

Application of transport model for building contingency maps of oil spills on the North Sea

by

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Chapter 1

Introduction

1.1 General issues

The North Sea is one of the busiest seas on the planet. Around 420000 vessels (excluding fishing vessels) pass this area each year. Many of these vessels carry products that pose a threat to the environment, particularly oil which can cause serious pollution if spilled at sea. On the NCP (Netherlands Continental Plate, Dutch part of the Continental Shelf) an average of 24 incidents occur annually. These incidents, are for example, collisions between ships, ships grounding, fires and lost cargos. Moreover, many pollutants are accidentally spilled from ships during "normal" operations. These spills are probably small, but become significant due to the large number of ships. Every year, there is a certain number of tankers that run aground in stormy weather and sometimes they leak chemicals. At the other hand, the growth of industry in the area is playing an important role with respect to maritime pollution. The Dutch Rijkswaterstaat, part of the Ministry of Transport, Public Works and Water Management, has been doing research in this context for many years. From observations we can see that the Waddenzee, the inner sea in the north of the Netherlands, is an especially vulnerable marine ecosystem. Any action that affects this area requires careful consideration.

The goal of this project is to develop "the map of risk areas" for the Netherland coastal zone, a map defining the most dangerous and vulnerable areas the Netherland sea. This type of map can be extremely important and helpful in predicting dispersion of dangerous contamination released into the sea. To

obtain such a map we carry out an analysis of modelled spill trajectories from various locations and under various sea conditions.

1.2 An overview of the procedure to build the risk map

The goal of this thesis is to build the risk map for part of the North Sea. To do it we first need to generate a certain number of scenarios, where one scenario describe one situation, that can occur in real. This situation contains relevant information about spill and weather (more details are given in chapter 5). Having the set of all scenarios we use the Gnome software package to simulate the oil movement for each scenario (basic information about Gnome are given in chapter 3). As the outcome from the simulation Gnome gives the amount of pollution on the beach, the amount of the pollution still floating and the amount of oil that evaporate. In order to compute the risk we need to quantify the damage associated with a scenario. In this thesis we decide to choose as the damage the amount of oil on the beach, which is given by Gnome. Having the risk we can easily build the risk map (more details can be found in chapter 6, where we introduce the definition of risk and show with the details the way the risk map is obtained.

1.3 Overview of thesis

This thesis includes 8 chapters.

Chapter 1 gives the main information about this thesis, describes the main goal and gives basic information about risk maps.

Chapter 2 starts with a mathematical introduction to stochastic differential equations (SDEs). This chapter describes with details SDEs for the oil spill trajectory model.

Chapter 3 contains the basic information about two software packages: Simpar and Gnome and Chapter 4 presents a comparison between the two.

In chapter 5 we describe with details all collected data that we need to build a scenario. We discuss in this chapter the method that we use to generate the scenarios.

In Chapter 6 we can see how to build the risk map for one small example. In this chapter we can find also the final result, that is the risk map for all scenarios.

Next chapter gives conclusions and the last chapter gives some ideas and suggestions about the continuation of this project in the future and how it can be made more realistic.

At the end of this thesis, in the appendix, we can find all Matlab codes that were used to obtain the results.

Chapter 2

General mathematical descriptions for the oil spill trajectory model

Let consider a shallow water area with a depth $H(x, y, t)$ and the velocities $U(x, y, t)$ and $V(x, y, t)$ in x - and y - directions respectively. It is assumed that $H(x, y, t)$, $U(x, y, t)$ and $V(x, y, t)$ satisfy the following equation:

$$\frac{\partial H}{\partial t} + \frac{\partial UH}{\partial x} + \frac{\partial VH}{\partial y} = 0 \quad (2.1)$$

To model dispersion in a shallow water area, we use a random walk model, that is consistent with the depth integrated advection-diffusion equation.

When particles are moving in the water, the molecules of the water will collide with the particles causing random displacements of the particles. The migration and the fluctuation in the displacement of the particles are described with the so-called Langevin equation, written as a Markovian stochastic differential equation. Let assume that the position (X_{t_0}, Y_{t_0}) represents the position of the particle at time t_0 , similar (X_t, Y_t) represents the position of the particle at time t , then there holds:

$$\frac{d}{dt}(X_t) = f_1(t, X_t, Y_t) + g_{11}(t, X_t, Y_t)\Gamma_{1,t} + g_{12}(t, X_t, Y_t)\Gamma_{1,t} \quad (2.2)$$

$$\frac{d}{dt}(Y_t) = f_2(t, X_t, Y_t) + g_{21}(t, X_t, Y_t)\Gamma_{2,t} + g_{22}(t, X_t, Y_t)\Gamma_{1,t} \quad (2.3)$$

where f_1 and f_2 represent the advection process and are the components of the so-called drift vector, $(g_{i,j})$ is the noise tensor and constitutes the elements of the diffusion matrix ($i,j = 1,2$), and Γ_j represent the stochastic Langevin force (called also the Gaussian white noise process with the mean equal to zero and the Gaussian distribution with δ correlation).

The Markov property implies that if the present state is known, the future will be independent of the past. Due to this fact, this process is completely determined by the initial condition given at $t = t_0$.

We can use the Wiener increment $dW_{j,t} = \Gamma_{j,t}$ to express the stochastic influence of the process. Then:

$$W_{1,t} = \int_0^t \Gamma_{1,s} ds \quad (2.4)$$

$$W_{2,t} = \int_0^t \Gamma_{2,s} ds \quad (2.5)$$

where $W_{1,t}$ and $W_{2,t}$ are the independent components of the Wiener process with $E(dW_t dW_t^T) = Idt$.

To obtain the incremental Brownian motion process we differentiate equations (2.4), thus

$$dW_{1,t} = \Gamma_{1,t} \quad (2.6)$$

$$dW_{2,t} = \Gamma_{2,t} \quad (2.7)$$

The drift vector can be represented as follows:

$$f_1 = u + \left(\frac{\partial D}{\partial x} + \frac{D \partial H}{H \partial x} \right) \quad (2.8)$$

$$f_2 = v + \left(\frac{\partial D}{\partial y} + \frac{D \partial H}{H \partial y} \right) \quad (2.9)$$

By substituting equations (2.6) into equations (2.2) and (2.3) we obtain:

$$dX_t = f_1(t, X_t, Y_t) + g_{11}(t, X_t, Y_t)dW_{1,t} + g_{12}(t, X_t, Y_t)dW_{2,t} \quad (2.10)$$

$$dY_t = f_2(t, X_t, Y_t) + g_{21}(t, X_t, Y_t)dW_{1,t} + g_{22}(t, X_t, Y_t)dW_{2,t} \quad (2.11)$$

In order to find out how the probability density of the process (2.10-2.11) behaves in space and time we introduce the so-called Fokker-Planck equation:

$$\begin{aligned} \frac{\partial p}{\partial t} = & -\frac{\partial}{\partial x}(f_1 p) - \frac{\partial}{\partial y}(f_2 p) + \frac{\partial^2}{\partial x^2}(B_{11} p) \\ & + \frac{\partial^2}{\partial x \partial y}(B_{12} p) + \frac{\partial^2}{\partial y \partial x}(B_{21} p) + \frac{\partial^2}{\partial y^2}(B_{22} p) \end{aligned} \quad (2.12)$$

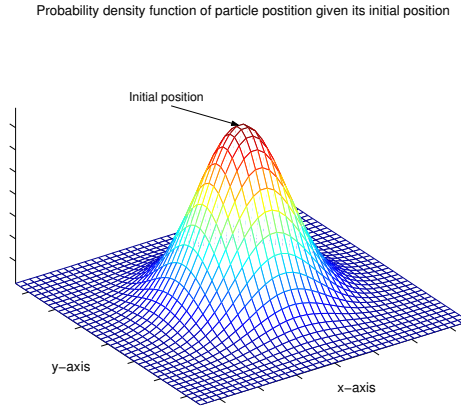


Figure 2.1: The probability density function

with initial condition:

$$p(x, y, t_0) = \delta(x - x_0)\delta(y - y_0) \quad (2.13)$$

where:

$$B_{11} = \frac{1}{2}g_{11}^2 + \frac{1}{2}g_{12}^2 \quad (2.14)$$

$$B_{12} = \frac{1}{2}g_{11}g_{12} + \frac{1}{2}g_{12}g_{22} \quad (2.15)$$

$$B_{21} = \frac{1}{2}g_{21}g_{11} + \frac{1}{2}g_{22}g_{12} \quad (2.16)$$

$$B_{22} = \frac{1}{2}g_{21}^2 + \frac{1}{2}g_{22}^2 \quad (2.17)$$

To understand better the idea of probability function see figure above.

This figure shows the probability function of the position of given particle in time and space and given some initial condition (see equation (2.13)). We assume here that the drift terms in equation (2.12) are zero. In other words we consider only dispersion.

In general we are also interested in the drift terms, so in the future analysis we use the equation (2.12). Using the fact that:

$$B_{ij} = D_{ij} \text{ for } i, j = 1, 2$$

and that D represents the diffusion matrix coefficient as:

$$D = \begin{bmatrix} D_{11} & 0 \\ 0 & D_{22} \end{bmatrix}$$

We also notice that, the off-diagonal elements of the diffusion matrix are set to zero, while the diagonal elements equal $D_{11} = D_{22} = D_H$

Hence for this case

$$g = \begin{bmatrix} \sqrt{2D_H} & 0 \\ 0 & \sqrt{2D_H} \end{bmatrix}$$

So finally we obtain following equations:

$$dX_t = \left[u + \left(\frac{\partial D}{\partial x} + \frac{D \partial H}{H \partial x} \right) \right] dt + \sqrt{2D} dW_{1,t} \quad (2.18)$$

$$dY_t = \left[v + \left(\frac{\partial D}{\partial y} + \frac{D \partial H}{H \partial y} \right) \right] dt + \sqrt{2D} dW_{2,t} \quad (2.19)$$

To show that the model (2.18)-(2.19) and is indeed consistent with the advection-diffusion equation we note that the stochastic process (X_t, Y_t) is Markov and that the probability function $p(x, y, t)$ for $t \geq t_0$ is determined by the so called Fokker-Planck equation:

$$\begin{aligned} \frac{\partial p}{\partial t} &= -\frac{\partial}{\partial x} \left[\left(u + \left(\frac{\partial D}{\partial x} + \frac{D \partial H}{H \partial x} \right) \right) p \right] - \frac{\partial}{\partial y} \left[\left(v + \left(\frac{\partial D}{\partial y} + \frac{D \partial H}{H \partial y} \right) \right) p \right] \\ &+ \frac{\partial^2}{2\partial x^2} [2Dp] + \frac{\partial^2}{2\partial y^2} [2Dp] \end{aligned} \quad (2.20)$$

with initial condition:

$$p(x, y, t_0) = \delta(x - x_0) \delta(y - y_0) \quad (2.21)$$

The particle concentration $C(x, y, t)$ is related to this probability function through:

$$C(x, y, t) = \frac{p(x, y, t)}{H(x, y, t)} \quad (2.22)$$

Now by substituting equation(2.22) into the Fokker-Planck (equation(2.20)) we obtain the following advection-diffusion equation

$$\frac{\partial(HC)}{\partial t} = -\frac{\partial(HuC)}{\partial x} - \frac{\partial(HvC)}{\partial y} + \frac{\partial}{\partial x} \left(DH \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(DH \frac{\partial C}{\partial y} \right) \quad (2.23)$$

The initial condition for the concentration can be easily obtained by substituting equation (2.21) into equation (2.22).

In this way, we show that the model (2.18)-(2.19) is consistent with the advection-diffusion equation (2.23). Now we can simulate the stochastic differential equations (2.18) and (2.19) for many different particles.

Chapter 3

Simpar and Gnome

In this chapter we give some basic information about SIMPAR and GNOME. We describe our feelings about the two and we present the list of the advantages and disadvantages of both.

3.1 SIMPAR - basic information

SIMPAR simulates the transport of floating particles or particles that behave like dissolved substances. It is a program that calculates the movement of particles in two dimensions due to advection, diffusion and wind and is based on the random walk model. Matter transport of different compositions may be simulated with SIMPAR. The relevant input data are given by the WAQUA water movement model in a SDS-file. The diffusion is represented by a stochastic model in which the particles make random jumps in the direction either parallel or perpendicular to the water flow. The size of the jump is determined randomly. The displacement of a particle by drift is determined by a time integration of the WAQUA given flow velocity and the gradients of the bottom topography. The random displacement is based on a so-called Wiener process, in which the particle undergoes a longitudinal (in the direction of flow) as well as a transversal deviation. To this end a random number is drawn for each direction from a probability distribution. Now based on results given by WAQUA module, we can run the simulations in SIMPAR. Figure(3.1) gives an illustration of the basic idea of the model. On this figure position (X_{t_0}, Y_{t_0}) represents the position of the particle at time t_0 , similar (X_t, Y_t) represents the

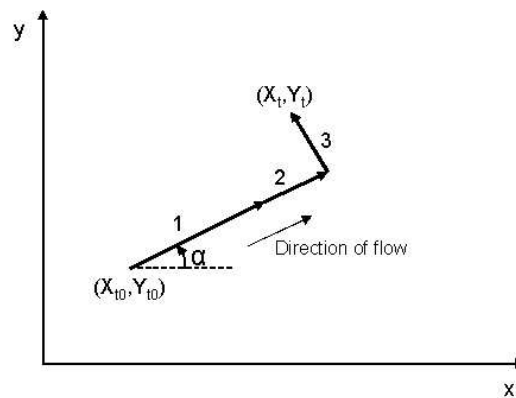


Figure 3.1: Movement of the particle by advection and diffusion

position of the particle at time t . The number 1 to 3 represent respectively advection part, diffusion part parallel to the flow direction and diffusion part normal to the flow direction.

3.2 GNOME - basic information

GNOME is a publicly available oil spill trajectory model that simulates oil movement due to winds, currents, tides, and spreading. GNOME was developed by the Hazardous Materials Response Division (HAZMAT) of the National Oceanic and Atmospheric Administration Office of Response and Restoration (NOAA OR&R). HAZMAT uses GNOME during spill events to calculate the spill trajectory and the associated uncertainty in that trajectory. In more details, GNOME can be used to:

- Predict how winds, currents, and other processes might move and spread oil on the water;
- Study how predicted oil trajectories are affected by inexactness (uncertainty) in current and wind observations and forecasts
- Predict the chemical and physical changes of the oil during the time that it remains on the water surface.

After each simulation GNOME creates and displays an oil spill "movie" showing the predicted trajectory of the spilled oil of the simulated scenario. This

trajectory shows the movement of the particles in the water, under the specified condition regarding wind speed and direction, location of polluted areas and the amount of oil. From the total amount of the spilled oil Gnome computes the amount of the pollution that will be on the beach, that will be still in the water and that will evaporate.

Gnome can make use of external files containing information on tides and currents, etc.. If added, then Gnome uses this information to make the trajectory prediction of the spill in the specified region. If such files are not included, then Gnome still performs the computations, however, it is not known to us what Gnome does with the hydrodynamical part. If available, we have used external files presenting the flow data, i.e. in chapter 4. In other cases we have chosen to use the internal Gnome feature, i.e. in chapter 6. If Gnome is used in the above defined manner (computing a single trajectory under fixed conditions), then this is referred to as the best guess trajectory. In a second option, called the minimum regret solution, Gnome can account for uncertainty. Thanks to this feature, GNOME can compensate for typical errors in the wind and current input data. For example, the weather forecast may be inaccurate in the timing of a frontal passage, in the speed or direction of the winds, or in the strength of the currents. By taking these uncertainties into account, GNOME can predict many possible trajectories for the spill. The figures below (Figure 3.2) show the differences between best guess and minimum regret trajectory.



Figure 3.2: Position of particles after one day (on the left without uncertainty and on the right with uncertainty).

We can see that the trajectories are somewhat different. To make the best guess, Gnome assumes that the wind continue to blow steadily at the speed and from the direction that was entered into Gnome. When making a best guess, Gnome accounts as well for the turbulence that is inherent in natural processes, such as winds and currents, but not for errors in wind forecast or current patterns. To predict the minimum regret trajectory, Gnome accounts for uncertainty in the wind and current information that was entered by the user. Using uncertainty in the simulation guarantees that the chance that the spilled oil will remain within the area covered by the plots is of the order of 90 percent. It is impossible to assign a more precise probability, because little is yet known about uncertainties in wind and current forecast. Predicting a minimum regret trajectory allows to consider spill outcomes that are less probable than the best guess, but are potentially either more harmful or more costly. However for the further analysis we only need the amount of oil on the beach and this amount does not change regardless of the type of simulation (with or without uncertainty), therefore all simulations are made without uncertainty, it makes the simulation time shorten.

In the next section the advantages and disadvantages of SIMPAR and GNOME, with respect to the direct usage, are discussed.

3.3 Functional advantages and disadvantages of SIMPAR and GNOME

3.3.1 SIMPAR

Advantages

1. The map of Dutch Coast is already incorporated into the software,
2. Large number of parameters that can be set. We can specify for example:
 - the type of model that is used for the transport of particles (floating or dissolved);
 - the type of particle movement (only advection or advection and diffusion);

- the number of particles that are tracked, with their starting position, starting and ending time of writing;
 - the weathering conditions such as wind speed and direction;
 - the time step that is used for Simpar simulations
 - the first and the last writing time of particle positions relative to the start of simulation;
 - the time interval of writing;
 - the starting and ending date of writing
 - the influence of wind in conjunction with floating constituents (the wind factor is a constant (in terms of a percentage) that represents an additional displacement of floating constituents caused by wind), etc.
3. The simulation in SIMPAR can be based on momentaneous sources as well as continuous sources. In momentaneous sources, particles are released at the same time and in continuous sources in a continuous way during a certain period,
 4. In each simulation SIMPAR uses the hydrodynamics data that are computed by the users,
 5. SIMPAR gives the opportunity to track only individual particles
 6. We can make one simulation for various locations of pollution,
 7. We can make one simulation for many polluted areas.

Disadvantages

1. There is no graphical interface
2. This software package is quite user unfriendly. It is in fact part of a group of packages working under the SIMONA environment,
3. For people that use only Windows the disadvantage is that Simpar works under Unix systems,

4. Particles reaching the boundaries are considered as follows. If during the random step the particle would cross the boundary, the particle is put back to its old position and a new random step is made. This procedure is repeated until the particle stays within the simulation area. Because of this restriction there is no possibility to see how many particles are on the beach after simulation,
5. The results give us only the trajectory, there is no information about amount of pollution on the beach or in the water,
6. The results of the Simpar simulation are stored in the so called SDS-file, this file is a structured ASCII file, so to see these results, for example in Matlab, we have to convert them first and unfortunately there is no good solution to do it easily.

3.3.2 GNOME

Advantages

1. Gnome shows the movie with the best trajectory of oil spill
2. Gnome allows to use the uncertainty during the simulation
3. Gnome is user friendly and has a nice and simple graphical interface
4. Gnome allows to make one simulation including multiple locations in one simulation, the only condition for that is that the weather conditions have to be the same for each location.
5. After each simulation Gnome displays: the amount of pollution
 - released
 - floating
 - on the beach
 - evaporated
 - dispersed

for each location separate and for total ensemble of locations.

6. Gnome has an option that allows to save the result as a movie file
7. Because Location Files contain only climatological information, rather than information about the specific conditions at a particular date and time, they are not designed to accurately model real spills. To solve this problem Gnome gives the opportunity to use the special kind of mode(diagnostic mode)
8. User can also enter more exact, real-time current and tide information, and can track the movement of the oil to fine-tune their trajectory predictions.
9. For one simulation it is possible to get diverse outputs such as:
 - Gnomes best guess trajectory estimate of the oil spilled.
 - Gnomes larger minimum regret trajectory estimate for the same spill.

The oil will most likely follow the smaller best guess trajectory (the first situation). There is a roughly 0.9 probability that the spilled oil will not extend beyond the minimum regret trajectory (the larger area covered by the second situation).
10. Predicting a minimum regret trajectory allows user to consider spill outcomes that are less probable than the best guess outcome, but that are potentially either more harmful or more costly.

Disadvantages

1. In trajectory modelling, even the best-available information on winds and currents can often contain errors, because winds and currents can not accurately predictable.
2. There is no mathematical description available and the manual for Gnome is not sufficiently detailed,
3. There is a restriction about the size of spill, it can not be bigger than $76000m^3$. This is a very relevant problem, because our last category of the volume data contains information (volume = 178455) that we can

not use in Gnome. This forces us to eliminate at least for now the case when the size of pollution is equal to $76000m^3$. And this case although not so probably but for sure most dangerous could not be considered in the rest of this thesis,

4. GNOME can not compute by itself the hydrodynamical data
5. GNOME does not offer the possibility to run more than one simulation in the same time.

Next chapter shows how the simulations look like in both softwares SIMPAR and GNOME, what are the differences between them and what we can see from the results that are given after simulations

Chapter 4

Comparison between Simpar and Gnome

This chapter gives us the differences between SIMPAR and GNOME. We also have written here our feelings about those two softwares. We tried to show how the simulations look in SIMPAR and how in GNOME.

4.1 Basic assumptions

To make comparison of SIMPAR and GNOME we made simulations with both softwares under the same assumptions.

We assume:

- Simulation time is equal 4 days;
- Size of pollution for SIMPAR is equal 1000 particles and for GNOME 1000 barrels;
- Time step is equal 0.5 hour
- Starting positions is at 53 25 N and 5 00 E in GNOME (which is 129 and 603 km in SIMPAR)
- Type of oil used in Gnome is medium crude;
- Two types of weather conditions:

1. Wind with speed equal 7 m/s from north-west (315 degrees)
2. Wind with speed equal 7 m/s from south-west (225 degrees)

4.2 Results

Since the map of the coast is large and we consider one polluted area, we make for each figure the enlargement. However to show the initial position we use also the original size of figure. On the following figures below we can see the starting position in SIMPAR (Figure4.2) and in GNOME (Figure4.1).

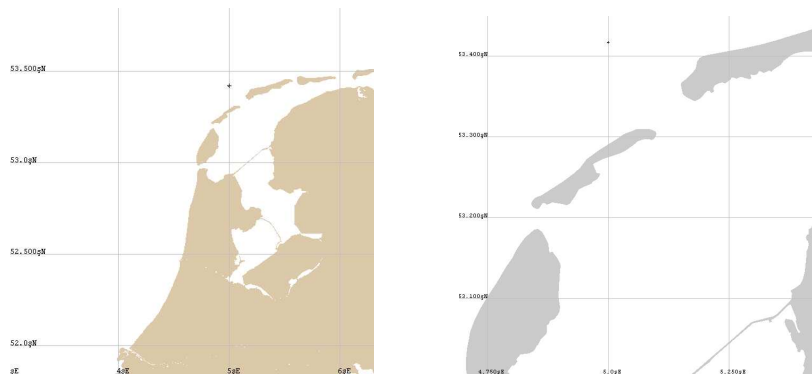


Figure 4.1: First position of pollution in GNOME

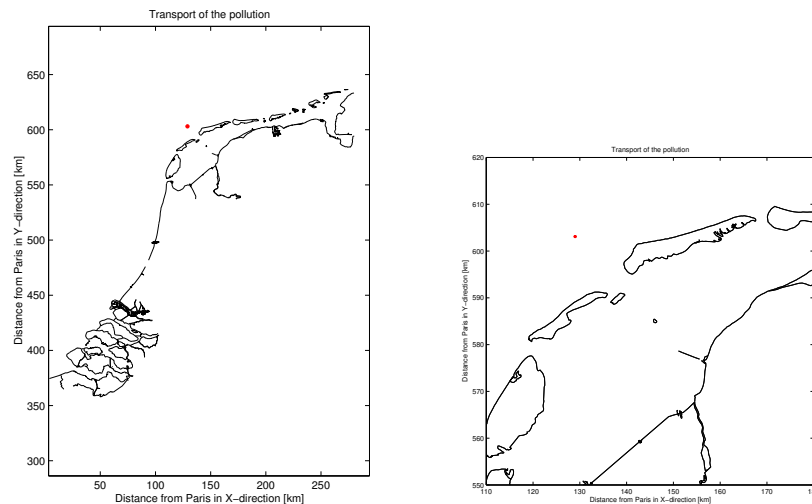


Figure 4.2: First position of pollution in SIMPAR

We made the simulation for 4 days so the next figures show us the position of the pollution after each day. In these figures the left subfigure always presents the Gnome results (best guess trajectory) and the right subfigure the Simpar result. Because of the fact that we took two assumptions about wind direction we obtained two sets of results. Let analyze first the case of south-west wind.

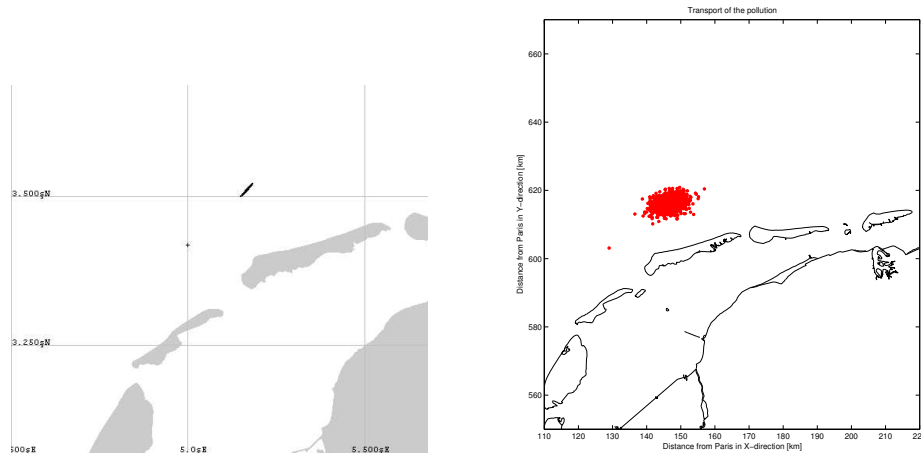


Figure 4.3: Position of pollution after one day simulation.

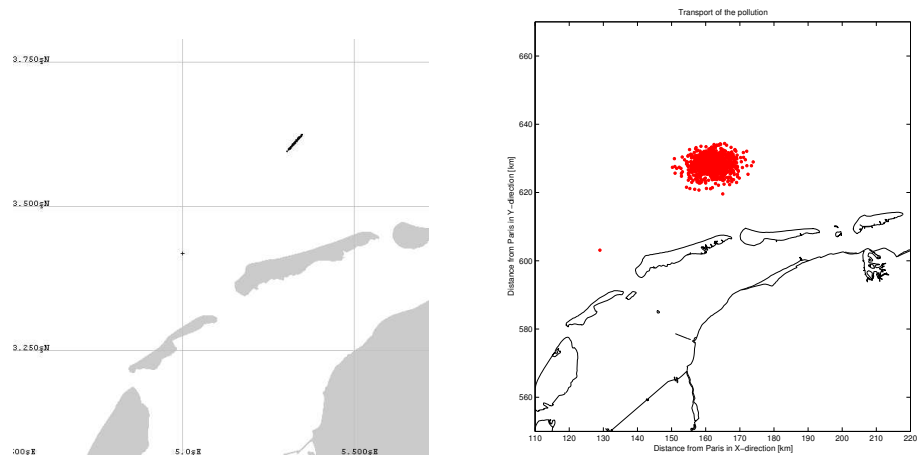


Figure 4.4: Position of pollution after two days simulation.

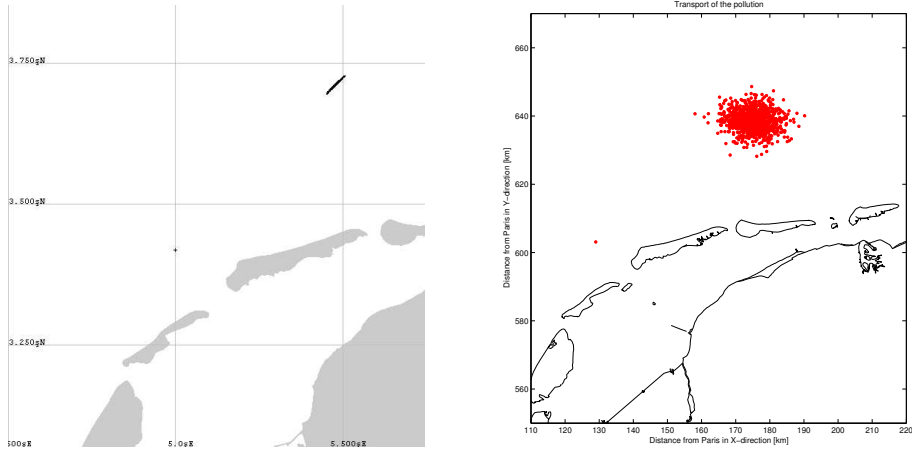


Figure 4.5: Position of pollution after three days simulation.

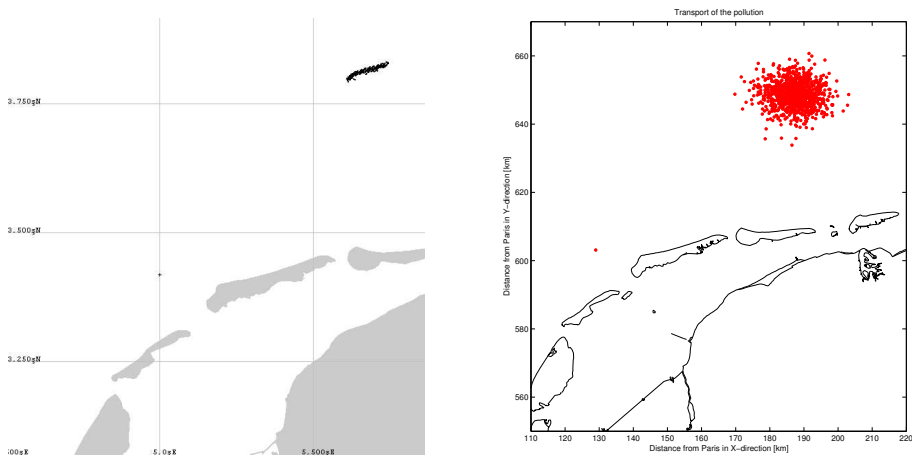


Figure 4.6: Position of pollution after four days simulation.

On the next figures we can see the results for the case of north-west wind.

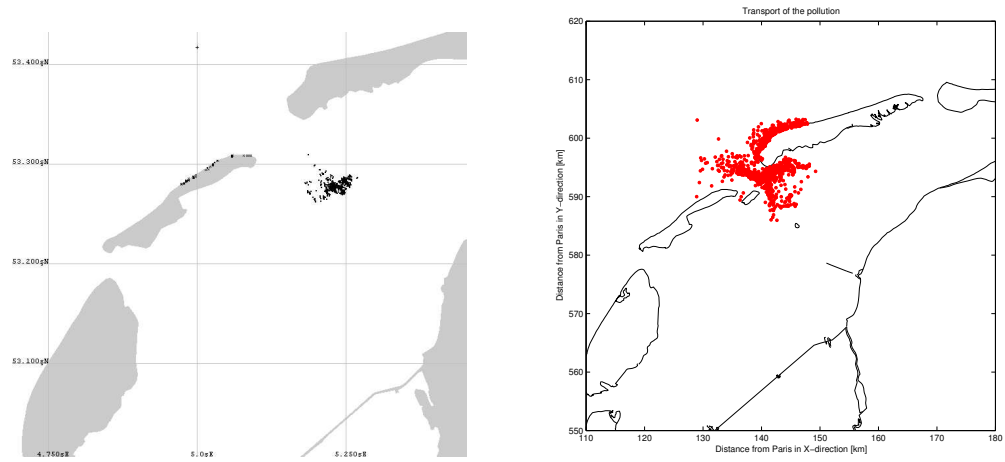


Figure 4.7: Position of pollution after one day simulation.

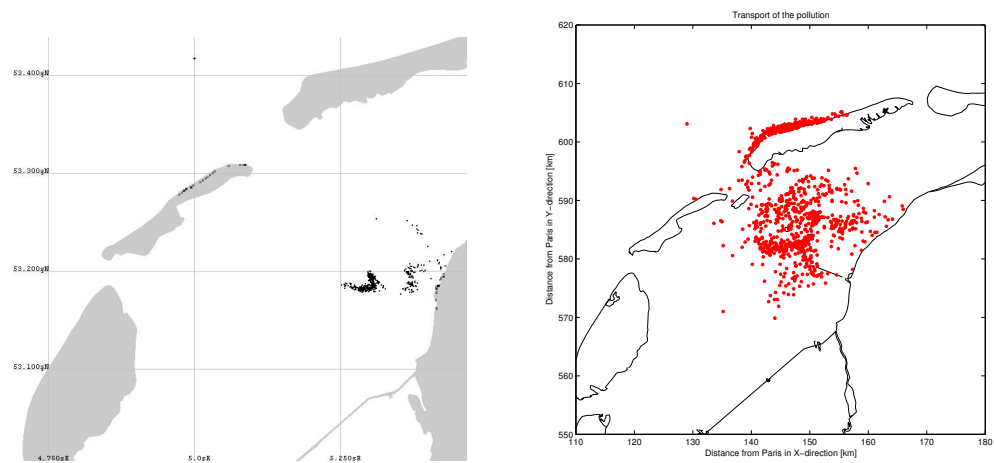


Figure 4.8: Position of pollution after two days simulation.

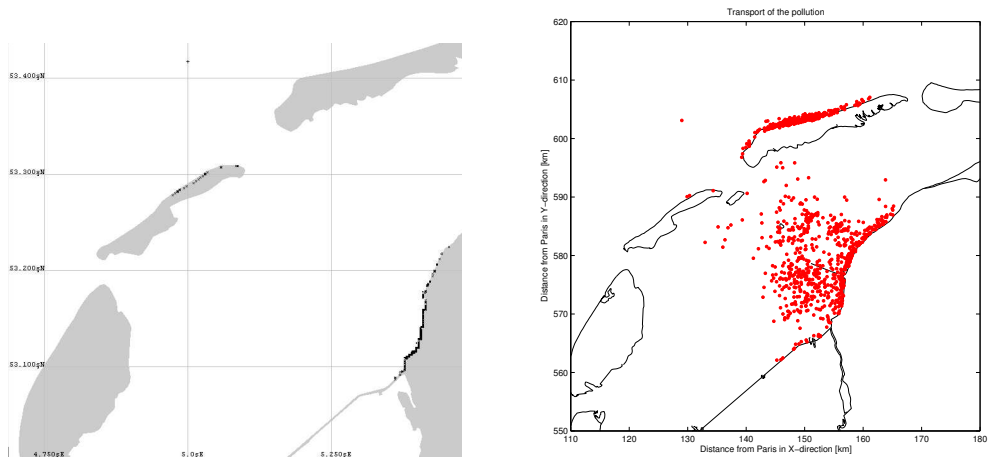


Figure 4.9: Position of pollution after three days simulation.

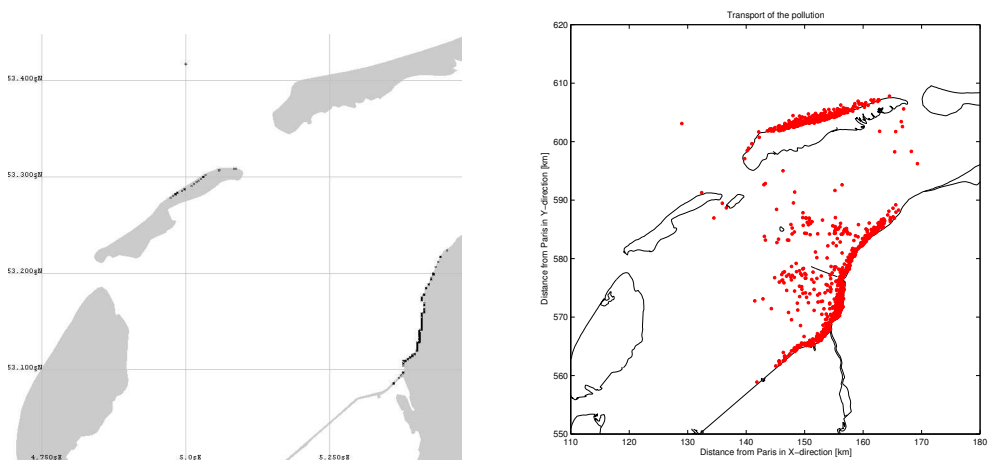


Figure 4.10: Position of pollution after four days simulation with Gnome

We can conclude that both softwares calculate and show the trajectory in a similar way. Distinct from SIMPAR, GNOME gives besides the trajectory, the exact amount of the oil still in the water, on the beach and evaporated. Looking at the trajectories, we can see also some differences between the size of polluted regions in SIMPAR and GNOME. This is due to the fact that in SIMPAR the unit of volume of spill is equal to the number of particles and in GNOME is equal to the number of barrels. We could not find the relation between the number of particles and barrels so we assumed that one particle in SIMPAR is equal one barrel in GNOME. There is also the difference between axes, the unit for Simpar is kilometer and at output coordinates are given in kilometers with respect to Paris. In Gnome the coordinates of pollution are given in degrees with respect to the North and East direction. Also, as we can see the enlargements are not the same for both software packages. Due the fact that the figures with Simpar results are made with Matlab, we can have exactly the enlargement that we need. In Gnome the only way to have the enlargement is by using one of the tools and simply by clicking on the original figure. In the case of north-west wind we can see also some differences between the layout of the polluted areas at different dates. These differences are probably due to way the hydrodynamic data is computed for both software packages. For SIMPAR, the data is computed separately using the package WAQUA, whereas GNOME uses the so called "current data" which contain information about tides, shorelines, etc..

4.3 Conclusion

From the figures in previous section we can see that the trajectories in both cases (Gnome and Simpar) look very similar. There are some differences, which we discussed also in the previous section, however when we look more general we can say that the results (trajectories) given by Gnome and Simpar are similar. However, as we mentioned in the chapter 3, we are interested in the amount of oil on the beach, this amount we need because to build the risk map. Due this fact we choose to make all simulation in Gnome.

In the next chapter we discuss, with details all data that we collected and needed to simulate one scenario. We demonstrate how we can find the distri-

butions for each type of data and how we can generate the samples from the distributions.

Chapter 5

Collected data

In this chapter, we analyze the data necessary to obtain the set of scenarios. In this thesis we speak of a scenario to refer to a situation with some fixed physical conditions, which are described with details in the next section. We assume at this moment that 1000 scenarios are enough for getting good results and that each scenario includes information about the wind speed and direction, the size of pollution and the location of spill. Therefore we need to carefully analyze the data carefully in order to find the distribution for each type and then generate 1000 scenarios. The data contain the relevant information about each variable with the probability.

5.1 Data analysis

To get 1000 scenarios we needed 1000 set of locations, wind conditions (speeds and directions) and volume variables and therefore we assign for each data some distribution. In the next part of this chapter, we will explain also how to generate samples from a distribution. A scenario is one possible situation with physical conditions. In our case these physical conditions are described by four parameters: wind speed and direction, amount of spill and location. In general wind speed and wind direction can be correlated. For the ease of analysis we have omitted taking this into account, assuming the correlation to be of minor importance. Let us consider the set of all scenarios

$$S = (W_s, i_{W_d}, i_V, i_L)$$

where: W_s represents wind speed and is Weibull distributed (see section 5.1.1), i_{W_d} , i_V and i_L denote indices corresponding to the wind direction (see section 5.1.2), amount of the spill and the location respectively (see section 5.1.3). We use two sampling methods to generate 1000 scenarios. First, in case of the wind speed, we use the Weibull distributed random numbers generator by inverting the cumulative distribution function (more details can be found in section 5.1.1). In the remaining cases, since we are generating samples from the discrete distribution given in a form of the probability table, we developed our own algorithm. Suppose we have a vector A of 36 directions, each direction is given with corresponding probability of occurrence a_i , $i = 1, 2, \dots, 36$. We assume that the sum of all probabilities is equal to one. We start with constructing a vector B of length 36, with elements b_i given by following formula:

$$b_i = \sum_{j=1}^i a_j, \text{ for } i = 1, 2, \dots, 36.$$

Then we generate a uniformly distributed random number n on the interval $[0, 1]$. By the definition of vector B, there is an index i such that $b_i \leq n \leq b_{i+1}$. We take i as index of generated wind direction given in vector A. The same approach we use in case of generating amount of spill and locations.

The next sections will give descriptions of the data, that we use in further analysis.

5.1.1 Wind speed data

Table 5.1 below includes the data that we used in our analysis.

Table 5.1: Wind speed data.

Wind speed (in unit m/s)	Probability
0 – 4	0,33
5 – 9	0,5
10 – 14	0,15
> 15	0,02

This table contains information about wind speed with the corresponding probability (measured 20 km on sea near IJmuiden). We have analyzed these data by using the two-parameter Weibull distribution, which adequately fit the data. Next we remind the basic definition of Weibull distribution.

The Weibull distribution

The Weibull probability density function (pdf) of a random variable V , with parameters A and C , is expressed mathematically as

$$f(V; A, C) = \frac{C}{A} \left(\frac{V}{A}\right)^{C-1} \exp\left[-\left(\frac{V}{A}\right)^C\right] \quad (5.1)$$

with

$$V \geq 0, A > 0, C > 0.$$

In this case V is a wind speed expressed in $\frac{m}{s}$, A is a scaling parameter also in $\frac{m}{s}$ and C is a dimensionless shape parameter.

We can see that for $C < 1$ the function decreases monotonically and when $C = 1$, f is an exponential distribution with mean value A .

The cumulative distribution function (cdf) is obtained by integrating (5.1):

$$F(V; A, C) = 1 - \exp\left[-\left(\frac{V}{A}\right)^C\right] \quad (5.2)$$

Other statistical quantities can be given in terms of the parameters, i.e.,

the mean value:

$$\bar{V} = A\Gamma\left(1 + \frac{1}{C}\right) \quad (5.3)$$

variance:

$$\sigma^2 = A^2\left[\Gamma\left(1 + \frac{2}{C}\right) - \Gamma^2\left(1 + \frac{1}{C}\right)\right], \quad (5.4)$$

Estimation of the parameters

Several method can be used to estimate the parameters of Weibull. One possible way consists of using the least-squares approach. In order to obtain a linear problem, we can take twice the logarithm of equation (5.2) and then minimize an expression of the form:

$$\sum_{j=1}^K (\epsilon^2) = \sum_{j=1}^K ([\ln(A^{-C}) + C \ln V_j - b_j]^2) \quad (5.5)$$

where K is the number of points we use to fit the curve. Using eq.(5.2) we can determine that

$$b_j = \ln(-\ln[1 - F(V_j)]) \quad (5.6)$$

Note that this approach actually fits the cdf to the ogive, which is analogous to fitting the pdf to the histogram. Because our data is not a vector of observations of wind speed, but is intervals with probabilities we use the definition of Weibull distribution to estimate the parameters A and C . In other words, from our data and from equation(5.2) we can write:

$$P(X \leq 4) = 1 - \exp(-(4/A)^C) \quad (5.7)$$

$$P(4 < X \leq 9) = \exp(-(9/A)^C) - \exp(-(4/A)^C) \quad (5.8)$$

$$P(9 < X \leq 14) = \exp(-(14/A)^C) - \exp(-(9/A)^C) \quad (5.9)$$

$$P(X > 14) = \exp(-(15/A)^C) \quad (5.10)$$

which gives the following vector of probabilities:

$$R1 = \begin{pmatrix} 1 - \exp(-(4/A)^C) \\ \exp(-(9/A)^C) - \exp(-(4/A)^C) \\ \exp(-(14/A)^C) - \exp(-(9/A)^C) \\ \exp(-(15/A)^C) \end{pmatrix}$$

The data that we consider provide another vector of probabilities:

$$R = \begin{pmatrix} 0.33 \\ 0.5 \\ 0.15 \\ 0.02 \end{pmatrix}$$

Now, we have to find parameters A and C such that the difference between vector R and vector $R1$ is minimum. In other words, we have to minimize the following function:

$$f(A, C) = \|R - R1\|^2 \quad (5.11)$$

After all computations done we obtain that

$$A = 6.8005$$

$$C = 1.7243$$

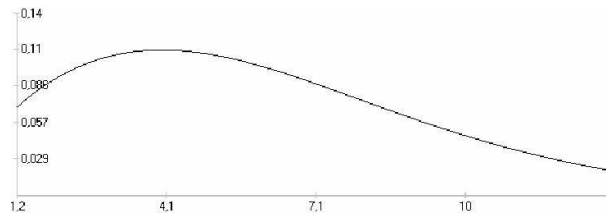


Figure 5.1: The Weibull probability density function.

To check if these parameters are good enough we put them into the vector R1 and we calculate it once again to obtain:

$$R1 = \begin{pmatrix} 0.33 \\ 0.54723 \\ 0.1666 \\ 0.02 \end{pmatrix}$$

We can see that the difference between vector R and R1 is quite small (is order around 10^{-2}). The figure 5.1 represents the Weibull probability density function with parameters A and C. We can also compute the main quantiles and the moments for this distribution.

Main quantiles:

$$5\%q = 1.2 \Rightarrow P(V < 1.2) = 0.05$$

$$50\%q = 5.5 \Rightarrow P(V < 5.5) = 0.5$$

$$95\%q = 13 \Rightarrow P(V < 13) = 0.95$$

Moments:

$$\text{Mean} = 6.1$$

$$\text{Standard Deviation} = 3.7$$

Once we have the parameters of Weibull, we can choose randomly any number from the Weibull distribution. We do this using some built in functions in Matlab.

5.1.2 Wind direction data

In this section we discuss with details the wind direction data. Table (5.2) shows the probability corresponding to different wind directions. In this table

Table 5.2: Direction data.

Direction	Probability	Direction	Probability
0	0.0185	180	0.0287
10	0.0195	190	0.0295
20	0.0196	200	0.0363
30	0.0225	210	0.0484
40	0.0209	220	0.0503
50	0.0213	230	0.0482
60	0.0225	240	0.0483
70	0.0204	250	0.0408
80	0.0215	260	0.0383
90	0.0214	270	0.0387
100	0.0215	280	0.0382
110	0.0194	290	0.0308
120	0.0182	300	0.0285
130	0.0161	310	0.0271
140	0.016	320	0.0278
150	0.0177	330	0.0303
160	0.0203	340	0.0258
170	0.0231	350	0.0232

the wind direction is divided into 36 groups. We assume that:

$$P(0 \leq X < 10) = 0.0185.$$

$$P(10 \leq X < 20) = 0.0195.$$

$$P(20 \leq X < 30) = 0.0196.$$

$$P(30 \leq X < 40) = 0.0225.$$

and so on. With these assumptions, we can now assign to this data a discrete distribution and we can start generating the samples from it. For this purpose we wrote a simple generating algorithm with Matlab.

5.1.3 Volume and location data

In this section, we present data that contain information about volume and location of pollution. We discuss these data in the same section because they

are connected with each other. We received 8 different volumes of pollution with their corresponding probabilities and for each volume, we had 1096 locations of spill also with their corresponding probabilities. The longitudes and latitudes of different locations are the same for each type of volume, the differences are in probabilities of locations (those differences depend on the type of spill of volume). Because of the large size of location data we present only the volume data in table below (Table 5.3).

Table 5.3: Volume data.

number of class of volume	class of volume	volume in m^3	probability
1	0.1-10	11.3	0.0016
2	20-150	87.4	0.0034
3	150-750	431	0.0151
4	750-3000	1824	0.0239
5	3000-10000	6084	0.0243
6	10000-30000	17840	0.0161
7	30000-100000	58649	0.0116
8	> 100000	178455	0.0068

The locations of pollution given in the data set cover the main part of the Netherland region on the North Sea (see figure 5.2).

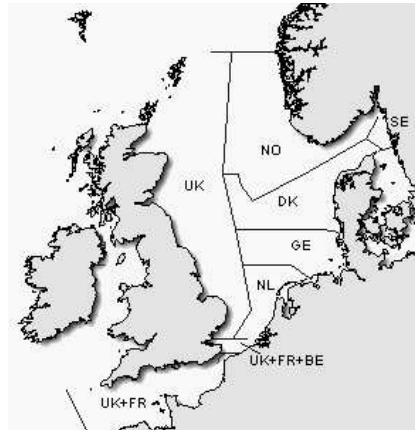


Figure 5.2: Map of the Netherland region on North Sea.

Again, we have intervals with probabilities and to which discrete distribution are assigned. Having the distribution we can generate the samples from it (using the same Matlab algorithm used for the wind direction data).

Chapter 6

Maps of Risk

In this chapter, we demonstrate based on one simple example how we can build the risk map. Then we describe in general all possible cases that we got from 1000 generated scenarios and finally we show one big map of risk for all scenarios.

6.1 The generated scenarios

We assumed earlier that on this moment 1000 scenarios is enough for our analysis. We also decided that all our analysis will be based upon the results obtained using Gnome. Since Gnome give the possibility to include many locations in the same simulation we classify our scenarios with respect to the weather conditions. This means that we divide the set of scenarios into small subsets. This reduces the number of cases from 1000 to 155.

Before starting the analysis, we mention the assumptions made for the simulations with Gnome:

- The simulated period time is 6 days,
- Because of the large number of cases (155), all the simulations are achieved without "current data"
- The type of oil is "medium crude"
- the simulations are computed without taking uncertainty into consideration, because the uncertainty does not change the final results. Only the trajectory looks different.

The next section we will give the definition of risk that we used.

6.1.1 Definition of Risk

As a final results we should present the map of risk. To do it we need to know what is the risk, in other words we need to define the risk. In this thesis, we use the following definitions:

$$R(i) = P(i) * D(i) \quad (6.1)$$

where:

$R(i)$ is the risk for i -th scenario

$P(i)$ is the probability of i -th scenario

$D(i)$ is a damage for i -th scenario

For our analysis, we assume that the damage is equal to the number of particles on the beach and that the probability that the i -th scenario occurs is given by:

$$P(i) = \frac{\text{number of times scenario } i \text{ appears in set } S}{\text{total number of scenarios}} \quad (6.2)$$

where definition of set S is given in chapter 5 and the total number of scenarios is equal 1000.

In the next section we will discuss the analysis of results for one single case (corresponding to one subset).

6.1.2 Example of Analysis

For completeness, we first present Gnome plots describing the transport of the oil during the six days. The reason for presenting these figures is to show exactly which location of the spilled oil will be associated with risk.

In the next part of this section we show analysis of the results of the simulation of the first subset, say s_1 . The descriptions for this subset s_1 are given in table 6.1. Table 6.1 gives the information about scenarios. We notice that this table contains 8 different location of the pollution and also that the wind speed and direction are the same for all scenarios, and this allows to include all 14 scenarios in one simulation in Gnome.

Table 6.1: Table of first subset of scenarios .

scenario number	speed	direction	volume	longitude	latitude
1	7	330	6084	3.8	52.09
2	7	330	1824	3.2	51.44
3	7	330	87.4	2.7	51.8
4	7	330	11.3	2.5	51.87
5	7	330	1824	3.4	53.74
6	7	330	6084	3.8	52.09
7	7	330	6084	3.8	52.09
8	7	330	58649	4	52.02
9	7	330	6084	3.8	52.09
10	7	330	432	2.9	52.02
11	7	330	11.3	3.7	51.8
12	7	330	1824	3.2	51.44
13	7	330	58649	4	52.02
14	7	330	431	2.9	52.09

In the figures 6.1- 6.7 we can see the best guess trajectories given by Gnome for the simulation associated with this subset.

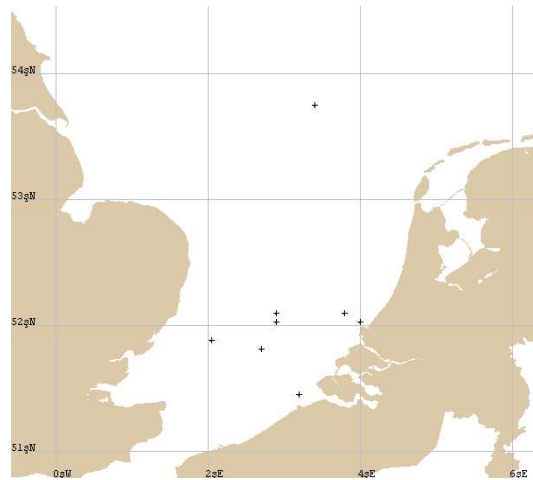


Figure 6.1: Starting position of pollution.

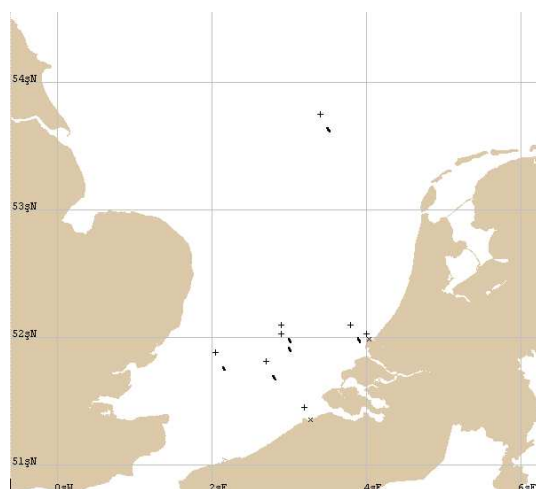


Figure 6.2: Position of particles after one day.

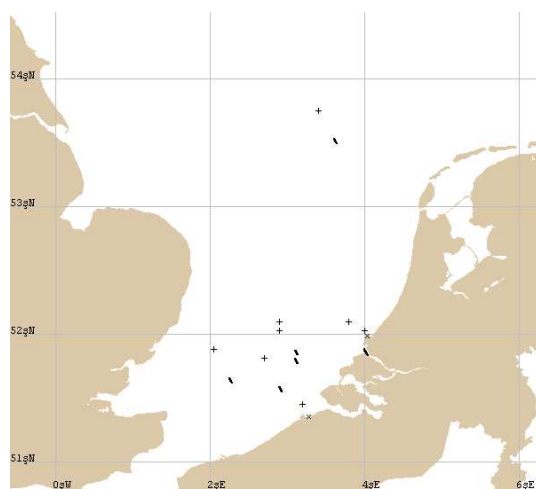


Figure 6.3: Position of particles after two days .

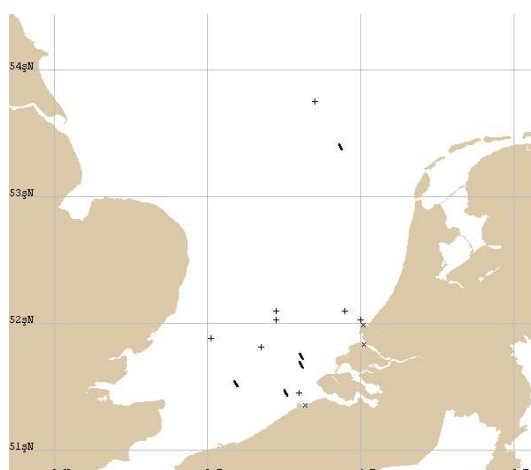


Figure 6.4: Position of particles after three days.

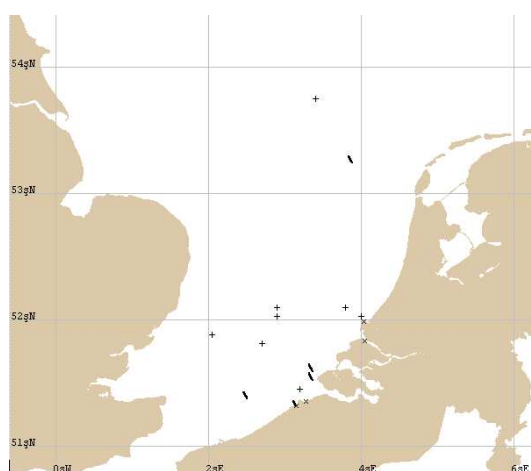


Figure 6.5: Position of particles after four days.

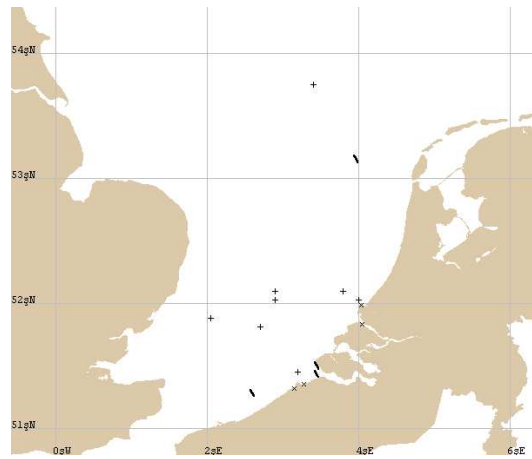


Figure 6.6: Position of particles after five days.

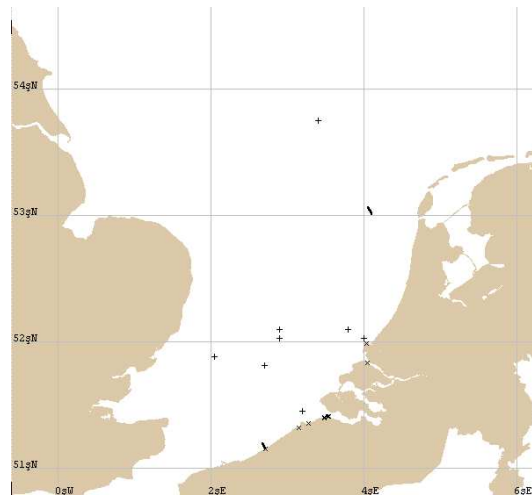


Figure 6.7: Position of particles after six days.

From these figures we can see which locations are associated with risk after one day, two days, etc.. We can see that with time there are more risky locations and also that some locations are harmless in our context, because we only refer to oil on beaches in our definition of damage.

On the tables 6.2 and 6.3 we can see the results given by Gnome. First table

6.2 recapitulates the global results. It gives the amounts of floating, beached and evaporated pollution as a function of time. Table 6.3 gives more detailed information corresponding to different scenarios.

Table 6.2: Results for all pollution together

number of parti- cles	after 1 day	after 2 days	after 3 days	after 4 days	after 5 days	after 6 days
released	148078	148078	148078	148078	148078	148078
floating	21053	18359	1764	1651	1550	1016
beached	94382	83096	90976	85691	82546	80978
evaporated and dis- persed	32643	46623	55338	60735	63982	66084

Table 6.3: Results for all location of pollution separately

	number of particle on the beach after					
scenario number	1 day	2 days	3 days	4 days	5 days	6 days
1	0	0	3882	3699	3590	3468
2	1415	1226	1113	1073	1029	989
3	0	0	0	7.9	48.4	47
4	0	0	0	0	0	0.6
5	0	0	0	0	0	0
6	0	0	3717	3517	3407	3298
7	0	0	3705	3535	3456	3340
8	46098	41172	37301	35198	34134	32961
9	0	0	3760	3596	3510	3425
10	0	0	0	0	0	242
11	0	0	0	1	6.5	6.4
12	1415	1228	1136	1058	1023	992
13	45453	39471	36362	34016	32961	31964
14	0	0	0	0	256	246

Table 6.4: Table of the probability for each scenario

scenario number	probability
1	0.004
2	0.002
3	0.001
4	0.001
5	0.001
6	0.004
7	0.004
8	0.002
9	0.004
10	0.001
11	0.001
12	0.002
13	0.002
14	0.001

To compute the risk we need also the probability of each scenario given in table 6.4. Then using equation 6.1 we can compute the risk for each scenario. Table 6.5 shows the results. As we notice on the beginning of this section, some of the scenarios are the same (see Table 6.1). Therefore first we calculate the risk for each scenario separately (see Table 6.5), then for the same scenarios we simply take the average of their risks (Table 6.6 presents the results). So for example the scenario number 2 is the same as scenario number 12. The risks for these two are given by table 6.5, and then taking the average of these two risks we obtain the first case in table 6.6. We do the same analysis for scenarios 1, 6, 7, 9, scenarios 8 and 13 and scenarios 3 and 11. We also exclude from our analysis scenario 5 because the risk is equal to zero at the beginning and at the end of the simulation. Finally, we obtain 8 different cases for which the summary of risks is given by table 6.6. From these tables, we obtain the risk maps presented in figures 6.8 to 6.13.

Table 6.5: Table of the risk for each scenario

	risk after					
scenario number	1 day	2 days	3 days	4 days	5 days	6 days
1	0	0	15.528	14.796	14.36	13.872
2	2.83	2.45	2.226	2.146	2.058	1.987
3	0	0	0	0.0079	0.0484	0.047
4	0	0	0	0	0	0.0006
5	0	0	0	0	0	0
6	0	0	14.868	14.068	13.628	13.192
7	0	0	14.82	14.14	13.824	13.36
8	92.196	82.344	74.602	70.369	68.268	65.922
9	0	0	14.824	14.384	14.04	13.7
10	0	0	0	0	0	0.242
11	0	0	0	0.001	0.0065	0.0064
12	2.83	2.456	2.272	2.116	2.046	1.984
13	90.96	78.942	72.724	68.032	65.922	63.928
14	0	0	0	0	0.265	0.246

Table 6.6: Table of the risk for each scenario

		average risk after					
latitude	longitude	1 day	2 days	3 days	4 days	5 days	6 days
52.09	3.8	0	0	15.01	14.347	13.963	13.531
51.44	3.2	2.83	2.453	2.2473	2.131	2.052	1.981
51.8	2.7	0	0	0	0.00445	0.02745	0.0267
51.87	2.5	0	0	0	0	0	0.0006
52.02	4	91.578	80.643	73.663	69.214	67.095	64.925
52.02	2.9	0	0	0	0	0	0.242
52.09	2.9	0	0	0	0	0.265	0.246

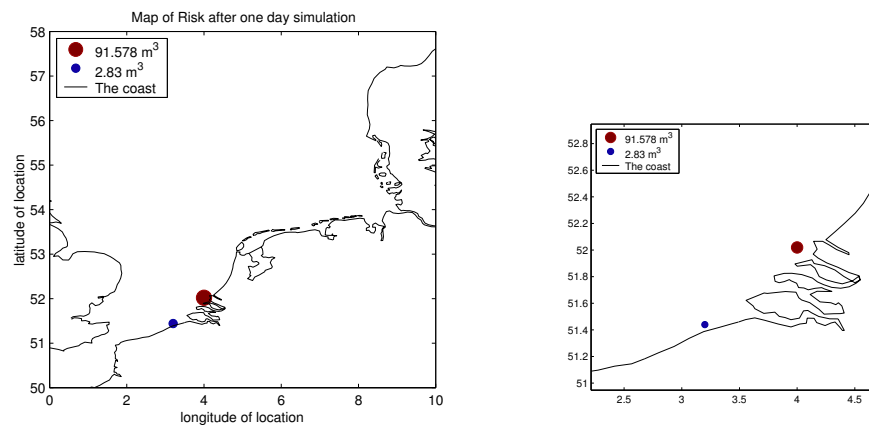


Figure 6.8: Map of Risk after one day from the pollution release.

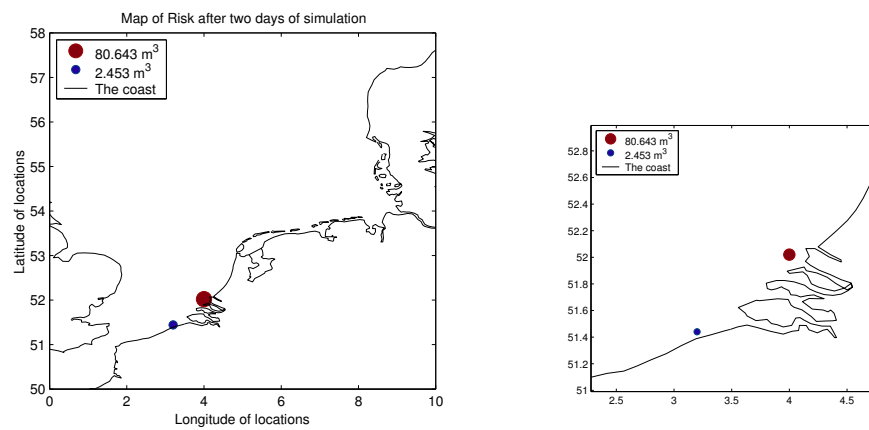


Figure 6.9: Map of Risk after two days from the pollution release.

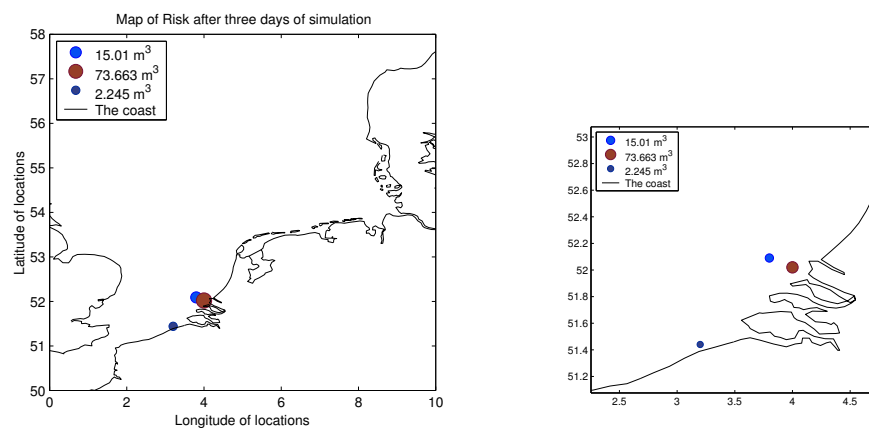


Figure 6.10: Map of Risk after three days from the pollution release.

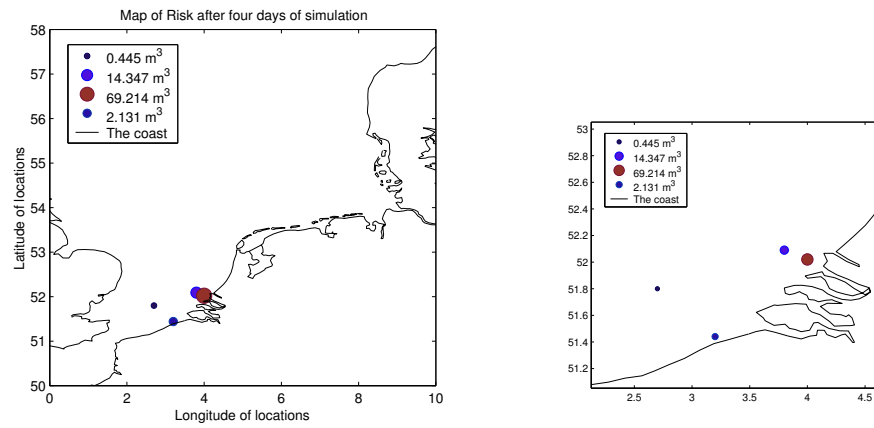


Figure 6.11: Map of Risk after four days from the pollution release.

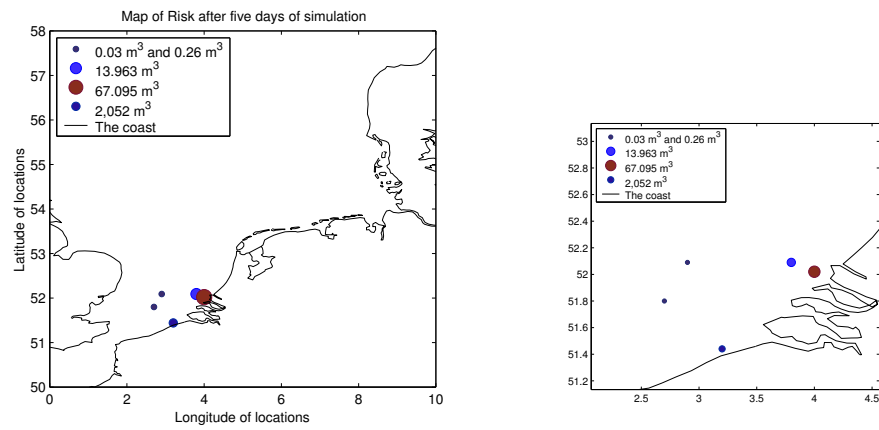


Figure 6.12: Map of Risk after five days from the pollution release.

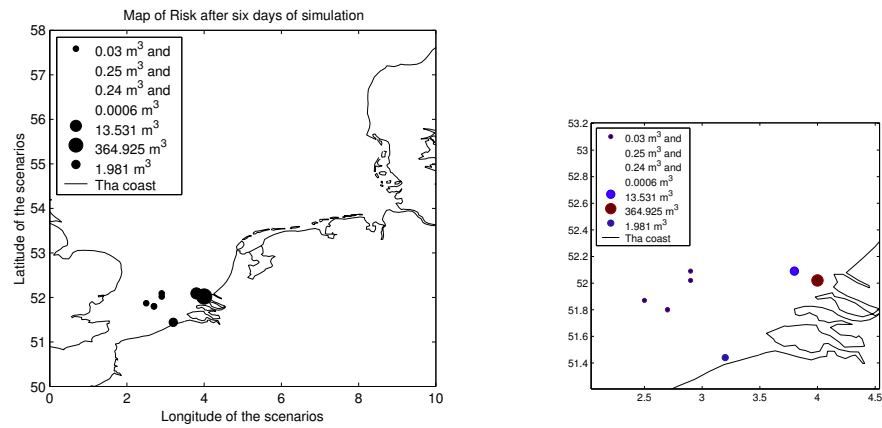


Figure 6.13: Map of Risk after six days from the pollution release.

We can conclude from the results that if we have an oil spill near to the coast, probably after 1 day around 50 percent of it reaches the beach. Then the dangerous area grows. At the same time, some of the particles that are already on the beach evaporate as we can see in Table 6.3 where the damage in some cases decreases with time. In this example, we have chosen to present risk maps for each day within the 6-days period. In order to show once how the risk evolves and builds up. For example, we can see how and when new locations enter. In our final results, to be presented in the next section, we only present the 6-days risk map, because this result suffices for the moment.

6.2 Map of Risk for all scenarios

In this section, we present a short analysis of the results of the simulations of all scenarios. We show the final tables of risks and we generate the map of risks. In these tables we present only the risk for those scenarios that lead to oil on the beach and as a consequence to a nonzero risk. It turns out that this is the case for 55 scenarios out of the original 1000 (after combining and averaging of some location). We also compare this map with the real map of Holland to see which areas are most vulnerable.

Tables 6.7 and 6.8 present the final results for all scenarios.

Table 6.7: Final results of risk values

number	risk	longitude	latitude
1	3239.9554	4	52.02
2	177.2084	3.8	52.09
3	80.751	3.8	52.02
4	30.31	3.8	51.95
5	28.127	3.5	51.44
6	26.994	3.9	52.02
7	17.154	3.4	51.44
8	14.07	3.2	51.44
9	14.007	3.2	52.02
10	13.385	3.7	52.45
11	10.136	3.7	52.09
12	10.099	3.7	51.95
13	8.286	3.6	53.24

Table 6.8: Final results of risk values

number	risk	longitude	latitude
14	6.844	3.7	52.16
15	6.093	3.5	52.09
16	5.962	3.6	53.16
17	4.092	3.5	52.02
18	3.541	3.7	52.38
19	3.352	3.7	52.3
20	3.322	3.7	52.02
21	3.316	3.7	52.24
22	3.316	3.7	52.53
23	3.285	3.7	53.38
24	3.094	3.5	51.95
25	2.93	3	52.02
26	2.07	3.4	52.02
27	2.003	3.1	52.3
28	2.001	3.4	53.16
29	1.95	3.5	51.58
30	1.871	2.7	52.02
31	1.424	3	51.95
32	1.205	2.9	52.09
33	1.062	3.2	51.8
34	1.02	3.4	52.88
35	1.018	3.4	52.09
36	1.01	3.2	52.74
37	1.001	3.8	52.16
38	1.001	3.1	52.16
39	1.001	3.5	52.24
40	1.001	3.1	52.38
41	1.001	3.2	52.38
42	0.987	3.2	52.95
43	0.962	2.9	52.02
44	0.9187	2.7	51.95
45	0.74	2.9	52.16
46	0.718	2.8	51.87
47	0.509	2.8	52.02
48	0.481	3.6	53.31
49	0.469	3	51.87
50	0.241	2.8	51.8
51	0.233	2.8	52.09
52	0.232	2.8	51.95
53	0.18185	2.7	51.8
54	0.096	2.7	51.87
55	0.0385	2.5	51.87

These tables exclude all scenarios which have the damage equal zero. As result it gives the value of risk for each position of oil spill. The value of risk was calculated in following way. First we calculating the risk for all scenarios, which have the damage bigger than zero, then for each scenario that contains the same four values (have the same speed, direction, amount of pollution and location) we take as the risk the average from all risks, so at this stage we reduce our number of scenarios by subtracting the same scenario and scenarios which have the zero damage. In other words we obtain the subset s_r of S ($s_r \subset S$) that contain only scenarios, that are not the same and are with nonzero damage. Now for scenarios with the same location we take as a risk the sum of all risk for this location. Finally we obtain the subset $s_{rf} \subset s_r \subset S$, that contain only the scenarios that have different locations and nonzero risk. Tables 6.7 and 6.8 describe the subset s_{rf} and figure 6.14 shows the graphical interpretation of those tables, so represents the final risk map.

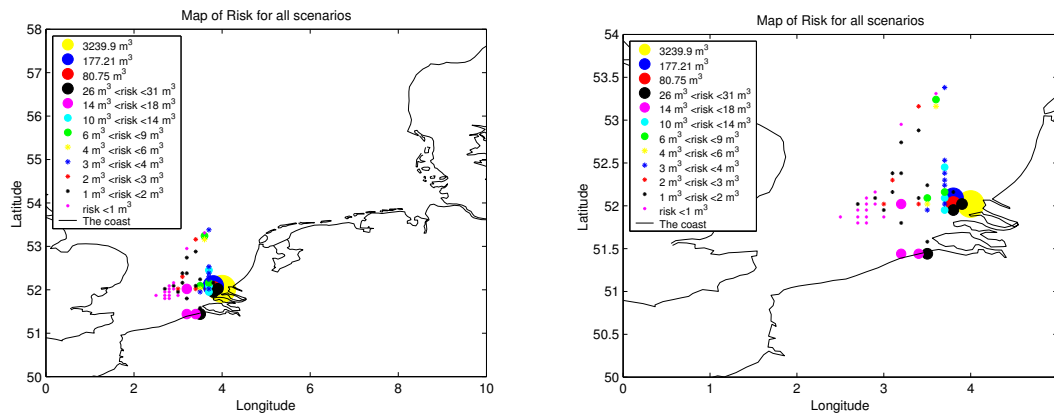


Figure 6.14: Map of Risk after six days for all set of scenarios

We can also conclude after all analysis that the most often chosen location was the location with longitude 4 East and latitude 52.02 North (among 1000 scenarios this location was chosen 311 times). This location was also strictly connected to large size of pollution ($17840 m^3$ or $58649 m^3$). And if we look on the map of Holland we can conclude that the most risky areas are near the Europoort and Middelburg.

Chapter 7

Conclusions

In this chapter we will sum up conclusions and observations. First we will write the remarks about Simpar and Gnome, then we will discuss the results from simulation with these two. Next we will write the conclusion about the risk maps that we have obtained. Gnome and Simpar are two software packages that simulate the transport of floating particles, as result they give us the trajectory of the particles and in this manner we can see the movement of the spilled oil. As illustrated both packages are useful to analyze the movement of oil in this sense. In this thesis the main goal is to build the risk map and therefore besides the trajectory of the pollution we also need information about the amount of the polluted oil on the beach. Simpar does not give us this information, therefore we decide to use Gnome.

To build the risk map many scenarios have to be consider, leading to multiple Gnome simulations. The Gnome software allows for only one simulation running within a single processor, starting a second simulation is only possible after the first has finished up. As a consequence, we spend a lot of time running all simulations and in this aspect Gnome is not very suitable.

For building the final risk map we randomly generated 1000 scenarios using realistic data from Rijkswaterstaat taking into account the geographical distribution of probabilities of oil spills. To quantify the risk we have defined the damage of an oil spill as the amount of oil that reaches the beach. Using 6-days Gnome simulations we have computed the damage of all 1000 spills in order to generate the risk map. It turns out that there are two regions of high risk near the Europort and near Middelburg. In fact, the largest risk found

($3240m^3$) is located at $52.02E$ and $4N$, all associated with all spills of average volume $17840m^3$ or $58649m^3$.

As has been said we have generated 1000 scenarios out of the data. Among others the data contained 1096 possible locations. From the locations present in the 1000 scenarios only 55 locations turned out to be risky in the sense that they had a nonzero risk. These 55 locations were found to be located nearly all near the Europort and Middelburg. Because our sampling procedure takes account of the probabilities of oil spills, it seems that high probabilities of accident are associated with these regions. Similar remarks can be made with respect to the wind. From the 1000 scenarios only 435 scenarios were found to be risky. In almost all of these 435 risky scenarios the wind direction is between 200 and 330 degrees and a few with directions between 110 and 190 degrees. The wind speed within the 435 risky scenarios was distributed around $7m/s$, i.e. $7m/s$ (64 times), $5m/s$ (54 times), $4m/s$ (49 times), $8m/s$ (48 times) and $9m/s$ (42 times). Of course, all of this is directed related to the bias in the data in combination with our definition of the damage and turns out to lead to the exclusion of important areas in the more Northern part of the studies region. Against this background, it is at least suggested to enlarge the number of 1000 scenarios in future research.

Chapter 8

Future Research

This chapter will give the recommendations for future research. It will tell what can be changed or added to make the problem of oil spill more realistic.

At present one scenario takes into consideration four parameters: the location of the pollution, the wind speed and the direction and the volume of the oil spill. In the future more parameters can be included such as the season, the type of oil, the tide effects and other.

It is also recommended to try to use other software packages like for example OLIMP. For this project we have decided to use Gnome. As mentioned previously this software package can not compute by itself the hydrodynamical data like for example Simpar. The second reason for using other software packages in the future is that Gnome has a restriction about the size of oil spills. In our simulations we have excluded the most dangerous case (volume of pollution larger than $178455m^3$). And even though this case does not happen too often, it can have a big influence on the final result (risk map).

It can be also a good idea to make the risk map after each day of simulation. So if the simulations take 6 days, six risk maps are built. As we have seen in chapter 6 the evaluation of the risk over the days might be useful. We should also think about a alternative definition of damage. The definition that we use in this thesis cause that from 1000 scenarios we analyze only 435 scenarios. Maybe in the future we should consider also the amount of floating oil as a damage.

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Appendix A

MatLab code generating the set of scenarios

```
clear all
load all_location_volume_direction;
n = 1000;

%volume
prob=prob/sum(prob);
cumul_prob = cumsum(prob);
random_numbers = unifrnd(0,1,n,1);
for i = 1:n
    v = find(cumul_prob >= random_numbers(i));
    indices(i) = v(1);
    volume(i)=number(indices(i))
end

%location

prob1=prob1/sum(prob1);
prob2=prob2/sum(prob2);
prob3=prob3/sum(prob3);
prob4=prob4/sum(prob4);
prob5=prob5/sum(prob5);
prob6=prob6/sum(prob6);
prob7=prob7/sum(prob7);
```

```

prob8=prob8/sum(prob8);
cumul_prob1 = cumsum(prob1);
cumul_prob2 = cumsum(prob2);
cumul_prob3 = cumsum(prob3);
cumul_prob4 = cumsum(prob4);
cumul_prob5 = cumsum(prob5);
cumul_prob6 = cumsum(prob6);
cumul_prob7 = cumsum(prob7);
cumul_prob8 = cumsum(prob8);

for j=1:n
    if indices(j)==1
        l=find(cumul_prob1>=random_numbers(j));
        indices1(j)=l(1);
        location(j,1)=dlugosc1(indices1(j));
        location(j,2)=szerokosc1(indices1(j));
    elseif indices(j)==2
        l=find(cumul_prob2>=random_numbers(j));
        indices1(j)=l(1);
        location(j,1)=dlugosc2(indices1(j));
        location(j,2)=szerokosc2(indices1(j));
    elseif indices(j)==3
        l=find(cumul_prob3>=random_numbers(j));
        indices1(j)=l(1);
        location(j,1)=dlugosc3(indices1(j));
        location(j,2)=szerokosc3(indices1(j));
    elseif indices(j)==4
        l=find(cumul_prob4>=random_numbers(j));
        indices1(j)=l(1);
        location(j,1)=dlugosc4(indices1(j));
        location(j,2)=szerokosc4(indices1(j));
    elseif indices(j)==5
        l=find(cumul_prob5>=random_numbers(j));
        indices1(j)=l(1);
        location(j,1)=dlugosc5(indices1(j));
        location(j,2)=szerokosc5(indices1(j));
    elseif indices(j)==6

```

```

        l=find(cumul_prob6>=random_numbers(j));
        indices1(j)=l(1);
        location(j,1)=dlugosc6(indices1(j));
        location(j,2)=szerokosc6(indices1(j));
    elseif indices(j)==7
        l=find(cumul_prob7>=random_numbers(j));
        indices1(j)=l(1);
        location(j,1)=dlugosc7(indices1(j));
        location(j,2)=szerokosc7(indices1(j));
    elseif indices(j)==8
        l=find(cumul_prob8>=random_numbers(j));
        indices1(j)=l(1);
        location(j,1)=dlugosc8(indices1(j));
        location(j,2)=szerokosc8(indices1(j));
    end
end

%direction

cumul_prob_direction = cumsum(prob_direction);
for m = 1:n
    d = find(cumul_prob_direction > random_numbers(m));
    indices3(m) = d(1);
    direction(m)=direction(indices3(m));
end

%speed

alfa=6.8005;
beta=1.7243;
S=weibrnd(1/(alfa)^beta,beta,n,1);
S
data=zeros(n,1)
for k=1:n
    Z(k)=S(k);
    speed(k)=Z(k);
end

```

```
scenario=zeros(n,5);
for b=1:n
    scenario1(b,5)=location(b,1);
    scenario1(b,4)=location(b,2);
    scenario1(b,3)=volume(b);
    scenario1(b,2)=direction(b);
    scenario1(b,1)=speed(b);
end
scenario1(:, :)
save 'scenario' scenario

for w=1:n
    longitude(w)=scenario(w,5);
    latitude(w)=scenario(w,4);
    volume(w)=scenario(w,3);
    direction(w)=scenario(w,2);
    speed(w)=scenario(w,1);
end
```

Vita

Katarzyna Wojtaszek was born in Poland in 1979. In 1998 she began mathematical studies at the Technical University of Zielona Góra, Poland. In 2001 she became a regular MSc student at the Delft University of Technology participating in a two year master of science course in *Risk and Environmental Modelling*.