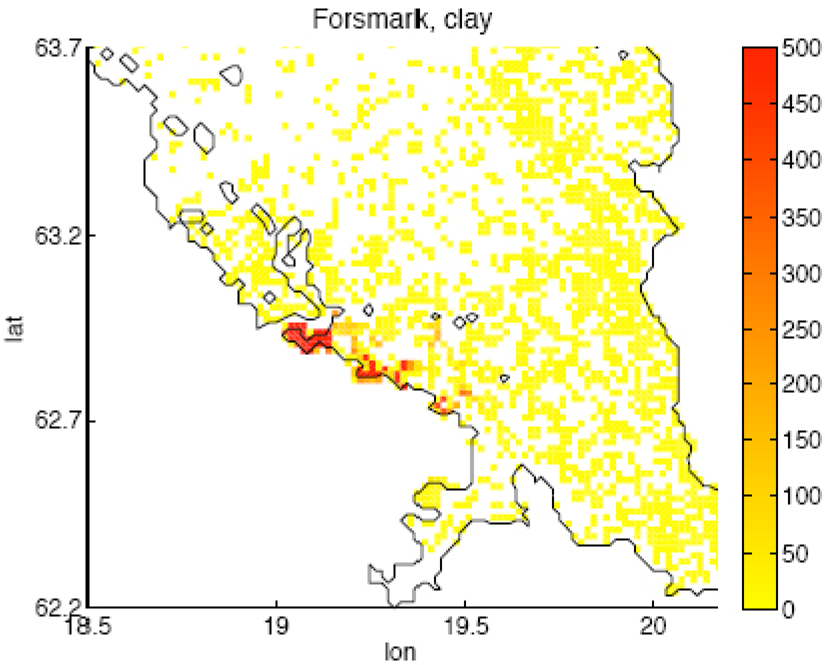


(a) Forsmark

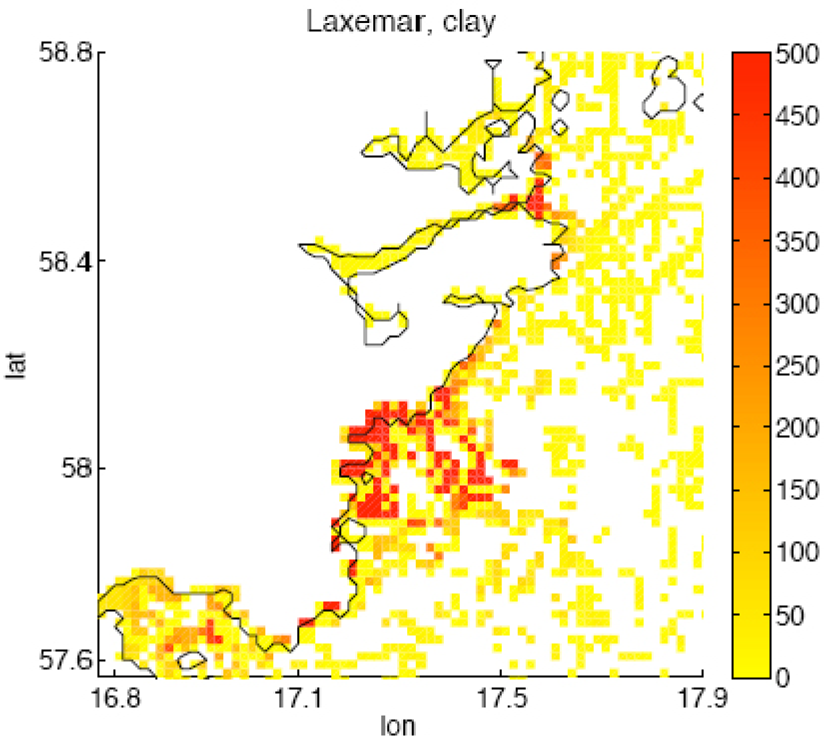


(b) Laxemar

Figure 3-1. *Sedimented particles after one year simulation. The particles that have left the simulation area are shown as sedimented on the edge of the domain.*

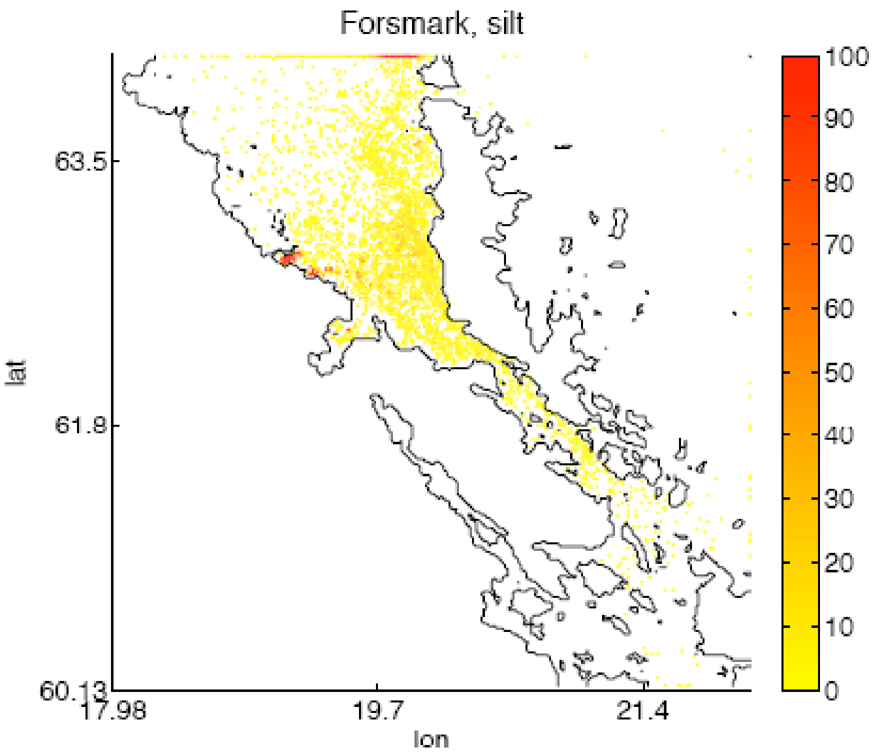


(a) Forsmark

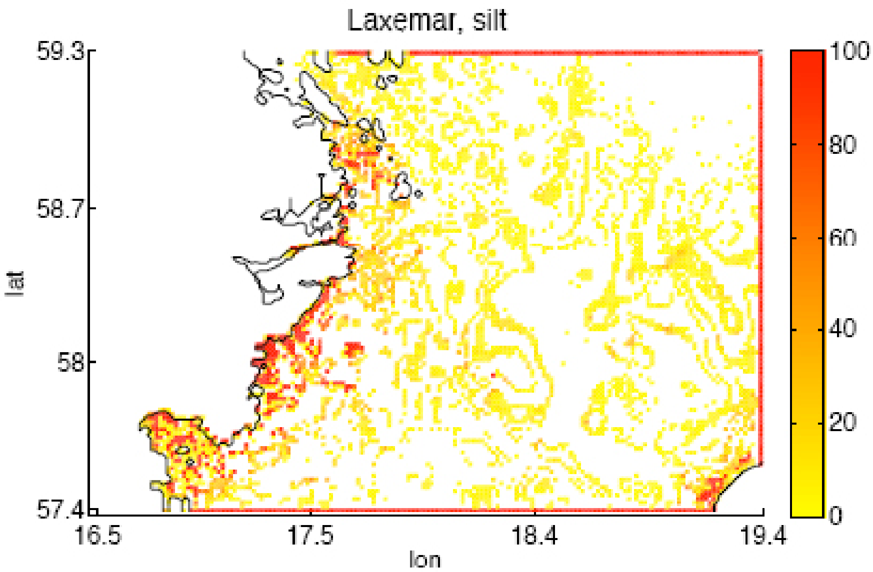


(b) Laxemar

Figure 3-2. *Sedimented particles after one year simulation. Close-up of the area near the release points.*

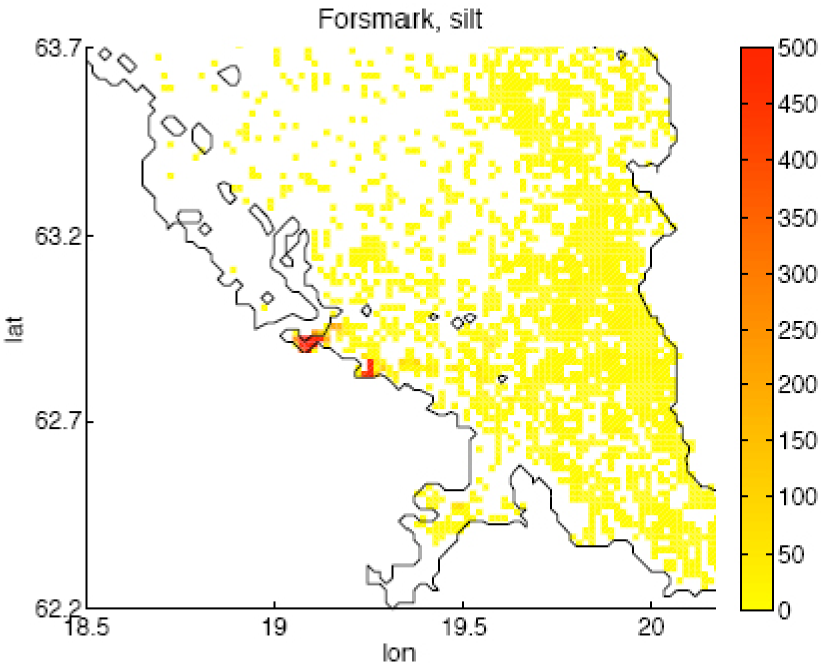


(a) Forsmark

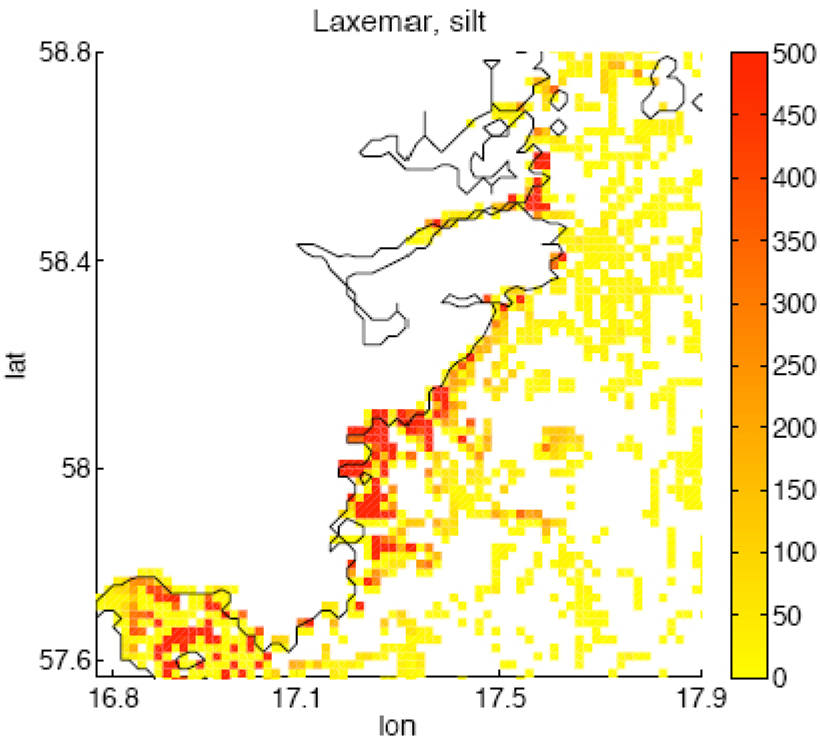


(b) Laxemar

Figure 3-3. *Sedimented particles after one year simulation. The particles that have left the simulation area are shown as sedimented on the edge of the domain.*



(a) Forsmark



(b) Laxemar

Figure 3-4. *Sedimented particles after one year simulation. Close-up of the area near the release points.*

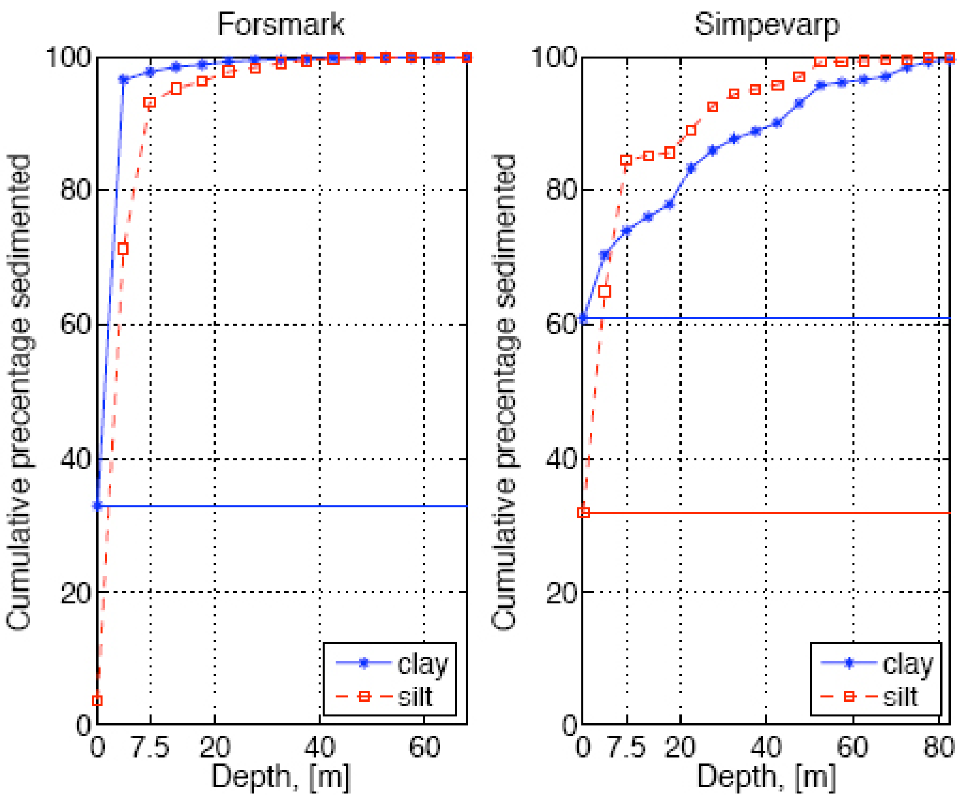


Figure 3-5. *The cumulative percentage of particles sedimented as a function of depth. The blue and red lines indicate the percentage share of particles that have left the simulation area.*

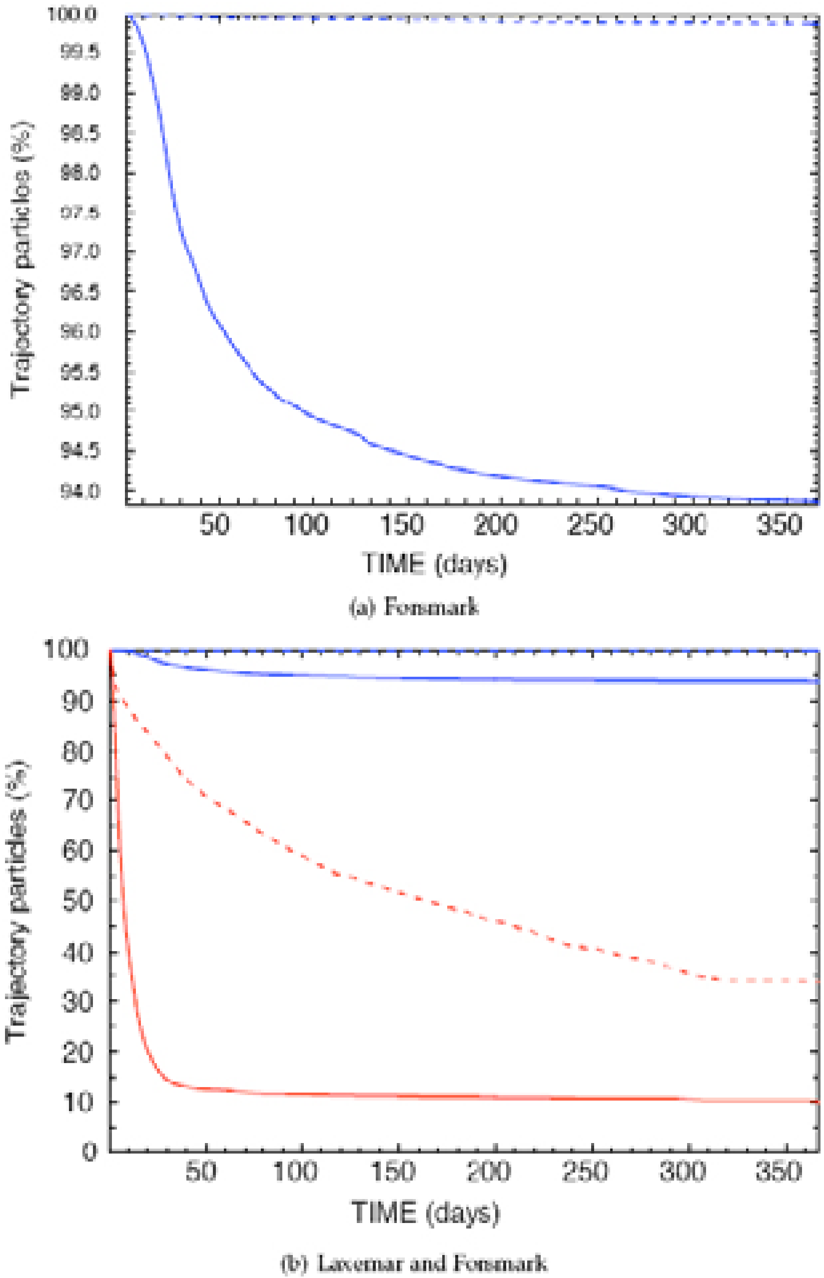


Figure 3-6. *Average time evolution of the decay of the number of particles in the model domain, which have been released during the whole year in the discharge areas and followed until they fall to the sea floor or exit the model area. The yearly average has been constructed from all the 8,760 (24×365) clusters of particles, which were released during one year. Blue lines for Forsmark and red lines for Laxemar. Solid lines for clay particles and dashed lines for silt particles. Top figure a) only for Forsmark and bottom figure b) for both Laxemar and Forsmark.*

4 Discussion and general conclusions

The results show that particles released in the more open coastline of the Laxemar area tend to leave the model domain, while the narrower waters around Forsmark makes the bulk of the particles stay. The very large amount of particles stuck right at the release points in Forsmark may be a result of an inability of the model to handle the particle transport in a good way in shallow areas with low water velocity. Still, it does not seem unreasonable that more particles would stay around Forsmark than Laxemar, due to the differences in geography and bathymetry.

The sediment model was originally developed using the velocity fields form the Rossby Centre regional Ocean climate model (RCO). In this setting the lack of surface waves in the circulation model was accounted for. Shallow waves give rise to an orbital water motion that enhances the shear stress on the bottom, and thereby influence the resuspension. To come to terms with this a calculation of the orbital velocity vas done and this was added to the horizontal velocities in the bottom box. The calculation included values of wave amplitude, wave number and period time. These values were estimated for the Baltic Proper. Since the coastal areas outside of Forsmark and Laxemar have dramatically different oceanographic properties than the Baltic Proper the approximations are not valid. Due to lack of suitable wave parameters for the model areas the calculation has been omitted from the simulations presented in this report. This may have caused less resuspension events in the simulations than if the orbital velocity had been added, and thus the particles might have travelled a shorter distance then they otherwise would have. This limitation in the simulation can be accepted with reference to the principle of precaution.

To model the settling sediment particles the principle of equivalent spheres is used; the size of a sphere that has the same settling velocity as a less spherical natural grain. The use of this should be acceptable for grain such as sand and silt. However, I have found no estimation in the literature as to how good this approximation is when it comes to clay particles, which tend to be very far from spherical. It may be the case that the clay particles in reality settle slower than in the simulations. This would mean that they are transported longer distances while they are sinking than the results show. For some particles this would mean that they might get further in to bays, but the majority of the particles would be transported further out to sea.

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We thank Swedish Nuclear Fuel and Waste Management Co. (SKB) for financing the present work and Anders Engqvist and Oleg Andrejev for helpful discussions and for the Baltic circulation model AS3D.

Appendix A

The trajectory model TRACMASS

The Lagrangian trajectories in the present study have been calculated with the trajectory model TRACMASS, which is based on /Döös 1995/ and /Blanke and Raynaud 1997/. Velocities calculated by the sea circulation model AS3D are known on the sides of the C-grid boxes. From these velocities, volume transports are derived. The volume transport through the eastern wall of the *ijk* grid box is given by:

$$F_{i,j,k} = u_{i,j,k} \Delta y \Delta z_k \qquad \text{Equation A-1}$$

in which *i, j, k* denote the discretised longitude, latitude and depth, respectively; *u* is the zonal velocity; and $\Delta y \Delta z_k$ defines the meridional-vertical area. Meridional transports are defined analogously, while vertical transports simply follow from the non-divergency of the velocities. Inside a grid box, volume transports are obtained by interpolating linearly between the values of the opposite walls. For the zonal direction, for example, using $r = x/\Delta x$, one obtains:

$$F(r) = F_{i-1,j,k} + (r - r_{i-1})(F_{i,j,k} - F_{i-1,j,k}) \qquad \text{Equation A-2}$$

Local transport and position are related by F = dr/ds, where the scaled time variable $s \equiv t/(\Delta x \Delta y \Delta z_k)$, where the denominator is the volume of the particular grid box. The approximation in Equation A-2 can now be written in terms of the following differential equation:

$$\frac{dr}{ds} + \alpha\, r + \beta = 0 \qquad \text{Equation A-3}$$

with $\alpha \equiv F_{i-1,j,k} - F_{i,j,k}$ and $\beta \equiv -F_{i-1,j,k} - \alpha\, r_{i-1}$. Using the initial condition $r(s_0) = r_0$, the zonal displacement of the trajectory inside the considered grid box can be solved analytically and is given by:

$$r(s) = \left(r_0 + \frac{\beta}{\alpha}\right) e^{-\alpha(s-s_0)} - \frac{\beta}{\alpha} \qquad \text{Equation A-4}$$

The time s_1 when the trajectory reaches a zonal wall can be determined explicitly:

$$s_1 = s_0 - \frac{1}{\alpha} log \left[\frac{r_1 + \beta/\alpha}{r_0 + \beta/\alpha}\right] \qquad \text{Equation A-5}$$

where $r_1 = r(s_1)$ is given by either r_{i-1} or r_i. With the use of Equation A-1, the logarithmic factor can be expressed as *log*[F(r_1)/F(r_0)]. For a trajectory reaching the wall r = r_i, for instance, the transport F(r_1) must necessarily be positive, so in order for Equation A-5 to have a solution, the transport F(r_0) must then be positive also. If this is not the case, then the trajectory either reaches the other wall at r_{i-1} or the signs of the transports are such that there is a zero zonal transport somewhere inside the grid box that is reached exponentially slow. For the meridional and vertical directions, similar calculations of s_1 are performed determining the meridional and vertical displacements of the trajectory, respectively, inside the considered grid box. The smallest transit time $s_1 - s_0$ and the corresponding r_1 denote at which wall of the grid box the trajectory will exit and move into the adjacent one. The exact displacements in the other two directions are then computed using the smallest s_1 in the corresponding Equation A-4. The entire procedure is then repeated for as long as is desired. The above considerations can easily be translated into an efficient numerical algorithm. The differential Equation A-3 is strictly only valid for stationary velocity fields. /Vries and Döös 2001/ developed a code for time dependent velocities. It is however possible to use the present code with neglible loss of accuracy by simply changing the velocity fields at regular time intervals, which in our case is every hour, since the Sea circulation model AS3D output data is stored at this frequency.

Appendix B

Residence time definition

It is possible to calculate the residence time R of a trajectory particle, by integrating the trajectory forward in time so that:

$$R_n = t_n^O - t_n^L \qquad \text{Equation B-1}$$

where n is the the considered trajectory, t_n^0 the time when trajectory n flows out through the open boundary and leaves the model domain and t_n^L when it is released from the discharge area. The *AvR* of the trajectories is then obtained by making an average over all the trajectories that are released in the discharge area until they reach the open boundary so that:

$$AvR = \frac{1}{N}\sum_{n=1}^{N}\left(t_n^O - t_n^L\right) \qquad \text{Equation B-2}$$

where N is the total number of trajectories.