Risk analysis on groundwater contamination at the megasite Port of Rotterdam

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Abstract Groundwater contamination at the Port of Rotterdam is studied using a regional scale model. Reactive transport is calculated along pathlines accounting for redox-dependent biodegradation. The contaminant flux is calculated on so-called planes of compliance. These are the main receptors where there is potential danger of receiving contaminant. In this case the receptors are surface water, the first main aquifer and the border of the port area. Due to the comparatively high degree of uncertainty in the input parameters, a Monte Carlo analysis is performed. The input parameters cause the highest degree of uncertainty in the model. An uncertainty distribution was derived based on all information available. These parameters are: contaminant concentration at the source, degradation rates, redox conditions, and sand-filled vertical drain parameters such as depth and permeability. The Monte Carlo analysis uses the combined uncertainty of the individual input parameters to obtain an uncertainty distribution for the entire megasite. A number of realizations of the pathline analysis obtain different modelling outcomes which can be interpreted as an uncertainty distribution itself. In this case, we have chosen to express the outcome as the chance of exceeding the intervention value on a plane of compliance.

Keywords groundwater contamination; Monte Carlo analysis; reactive transport; regional scale

INTRODUCTION

The Rotterdam mainport is situated at the delta of the rivers Rhine and Meuse and covers an area of 42.5 km^2, which makes it one of the world's largest harbours. As shown in Fig. 1, it is divided (from right to left) into the eastern harbours, the Pernis area, the Botlek area and the western harbours. Among the main activities that take place in the Rotterdam harbour are the transhipment and processing of bulk goods such as oil, chemicals, coals and ores. At the Port of Rotterdam, groundwater contamination has occurred at numerous locations during more than five decades. Until now, the contaminations were studied (and treated) at the local scale. We studied the risk of groundwater contamination on a regional scale and analysed different management scenarios (ter Meer *et al.*, 2004). Furthermore, Fig. 1 shows seepage and infiltration fluxes determined from earlier modelling. The infiltration flux is the vertical flux from the harbour downwards to the groundwater system. The seepage flux is the flux from the groundwater systems upwards to the polders.

Three major receptors were studied: the surface water, the deep groundwater below the harbour (the first regional aquifer) and the border of the port area. These are called planes of compliance (see Fig. 2). The planes of compliance are the boundaries

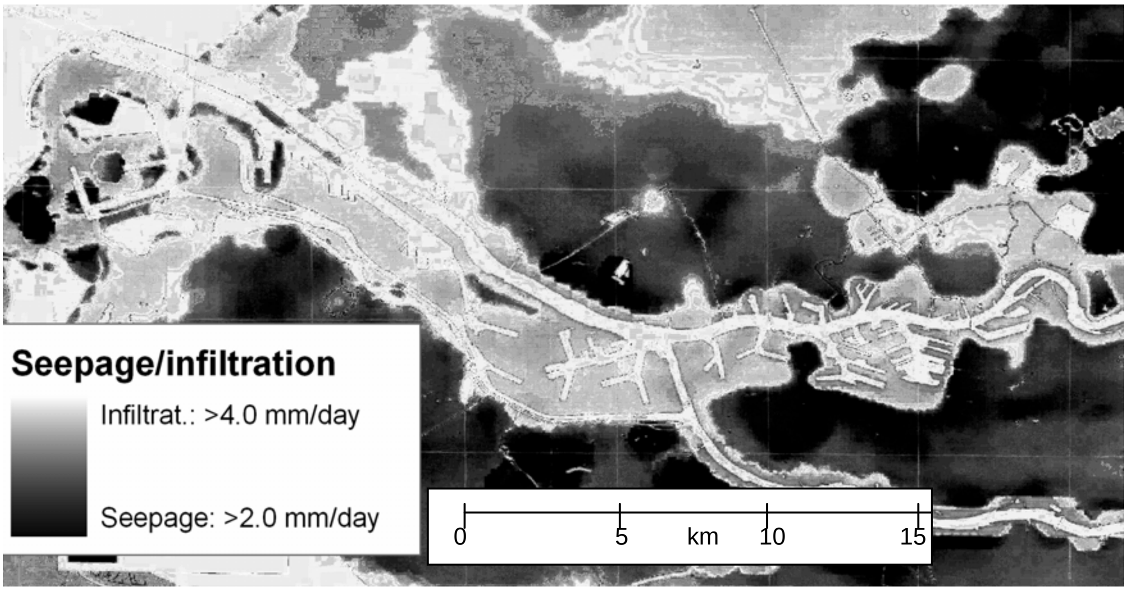

Fig. 1 Geohydrology of the port of Rotterdam: seepage and infiltration flux.

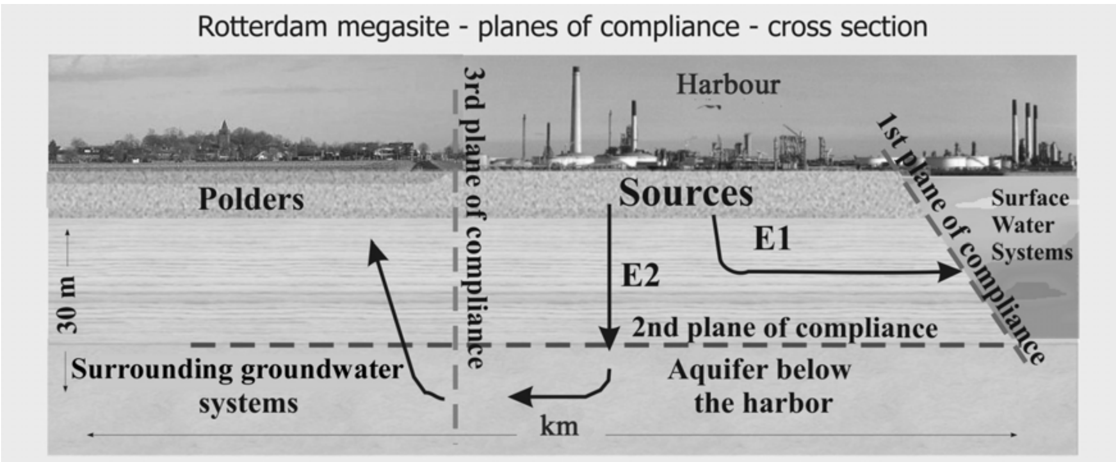

Fig. 2 Conceptual model for the Rotterdam megasite, including contaminant sources, pathways and receptors, as well as the planes of compliance. The pathways E1 and E2 are the fluxes directly to the surface water systems (E1) and the fluxes that reach the surface in the polders through infiltration and seepage.

of receptors that need to be protected. The chance of exceeding the legal targets is calculated on the planes of compliance. Also, because of the introduction of the European Water Framework Directive, it is very important to obtain information about the spreading of the contaminant and to define planes where risk-based clusters have to be defined at regional scale, like the planes of compliances as defined in this study.

Furthermore, Fig. 2 shows a cross-section of the infiltration and seepage fluxes as shown in Fig. 1. There are two possible fluxes: E1 and E2. E1 is the flux directly from the sources to the surface water systems (1st plane of compliance). E2 is the flux that infiltrates from the sources into the aquifer below the harbour (2nd plane of compliance), flows horizontally in the aquifer until it crosses the boarder of the harbour (3rd plane of compliance) and finally reaches the surface in the polders through seepage.

METHODOLOGICAL CONCEPT

Geohydrological model

A MODFLOW based geohydrological model calculates the pathlines (Pollock, 1994) along which the contaminant moves with the groundwater. In the centre of the harbour, water infiltration dominates (see Fig. 1). A complete source–path–receptor evaluation is made to estimate the flux of contaminants and the risk to the receptor. Each pathline starts at a perpetual contaminant source with simulated concentration, water flux and contamination time. Along the pathline, contaminant concentrations (for example benzene, PCE, TCE, etc.) decrease due to redox-dependent biodegradation. This is a so-called “fast” pathline analysis because of its small computational effort. This approach has been used before (e.g. by van den Brink & Zaadnoordijk, 1997) and is especially useful when extensive input data are not available so that detailed three-dimensional or stochastic models cannot be applied. At several periods in time it was checked if the contaminant has reached the planes of compliance, giving a contribution to the contaminant mass flux over these planes of compliance. Moreover we corrected for conceptual errors in the flow model due to the presence of sand-filled vertical drains in the Holocene clay. By using Darcy we performed analytical calculations to derive the estimated water flux that flows through these drains or through the Holocene clay, and the reduction and multiplication factors for the respective travel times.

Monte Carlo analysis

Uncertainty is essential for stakeholders in Rotterdam to make decisions on risks and risk management scenarios. In earlier calculations uncertainty was taken into account by considering different scenarios: the best case, the worst case and the most likely case. Although the results gave a range of outcomes, they did not give the probability of the outcomes. In order to obtain this information carrying out a Monte Carlo analysis as part of the modelling was proposed.

The quantification of the uncertainty in the modelling results is used by the stakeholders to judge the validity of the decisions to be taken on the future strategy for managing contaminated land in the Rotterdam harbour. For a number of input parameters which cause the highest degree of uncertainty in the model (this is determined from earlier modelling), an uncertainty distribution was derived based on all the information available. These parameters are: contaminant concentration at the source, degradation rates for all contaminants, redox conditions and sand filled vertical drain parameters such as depth and permeability. The Monte Carlo analysis uses the combined uncertainty of the individual input parameters to obtain a resulting uncertainty distribution for the entire megasite. A number of realizations of the pathline analysis obtain different modelling outcomes which can be interpreted as an uncertainty distribution itself. This again emphasizes the relevance of the rapidity of the pathline analysis approach.

In a Monte Carlo analysis, the computer uses a random number generator to sample, in an unbiased fashion, values from the uncertainty distribution of a certain input parameter (e.g. contaminant concentration). These values will be used as input at

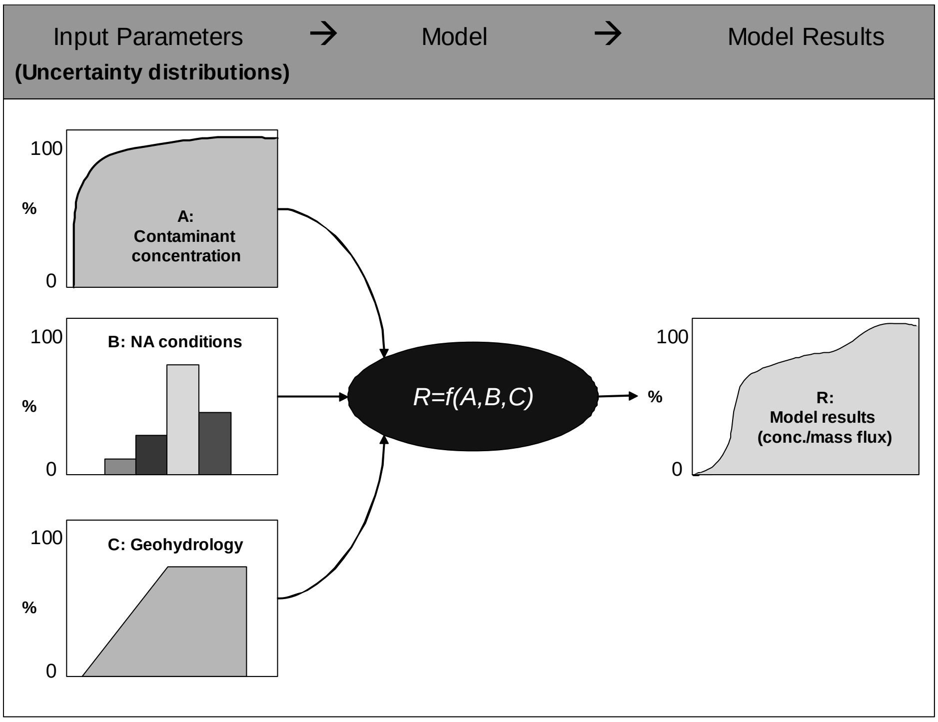

Fig. 3 Basic principle of Monte Carlo simulation.

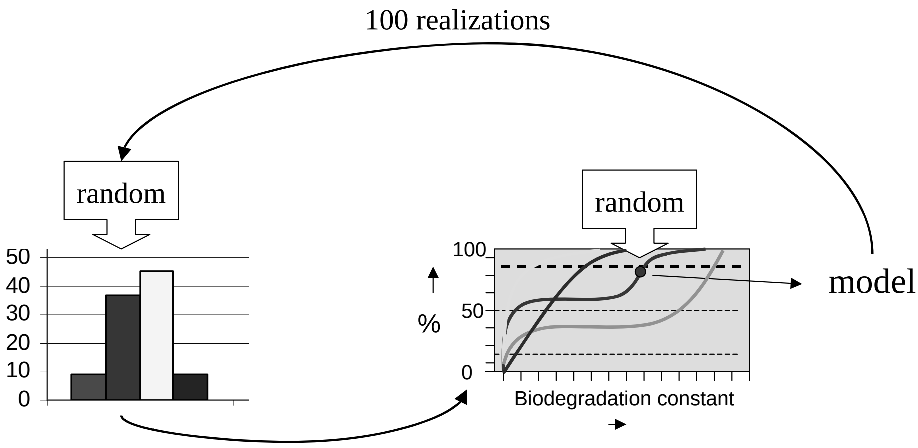

Fig. 4 Representation of the methodology to describe the process conditions as part of a Monte Carlo analysis. The colours indicate the different redox classes: nitrate reducing, iron reducing, sulphate reducing and methanogenic. The Y-axis indicates the relative occurrence (percentage) of the classes.

the grid cell level for the groundwater model. By repeating this exercise many times (e.g. 100 realizations), many different modelling outcomes will be obtained, which can be interpreted as an uncertainty distribution which reflects the combined uncertainty of all the individual input parameters. This is shown in Fig. 3, where the uncertainty of the contaminant concentration, the uncertainty of the natural attenuation conditions (redox and biodegradation) and the uncertainty in the geohydrology (sandpiles) are used as input (on the left in the figure) for the model, which results in model results with a certain uncertainty profile.

Previous modelling exercises on the mainport of Rotterdam have shown that the following input parameters cause the highest degree of uncertainty in the model, and therefore need to be considered in the Monte Carlo analysis:

– contamination (variation of source concentrations);
– natural attenuation (NA) conditions (variation redox conditions and biodegradation);
– geohydrology (effect of vertical sand drains: length and with of the sandpiles).

During one analysis, one random number is used to determine the redox conditions, the accompanying biodegradation rate and the sandpile geometry for the complete area. Moreover, a changing random number is used to determine the initial contaminant concentrations for the total area during one realization. This way, one analysis contains a spatial contamination distribution that varies per cell according to the contaminant probability distribution (see Fig. 4).

RESULTS

In order to get an impression of the spatial distribution of the contaminant situation, the chance of exceeding the legal targets is shown in Fig. 5. The contaminant situation has been predicted at different times. Figure 5 gives the chance of exceeding the intervention values of all priority contaminants and indicates the situation for the year 2030. The highest chances of exceeding the legal targets at the 2nd plane (first main aquifer below the industrial area) are present in the eastern harbours, the Pernis area and the eastern parts of the Botlek area. The western parts of the Rotterdam harbour area have a lower chance of exceeding intervention values. The distinction can be explained by

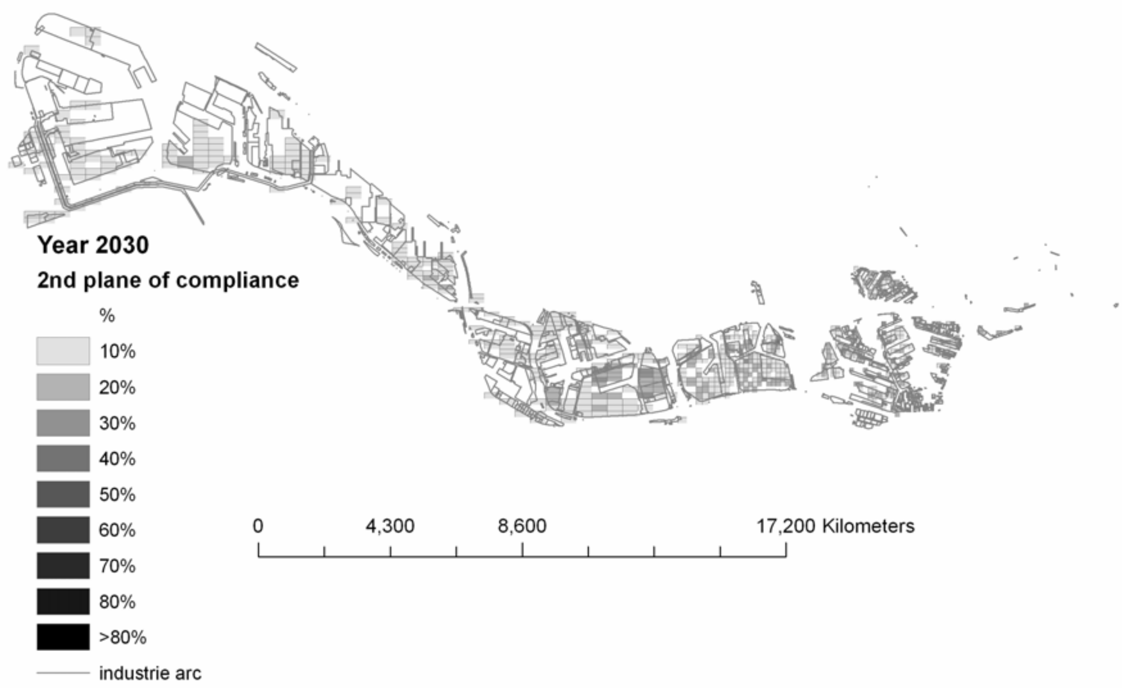

Fig. 5 Spatial distribution of the chance of exceeding the intervention value in the year 2030 on the second plane of compliance.

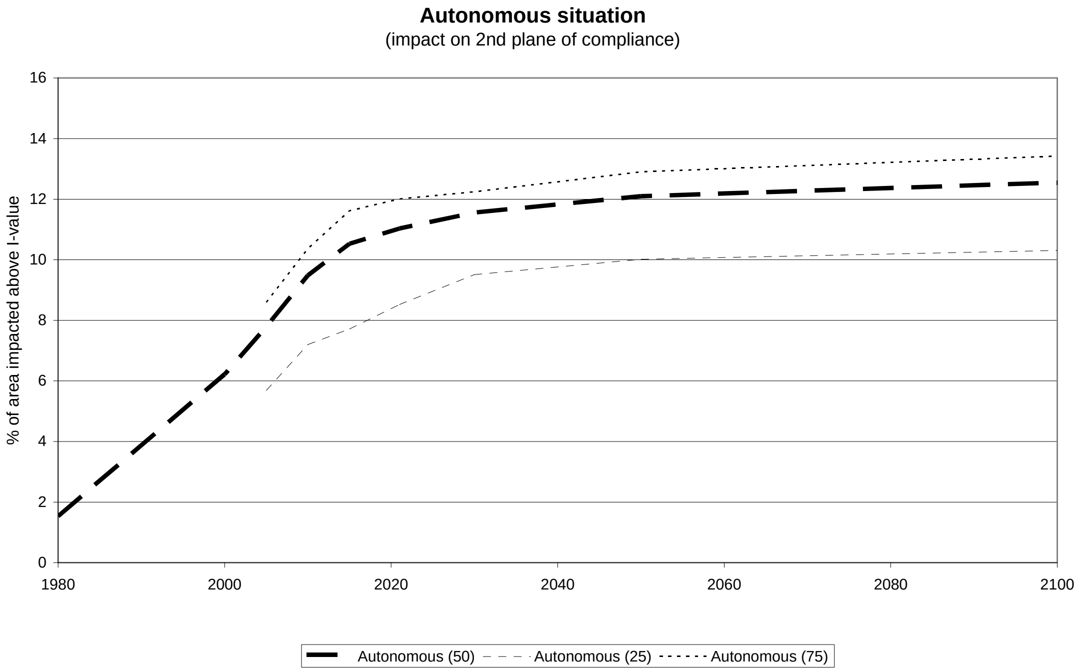

Fig. 6 Prediction of the impact at the 2nd plane of compliance as a function of time. The bold dashed line indicates the most likely impact (at the 50th percentile), the thin dashed lines the uncertainty range (respectively at the 25th and 75th percentile).

differences in NA and contaminant situation in these areas. In general, the contamination is stronger in the eastern parts and the biodegradation of the most predominant contaminants (e.g. benzene) is less favourable due to the adverse redox conditions.

In Fig. 6 the modelling results are shown as a function of time (again for the first regional aquifer below the industrial area). The modelling results indicate that the 2nd plane of compliance is impacted by contamination and that this impact increases in time. The increase rate is high between 1980 and 2030 and slows down after 2030 because of a decrease of contamination and because of biodegradation. The impact is expressed as the percentage of the 2nd plane of compliance that has a concentration higher than intervention value.

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