Delft Cluster

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Abstract

Studies and reports into the consequences of flooding events are usually focused on damage to buildings, infrastructure, economic losses and casualties yet ignore the risk of environmental damage. In this project, a model study was made to assess the environmental consequences of the release of pollutants during the flooding of a polder district in the Netherlands following a river dike breach. A conceptual framework was established for the sequence of events or ‘chain reaction’ during a flood: a dike breach is formed, the scour of the flood waters and/or high water levels damage or destroy objects like homes, industrial complexes and farms; damaged objects release hazardous substances that will be dispersed in the flood waters and the released material will affect people and ecosystems in the inundated area. The analyses were made in the 50,000ha case study area ‘Krimpen’, located in the western Netherlands near the cities of Rotterdam, Delft and The Hague. The simulated period of flooding was ten days. The failure of objects, where hazardous chemicals are stocked, was linked to water height and -velocity. The release, migration and fate of pollutants like BTEX, micro-organisms, PAH, PCB, NAPLs, heavy metals, nutrients and pesticides was simulated with an innovative modelling tool, in which hydraulic an chemical characteristics were combined. Despite the inherent shortcomings of this innovative prototype computer model, it was established that the potential impact of the pollutants on the environment could be substantial. Small yet numerous potential sources of contamination like cars may release substantial amounts of toxic chemicals into the flood waters and suspended sediments during and after the flood, whereas large installations, like those on chemical plants, may give problems only near the dike breach where high flow velocities are present.
Areas of improvement of the model, that would enable sustantiating the above observations, were clearly identified. It is envisaged that these improvements can be implemented in a follow-up study and that more detailed studies can be carried out, also in regions where verification data can be obtained.

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1 Introduction

1.1 Problem description

In the most recent study of the Dutch TAW (=Technical Advice Committee for Flood Defences), which was established to assess the consequences of a flood resulting from a river dike breach in the Netherlands, much attention has been paid to casualties, economical losses and infrastructural losses. An issue relatively unknown so far is the environmental impact of flooding. Yet pollutants, released during flooding, e.g. as a result of damage to structures where they are stocked, the deposition of polluted sediments, or merely the presence of floodwaters covering a large area may significantly affect (the future use of) rural areas like nature reserves and agricultural land and may lead to health problems in inhabited areas. After a flood event, very expensive clean-up efforts can be envisaged like large-scale removal and disposal of contaminated sediments.

1.2 Aim of the study

The aim of the study is to assess the possible environmental consequences of a release of pollutants as a result of flooding. This study was done through a literature investigation followed by a model study of a hypothetical breach of a dike around a polder district in the western part of the Netherlands (near the city of *Krimpen aan de Lek*). The relative importance of the environmental damage as compared to economic losses, infrastructural damage and number of casualties is assessed.

1.3 Perception of the problem and approach of the analysis

The first step in this study was a comprehensive literature study into the environmental consequences of floods that have occurred in industrialised countries, focusing on the relative importance of aspects like water height, water velocity, contaminated suspended sediments and types of pollutants. The results of this investigation are discussed in Chapter 2. In the second part of the study, a conceptual framework was defined, based on the sequence of events during flooding. This so-called *chain reaction* is depicted and explained in Figure 1.

1 Dike breach and flood	→	2 Source object fails	→	3 Pollutants are released	→	4 Pollutants are dispersed	→	5 Pollutant affects targets	→	6 Environmental damage assessed
Initiating mechanism				**Dispersion mechanism**						**Consequence mechanism**

Figure 1 Sequence of events in a chain reaction after a river dike breach

1. A dike breach releases water into one or more polder districts; the subsequent flooding event is simulated with the Delft1D2D-model of WL|Delft Hydraulics (see paragraph 3.2).
2. The scour of the water flow and/or the high water level may cause damage to, or may destroy *source objects* (constructions, houses, industrial complexes and farms).
3. The damaged *source objects* may fail and subsequently release chemicals and micro-organisms into the water. The volumes of pollutants that will be released from the source objects are estimated on the basis of investigations of (locations with) stocks of chemical substances in the area, expert knowledge and information from the literature study The criteria for failure are described in paragraph 3.2.
4. Pollutants are dispersed in various ways, e.g. through the air (not included in this study), dissolved in water and adsorbed to suspended matter. The release, migration and sedimentation of

the pollutants is simulated with the sediment- and flow models, discussed in Chapter 3. The results of the simulations are discussed in Chapter 4.
5. The polluted water and suspended matter may affect people and ecosystems - the *targets* - in the flooded region.
6. The assessment of the environmental damage in the region is made in Chapter 5.

1.4 Research partners

In order to be able to establish a complete overview of the processes during a flood and of the effects on the different threatened objects, several participants cooperated in this project. Alterra, a research unit of Wageningen University and Research Centre, have calculated the release of pollutants from agricultural and rural areas as well as the impact of a flood on these areas. GeoDelft investigated the release of pollutants from, and their impact on residential areas, commercial areas and other objects. TNO-MEP supplied data on harmful compounds, in use at industrial complexes and various types of businesses. CSO calculated the migration and sedimentation of suspended material. From existing modules, WL|Delft Hydraulics developed the integrated modelling tool that was used for the simulations.

2 Literature study and field trips

2.1 Introduction

The phenomenon of flooding is a natural occurrence, which has both adverse and beneficial effects on the environment. The adverse effects include loss of life, damage to property, stress, and - in our modern world - environmental pollution; the beneficial effects include an inflow of water and sediment. Floods form a widely studied field of research. Various researchers, in the fields of engineering, earth sciences, economy and policy analysis are interested in the causes, nature and consequences of floods. Since floods are very different in their causes, sizes, frequency and consequences a comparison is very difficult. This report focuses on flooding of polder districts after a river dike breach. Hence rainfall floods, snowmelt floods, tidal floods and flash floods are not taken into account. GeoDelft have made an extensive literature search on the topic of environmental impact of floods. Most of the material in this chapter is based on this investigation.

2.2 Previous Delft Cluster research

Flood losses can be categorised as *direct* and *indirect* (Smith and Ward, 1998). In particular, attention is given to direct losses, which occur immediately after the event as a result of the physical contact of the floodwaters with human and the damageable property. However, indirect losses, which are less obvious yet become apparent in the longer term, may be equally or even more important. Depending on whether or not these losses can or cannot be expressed in monetary terms, they are termed tangible or intangible. Primary losses result from the event itself while secondary losses are at least one causal step removed from the flood.

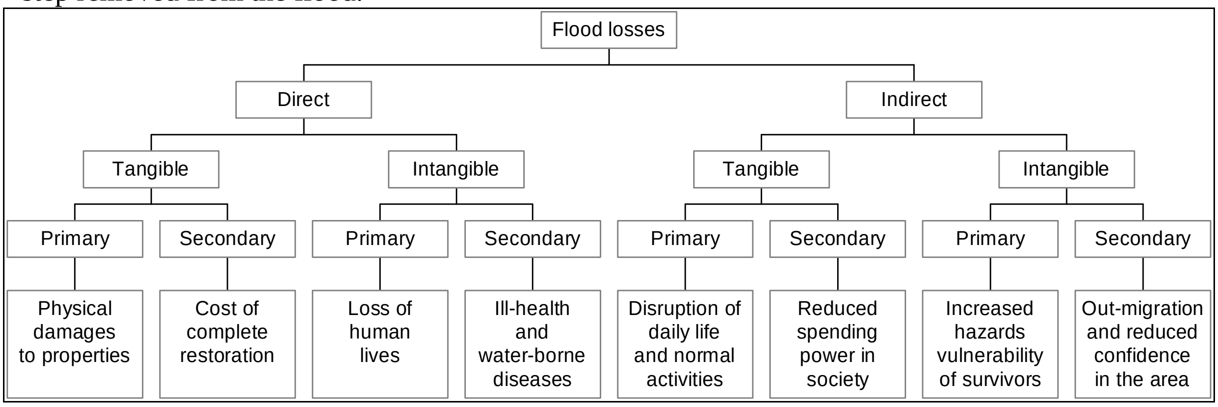

Figure 2 Flood loss classification (source: Smith and Ward, 1998)

Previous research into floods within the Delft Cluster research programme was focused primarily on the direct impacts of floods. On 17 October 2001 a conference was organised by the Delft Cluster partners to discuss the likelihood and consequences of a flood. During this and later sessions it became apparent that the so-called indirect damage, like damage caused by the environmental impact of floods, may be an important part of the total damage. Therefore, a research project into the environmental impact of a flood was started.

2.3 Assessment of environmental losses

Little previous research has been carried out into the environmental impacts of floods. In spite of the fact that many floods have been described in the literature, no integrated assessment of the environmental impact of a flood was found in the literature search, cf. Paragraph 2.5.

Normally, intangible losses are not taken into account while calculating the flood losses. Some drastic consequences of flooding such as ill health due to waterborne diseases or contamination of agricultural lands are difficult to express in monetary terms. Even less tangible are psychological effects like the stress caused by an event itself, the worry of future flooding, subsequent health deterioration, loss of memorabilia or other irreplaceable and non-marketable goods; disruption of the normal way of life and possible evacuation and migration. It has been demonstrated that to the households affected, these non-monetary aspects are much more important than tangible effects. Traditionally, assessment of environmental losses is not considered to be very relevant. Therefore, systematic and scientific environmental impact assessment of a flood is very rarely investigated, recorded and published.

2.4 Environmental impact of floods in the Netherlands

Very little research is carried out into the environmental impact of floods in the Netherlands. Documented research that could be found involved impacts of the 1993 and 1995 floods in The Netherlands studied by Zwolsman et al. (2000). Effects were assessed in terms of the composition of suspended matter in rivers and the associated ecotoxicological consequences. According to these studies, a major fraction of the suspended matter transported during river floods was deposited in the floodplains of the Rhine and Meuse rivers. The floodplains had been moderately to strongly polluted during earlier depositions of suspended matter, particularly during the period 1960-1980. As for the Rhine, the quality of suspended matter deposited during a flood is similar to or better than sediments deposited under average flow conditions.

Inundation of floodplains of large rivers differs fundamentally from the type of flood being investigated in this study. The scale is much smaller and, since the number of buildings and objects in the flooded area is limited, the release of pollutants is comparatively small.

Investigations were made by the Department of Health Risk Analysis and Toxicology of Maastricht University, reporting on soil contamination with heavy metals after flooding of the River Meuse during the winter of 1993-1994 (Albering et al., 1999).

2.5 Environmental impact of selected floods in other countries

2.5.1 Case: Environmental impact of the 2002 Moldau / Elbe floods in the Czech Republic and Germany

Within the scope of the research project that is described in this report, a trip to a recently flooded area was made: Prague in the Czech Republic (see figure 3). The goal of this visit was to find out whether the chain reaction of flooded industries and release of pollution had been a problem in this area.

Before our trip, we were informed on the flooded chemical plant *Spolena* and the associated pollution. This plant is located close to the river Moldau. During the flood, tanks were forced upward and torn from their pipe connections. Large quantities of heavy metals and chlorine were released into the river. A chlorine gas cloud escaped from the plant twice. Greenpeace, which had warned that the plant was situated in a vulnerable location, suspected that mercury, stocked at the plant was released as well. In the town of Neratovice a plant for PVC components had its old storages with dioxin and the polluted soil washed over, releasing the dioxin. These are all very hazardous materials yet no effects have been measured.

A tour along the flooded area clearly showed that Spolena was not the only chemical plant that was washed over and had its chemicals released. In Prague many tanks, ships and drums were drifting along the river. The fire brigade's main concern was to clear the famous and old Karelsbridge from this drifted material. Refrigerators, parts of buildings, LPG tanks and others were hoisted up or passed under the bridge, without concerns for tank leakage and risk of explosion.

Mark Rider of the ČHMÚ indicated that there had been some monitoring for contaminants by taking samples of water and floating particles. The concentrations were however not above average, except for radioactivity. Nevertheless, Mr. Rider suspects that various factories abused the flood event for illegal disposal of contaminants. Three months after the flood, many industrial water treatment plants and sewage treatment plants that had been washed over were still malfunctioning. Many chemical plants and petrochemical industries are situated along the river. Although they have a better reputation than Spolena, harmful substances might have been released. In the Czech Republic, the water from the rivers Moldau and Elbe is not used for drinking water production, yet in Germany it is. In Germany higher concentrations of contaminants have been monitored in the water than in the Czech Republic.

Figure 3 The 2002 flood in Prague, Czech Republic

The following news on the 2002 floods in Central Europe was found on the internet:

- First results from surveys made in August and September 2002 revealed that the Elbe flood had only minor short-term effects on the water quality in the German Bight and the Wadden Sea.
- Concentrations of nutrients (phosphate, nitrate, silicate) and most heavy metals were within the normal range. Although mercury concentrations increased at some sampling stations, the values were still below those recorded in the mid-1990s. Unusually high values were recorded for alpha-HCH and beta-HCH with up to 10-fold higher concentrations. Also some herbicides like Atrazin showed about 5-fold higher concentrations in areas directly influenced by the Elbe.
- Flood levels along Germany's River Elbe reached a peak on saturday in the historic city of Dresden, and threatened to send water pouring into a chemical plant in a nearby town.
- The centre of the town of Bitterfeld is completely inundated with water contaminated with diesel and other types of oil, reaching as high as one metre in some areas.
- Local officials are primarily concerned with one chemical plant, which is at risk if the dam bursts. and could send hazardous chemicals pouring into the surrounding areas.

ČHMÚ does not analyse silt- or sediment samples, but a press report in February revealed that measurements in the sediment of the river Elbe downstream of Spolena indicate high contents of PCB’s.

2.5.2 Other cases of environmental impact of floods

The literature study mentioned above has been carried out by using literature databases (e.g. Cambridge Scientific Abstracts, Environment Abstracts). In addition, an extensive internet search was made, mainly for finding case studies of various floods with environmental impact. Some general textbooks on floods were used. In 2002, according to the World Meteorological Organisation, floods in more than eighty countries caused more than 3000 casualties and hardships for more than 17 million people worldwide. WMO estimates the total damage from floods at over $30 billion. In August 2002, floods occurred in parts of Germany, the Czech Republic, Austria, Hungary, and China, India, Nepal and Bangladesh. The environmental impacts of floods are wide-ranging: from debris after floods to the spread of millions of tonnes of polluted sediments and the spread of diseases by mosquitoes.

Environmental health aspects on the 1997 Red River Flood
The 1997 Red River flood in Grand Forks, North Dakota, USA caused serious health problems. According to an environmental health professional, the main problem was the loss of the municipal water treatment plant and more than half of the city's sewage lift stations. The water treatment plant became non-operational for four to six weeks and some 17,000 homes were cut off from power. Another problem was the oil spill that contaminated the pipes of the municipal water system. This permanently contaminated the pipes since there is no way to remove enough residue to supply potable water through them. This fact has provoked the evacuation of the hospital. The growing of moulds, mainly in flooded basements, caused another public health risk.

Flood in Romania
On January 30th 2002, a tailings dam failure (due to heavy precipitation) at the Aurul S.A. plant in Baia Mare, Romania resulted in the release of 100,000 m^3 of cyanide-contaminated liquid into the Lapus stream, a tributary of the Somes, Tisza and Danube river respectively. This killed hundreds of tonnes of fish and practically all aquatic life. Hungarian otters, used as a European seed group, were killed by the accident as well. The accident affected the uptake of drinking water of more than 2 million people in Hungary. The long-term effects on the ecological system cannot be estimated yet, but experts fear that it will take years until the rivers will be back to pre-disaster stage, and that some of the effects may be non-reversible.

Case study Pittsburgh, USA
The spill of diesel oil in January 1990 raised a number of environmental problems (Clark et al, 1990). A storage tank containing more than 14,000 m^3 of diesel oil collapsed near Pittsburgh and the oil entered the Monongahela River. Water stations were forced to close down for several weeks. The total damage of the spill was never established.

Floods in Bangkok, Thailand
Bangkok, located only one meter or so above MSL, faces river floods at least every decade. In this huge metropolis (population over 10 million), a flood causes dramatic environmental and health problems (@ESCAP secretariat, 2001). Among the sources of pollution are household waste, hundreds of thousands of small shops, workshops, garages, small factories etc. etc. A 1983 flood lasted for several months. This must have had severe impacts on public health. Unfortunately no specific data of water quality during floods is available.

2.6 Conclusions and recommendations

Several conclusions were drawn from the literature study:

- Very limited research has been done investigating the impact of a flood on flora and fauna. Furthermore, there appears to be a lack of research on short-term and long-term environmental impacts of flooding. The number of studies on chemical hazards due to flooding and inundation is limited.
- Sediment transport is a well-studied engineering science. However, contamination of sediment due to flooding and spreading of any such contamination and the associated consequences is still an ongoing research subject.
- Traditionally, the assessment of environmental damage is not considered important. Therefore, systematic and scientific environmental impact assessment of a flood is rarely investigated and reported.
- The greater part of the environmental consequences of floods cannot be expressed in monetary terms.
- Many models can simulate flooding events; others can simulate environmental hazards. This research indicates that there is a need for an integrated model, which can simulate environmental problems along with the hydraulic modelling of a flood event.

- Flood management scenarios seem to be available in many flood prone countries. Some countries have developed protocols of safety and evacuation of chemical plants in case of flooding. Such protocols are however not accessible in the public domain, e.g. the internet.

The findings of the literature study were used for establishing the ‘Krimpen’ case study. An inventory was made of the types of substances that might be released and, if so, how they were likely to be released. This aspect and the development of the Environmental Impact Model are described in the remainder of this report.

3 The 'Krimpen' case study: description of relevant parameters

3.1 The modelling area and its interaction with flooding conditions

A river dike breach near the city of *Krimpen aan de Lek* was the starting point of the analysis. For the environmental impact, the focus was on the immediate and longer-term effects of dangerous chemicals released, dispersed and /or deposited during the flooding. Inundation time and flow characteristics like velocity and direction are mainly determined by elevation gradients of the soil surface in the flooded area. Differences in elevation, including the presence of barriers and local depressions or channels, therefore also determine the spatial variations in sedimentation rates. Barriers, like minor dikes, obstruct water flow and cause local changes in flow velocities. In addition, only the finer suspended sediment, which is present in the upper parts of the flood waters, may enter areas located behind such barriers. Maximum sedimentation rates occur at locations where water flows over barriers.

The effect of channels, canals and ditches is twofold. At first instance, at relatively low flow velocities, sediment can be conveyed into the channel where it accumulates. This is especially relevant for channels that lie perpendicularly to the flow direction. In the second instance, at relatively high flow velocities, the water current increases even more through the channels. This effect is in particular significant during the first phase of flooding when the channels are part of the preferred flow paths. High flow velocities in channels, depressions and alongside barriers can cause erosion of soil, which results in local increases of the sediment load (Middelkoop, 1997).

During the recession of the flood, low lying areas and areas which are enclosed within barriers are susceptible to ponding. As suspended sediments will settle easily in ponded waters, large accumulations of fine sediments may be found here.

Before the recession of the flood, the water height above low-lying areas is greater than the height in areas where the soil surface elevation is greater. The bulk load of suspended sediment available for accumulation is therefore also larger in low-lying areas. An important condition for this mechanism is that the flow velocity and water movement caused by wind-induced waves are low enough to allow for sedimentation.

When a dike breach occurs, sediment is transported into the flood area by different mechanisms. Coarse sediment (sand) may be transported by traction as bed load and is deposited close to the dike breach. Suspended sediments, however, make up the greater part of the solid sediment. This suspended load is dominated by silt- and clay sized material (i.e. $<16\mu m$ particle diameter). Suspended sediment is generally transported in suspension and accumulates at greater distances from the dike breach.

The yearly load of suspended sediments transported by the river Rhine through the Dutch-German border into the lower Rhine delta is 3.1 million tonnes on average. Under normal conditions, these sediments are deposited in the lower Rhine delta, and, during high water periods, on the floodplains of the river. Approximately 36% of the annual suspended load is transported through the lower river Rhine tributaries when discharge exceeds 3500 $m^3.s^{-1}$ and the lowest floodplain sections inundate. 19% of the annual load is transported when the discharge exceeds 5000 $m^3 s^{-1}$, and 6% by flows larger than 7000 $m^3 s^{-1}$. The highest suspended sediment concentration usually occurs just prior to peak discharge of the river (Middelkoop, 1997). Hence, at a dike breach, when the river discharge is still rising, relatively more sediment is transported into the flooded area than during a dike breach which occurs in a later stage when the river discharge decreases.

The amount of sediment transported into the area is clearly linked with the sediment concentration in the river. This concentration not only varies with the river discharge but also with space and time. Conveyance losses on the floodplains along the river may cause a concentration gradient in downstream direction. The amount of sediment transported into a flooded area therefore depends on the location of the dike breach. The same principle applies to the flooded area, where a concentration gradient exists as well. This is caused by increasing conveyance losses in ‘downstream’ direction from the dike breach. Maximum sedimentation rates occur near the breach, resulting in a relatively large accumulation in a radial pattern. This pattern largely consists of comparatively coarse silt and sand particles. Finer sized particles will be deposited at greater distances from the dike breach where the flow velocity has been reduced substantially.

Besides the river, another source of sediment is the soil in the flooded area itself. Particularly in areas where high flow velocities occur, erosion may enhance the sediment concentration of the water. The most profound example of this is the scour cavity which is eroded beyond the breach in the dike. Soil eroded from this location is deposited in a radial pattern and substantially increases the thickness of the sediment layer near the breach. Other potential sources of sediment are channels/depressions and bare arable lands.

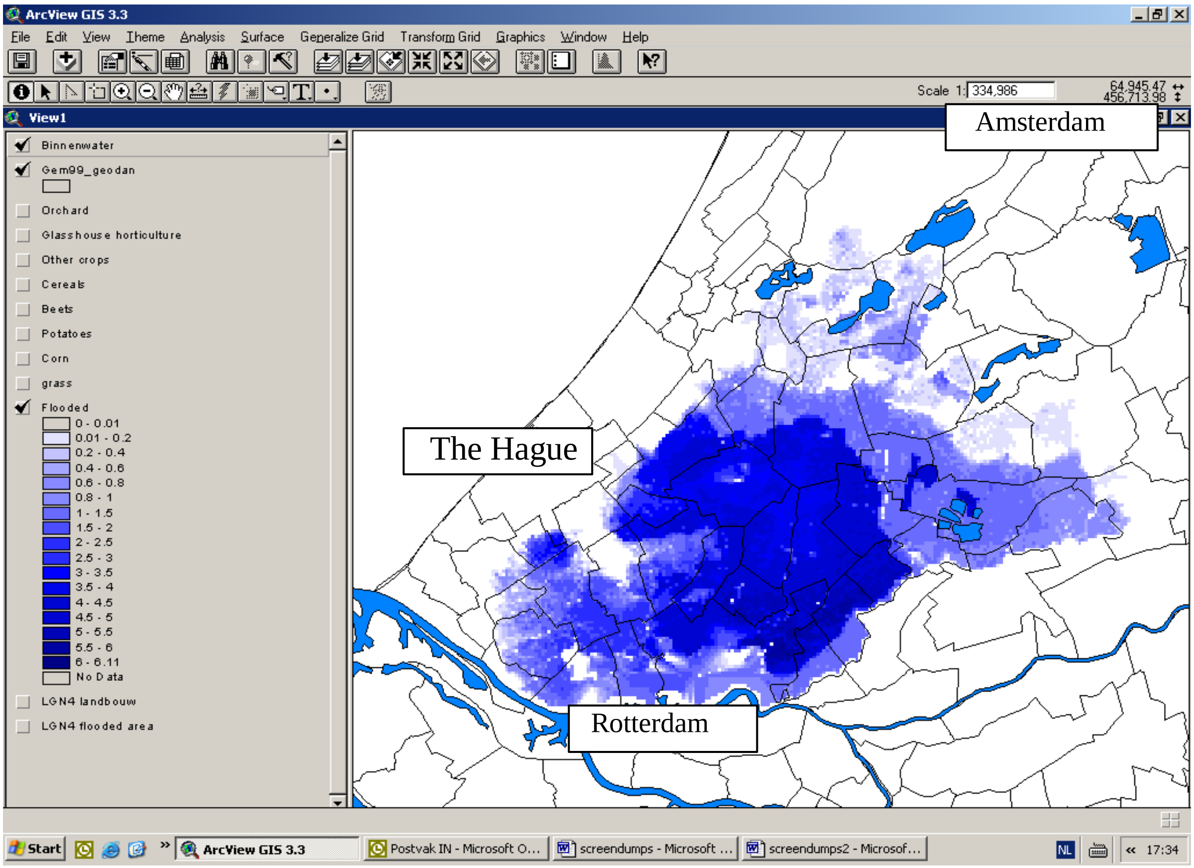

Figure 4 Gross view of the flooded area (46645 ha) after a dike breach near Krimpen aan de Lek, east of Rotterdam. The flooded area is very densely populated.

3.2 The integrated modelling tool Sobek-Delwaq

To investigate the fate of released pollutants and suspended sediments, and to map the locations where the pollutants will settle, a water quantity and a water quality model needed to be integrated. This was done by WL|Delft Hydraulics. A modelling period of ten days was chosen, after which an area of 46645 ha was covered with a water layer of at least 0.01m thickness, which was the area considered for the environmental assessment. This is shown in Figure 4. The flood covers many residential areas, including parts of Rotterdam and Delft, Zoetermeer and Gouda, cf. Figure 4.

The hydraulic simulations were carried out using the SOBEK model developed by WL|Delft Hydraulics. SOBEK Overland Flow consists of a 2-D modelling system, based on the Navier-Stokes equations for depth-integrated free surface flow. All equations are solved through a fully implicit finite difference formulation for all terms in the Navier-Stokes equations, based upon a staggered grid. The special way in which the convective momentum terms have been formulated allows for the computation of mixed sub- and supercritical flows. Based upon this formulation it is also possible to compute the behaviour of standing and moving hydraulic jumps. For these computations to be robust and accurate, there is no need to introduce artificial viscosity.

In combination with the 2-D modelling system, SOBEK is able to handle 1-D elements like (small) water courses and hydraulic structures. In this 1D-2D combination, the 2-D overland flow, including the obstructing effects of embankments and natural levees, is simulated through the 2-D equations of SOBEK Overland Flow, while the sub-2-D-grid gullies and the hydraulic structures are modelled with SOBEK Channel Flow. Both modelling systems produce implicit finite difference equations, which are also linked through an implicit formulation for joint continuity equations at locations where both modelling systems have common water level points, as shown in Figure 5.

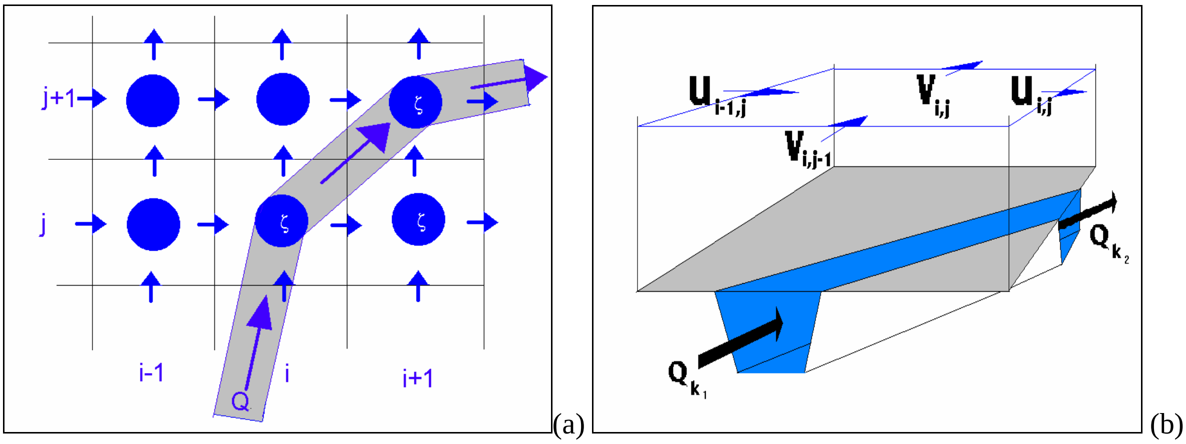

Figure 5 Schematisation of the hydraulic model: a) combined 1D/2D staggered grid; b) combined continuity equation for 1D2D computations

The main advantages of integrated modelling of flow in the 1-D and 2-D domain are:
- 2-D grid steps can usually be significantly larger, as no refinement of the 2-D grid is required for the correct representation of hydraulic structures and gullies;
- as a result, the simulations will run much faster for a comparable level of accuracy;
- a wide variety of hydraulic structure descriptions can be used;
- robustness and accuracy.

The Overland Flow and the Channel Flow modules of SOBEK are based upon the same numerical principles and both allow for stable and robust computations due to the properties of the numerical schemes applied. In addition, at every step in the computation checks are made to prevent physically unrealistic results, such as negative water depths. If such a constraint is not satisfied, the time step is reduced. This procedure is also applied in the flooding and drying of cells in the Overland Flow module. Every time only one neighbouring computational cell can be wetted or dried, otherwise the time step will be reduced to satisfy this criterion. For proof of accuracy, comparison of results has been made with experimental studies, both with published data and obtained through own laboratory experiments. Of particular interest is the strict volume conservation. This feature is of particular importance in the simulation of transport of pollutants. Both the Overland Flow and the Channel Flow modules of SOBEK allow for the inclusion of meteorological effects, such as wind, precipitation and evapotranspiration. In the case of a flooding event caused by a dike break these processes can, however, be neglected. Both the Overland Flow and the Channel Flow modules of SOBEK allow for the specification of spatial variations in roughness. Hydraulic roughness can be specified as Manning-, Chézy- or White Colebrook values. Every grid cell can have its own roughness value, which can be modified through import from GIS or through the editor available in the user interface.

The DELWAQ module imports velocity- and water level (volume) data from the hydrodynamic modules and uses these as a basis for the simulation of the transport of pollutants and the description of water quality processes. DELWAQ contains a library of more than 200 chemical and (micro)biological processes, which can be activated by the modeller.

In the initial phase of this project, the DELWAQ module could not be used in combination with the Overland Flow module. During the project it was decided to integrate both modules in a provisional way so as to allow for simulation of advection of various harmful substances with the flood waters. In the resulting innovative integrated modelling tool, the greater part of the DELWAQ library could not be made available yet. Hence, the physical and chemical processes have been simulated in a very simple yet straightforward manner. More information on the DELWAQ model can be found on www.sobek.nl.

The potential sources of contamination in an area which may be flooded are quite diverse. Hazardous substances are found at farms (herbicides, pesticides), in garbage dumps, in oil tanks near petrol stations or as diffuse sources of contamination in the soil. Given the diverse, and often ill-defined physical and chemical reactions that will be brought about by a flooding event, it was proposed to establish a generic and simple concept, describing the release and subsequent migration of these substances in the area of flooding in general terms, and with a limited set of parameters. In reality, the processes being modelled are much more complex than the simple model used here can account for. The following simplifying assumptions are made:

- all substances are stored in the soil or in various types of containers in-, or outside buildings;
- the substances are released if i) the *inundation depth* exceeds a predetermined threshold value, or ii) the *flow velocity* of the flood water exceeds a threshold value (m/d);
- the release of contaminating substances is quite diverse and complex (e.g. failure of various types of containers, erosive processes at soil/water interfaces). In the DELWAQ model, two release mechanisms are available: i) a constant release flux K_1 with time, from the contaminating source into the water, and ii) a release flux K_2 which decreases proportionally with the decreasing supply of contaminant at the source (first order process);
- once released, the substances (i.e. contaminants) will be transported with the flowing water (advection);
- released substances will not be transported through the soil, nor on top of a soil layer;
- the adsorption of contaminants to suspended particles and the sedimentation (and resuspension) characteristics of suspended matter are merely being modelled implicitly, i.e. as the sedimentation (resuspension) behaviour of the contaminants. Hence, the physical processes of sedimentation and resuspension of floating particles as such are not being modelled;
- any dissolved or suspended substance will decay with time, e.g. through evaporation, bacterial degradation, chemical reactions or combinations of these;
- as the 10-day modelling period is very short as compared to typical decay rates in soils, the decay of contaminants in soils is not included in the modelling concept.

Parameters
In the model, two parameters are defined: the stock at the potential source of contamination (soil, container, bag etc.), C_s ($g.m^{-2}$), and the concentration of a substance in the water, C_w ($g.m^{-3}$), where C can be any substance.

Material balance in the water and in the soil
The substances in the water (C_w) are subject to transport, supply from the soil, sedimentation and decay, viz.:

$$\frac{dC_w}{dt} = \text{net transport + release - sedimentation - decay}$$

Stocks of substances (C_s) in soils will increase by sedimentation and decrease due to release into the water:-

$$\frac{dC_s}{dt} = \text{sedimentation - release into the water.}$$

The release of substances from the soil to the water

In the initial phase, immediately prior to the flooding event, the potential contaminants are in stock, either in the soil or in some sort of container. As outlined above, two release mechanisms are available: i) a constant flux, with time, from the contaminating source into the water until the source is depleted, and ii) a flux which decreases linearly with the decreasing supply of contaminant. Or, expressed in model code:

IF (($V \gtrsim V_{thr}$) OR ($H \gtrsim H_{thr}$)) AND ($C_s > 0$) THEN
IF (Method = 1) THEN $FluxC_{s\rightarrow w} = K_1$
IF (Method = 2) THEN $FluxC_{s\rightarrow w} = K_2 * C_b$
ELSE $FluxC_{s\rightarrow w} = 0$

where

V	= flow velocity of the water	($m.s^{-1}$)
V_{thr}	= threshold flow velocity above which contaminants are being released	($m.s^{-1}$)
H	= water depth	(m)
H_{thr}	= threshold water depth beyond which contaminants are being released	(m)
$FluxC_{s\rightarrow w}$	= Flux density of substance C from the soil to the water	($g.m^{-2}.s^{-1}$)
Method	= indicating the release mechanism	(-)
K_1	= flux density of substance C from the soil to the water	($g.m^{-2}.s^{-1}$)
K_2	= Constant in the first order equation for the release of subatsnces	(s^{-1}).

Sedimentation

Sedimentation of suspended matter occurs when the flow velocity is lower than some preset threshold velocity. The settling velocity of suspended particles is assumed to be a constant.

IF ($V < V_{thr,sed}$) THEN $FluxC_{w\rightarrow s} = V_{sed} * C_w$

Where:

$V_{thr,sed}$	= threshold value of flow velocity for sedimentation	($m.s^{-1}$)
$FluxC_{w\rightarrow s}$	= sedimentation flux	($g.m^{-2}.s^{-1}$)
V_{sed}	= settling velocity	($m.s^{-1}$)

Decay

The decay of substances in the water is simulated as a first order process:

$$Decay = C_3 * C_w$$

where

Decay	: decay rate in water	($g.m^{-3}.s^{-1}$)
C_3	: proportionality constant	(s^{-1})
C_w	: concentration of a substance in water	($g.m^{-3}$)

The modelling period of the flooding event was ten days and the time step of the model 5 min. Alterra have processed all data on chemical compounds (storage location and quantities), supplied by the Dutch Agricultural Economics Research Institute (LEI)[1], TNO-MEP and GeoDelft, after preparing these for input into the simulation models. Data analysis and preparation was done using the applications MS Excel and Arc View V3.3. Locations of storage of chemical compounds in the data files supplied was either linked to (*x*,*y*)-coordinates or assigned to clustered zip code zones within municipalities. All data was relocated geographically to model cells of an imaginary, regular 250×250m grid which was used in the simulation tools and superimposed on the flooded area. Grid cells were assigned ‘active’ in the water quality simulations only if the height of the flooding waters exceeded 0.2m in the water quantity simulations. The land use data, required to assess flood damage in rural areas, were retrieved from the LGN4 land use database of Alterra and have a resolution of 25×25m square grid cells (see Figure 6).

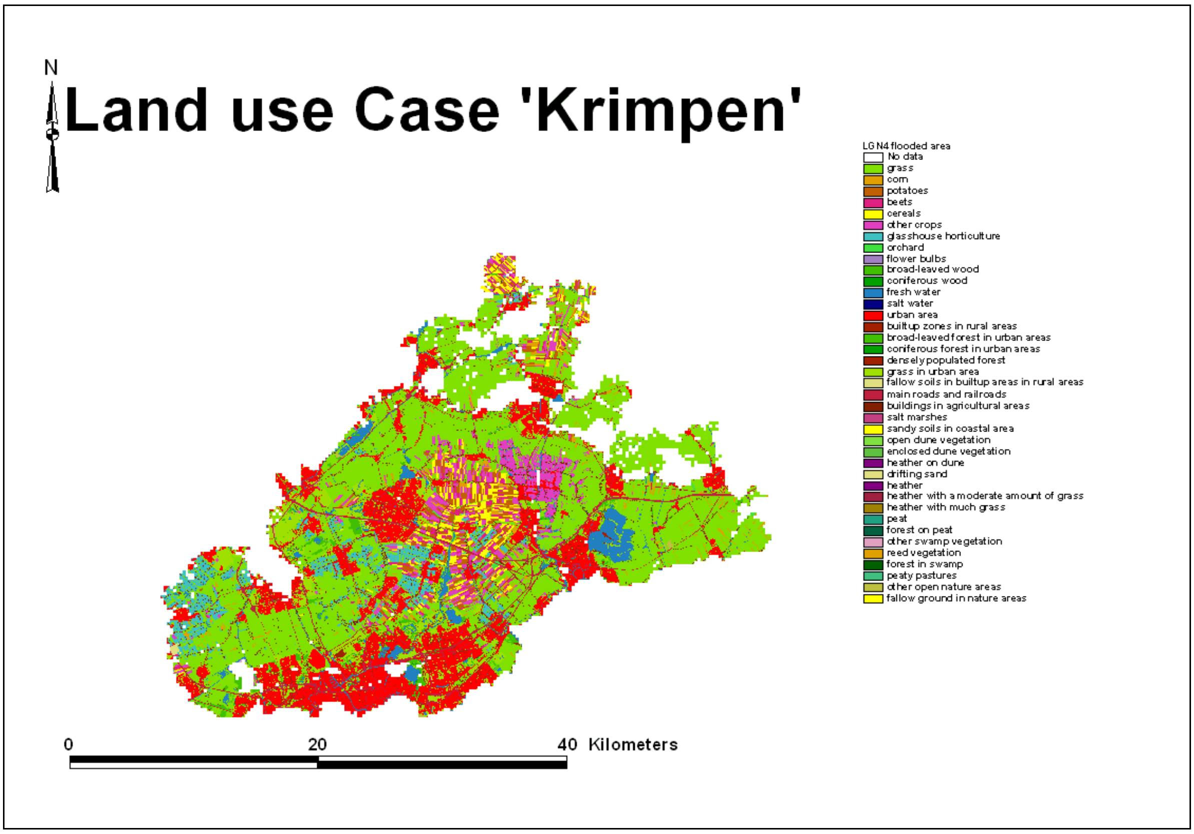

Figure 6 Land use at the flooded area after a dike breach near Krimpen aan de Lek (Source: LGN4 database of Alterra)

[1] The Agricultural Economics Research Institute (LEI) is the leading institute in the Netherlands for social and economic research on agriculture, horticulture, fisheries, forestry and rural areas. The focus of LEI at both national and international level is the increasing integration of agriculture and agribusiness with the social environment. LEI forms part of Wageningen University and Research Centre, a co-operative venture between the Agricultural Research Service, Wageningen University and Research in Practice, and is the central organisation for fundamental strategic and applied research.

3.3 The 'ERA' sediment transport model

3.3.1 Introduction

Suspended material is an important transport medium for pollutants since key pollutants like heavy metals and insecticides as found in rivers and at sources within the flooded area are easily adsorbed to (moving) soil particles. Understanding sediment accumulation therefore helps to assess the accumulation and spatial distribution of potential hazardous toxics. In The Netherlands, this problem has been recognized as a major factor in the management of the embanked floodplains of the rivers Rhine and Meuse, because accumulation of polluted sediments may seriously challenge ecology and agriculture in the floodplain and reduce its potential for other uses. The 'ERA' sediment transport model was developed to simulate sediment accumulation in such areas (Asselman, 2003). This model was also used in this study. The following factors are considered: topography and geometry of the flooded area; transport mechanisms; flood magnitude, concentration of sediment and erosion within the flooded area.

3.3.2 Application of the 'ERA' sedimentation model

3.3.2.1 Model approach

In order to study and visualize the accumulation of sediment during a flood, a dedicated 1-D model was developed using output data of the hydraulic Delft-1D2D model, provided by WL|Delft Hydraulics. The modelling approach is derived form the methodology used by Asselman (2003), who calculated 1-D estimates of sedimentation rates in Emergency Retention Areas (ERAs). Using this method, which was applied in the study of ERAs, it is possible to make a comparison with the results of the experimental DELWAQ model. The method assumes two stages during flooding: i) the *inundation stage*, the period in which the inundated area is flooded, and ii) the *settling stage*, during which the discharge stops and the remaining suspended material will settle. The total amount of sediment is the sum of the depositions that were accumulated during these two stages.

The Inundation stage

Sedimentation is modelled as an accumulation of particles in a settling tank which is related to the trapping efficiency of the tank (Chen, 1975). This efficiency is a ratio between area of the tank and the discharge trough it, which can be regarded as a measure of the residence time of the water and the sediment particles in the tank.

The equation for the sediment trapping efficiency, *E*, reads:

$$E = 1 - \exp(-w_s \, {}^{A}\!/_{Q})$$

where:

w_s	= settling velocity of the suspended sediment particles	($m.s^{-1}$)
A	= surface area of the tank	(m^2)
Q	= discharge through the tank	($m^3.s^{-1}$)

The sedimentation, *S*, is calculated as

$$S = Q_s E$$

where:

S	= sedimentation	(kg.time step^{-1})
Q_s	= suspended sediment load transported into the tank in	(kg.time step^{-1})
E	= trapping efficiency	(-)

The suspended sediment load in a tank, Q_s, is calculated as:

$$Q_S = QCT$$

where

Q	= discharge through the tank	($m^3.s^{-1}$)
C	= suspended sediment concentration	($kg.m^{-3}$)
T	= time step	(s)

In order to apply this method to the study area, each grid cell of the model is considered to be a settling tank. The discharge in a grid cell, Q_x, is calculated as:

$$Q_x = W_d W V$$

where:

W_d	= water depth	(m)
W	= width of grid cell	(m)
V	= flow velocity	($m.s^{-1}$)

The suspended sediment concentration in a grid cell, C_x**,** is calculated as

$$C_x = \exp(-w_s \, {WF}/{Q_x})C$$

where:

w_s	= settling velocity of the suspended sediment particles	($m.s^{-1}$)
W	= cell size width	(m)
F	= length of the flow path form the dike breach	(m)
Q_x	= discharge through the cell	($m^3.s^{-1}$)
C	= suspended sediment concentration at the dike breach	($kg.m^{-3}$)

The term exp(-w_s (WF)/Q) is an estimator of the loss of sediment (ratio) through the inundated area (Chen, 1975). The sedimentation is calculated for each time step in the inundation stage. The total sedimentation during the inundation stage, S_1 (kg), is the cumulative sedimentation which occurred during all time steps.

The settling stage

The sedimentation during the settling stage is assumed to be related to the water depth. In cells with a great depth the volume of water is greater and so is the available suspended sediment load; in cells with a small water depth the reverse is the case.

The total sediment load in the inundated area, L_{12}, (kg) is calculated as:

$$L_{12} = Q_t C$$

where:

Q_t	= total amount of water stored in the area	(m^3)

C	= suspended sediment concentration	($kg.m^{-3}$)

The available suspended sediment load in the settling stage, L_2 (kg), is calculated as:

$$L_2 = L_{12} - S_1$$

The available suspended sediment concentration C_2 ($kg.m^{-3}$) is calculated as:

$$C_2 = L_2 / Q_t$$

The sedimentation in the settling stage, S_2 (kg), is calculated as:

$$S_2 = (W_{dx} / W_{da}) C_2 V$$

where

W_{dx}	= water depth in a model cell	(m)
W_{da}	= average water depth over the inundated area	(m)
V	= stored water volume in a cell	(m^3)

3.3.2.2 Modifications made to the 'ERA'-model

As mentioned before, the method that was applied is derived from Asselman (2003), yet some modifications were made in this project.

Model resolution

- Asselman calculated sedimentation in serial compartments whereas the model used in this study calculates sedimentation from output that was generated by the Delft-1D2D model; no compartment delineation is used;
- the model resolution used by Asselman was equal to the serial compartments; the model used in this project generates results on a cell by cell basis.

Model assumptions

- Sedimentation is calculated using the approach of Chen (1975);
- sedimentation is largely caused by convective sediment transport;
- no sedimentation occurs when flow velocities exceed 0.5 $m.s^{-1}$ (bed shear stress ≈ 2 $N.m^{-2}$);
- during the flood event, the suspended sediment concentration is constant (0.284 $kg.m^{-3}$), this value is an estimated concentration, assumed to occur during a discharge of 16,000 $m^3.s^{-1}$ at the location where the river Rhine enters The Netherlands from Germany (Lobith);
- the total amount of sedimentation equals the stored water volume times the suspended sediment concentration;
- after the inundation stage, the residual suspended sediment is mixed evenly across the inundated area;
- no re-suspension or erosion occurs during the de-inundation of the area;
- the model takes account for the silt fraction of the sediment only;
- the settling velocity is assumed to be $7*10^{-5}$ $m.s^{-1}$ (≈ 6 m/d);
- erosion near the dike breach is not taken into account;
- during any time step, the water depth, flow velocity, flow path and suspended sediment concentration are constant.

Model input

The results of the Delft1D2D-model consist of a digital elevation model of the study area and maps of water depths and flow velocities. All results were provided as grids with a resolution of 250×250m.

The maps, containing water depths and flow velocities were provided as a series of time steps with a six-hour time interval. The flooding event was modelled for a period of ten days.

The travel length from any location in the flooded area to the dike breach was calculated using hydrological GIS functions. For each time step, the water depth was combined with the terrain elevation in order to obtain a water surface. Using this water surface a flow direction map was calculated. On the basis of this map, the travel length to the dike breach was calculated.

3.4 Compounds and mechanisms considered

Types, sources and volumes of the pollutants were determined for the flooded area, as well as release and sedimentation mechanisms. Only a limited number of components could be used for modelling purposes. Ten groups of harmful compounds that were considered the most relevant pollutants for the case study, were selected. They are shown in **Error! Reference source not found.**. The selection is based on a combination of 'toxicity' and volumes (likely to be) present, and was also based on known flood cases. Toxicity should be interpreted somewhat loosely, as the 'capacity to alter or disturb the receiving environment', as a result of which phosphates (enriching the soil of rural areas) are included.

Release / Sedimentation Code	Compound Code	Compound	Release criteria (threshold) for most industrial sites: v (m/s)	h (m)	and / or	Release rate K_2 1/d	Decay rate C_3 1/d	Sedimentation rate V_{sed} (m/d)	Sedimentation threshold v (m/s)
1	1	Floating particles				0.0	0.00000	6.048	
2v	2	Mono aromatics (BTEX)	2	0.5	AND	24.000	0.00864	0.000	
2h			0	1		0.500	0.00864	0.000	
4h	3	Micro-organisms	0	1		0.1	-3,4000	0.000	
4v	4	Poly Aromatic Hydrocarbons - PAH (sum PAH, naphthalene)	2	0.5	AND	24.000	0.00000	4.234	0.5
4h			0.25	1	AND	0.5	0.00000	4.234	0.2
5v	5	Persistent Organic Pollutants - POP (DDT, PCB, Dioxin)	2	0.5	AND	24.000	0.00000	5.443	0.5
5h			0.25	1	AND	0.5	0.00000	5.443	0.2
6v	6	alkanes (straight, cyclo)+ alkenes	2	0.5	AND	24.000	0.000864	5.443	0.5
6h			0.25	1	AND	0.5	0.000864	5.443	0.2
7v	7	Dense Non-aqueous Phase Liquids - DNAPL (TRI, PER)	2	0.5	AND	24.000	0.00864	0.000	
7h			0	1		0.5	0.00864	0.000	
8h	8a	Heavy metals (8a: Zn; 8b: Cd	2	0.5	AND	24.000	0.0000	4.234	0.5 OR 0.2
8v	8b		0.25	1	AND	24.000	0.00000	4.234	0.5 OR 0.2
9v	9	Nutrients (Phosphate)	2	0.5	AND	24.000	0.00000	3.024	0.5
9h			0	0.02		0.5	0.00000	3.024	0.2
10v	10	Pesticides	2	0.5	AND	24.000	0.000086	0.000	
10h			0	1		0.5	0.000086	0.000	

The first group of components, floating particles, is only relevant because the particles serve as the medium for sedimentation through adsorption for poly aromatic hydrocarbons, persistent organic pollutants (like DDT, PCBs), cyclo-alkanes, heavy metals and phosphates. Strongly adsorbed components will settle at the same rate as the floating particles. If adsorption is weaker, slower sedimentation rates are used.
The mono-aromatics (benzene, toluene, ethyl-benzene and xylenes) and PAHs are well-known and notorious soil pollutants, primarily derived from oil products in cars and industrial activities. Alkanes are less toxic yet included in the simulations because of their abundance in oil products. DNAPLs are

also well known pollutants. Because they have a higher density than water they tend to sink through the ground water and accumulate on less permeable layers. This makes removal very difficult. As DNAPLs have a relatively high solubility in water (for an oil-type product) they can be the source of ground water pollution for long periods of time. DNAPLs are abundantly used in dry-cleaning facilities and as de-greasing agents in industrial applications.

The persistent organic pollutants like DDT, PCBs and dioxins are hardly used anymore, but may still be present as a result of activities in the past (as can be seen from the literature study in chapter 2). Because of their high toxicity and tendency to accumulate in fatty tissues they are still a cause for concern. The use of heavy metals is also being reduced, but since they also are very persistent and highly toxic they should receive the necessary attention. Modern pesticides are much less persistent and toxic than conventional crop protection products like DDT. However, because of their abundance, especially in agricultural areas, they should be taken into account.

Finally there are the two 'non-toxic' components listed. Phosphates cause soil-enrichment in rural areas like nature reserves. This results in a significant alteration of the local flora. Micro-organisms may cause of diseases. Decomposing organic material like food and substances found in sewage systems are important sources for the growth of micro-organisms. The SOBEK model does not contain a proper growth model for micro-organisms. Therefore a negative 'decay' rate was used. The growth process is very temperature dependent. As no assumptions are made regarding the season / temperature regime during which the flooding occurs, it is assumed, rather arbitrarily, that the number of micro-organisms will double approx. every half a day, starting from 1% of the sources (food) present.

The criteria for the release of toxic material into the flooding waters are given in **Error! Reference source not found.**. Two criteria were used, labelled '*h*' and '*v*':

v: *High flow condition*: release will occur once water *velocity* exceeds a certain level (suffix '*v*' in the first column of **Error! Reference source not found.**), provided that a certain water height is present (set at 0.5 m). A water velocity of 2 m/s was chosen. The high flow condition represents collapse of a structure or vital parts of a storage container or the turnover of a car. This high-energy condition will generally result in an (almost) instantaneous release. Therefore a (first order) release constant (K_2 in the SOBEK model) is assumed of 1/hr = 24/d (i.e. a release constant of the complete contents of a container per hour).

h: *High water level condition*: release will occur once the water *height* exceeds a certain level (suffix '*h*' in the first column of **Error! Reference source not found.**). A threshold value of 1 m water height was chosen for most simulations. A water height in excess of one meter will result in a relatively gentle release, e.g. as a result of slow dissolution, or collisions of floating debris with containers. Therefore a release rate of 0.5 / day is assumed, half the value used in the high flow condition.

In the SOBEK model, sedimentation is subject to a flow velocity threshold. As sedimentation and release had to be modelled simultaneously, release of material could only take place if the flow velocity exceeded the sedimentation threshold value. Sedimentation threshold values are not well documented. For the '*v*' criterion a value of 0.5 m/s was used, that is, sedimentation will take place at flow velocities below 0.5 m/s. For the '*h*' criterion, however, such a value would prevent the release of much of the stored material Therefore a lower value of 0.2 m/s was chosen as the sedimentation threshold velocity, and 0.25 m/s as the minimum velocity required for the release of material in areas with water height above 1 m. Repercussions of these choices will be discussed in Chapter 4.

The release rate of the toxic materials can be modelled as either constant until depletion (parameter K_1, expressed as grams per m^2 per second) or as a first order process (parameter K_2 expressed as day^{-1}). Sedimentation was modelled as a velocity (V_{sed} in m/d). The choices made for the various components are shown in **Error! Reference source not found.**. The release mechanism will depend on the flooding conditions and the way the materials are used or stored. However, the SOBEK routine only allows for the use of two release mechanisms, based on water height and/or water velocity, as explained earlier.

3.5 Sources (locations) and volumes of pollutants

3.5.1 Information sources

Data on locations and volumes of compounds that have been prepared for the simulations originate from three sources:

1. Data on compounds, stored at or near farms and associated buildings (source: LEI);
2. data on small and large industrial sites (sources: estimations and expert judgement TNO-MEP and GeoDelft, using databases for soil protection, UBI-code and address databases);
3. data on compounds that might be released by cars, subject to flooding (expert judgement TNO-MEP and GeoDelft).

Data reported in these sources had to be converted to values for the components listed in Table 1. For oil type products, the conversions shown in Table 1 were used, based on work done by the 'Total Petroleum Hydrocarbon (TPH) Criteria Working Group' (TPHCWG, or 'Working Group') in the United States (Potter and Simmons, 1998). The TPH Working Group convened in 1993 to address the large disparity among cleanup requirements being used by states at sites contaminated with hydrocarbon materials such as fuels, lubricating oils and crude oils. The Working Group aimed to develop scientifically defensible information for establishing soil cleanup levels that are protective of human health at petroleum-contaminated sites.

Component	Mono aromatics *(BTEX, benzene)*	PAH (*PAK10*)	PCB	Alkanes + alkenes	(Zn)
Gasoline	19 (*19, 1.9*)	16	0	60	0
Paraffin oil, Diesel oil	6 (*0.8, 0.03*)	7 (*0.36*)	0	79	0.005
Fuel oil /Lubrication oil	4 (*0.7, 0.1*)	18 *(0.1*)	0.011	73	0.14

Table 1 Components (weight %) of oil products for commercially available fuels

If mono-aromatics were replaced by BTEX the values for Diesel and Lubrication oil would be significantly reduced (to 0.8% and 0.7% respectively). For gasoline, however, the bulk of the mono-aromatics are BTEX components. Of all BTEX components approximately 10% is Benzene.
If we were to concentrate on the 10 specific PAH components specified in Dutch legislation with respect to cleanup of polluted soil (PAK10), the values would be very much different for Diesel and Lubrication oil with values for the sum of these PAH components of 0.36% and 0.1% respectively. For gasoline no values are specified, but it is likely that also for this oil fraction a value significantly lower (say 5% of all PAHs) would be found.

3.5.2 Pollutants in rural areas

Data on potential pollutants, located at and near farms in 16 municipalities, which are located in the 'Krimpen' pilot area, was supplied by the Dutch Agricultural Economics Research Institute LEI. This data is assembled on the basis of data, gathered about individual farms yet made anonymous to the level of municipalities, cf. Figure 7. These pollutants may either be stored in containers in barns located at the farm, or applied on agricultural fields. Flooding may cause failure of these containers, followed by migration of (part of) their contents. The compounds on which data could be obtained in this study include various types of fertilizers, three types of oil products, farmyard manure and various sorts of pesticides; cf. Table 2 and Table 3. The data, summarised in Table 2 and Table 3 were retrieved from the so-called 'BIN[2]' database of LEI, for the period 1999/2000. In these tables, two scenarios are presented: the so-called maximum and the minimum one. The maximum scenario refers to assessments of stocks of many compounds, on a fixed date, namely April 30th. In this study, the maximum scenario has been used for the simulations. In order to enhance the reliability of the data,

2 'BIN' is an acronym for *Bedrijven Informatie Net*, an information data base on Dutch agricultural businesses.

data on farms, located outside the flooded area were also considered while establishing the data sets. Major facts and limitations on data retrieval are discussed below.

Fertilizers-N-P-K

Stocks of fertilizers in horticulture are not registered, hence these stocks are estimated on the basis of associated data found at other farms located in the region. Fertilizers are geographically linked to the land use type 'buildings in rural areas' of the 'LGN4' data base..

Oils

On April 30th, stocks of fuel oils at farms comprise approximately 10% of the annual consumption. Stocks are assessed by taking 20% (max) and 5% (min) of annual consumption. No data is available on stocks of fuel oils in horticulture. Here, too, stocks are assessed by taking 20% (max) and 5% (min) of the annual consumption. Paraffin oil and Diesel oil are geographically linked to the land use type 'buildings in rural areas' of the LGN4 database of Alterra. Fuel oil is assumed to be stored at/near greenhouse locations.

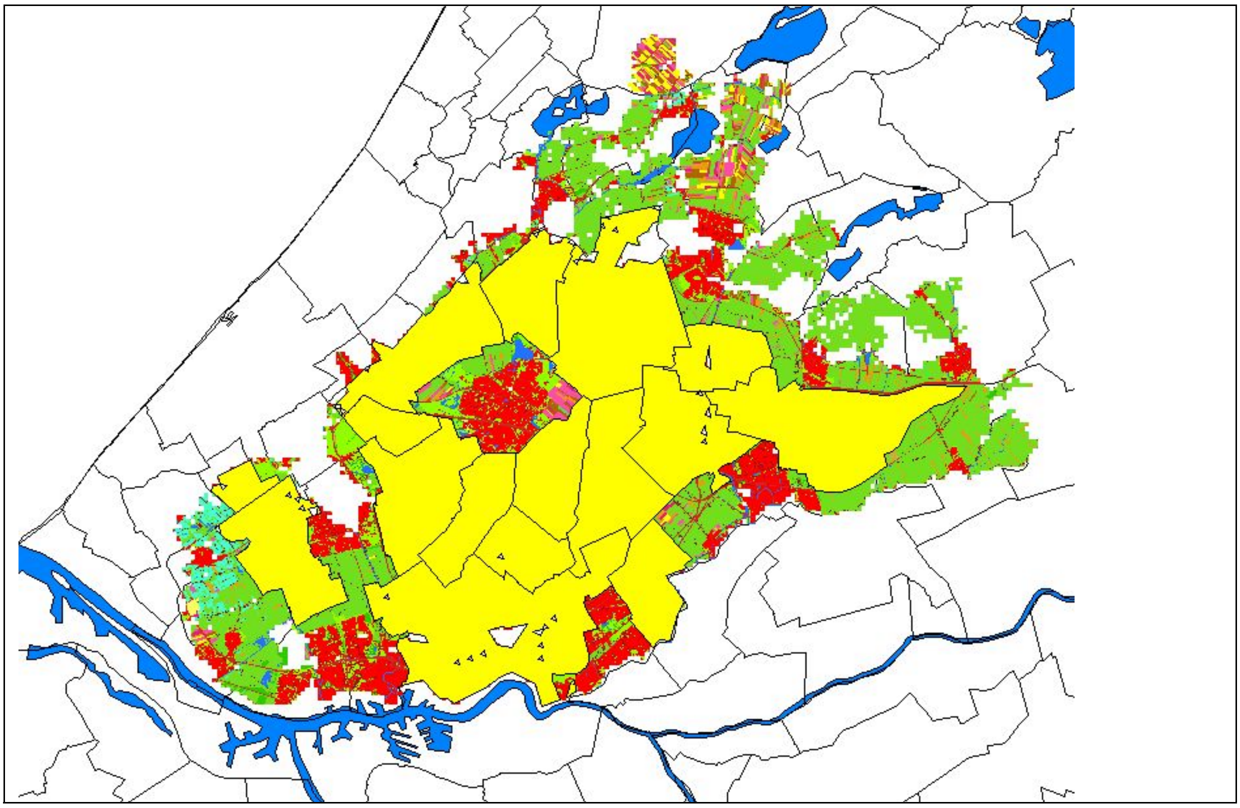

Figure 7 The flooded area after a dike breach near Krimpen aan de Lek (all areas with the water layer height exceeding 0.01m,; superimposed by yellow areas depicting the municipalities for which data concerning rural areas were supplied by LEI (see text)

Farmyard manure-N-P-K

Data on the total production of animal manure, which are estimated on the basis of excretion data, are supplied by Statistics Netherlands (*CBS Landbouwtelling*). During the period running from mid-September to mid-February, no animal manure may be applied on agricultural fields, located on sandy soils, nor on grasslands. On other soil types, manure must be covered by soil or injected into the upper soil layer. In the pilot area, there are hardly any sandy soils, yet 60% of the area consists of grassland. It is assumed that manure will be applied on 20% of the total area of agricultural lands. For the sake of convenience it is assumed that a quantity of manure produced during one month will be applied on the fields during the period running from mid-September to mid-February. Hence the remainder, i.e. the stock of manure covering a period of four months, will be the maximum amount which will be stored at any farm at the end of the winter. On April 30th, stocks of farmyard manure will amount to approximately 50% of the annual use, and the associated data set is the scenario with the maximum assumed stocks (Table 2). In the minimum scenario, data on farmyard manure amount to 10% of the annual use (Table 3).

Agrichemicals
This clustered category was not used in this study as it includes at least ten different chemical agents with widely different chemical compositions and hence properties. These quantities are specified here merely as a reference.

Pesticides (i.e. insecticides, fungicides, herbicides and nematicides)
The compounds, specified in the columns ‘nematicides’, ‘fungicides’, ‘herbicides’ and ‘pesticides’ are used in the model simulations, clustered into one category ‘pesticides’. Pesticides are geographically linked to the land use type ‘buildings in rural areas’ of the LGN4 database. Stocks of pesticides are not registered, yet the consumption is. Hence, stocks are estimated on the basis of consumption data. In general, stocks will be limited; in the minimum scenario, stocks are assumed to be 5% of the annual consumption; in the maximum scenario, these stocks are assumed to be 10%.

The harmful compounds that were selected to be included in the model simulations are:
- Fertilizer-P;
- Paraffin-oil, Diesel oil and Fuel oil (as one category);
- Farmland manure-P;
- Insecticides, Fungicides, Herbicides and Nematicides (as one category).

These categories are indicated as shaded columns in Table 2.

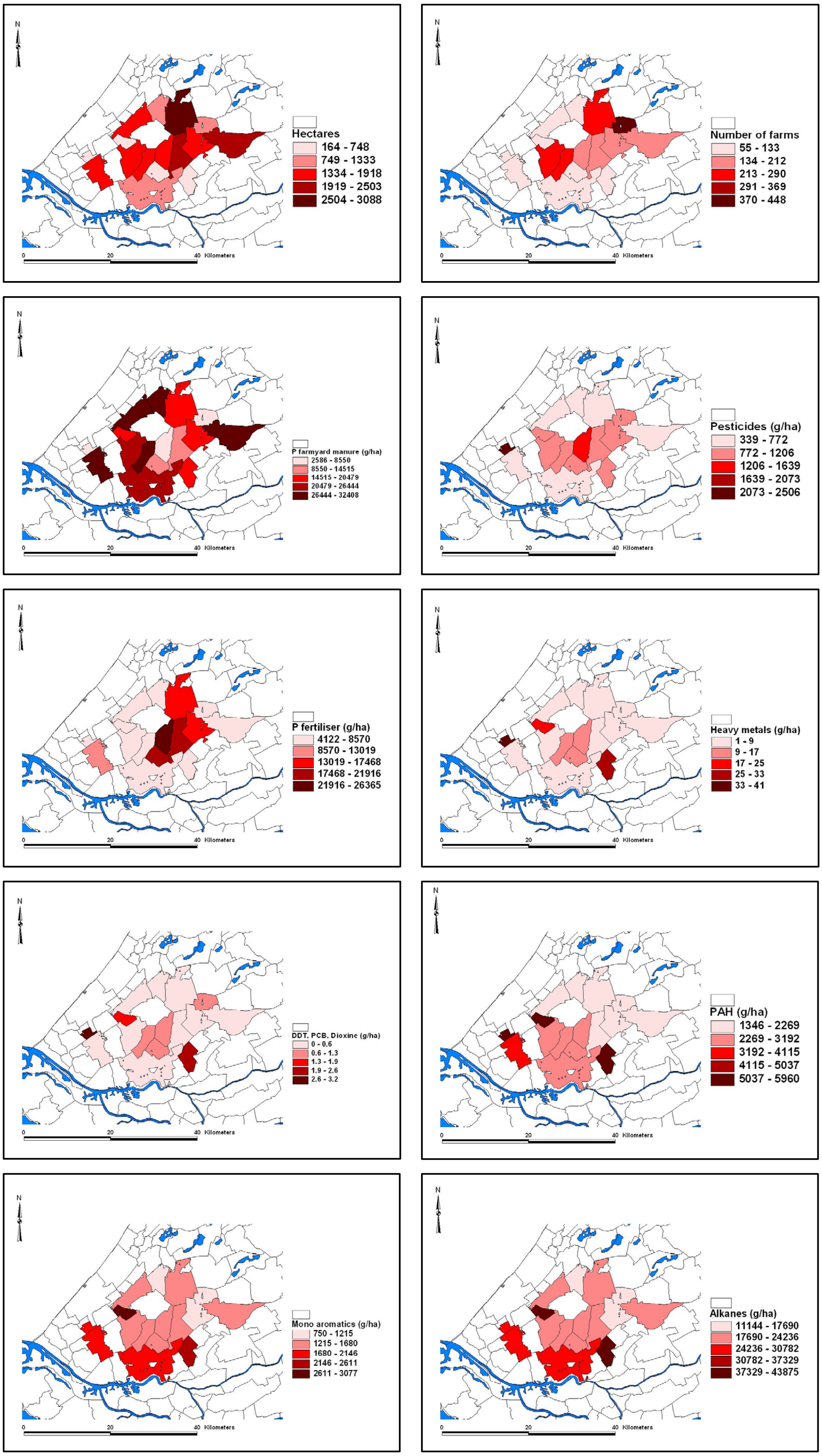

Figure 8 Statistics about farms in the pilot area 'Krimpen' and harmful compounds, stored at these locations, in 16 municipalities

Municipality	Number of farms	Total area (ha)	Fertilizer N (kg)	Fertilizer P (kg)	Fertilizer K (kg)	Paraffin oil (liters)	Diesel oil (liters)	Fuel oil (liters)	Farmyard manure (kg x 1000)	Farmyard manure N (kg)	Farmyard manure P (kg)	Farmyard manure K (kg)	Agrichemicals (kg)	Insecticides (kg)	Fungicides (kg)	Herbicides (kg)	Nematicides (kg)
Boskoop	448	1 201	54 800	6 977	718	1 500	10 250	8 853	4 316	29 508	8 925	35 546	1 360	152	597	316	169
Pijnacker	274	1 639	87 212	11 998	1 196	1 500	47 570	5 486	17 299	126 523	40 804	145 272	2 231	208	1 233	318	15
Rijnwoude	254	3 088	297 070	51 470	87 388	1 500	85 570	3 565	22 926	181 848	59 854	196 807	2 233	153	1 140	522	159
Berkel en Rodenrijs	233	1 461	94 725	11 992	1 624	1 500	31 210	14 397	19 399	146 849	45 666	163 987	1 987	207	1 076	253	11
Bleiswijk	208	1 426	183 205	37 596	103 729	0	27 590	11 976	1 221	9 772	3 687	10 119	2 769	258	1 331	288	99
Zevenhuizen-Moerkapelle	179	2 417	201 671	43 051	105 621	0	55 201	13 613	8 043	90 133	31 917	69 181	3 429	194	1 758	592	209
Reeuwijk	177	2 428	155 887	17 281	1 430	7 500	65 920	839	35 496	254 749	78 687	290 237	868	29	524	245	25
Waddinxveen	143	1 831	144 691	30 997	69 468	0	36 850	1 781	8 227	75 714	26 700	70 058	2 024	106	1 058	465	20
Schipluiden	114	1 395	133 332	15 328	801	3 000	49 380	9 091	20 271	134 097	39 396	170 031	821	72	436	181	2
Leidschendam	109	1 549	111 510	12 392	1 681	4 500	45 070	60	21 736	150 200	48 345	178 129	727	30	458	192	2
Nieuwerkerk aan den IJssel	98	686	39 371	4 238	256	3 000	21 140	15 240	6 587	44 094	13 364	54 117	793	74	456	100	10
Nootdorp	74	339	16 547	1 397	59	0	16 050	6 601	2 877	19 721	6 050	24 117	513	56	290	24	5
Zoeterwoude	68	1 314	83 931	8 899	401	0	31 010	30	18 257	123 796	36 569	154 763	595	12	368	187	0
Bergschenhoek	67	682	74 631	14 203	33 251	0	13 150	6 211	3 457	22 987	6 721	29 233	922	91	475	121	7
Wateringen	66	164	5 228	785	136	0	2 000	5 611	534	3 722	1 101	4 229	1 213	72	309	27	2
Rotterdam	55	834	39 366	4 441	229	1 530	30 500	1 721	8 604	58 489	17 330	73 441	396	18	245	88	1

Table 2 Harmful compounds located at farms or on agricultural fields in the pilot area; maximum scenario

Municipality	Number of farms	Total area (ha)	Fertilizer N (kg)	Fertilizer P (kg)	Fertilizer K (kg)	Paraffin oil (liters)	Diesel-oil (liters)	Fuel oil (liters)	Farmyard manure (kg x 1000)	Farmyard manure N (kg)	Farmyard manure P (kg)	Farmyard manure K (kg)	Agrichemicals (kg)	Insecticides (kg)	Fungicides (kg)	Herbicides (kg)	Nematicides (kg)
Boskoop	448	1 201	10 960	1 395	144	375	2 563	2 213	1 079	7 377	2 231	8 887	680	76	298	158	85
Pijnacker	274	1 639	17 442	2 400	239	375	11 893	1 371	4 325	31 631	10 201	36 318	1 116	104	617	159	7
Rijnwoude	254	3 088	59 414	10 294	17 478	375	21 393	891	5 731	45 462	14 964	49 202	1 116	76	570	261	80
Berkel en Rodenrijs	233	1 461	18 945	2 398	325	375	7 803	3 599	4 850	36 712	11 417	40 997	994	104	538	127	5
Bleiswijk	208	1 426	36 641	7 519	20 746	0	6 898	2 994	305	2 443	922	2 530	1 384	129	665	144	49
Zevenhuizen Moerkapelle	179	2 417	40 334	8 610	21 124	0	13 800	3 403	2 011	22 533	7 979	17 295	1 715	97	879	296	104
Reeuwijk	177	2 428	31 177	3 456	286	1 875	16 480	210	8 874	63 687	19 672	72 559	434	15	262	122	12
Waddinxveen	143	1 831	28 938	6 199	13 894	0	9 213	445	2 057	18 929	6 675	17 514	1 012	53	529	232	10
Schipluiden	114	1 395	26 666	3 066	160	750	12 345	2 273	5 068	33 524	9 849	42 508	410	36	218	90	1
Leidschendam	109	1 549	22 302	2 478	336	1 125	11 268	15	5 434	37 550	12 086	44 532	364	15	229	96	1
Nieuwerkerk a/d IJssel	98	686	7 874	848	51	750	5 285	3 810	1 647	11 023	3 341	13 529	396	37	228	50	5
Nootdorp	74	339	3 309	279	12	0	4 013	1 650	719	4 930	1 513	6 029	256	28	145	12	2
Zoeterwoude	68	1 314	16 786	1 780	80	0	7 753	8	4 564	30 949	9 142	38 691	298	6	184	94	0
Bergschenhoek	67	682	14 926	2 841	6 650	0	3 288	1 553	864	5 747	1 680	7 308	461	45	238	60	4
Wateringen	66	164	1 046	157	27	0	500	1 403	134	930	275	1 057	606	36	154	14	1
Rotterdam	55	834	7 873	888	46	383	7 625	430	2 151	14 622	4 333	18 360	198	9	123	44	0

Table 3 Harmful compounds located at farms or on agricultural fields in the pilot area; minimum scenario

3.5.3 Pollutants at small and large industrial locations

The volumes, locations and categories of chemicals stockpiled in the ‘Krimpen’ modelling area were established using the so-called Dutch UBI-list. The UBI-list was compiled in 2001, on request of the Dutch Inter-provincial Council (IPO) and the Ministry of VROM (Environment and Spatial Planning). This list consists of industrial activities that are potentially polluting for soils. In addition, the UBI-code gives information on the probability that the pollutants are released from their sources (under typical operational conditions), quantities present and the toxicity of the pollutants. This information is combined into the NSX-value. The NSX-value can be regarded as an indication for the environmental pollution risk resulting from industrial activities. This value is not assumed to be a reliable indicator for extreme situations like floods. Therefore, this information was combination with expert knowledge to obtain quantities of pollutants, representative for each industrial activity on the UBI-list and present in the flooded area in the ‘Krimpen’ case. From an location database, containing all commercial companies in the flooded area, the companies with activities referred to on the UBI-list were selected for inclusion in the modelling. This amounted to a total of 701 companies. In some cases, company specific information on types and quantities of chemicals present was used during modelling. This was the case for eight companies, subject to the so-called Seveso II Directive (1996).
The UBI categories are shown In Table 4, including the number of companies in each category and quantities assumed present per category. Data for the eight ‘Seveso II’ companies are shown as well.

Category on UBI-list	Number of companies	Amount present in each category used for modelling (kg)									
		Mono aromatics	Micro-organisms	PAH	POPs	Alkanes (straight, cyclo) + alkenes	DNAPLs	Heavy metals (zinc)	Heavy metals (cadmium)	phosphates	Pesticides
Aluminium (wholesale, plants)	3	600	-	-	-	-	3000	3000	-	-	-
Batteries (wholesale, plants)	3	-	-	-	-	-	-	-	300	-	-
Gasoline and oil (wholesale)	14	120960	-	97720	15.4	458220	-	26.6	-	-	-
Pharmaceutical raw materials (wholesale)	5	-	-	-	-	-	5000	-	-	-	-
Pharmaceutical industry and wholesale	27	-	-	-	-	-	27000	-	-	-	-
Colouring agents (wholesale, plants)	2	2200	-	-	-	-	200	200	-	-	-
Fertilizer (wholesale, plants)	1	-	-	-	-	-	-	-	-	12500	-
Synthetic materials (wholesale, plants)	18	18000	-	-	-	-	-	-	-	-	-
Synthetic materials processing plants	16	16000	-	-	-	-	-	-	-	-	-
Raw materials for foodstuffs (wholesale)	11	-	110000	-	-	-	-	-	-	-	-
Margarine, oil and fat (industry)	4	-	40000	-	-	-	-	-	-	-	-
Petrochemical industry	10	21600	-	17450	2.8	81830	-	4.8	-	-	-
Plastics processing industry	2	2000	-	-	-	-	-	-	-	-	-
Polishing materials (wholesale, plants)	2	-	-	-	-	-	2000	-	-	-	-
Steel cables and wires (plants)	4	-	-	-	-	-	4000	-	-	-	-
Petrol stations	89	768960	-	621220	97.9	2912970	-	169.1	-	-	-
Paints (wholesale, plants)	13	14300	-	-	-	-	1300	1300	-	-	-
Detergents (wholesale, plants)	2	-	-	-	-	-	-	-	-	1000	-
Cosmetics (wholesale, plants)	22	2200	-	-	-	-	-	-	-	-	-
Wire (wholesale, plants)	1	-	-	-	-	-	1000	-	-	-	-
Flour (wholesale, plants)	3	-	30000	-	-	-	-	-	-	-	-
Steel components (plants)	3	-	-	-	-	-	600	-	-	-	-
Rubber articles (wholesale, plants)	6	6000	-	-	-	-	-	-	-	-	-
Cleaning agents (wholesale, plants)	29	290000	-	-	-	-	-	-	-	-	-
Slaughter devices (wholesale)	2	-	20000	-	-	-	-	-	-	-	-

Illumination devices (plants)	2	-	-	-	-	-	400	-	-	-	-
Meats and meat products (whole-sale, plants)	62	-	620000	-	-	-	-	-	-	-	-
Recycling	20	4000	-	-	-	4000	-	-	-	-	-
Waste paper	5	-	-	-	-	-	1000	-	-	-	-
Industrial cleaning	9	-	-	-	-	-	1800	-	-	-	-
Litter	7	-	-	-	-	-	-	700	-	-	-
Glue	6	600	-	-	-	-	-	-	-	-	-
Lubrication oil and grease	10	400	-	1800	-	7300	-	40	-	-	-
Electric transformers	5	-	-	-	5	-	-	-	-	-	-
Self-adhesive materials	3	3000	-	-	-	-	-	-	-	-	-
Paraffin oil	1	2160	-	1745	0.28	8183	-	0.48	-	-	-
Fuels	3	6480	-	5235	0.84	24549	-	1.44	-	-	-
Car paints	7	7700	-	-	-	-	700	700	-	-	-
Coating	11	12100	-	-	-	-	1100	1100	-	-	-
Yacht painting and maintenance	1	-	-	1000	-	-	-	-	-	-	-
Spraying and electrolytic coating	11	12100	-	-	-	-	1100	1100	-	-	-
Ship maintenance and cleaning	4	-	-	4000	-	-	-	-	-	-	-
Slaughterhouses	4	-	40000	-	-	-	-	-	-	-	-
Chemical industry (raw materials)	11	15400	-	19800	12.1	80300	-	154	-	-	-
Print shops	162	16200	-	-	-	-	-	-	-	-	-
Dry cleaning	65	-	-	-	-	-	13000	-	-	-	-
Seveso II companies	8	10	10000	450	-	400	180	460	-	3350	1350
TOTAL		**1342970**	**870000**	**770420**	**134**	**3577752**	**63380**	**8958**	**300**	**16850**	**1350**
cars	75261	259350	-	277563	41.4	1172718	-	537	-	-	-

Table 4 Quantities of pollutants, stockpiled in industry and cars, used in the simulations

3.5.4 Pollutants from urban sources

Table 5 gives a summary of relevant elements present in the urbanised areas in the flooded ‘Krimpen’ area.

Category	Flooded units
Residential area	8.16 10^7 m^2
Recreational area (extensive)	3.21 10^7 m^2
Recreational area (intensive)	1.23 10^7 m^2
Houses	2.33 10^5
Low rise apartments	5.47 10^4
Medium rise apartments	7.05 10^5
High rise apartments	5.59 10^5
Cars and motors	3.57 10^5

Table 5 Summary of the flooded units in metropolitan areas for the ‘Krimpen’ area.

The following sources of pollution can be identified: households, cars and motorcycles, petrol stations, small printers, dry cleaners and offices. Petrol stations, dry cleaners and printers are included in the modelling exercise through the UBI-list (see above). Offices and households are not considered significant contributors of pollutants. They may however be sources of micro-organisms. Because of the lack of a proper modelling algorithm for growth of micro-organisms - as discussed above – these potential sources were not included in the analyses.

For cars (cf. Table 5) the following volumes are used: 20 kg fuel (half a tank) and 5 kg lubrication oil. 81% of the cars uses petrol, 14% Diesel; the remainder being LPG, which is not relevant for this study. Table 1 was used tot calculate masses of individual compounds from gasoline, Diesel and lubrication oil.

3.5.5 Pollutants in the flood (river) water

The incoming floodwater, which originates primarily from the river Rhine, typically contains the quantities of pollutants, shown in Table 6. These quantities were used during modelling.

ID Number	Component name	concentration in Rhine water (mg/l)
1	Floating particles	284
2	Benzene	0.000209
3	E-coli	-
4	PAH	0.055072
5	PCB	0.00589
6	Alkanes	0.1278
7	PER	0.000266
8a	Zn	0.163706
8b	Cd	0.000588
9	P	0.825317
10	Pesticides	-

Table 6 Concentrations of pollutants in incoming floodwater from river Rhine

3.6 Release of pollutants into the environment

The release mechanisms for pollutants (‘how’ and ‘when’) largely depend on the way the pollutants are stored or used. It is expected that pollutants are released in water levels exceeding 1m because containers will start to float. At water flow velocities greater than 2 m/s, vital (support) structures may start to collapse, resulting in released of material.

Table 7 contains the release criteria for pollutants for small, intermediate and large companies, as well as for cars and for farms in rural areas. Numbers in the table indicate the weight percentages of released pollutant (once the release thresholds, given in Table 7, are exceeded by the incoming water) that were used in the modelling exercise.

For most categories it is assumed that 50% of the material (100% for heavy metals) will be released if condition ‘h’ is met and 50% if the ‘v’ condition is exceeded (see also Table 8). As the ‘*v*’ (=velocity) condition was exceeded in a very small area near the dike breach, the ‘*v*’ criterion was used in limited number of cases only (see Chapter 4). For large storage tanks in the petrochemical industry containing large amounts of oil-products, and for petrol stations with underground storage tanks, only the high flow condition (velocities in excess of 2 m/s) is expected to cause sufficient damage for release of (max. 50% of the) product.

For cars, the release of lubrication oil and petrol is expected to occur once the ‘*v*’ or ‘*h*’ criterion is met. However, if only the - less severe - ‘*h*’ condition is met, 10% if the oil and petrol is expected to be released, instead of the 50%, stated for the ‘*v*’-condition.

Category	Mono aromatics		Micro-organisms	PAHs		POPs (DDT, PCB, Dioxine)		Alkanes (straight, cyclo) + alkenes		DNAPLs		Heavy metals (zinc (a) and cadmium (b))			Phosphate		Pesticides	
release criterion during the flood - see first column	2h	2v	3h	4h	4v	5h	5v	6h	6v	7h	7v	8ah	8av	8bh	9h	9v	10h	10v
Small and intermediate industry																		
Aluminium (wholesale, plants)	50									50		100						
Batteries (wholesale, plants)														100				
Gasoline and oil (wholesale)		50			50		50		50				50					
Farmaceutic raw materials (wholesale)										50								
Farmaceutic industry and wholesale										50								
Colouring agents (wholesale, plants)	50									50		100						
Fertilizer (wholesale, plants)																50		
Synthetic materials (wholesale, plants)	50																	
Synthetic materials processing plants	50																	
Raw materials for foodstuffs (wholesale)			50															
Margarine, oil and fat (industrie)			50															
Petrochemical industry		50			50		50		50				50					
Plastics processing industry	50																	
Polishing materials (wholesale, plants)										50								
Steel cables and wires (fabrieken)										50								
Petrol stations		50			50		50		50				50					
Paints (wholesale, plants)	50									50		100						
Detergents (wholesale, plants)																50		
Cosmetics (wholesale, plants)	50																	
Wire (wholesale, plants)										50								
Flour (wholesale, plants)			50															
Steel components (fabrieken)										50								
Rubber articles (wholesale, plants)	50																	
Cleaning agents (wholesale, plants)	50																	
Slaughter devices (wholesale)			50															
Illumination devices (fabrieken)										50								
Meats and meat products (wholesale, plants)			50															
Recycling	50							50										
Waste paper										50								
Industrial cleaning										50								
Litter													100					
Glue	50																	
Lubrication oil and grease	50			50				50				50						
Electric transformers						50												
Self-adhesive materials	50																	
Paraffin oil		50			50		50		50				50					
Fuels		50			50		50		50				50					
Car paints	50									50		100						
Coating	50									50		100						
Yacht painting and maintenance				50														
Spraying and electrolytic coating	50									50		100						
Ship maintenance and cleaning				50														
Slaughterhouses			50															
Chemical industry (raw materials)	50			50				50		50		100				50		
Print shops	50																	

Dry cleaning										50								
Large industries																		
'Seveso II'	50	50	50	50	50			50	50	50	50			100		50	50	50
cars (located in built-up areas and on motorways)	10	50		10	50	10	50	10	50			10	50					
Pollutants, located in rural areas																		
Fuel oils, fertilizers and pesticides on/near farms in rural areas		50			50				50				50		25		25	
Farmyard manure, applied on arable lands															50			

Table 7 Summary of percentages of total pollutants present that may be released once the release criteria are met

From farms, oil type products (fuel), phosphates and pesticides will be released following the mechanisms and criteria, shown in Table 8. Pesticides are stored in barns, mostly well protected against scour due to high velocity water flow, hence failure of bags and containers is associated with water table height ('*h*' criterion). Oils are kept in tanks that are assumed to fail only due to high velocity water flows, similar to the storage tanks on industrial sites. The percentages released that are specified in Table 8 are assessed on the basis of expert judgement (GeoDelft, Alterra and TNO-MEP).

Compound	**h>1m % released**	**h> 2 cm % released**	**v>2m/s % released**
Phosphates		50	
Oils (3 types)	--		50
Farmyard manure (P)	50	50	--
Pesticides	25		

Table 8 Release mechanisms and -criteria for compounds, stored at farms and rural areas

The vast majority of fertilizers in the flooded area is found on agricultural land. Phosphates from this source will dissolve in the water flooding the farmland. Even a very thin layer of water will suffice to do so. Also the liquid part of manure present on farms (assumed 50% of the total), will be easily transported by flowing water. Therefore, a threshold value of 2 cm of water (criterion 9h) was chosen for the release of phosphates. The release phosphates from other sources was not simulated in this study.

It is emphasised that the assumed release mechanisms are an substantial simplification of reality, and in many cases, would overestimate the amounts released. However, in order to assess *potential* consequences, this approach was considered very useful.

4 The 'Krimpen' case: results of the simulations, concentrations of pollutants during and after flooding

Results of the simulations are discussed in this chapter. For simulation of the sedimentation of floating particles and heavy metals, both the 'ERA' and the 'DELWAQ' models were run. Results for both models are shown in paragraphs 4.1 and 4.8 respectively. For the other components only the DELWAQ model was used. In Figure 9 and Figure 10, the maximum water depths and flow velocities reached during the flooding event are shown. It can be seen that the '*v*' criterion (maximum flow velocity exceeding 2 m/s) is only reached in a small area near de location of the dike breach. Therefore, this criterion was used only in a limited number of cases during modelling, essentially only for large and relatively abundant storage tanks and for cars (see Table 7). The '*h*' criterion, however, is exceeded in a very large area, and will be responsible for most of the releases of pollutants.

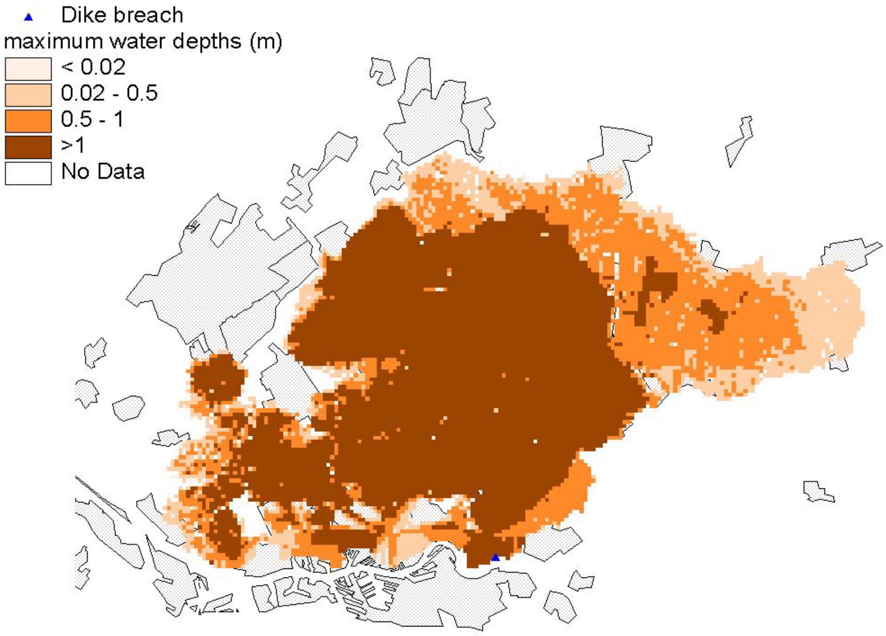

Figure 9 Maximum water depths reached during flooding

Table 9 summarises the modelled cases and release criteria that are discussed in this chapter. The situation at the end of the modelling period (after 10 days) is shown for all compounds, if present. For the compounds that are subject to decay (i.e. where $C_3 > 0$), the situation after two days is discussed too, in order to illustrate the effect of natural attenuation.

code	name of compound		after 2 days 'h'-criterion	after 2 days 'v'-criterion	After 10 days 'h'-criterion	After 10 days 'v'-criterion
1	Floating particles					
2	Mono aromatics		➽	➽	➽	➽
3	Micro-organisms		➽		(after 7 days)	
4	PAH				➽	➽
5	POP				➽	➽
6	alkanes (straight, cyclo)+ alkenes				➽	➽
7	DNAPL (TRI, PER)		➽	no release	➽	no release
8a	Heavy metals	8a: Zn			➽	➽
8b		8b: Cd			➽	not present
9	Phosphates				➽	➽
10	Pesticides		➽	no release	➽	no release

Table 9 Summary of the compounds and release mechanisms for which model output is discussed.

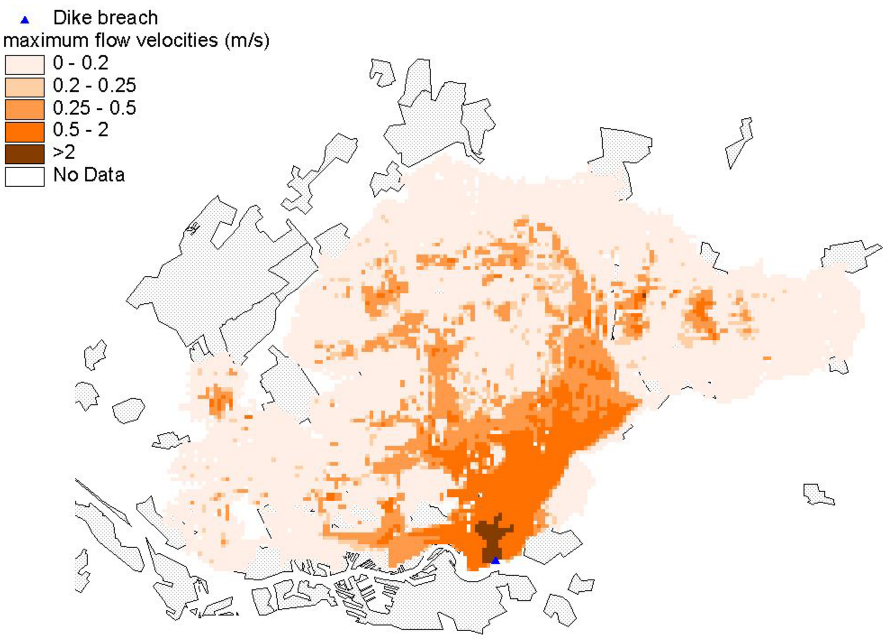

Figure 10 maximum flow velocities reached during flooding simulation

4.1 Floating Particles

In order to assess the sedimentation of particles, both the ERA and the DELWAQ models were used. In the ERA model, the only source of floating particles is the suspended matter imported with the floodwaters that originate from the river Rhine; in the DELWAQ simulations, suspended material may originate from the flooded polder district as well. In both models, a threshold water flow velocity of 0.5 m/s was used, below which sedimentation takes place. The total inundated area covers 654 km^2, whereby $1.37 * 10^9$ m^3 of water is stored Assuming a concentration of suspended material in the river water of 0.284 kg/m^3 (see Table 6), the amount of sediment, deposited in the area will be approximately $388 * 10^6$ kg. The average deposition in the area is therefore 0.59 kg/m^2 which, in theory, is similar to a uniform sediment layer of 0.35 mm, assuming a sediment density ρ_{sed} of 1700 kg/m^3.

Near the breach of the dike, land sourced material will contribute to the volume of suspended material. As said, in the DELWAQ model this material is taken into account. Assuming a cavity immediately beyond the dike breach of 25m diameter and 20m deep, from which soil is washed away, this would amount to $16.7 * 10^6$ kg. This accounts for approximately 5% of the total suspended sediment.

4.1.1 Deposition of riverine sediment (the 'ERA'-model)

Inundation stage

Deposition during the inundation stage accounts for 24% of the total sedimentation. This amount is comparable with the figure given by Middelkoop and Asselman (1998), who found a deposition of 19% of the total sediment in the floodplains of the river Waal during the flood of December 1993. The spatial distribution of the sedimentation in the area is shown in Figure 11. The area around the dike breach shows a concentric zone were no deposition occurs because of high stream velocities. Immediately beyond this zone, maximum deposition occurs (10 –13 kg/m^2). Further downstream, a flume of deposition is formed in north-eastern direction of about 8-14 kilometres, with the deposition decreasing to zero..

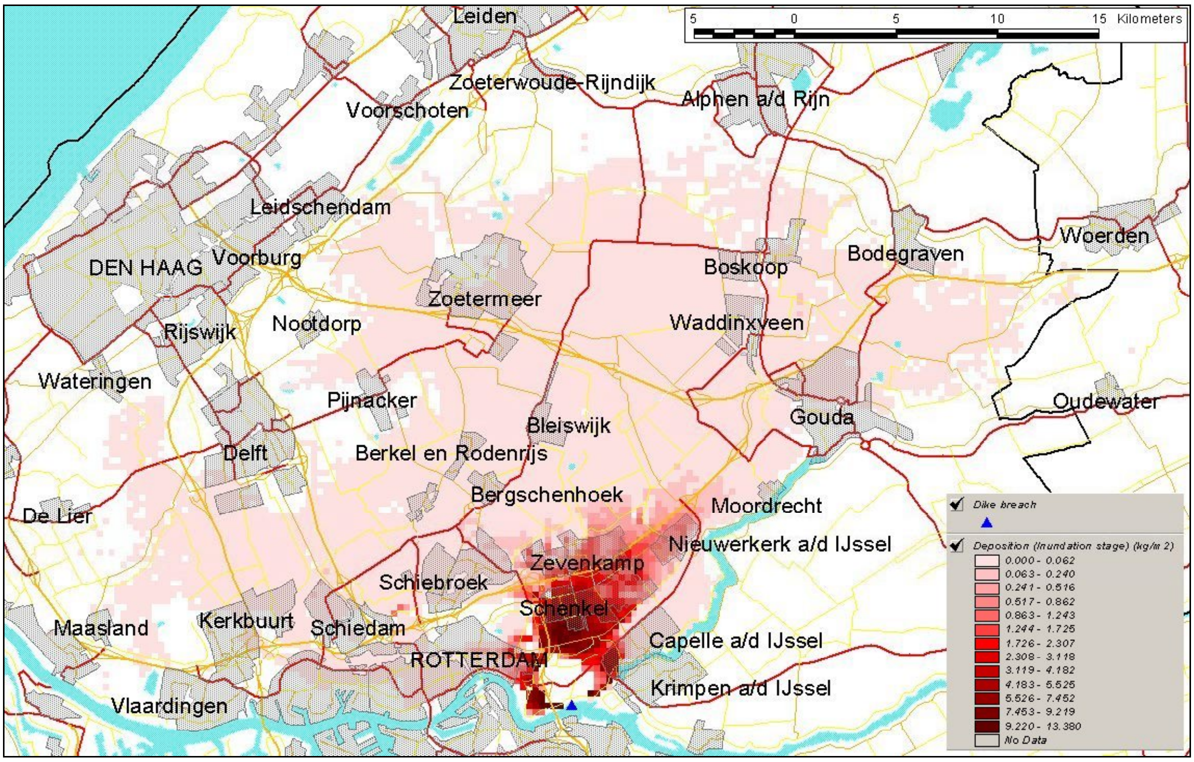

Figure 11 Deposition during the inundation stage, according to the ERA model [kg/m^2]

Settling stage

The remaining 76% of the total sediment load is deposited in the settling stage (Figure 12). As the deposition in this stage is assumed to be a function of the water depth, the spatial pattern of the deposition resembles the inverse of the soil surface elevation. In the lower parts of the area, sedimentation during the settling stage amounts up to 1.2 kg/m^2, elsewhere in this central peaty area the deposition ranges between 0.5 and 1 kg/m^2; in the remainder of the flooded area between zero and 0.5 kg/m^2.

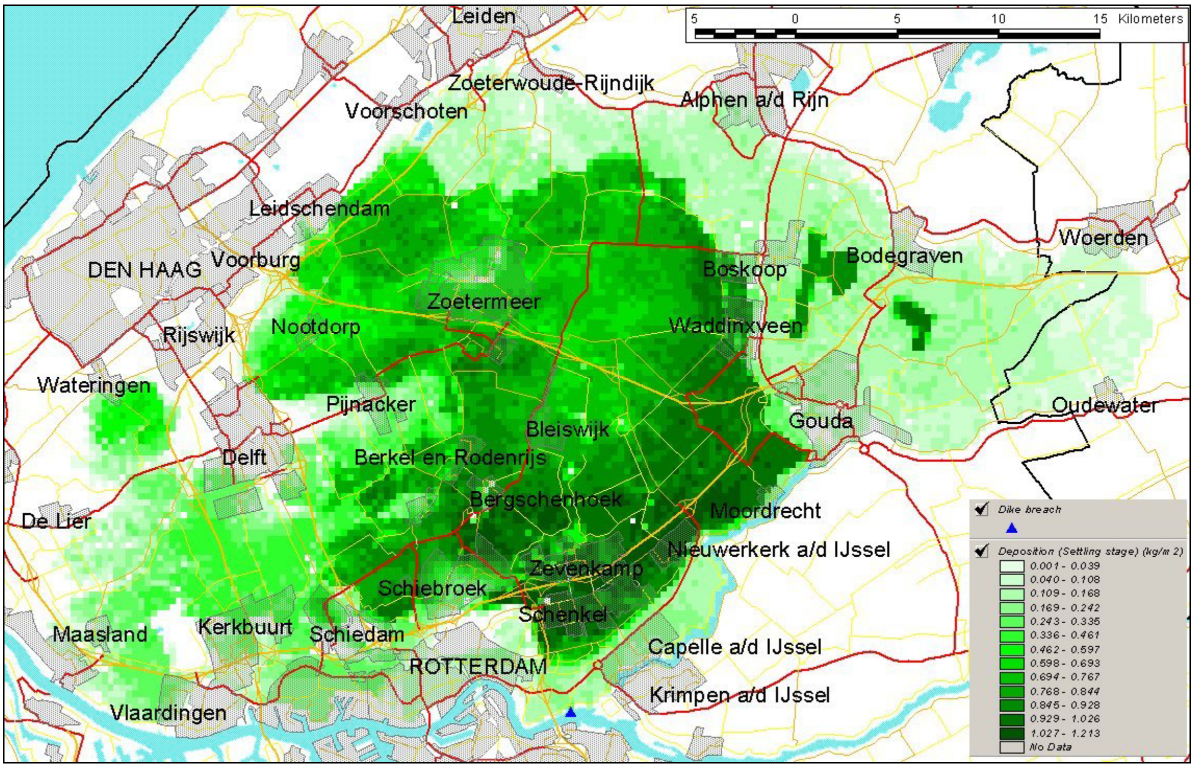

Figure 12 Deposition during the settling stage, according to the ERA model [kg/m²]

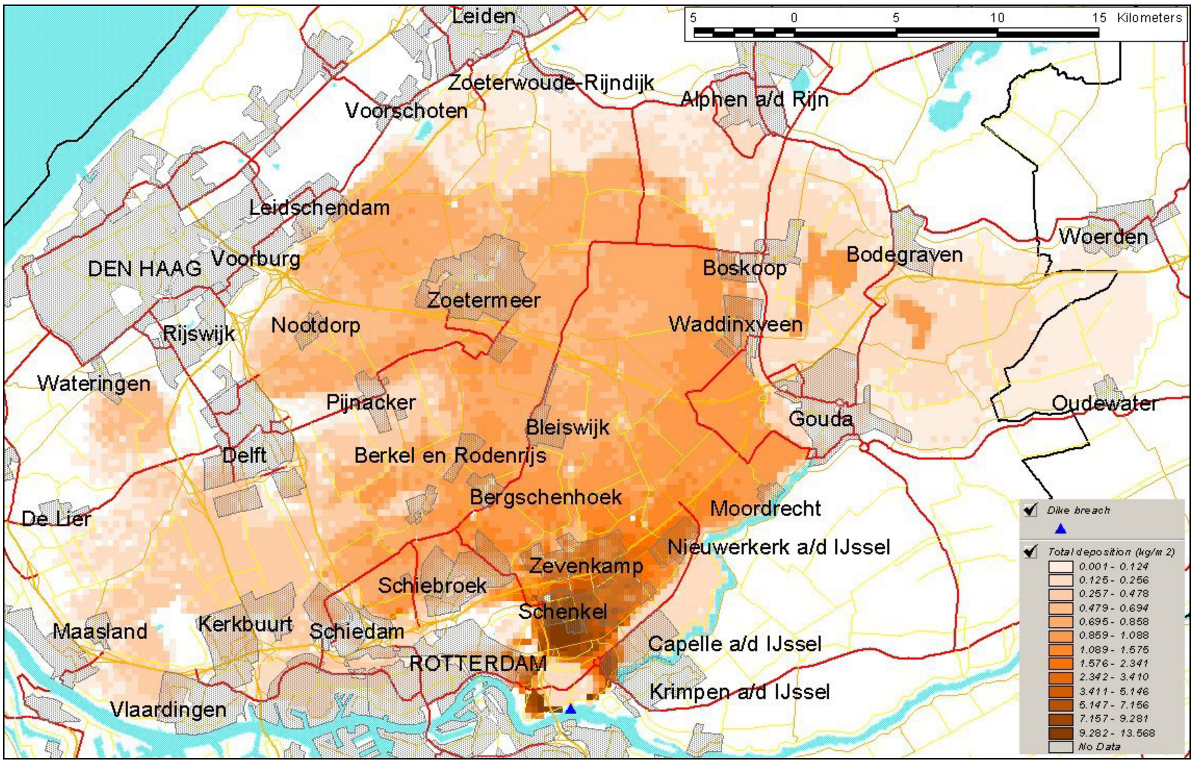

Figure 13 Total deposition, according to the ERA model [kg/m²]

Total deposition

Summing up sedimentation figures for both the inundation and settling stage results in a combined spatial pattern, cf Figure 13. Converting the sedimentation rates into layer thickness yields the following spatial pattern: up to 6 kilometres from the dike breach the sediment layers vary between 2-8 mm thickness, in the lower parts of the area from 0.4-2 mm, while the layers in the remaining higher areas layers are less than 0.4 mm thick (Figure 14).

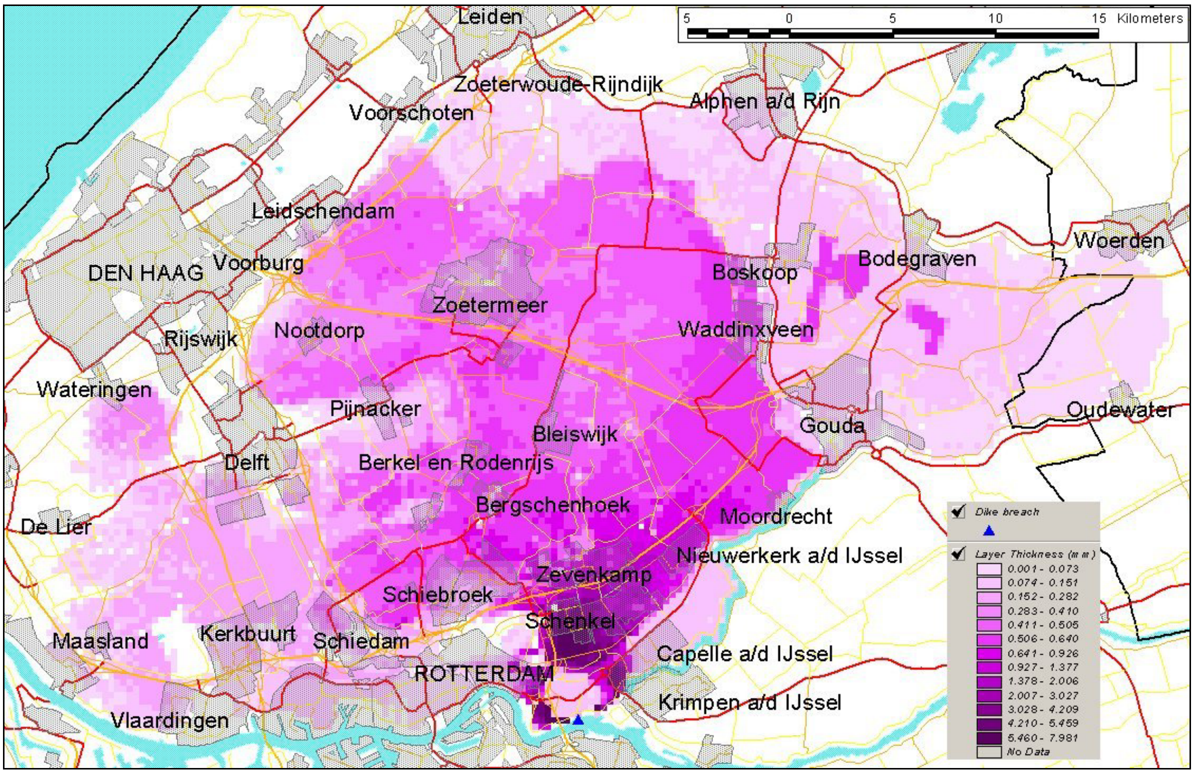

Figure 14 Sediment layer thickness, according to the ERA model [mm]

4.1.2 Deposition of local sediment (the 'DELWAQ'-model)

Deposition according to the DELWAQ model is shown in Figure 15. Although values appear similar to those predicted by the ERA model, some differences may be noticed. These are discussed in the following paragraph.

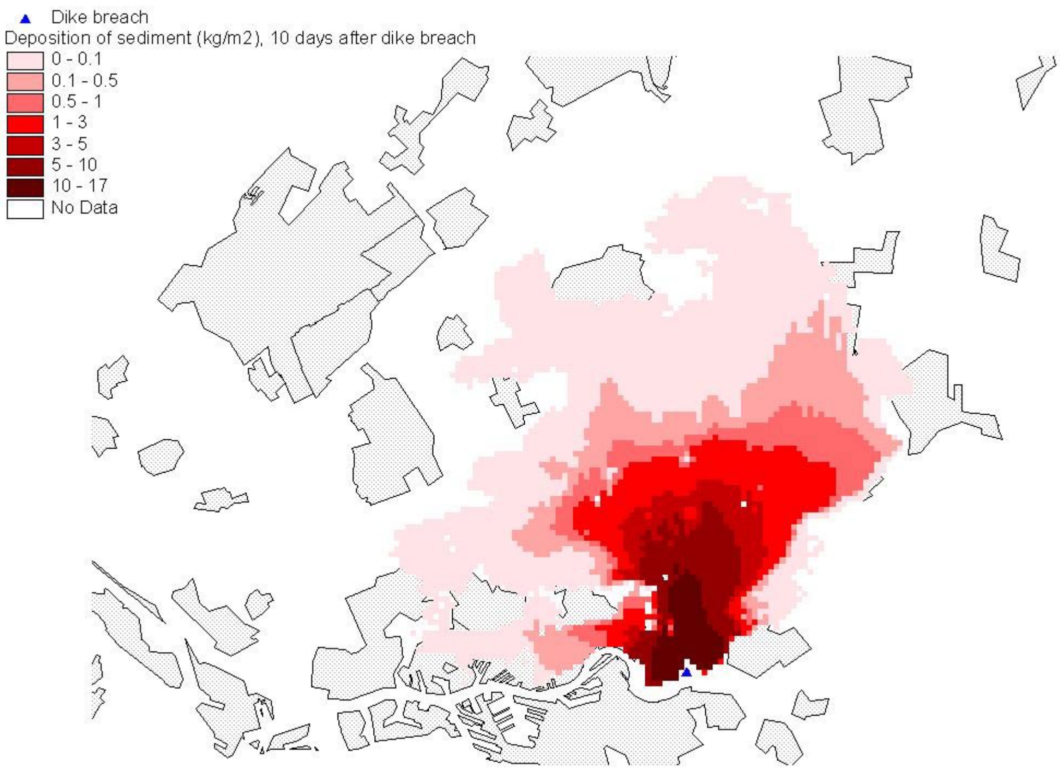

Figure 15 Sediment deposited during modelling period as predicted by DELWAQ model

4.1.3 Comparison of results of the simulations

In conceptual terms, the DELWAQ model is more sophisticated than the model used for emergency retention basins (ERAs). It is therefore likely to yield more accurate results. The 'ERA'-model relies on some major assumptions which simplify the model approach, yet allows for performing a quick scan with standard GIS-software which is a considerable benefit. Given the conceptual differences it is useful to analyse the model outputs generated by ERA and DELWAQ.

Figure 16 shows the result of a model comparison, produced by subtracting the deposition figures predicted with the ERA-model from those generated with DELWAQ. The map clearly illustrates that the DELWAQ-model predicts more deposition within a radius of about 8 to 10 kilometres from the dike breach and considerably less deposition in the remaining area, further from the dike breach. The 'increase' in deposition is partly caused by the incorporation of a scour cavity, just beyond the breach in the dike. Soil that is eroded here is deposited in a radial pattern and substantially increases the thickness of the sediment layer close to the dike-breach. As the rate of deposition beyond 10 kilometres from the dike-breach is considerable smaller, it is also clear that the DELWAQ-model predicts more and faster deposition during the 'inundation stage' of the flood, hence less suspended material reaches the downstream end of the flooded area. Less deposition, as predicted by the DELWAQ-model for a large part of the flooded area, translates to less harmful effects on soil quality. In contrast, the increase in deposition within a radius of 8 to 10 kilometres from the dike-breach results in a more severe reduction of soil quality in this area. Fortunately, due to the mixing of polluted river sediment with relatively clean soil material eroding from the cavity, the reduction will be less profound. Still, DELWAQ predicts a greater reduction of the soil quality near the breach in the dike then the ERA-model does. Data for verification are not available, simply because the 'Krimpen' case is a hypothetical one.

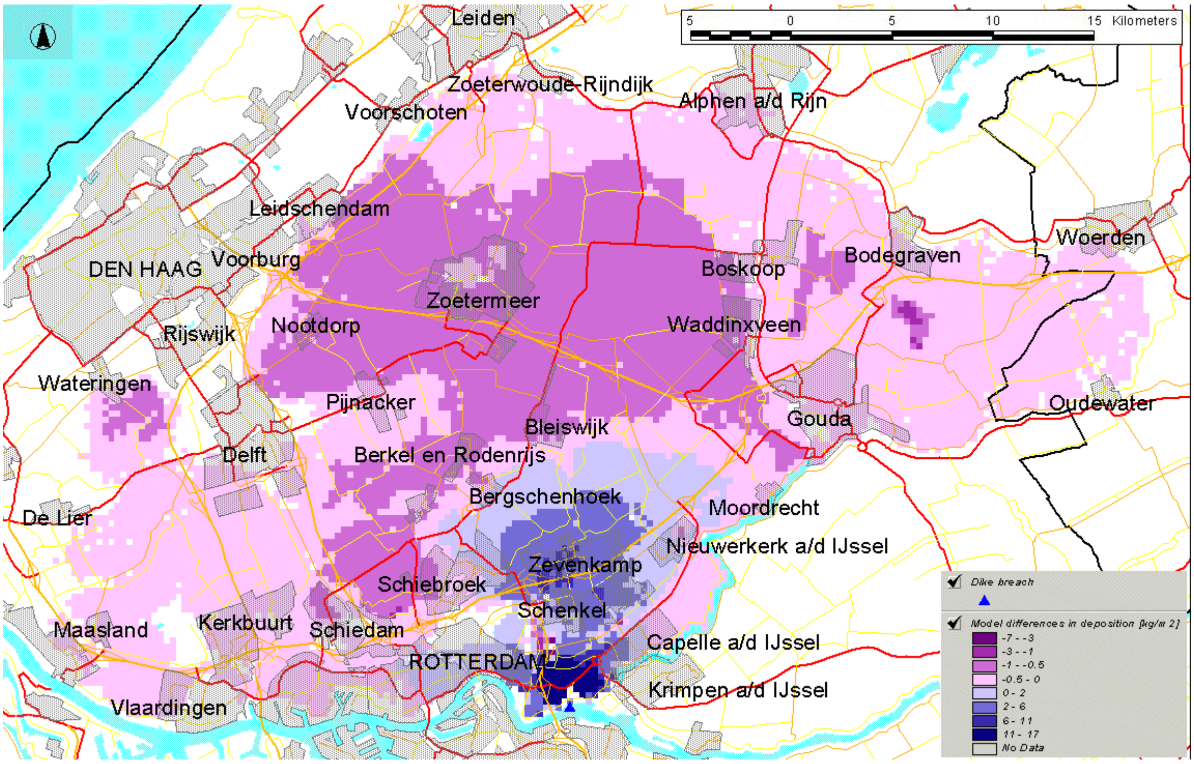

Figure 16 Difference between ERA and DELWAQ model

4.2 Mono-aromatics

In Figure 17 to Figure 20, concentrations of mono-aromatics, dissolved in water are shown, assuming that all released material will dissolve. It is important to realise that solubility values may be exceeded, in particular immediately after a release and close tot the source. In those cases a layer of pure phase oil product may float on the water surface.

All maps clearly show that material will be washed away from the dike breach and accumulate near the rims of the flooded area, where the water velocity approaches zero. Natural decay can be observed when comparing Figure 18 with Figure 20: the area containing mono-aromatics has decreased with time. As explained earlier, less than 10% of the total mono-aromatics shown will be benzene. Nonetheless, this would still amount to concentrations (say 5 mg/l) well in excess of the Dutch Intervention value (0.03 mg benzene /l), even after 10 days. In other words, a very large part of the inundated area will be covered with seriously contaminated water for more than 10 days. Figure 17 shows that, after two days, the highest concentrations of aromatics are found near the downstream borders of the flooded area. Since none of the release conditions '*h*' and '*v*' were met here, the aromatics must originate from upstream areas. Due to natural attenuation processes, the concentrations will gradually decrease further to values that won't pose any risk to human health.

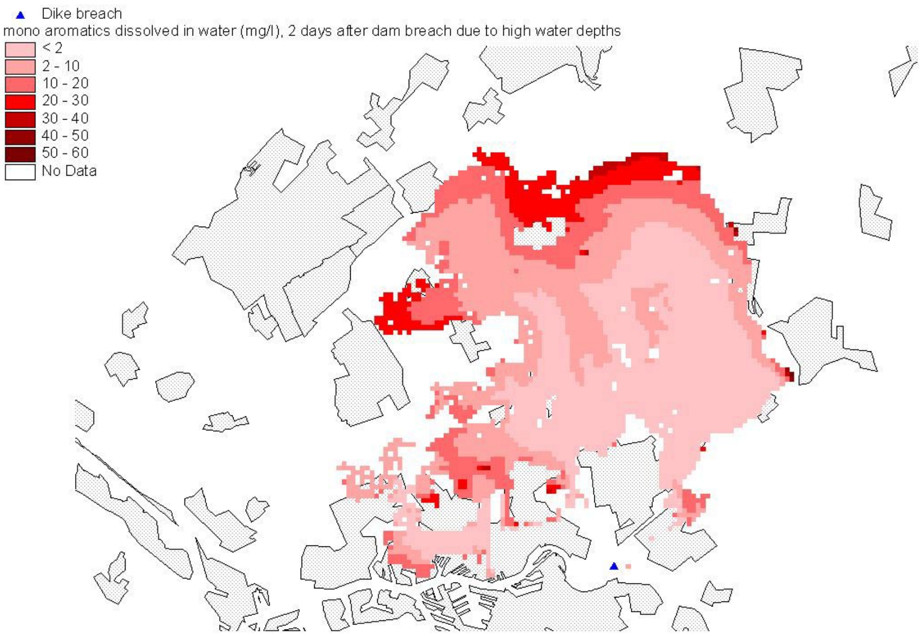

Figure 17 Mono-aromatic concentrations, released following the 'h'-criterion, two days after the dike breach.

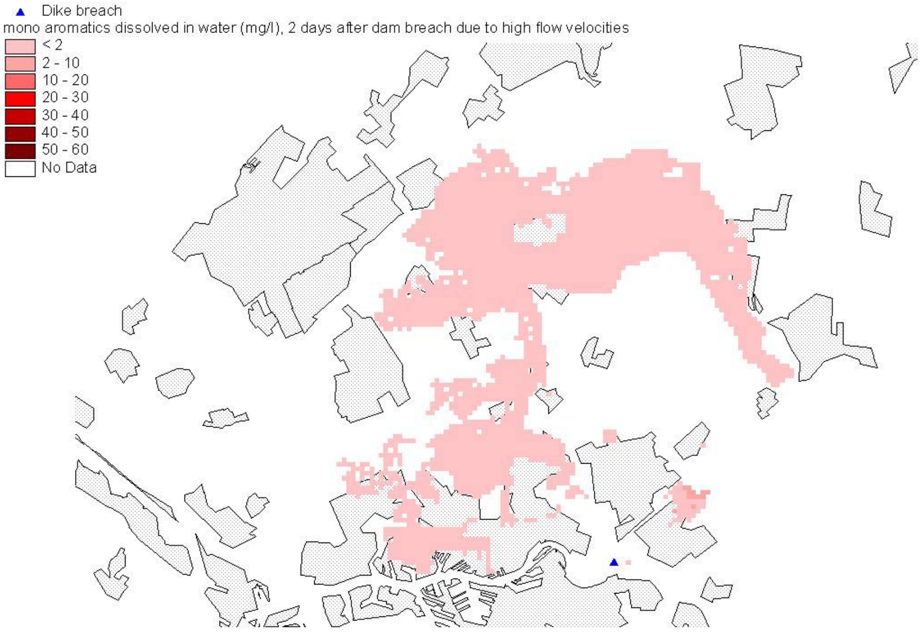

Figure 18 Mono-aromatic concentrations, released following the 'v'-criterion, two days after the dike breach

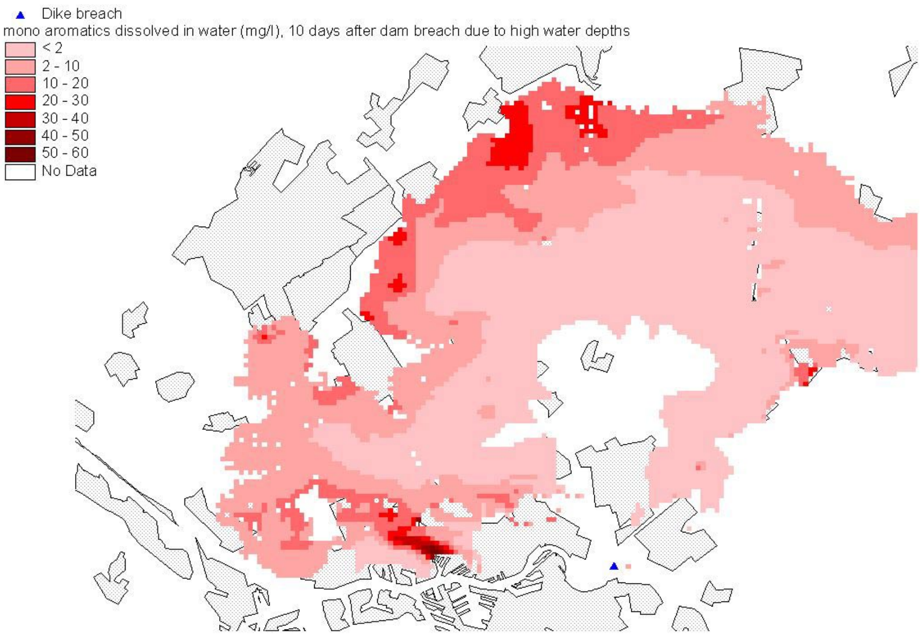

Figure 19 Mono-aromatic concentrations, released following the 'h'-criterion, ten days after the dike breach.

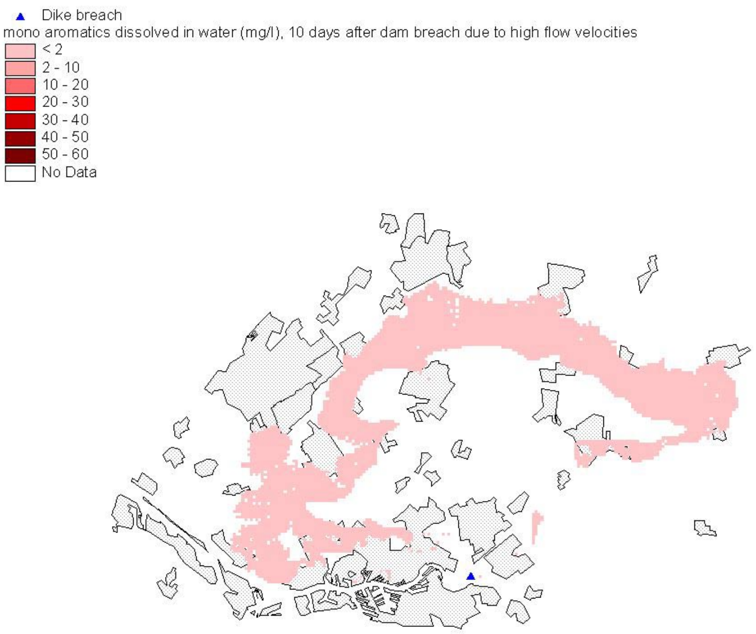

Figure 20 Mono-aromatic concentrations, released following the 'v'-criterion, ten days after the dike breach

4.3 Micro-organisms

As explained in earlier chapters, the SOBEK tool does not contain a proper algorithm to model the growth of micro-organisms. Figure 21 and Figure 22 merely serve as a demonstration of the growth of micro-organisms and associated potential health problems. Units in the figures are based on an initial concentration of micro-organisms derived from 1% of the source (food). The number of micro-organisms is assumed to double in approximately 12 hours. Again, problems appear to become most severe near the borders of the flooded area.

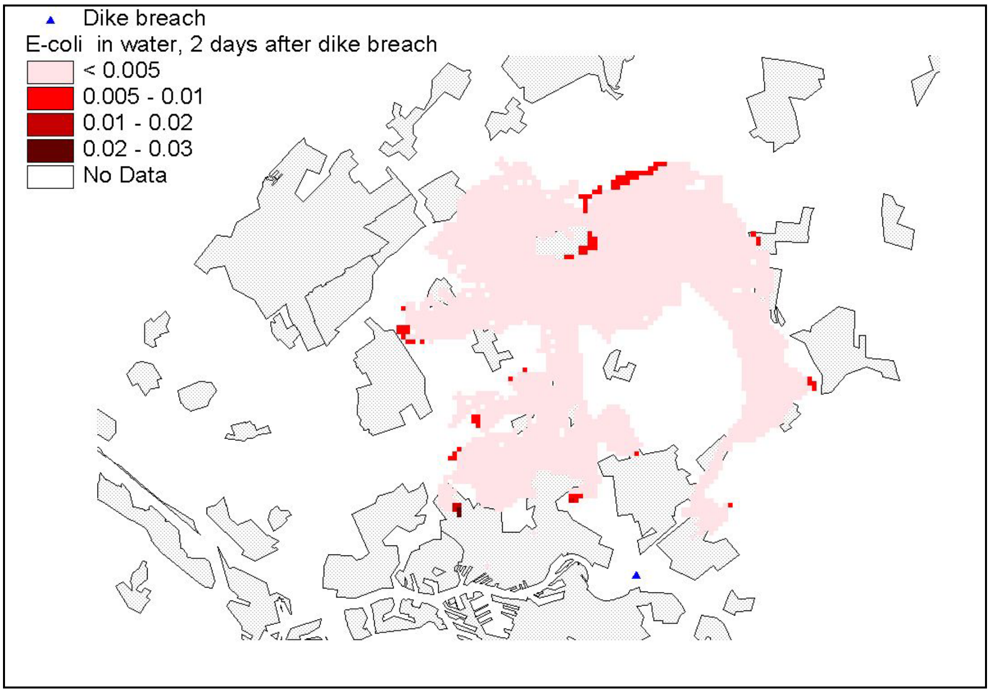

Figure 21 Concentrations of micro-organisms, released following the 'h'-criterion, two days after the dike breach

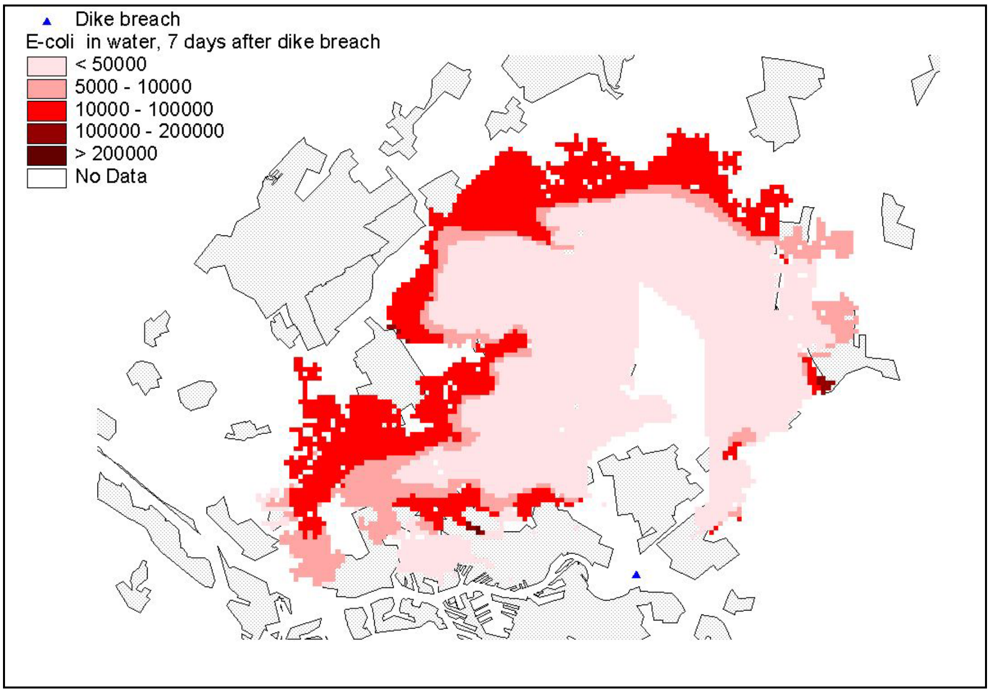

Figure 22 concentrations of micro-organisms, released following the 'h'-criterion, seven days after the dike breach

4.4 PAHs

The deposition PAH after 10 days is shown in Figure 23 and Figure 24, for both release criteria. For comparison, concentrations on the basis of the '*v*' criterion are also shown for a situation, assuming that the concentration of PAHs in the incoming floodwater equals zero, cf. Figure 25. It can be clearly seen that PAHs, imported with the incoming Rhine water are responsible for the bulk of the contamination.

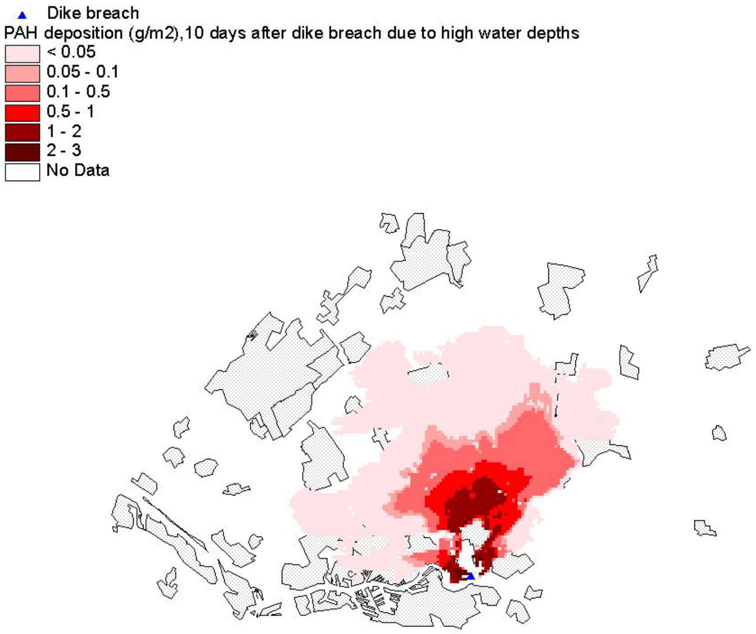

Figure 23 Concentrations of PAHs, released following the 'h'-criterion, ten days after the dike breach

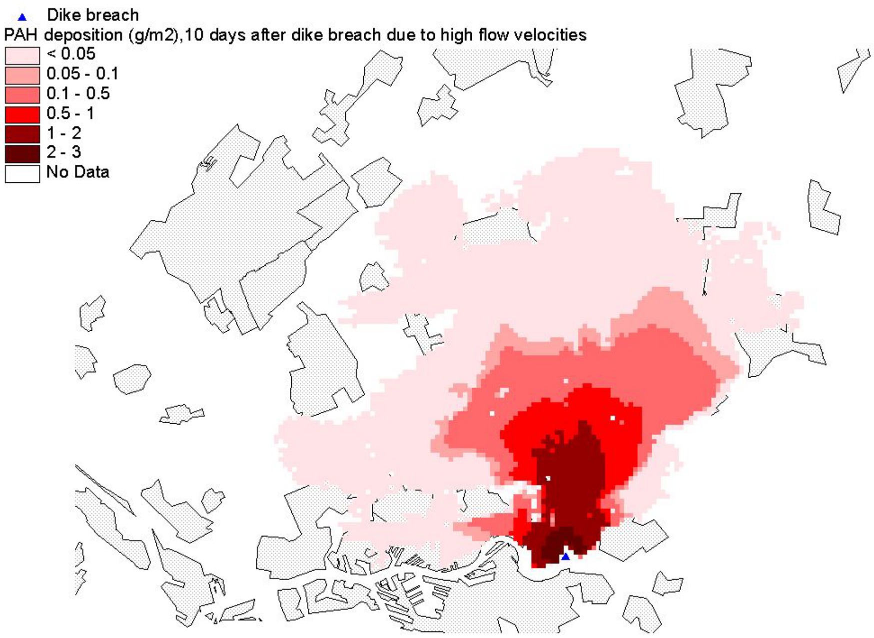

Figure 24 Concentrations of PAHs, released following the 'v'-criterion, ten days after the dike breach

However, as discussed in the paragraph 3.4, modelling of sedimentation was hampered by conceptual shortcomings in the SOBEK model as a result of which erosion and sedimentation of (contaminated) soil particles could not be accurately simulated. Release of material from areas with water heights in excess of 1m will only take place, if at the same time a minimum flow velocity of 0.25 m/s is present. This *means that material from many sources will not be released despite its presence in areas with a water height of more than 1m*, as can be seen from a comparison of Figure 9 and Figure 26. Hence, Figure 23 only shows material released relatively close to the dike breach. It can be expected that in areas further away from the breach release and deposition of PAHs (and other material) will take place as well. Figure 26 clearly illustrates that a significant land-based source of PAHs is formed by cars: motorways can clearly be identified.

As explained earlier, only 5% (by approximation) of the PAH consists of the toxic PAK10 components, so an average contamination rate of 100mg PAK10 per m^2 is a realistic estimate. PAHs will adsorb to, and settle with the floating particles. On average, 2 kg of floating particles will be deposited per m^2 of flooded area (cf. paragraph 4.1.1 and Figure 13), forming a layer of a few millimetres thickness (Figure 14). Contamination levels of the deposited materials would therefore be in the order of 50mg PAK10 per kg of sediment . The Dutch intervention value for PAK10 for a 'standard' soil equals 40 mg/kg dry matter. Hence, the contamination levels of the sediment, assessed in this study roughly coincide with the Dutch 'intervention values'.

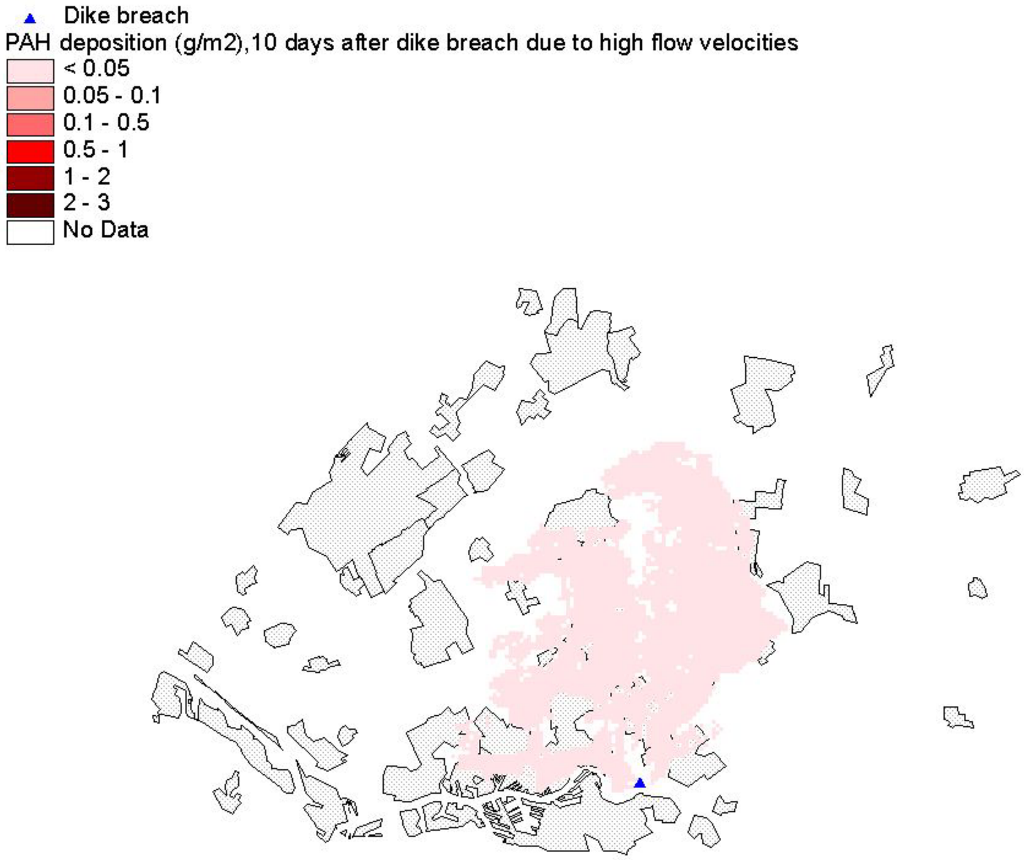

Figure 25 concentrations of PAHs, released following the 'v'-criterion, ten days after the dike breach., assuming PAH concentration in Rhine water equals zero

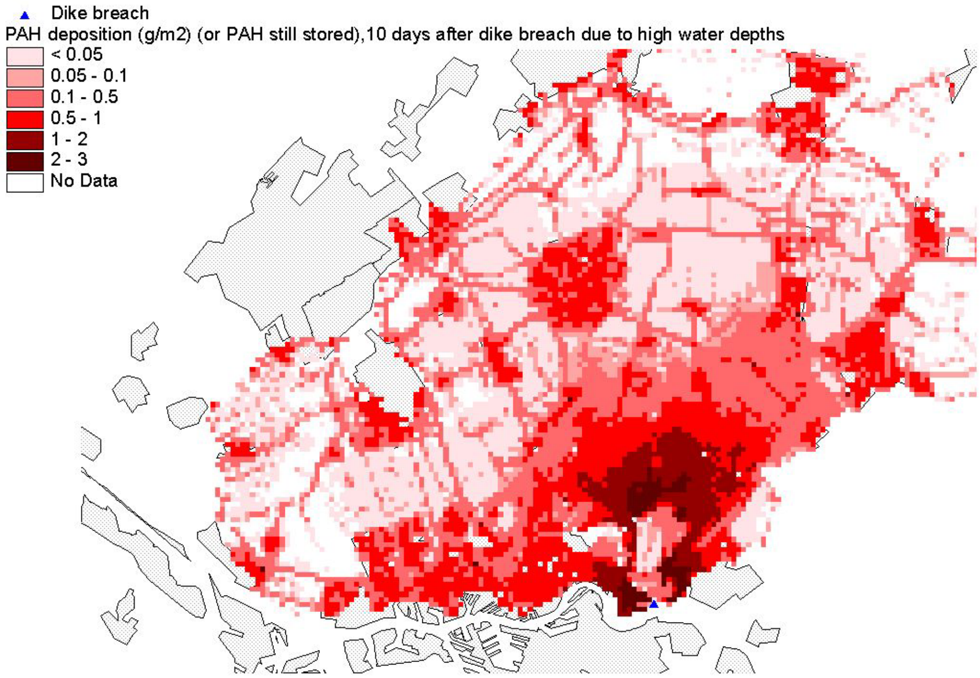

Figure 26 PAHs present after ten days, either as unreleased source or deposited after release. Release was subject to the 'h' criterion

4.5 Persistent organic pollutants (POPs)

The only POP, identified in the area was PCB, present in low quantities (0.011%) in lubrication oil. As this is about 1/3700th of land-sourced PAH (which makes up ca. 41% of the oily components) concentration levels at least 3 orders of magnitude lower than for land-sourced PAHs would be expected. Results, shown in Figure 27 and Figure 28, however, clearly show that higher values are calculated (cf. Figure 25), up to one tenth of the total PAH concentrations. As the PCB-concentrations in the incoming flood waters are also about one tenth of the PAH-values, this clearly indicates that PCB-contamination is also dominated by the concentrations, found in Rhine water. The (small) differences between Figure 27 and Figure 28 are a result of the different sedimentation conditions chosen for the '*h*-' and '*v*'-criterion. Using 2 kg/m^2 deposited sediment, to which PCB will be adsorbed, contamination values of 0.1mg PCB per kg sediment can be expected. This figure lies well within the range between the Dutch the Target value (0.02 mg/kg dry matter) and the Intervention value (1 mg/kg dry matter).

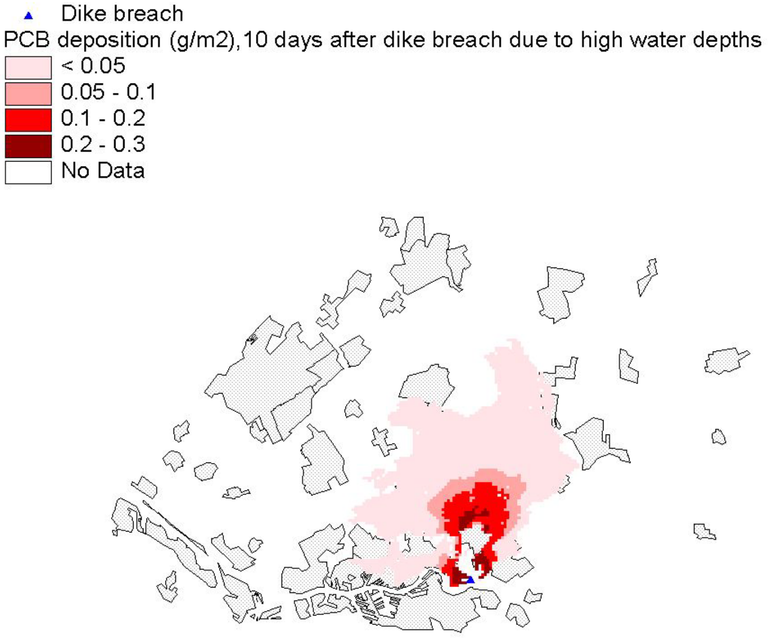

Figure 27 concentrations of POPs, released following the 'h'-criterion, ten days after the dike breach

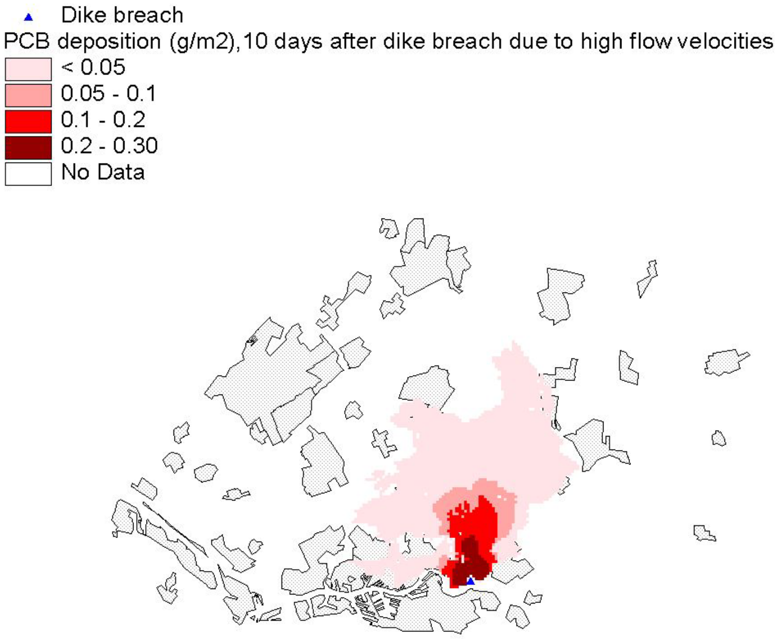

Figure 28 concentrations of POPs, released following the 'v'-criterion, ten days after the dike breach

4.6 Alkanes and alkenes

Maximum values of 4 to 7 g/m^2 are predicted for alkanes (Figure 29 and Figure 30), that is, twice the concentrations modelled for PAHs and twice the background concentration for PAHs in the Rhine water. Again, the contamination appears to be dominated by riverine sources. Values of 4-7 g/m^2 are equivalent to approximately 2g per kg of sediment, using the same rationale as outlined in the two preceding paragraphs. As a reference, component mineral oil is most suitable. A value of 2g/kg of sediment lies between the Dutch Target- and Intervention values for mineral oil, i.e. 0.05 - 5 g/kg dry matter. Again, limitations of the SOBEK model, as outlined for PAHs, also apply to alkanes. Only material that is released relatively close to the dike breach will contribute to the modelling results.

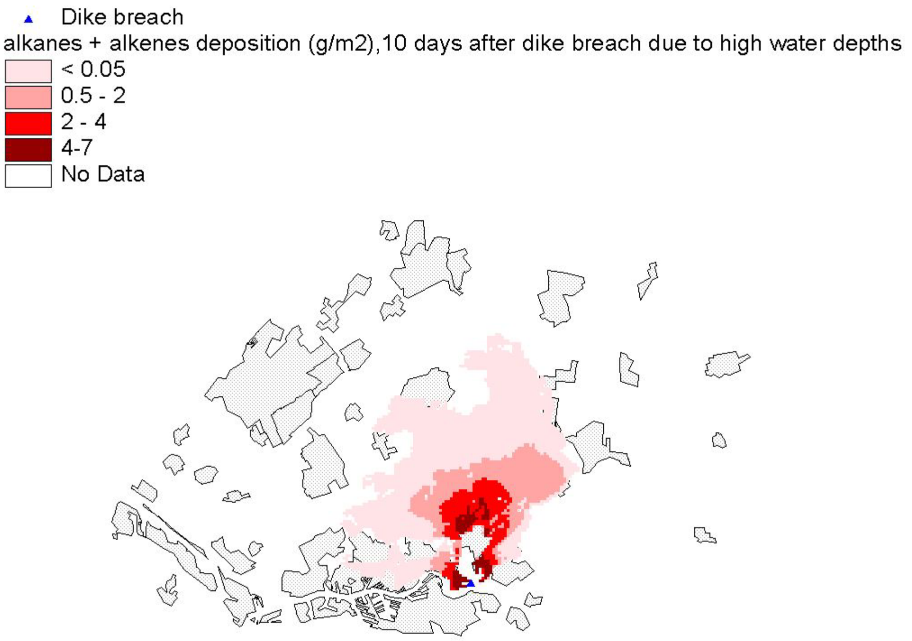

Figure 29 Concentrations of alkanes, released following the 'h'-criterion, ten days after the dike breach

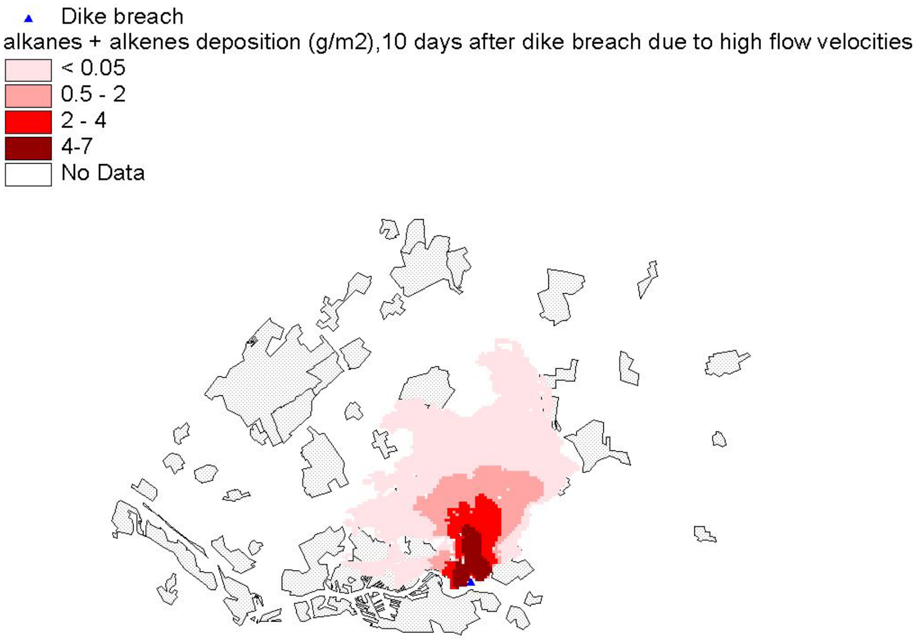

Figure 30 Concentrations of alkanes, released following the 'v'-criterion, ten days after the dike breach

4.7 DNAPL

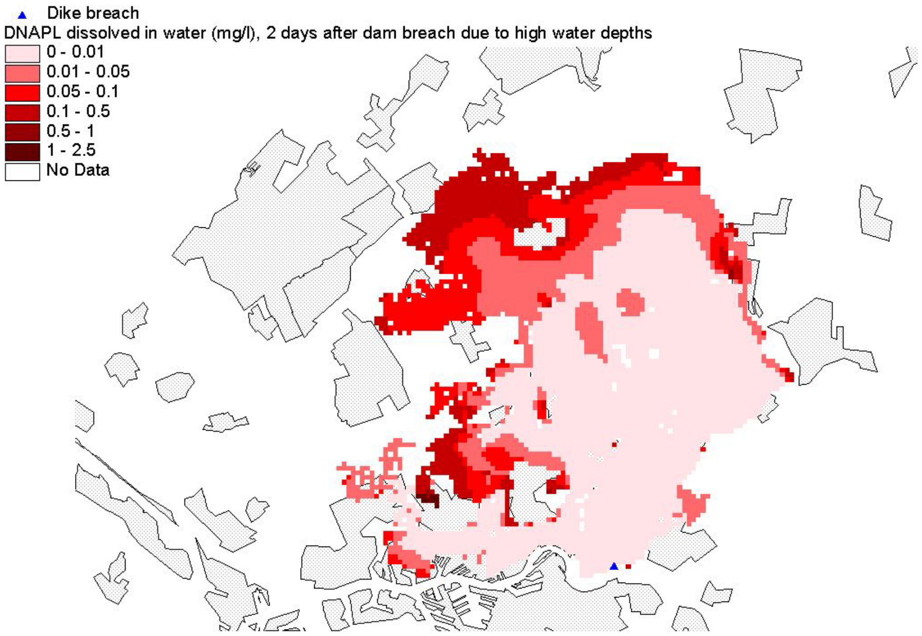

Figure 31 concentrations of DNAPLs, released following the 'h'-criterion, two days after the dike breach

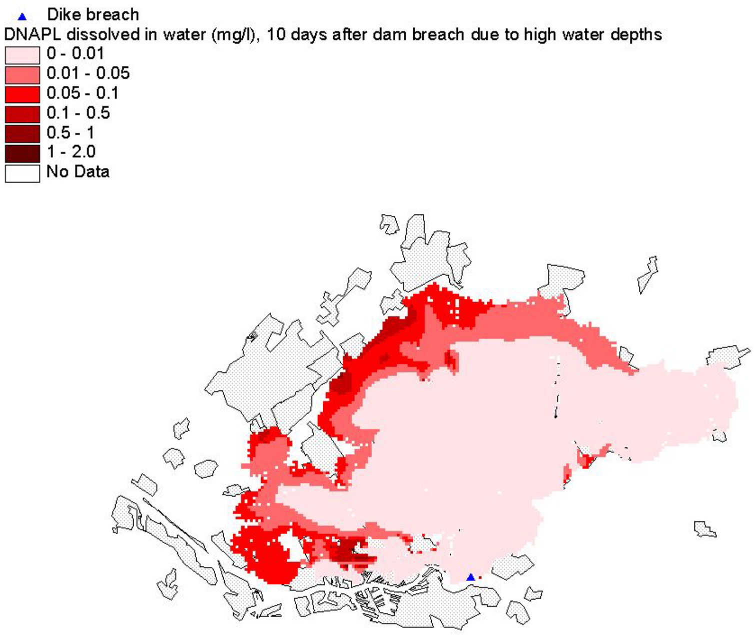

Figure 32 Concentrations of DNAPLs, released following the 'h'-criterion, ten days after the dike breach

Concentrations of DNAPLs, two and ten days after the breach, for the high water level condition, are shown in Figure 31 and Figure 32. In line with the other non-adsorbing components, accumulation takes place near the downstream borders of the flooded area. Effect of natural attenuation can clearly be seen when comparing both figures. Most typical examples of DNAPLs are Per (chloro-ethene) and Tri (chloro-ethene) with Dutch intervention values of 0.04 and 0.4 mg/l respectively. Again, these values will be exceeded (in particular when Per is released) in a large area for several days. Natural decay is likely to reduce the concentration to sub-toxic values in many areas. However, as DNAPLs are denser than water they may accumulate as a separate phase in basin-like structures, and even percolate through the ground surface, causing soil contamination that may last well beyond the period of flooding.

4.8 Heavy Metals

Both the ERA and the DELWAQ models were used to calculate the quantities of heavy metals, deposited during the flood. The ERA model however only takes into account the material imported into the area with the river water whereas the DELWAQ model also includes the land-sourced material.

4.8.1 DELWAQ model results

Depositions after 10 days, resulting from both release conditions as calculated by the DELWAQ model are shown for Zn in Figure 33 and Figure 34. For Cd only the ‘h’ condition was relevant. This is shown in Figure 35.

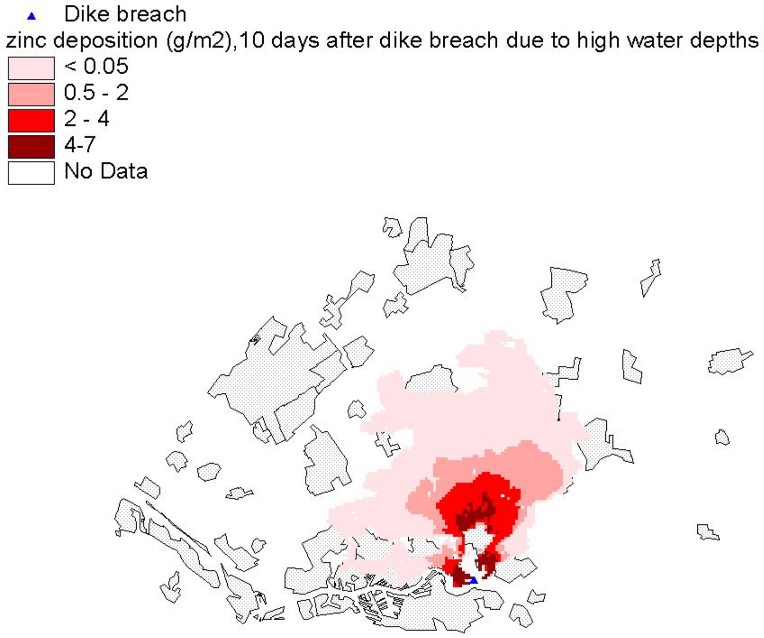

Figure 33 Concentrations of Zn, released following the ‘h’-criterion, ten days after the dike breach, as calculated with the DELWAQ model.

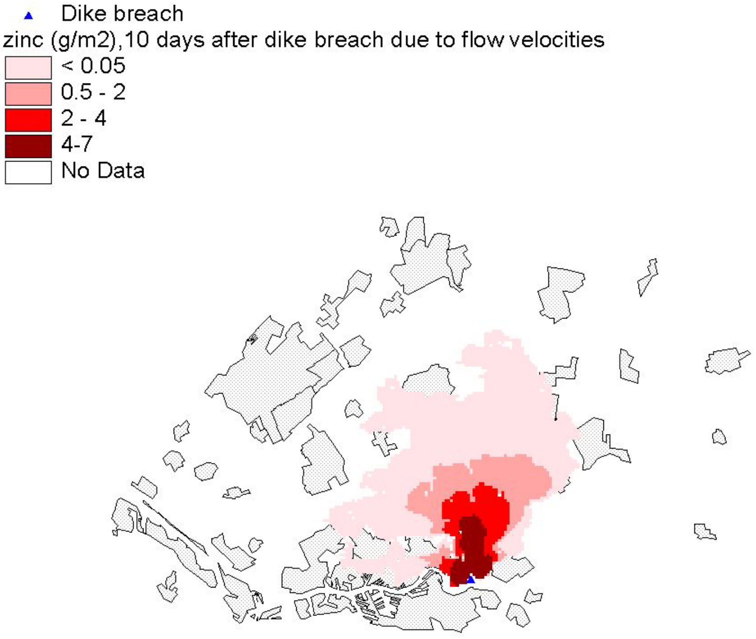

Figure 34 concentrations of Zn, released following the 'v'-criterion, ten days after the dike breach as calculated with the DELWAQ model.

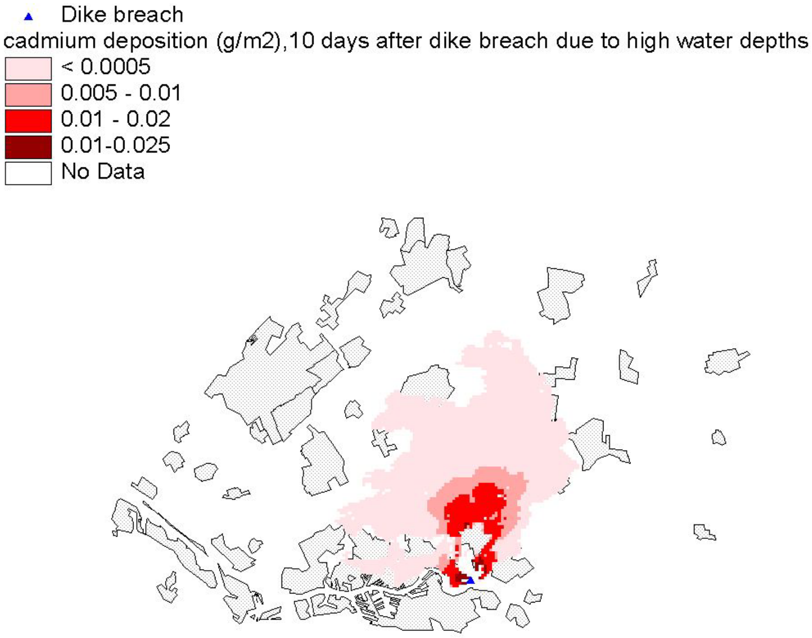

Figure 35 Concentrations of Cd, released following the 'h'-criterion, ten days after the dike breach as calculated with the DELWAQ model.

4.8.2 Results of the ERA model

Figure 36 shows the distribution of the total Zn deposition (sourced from river only) according to the ERA model. Since the mechanism of deposition of heavy metals (and all other adsorbing compounds) is identical to the sedimentation of floating particles, similar effects can be observed. The DELWAQ-model results in faster deposition than the ERA-model. Hence, less suspended material reaches the border of the flooded area.

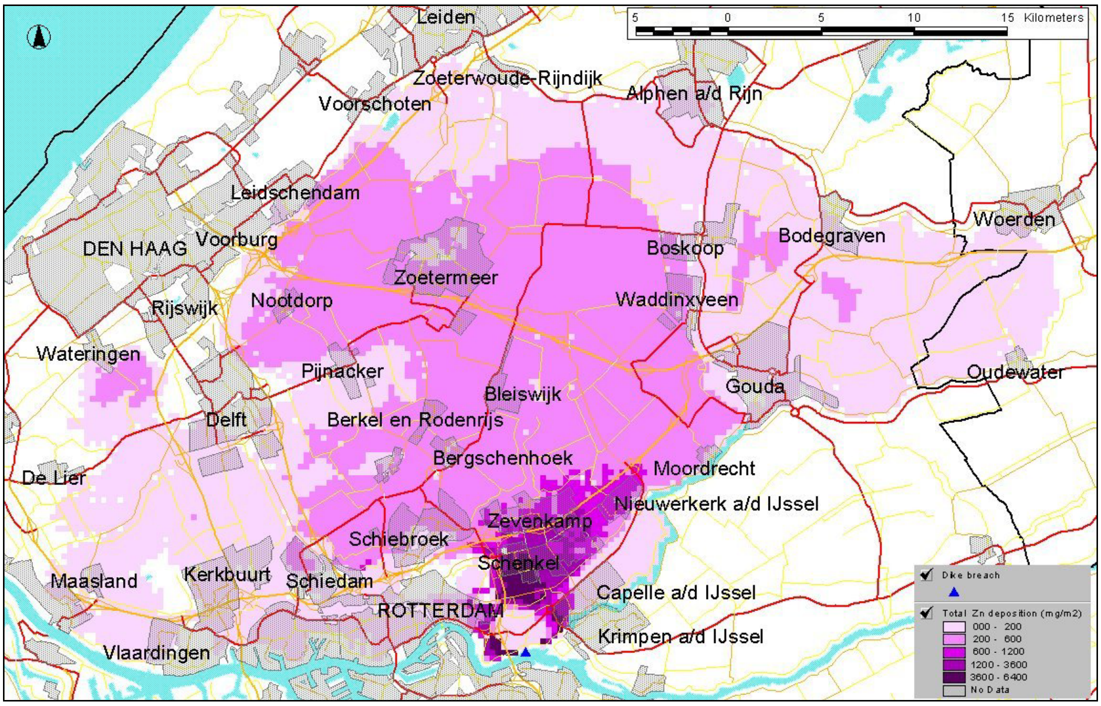

Figure 36 Total Zn deposition [mg/m^2] as calculated with the ERA model

4.8.3 Discussion on contamination levels

The deposited masses per m^2 and the spatial distribution for Zn are very similar for all events modelled, hence the dominant source for Zn contaminations appears to be the incoming Rhine water. Maximum deposition values of about 7 g/m^2 are predicted in all cases near the breach. In this area, 10 g sediment is deposited per m^2, on average. This would result in sediment contamination levels of about 0.7 g/kg sediment. The Dutch Target and Intervention values for Zn are 0.14 and 0.72 g/kg dry matter, respectively. This means that substantial Zn contamination can be expected from the incoming Rhine water.

For Cd, maximum deposition values of 25 mg /m^2 were calculated with the DELWAQ model. This would amount to 2.5 mg/kg sediment, again a number between the Dutch Target and Intervention values, being 0.8 and 25mg/kg dry matter, respectively. Thus, the land sources will cause moderate Cd contamination.

As mentioned earlier, the deposited layers of (contaminated) sediment will be very thin (a few millimetres). In urban areas this material may be collected from hard-covered areas and disposed of as chemical waste. In rural areas, however, removal of material will be difficult if not impossible at all. Most likely the sediment will be mixed with the underlying agricultural land. Essentially, the resulting topsoil concentration results from mixing the sediment layer with the underlying original subsoil. To do so, it is necessary to determine the mass of the subsoil, which can be done using the following equations:

$$m_{\text{subsoil}} = V_{\text{subsoil}}(1-\theta)\left(\%_{\text{organic matter}} * \rho_{\text{organic matter}} + \%_{\text{mineral fraction}} * \rho_{\text{mineral fraction}}\right)$$

where

m_{subsoil} = mass of the subsoil (kg.m^{-2})

$V_{subsoil}$ = (subsoil mixing depth * 1000) (m^{-2})
θ = porosity = 0,48 (-)
$\%_{organic\ matter}$ = 2% (arable land) or 10% (pasture)
$\rho_{organic\ matter}$ = 1,47 ($kg.l^{-1}$) (Cuypers, 2000)
$\%_{mineral\ fraction}$ = 1 - % organic matter
$\rho_{mineral\ fraction}$ = 2,65 ($kg.l^{-1}$) (Cuypers, 2000)

The resulting concentrations of contaminants in the mixed topsoil are calculated for two types of land use: arable land and pasture, cf Figure 37. Table 10 shows some general characteristics of these land use types for clay soils. The greater part of the flooded area in the test case has a clayey topsoil.

	arable land	pasture
grain size < 2μm [%]	20	20
organic matter content [%]	2	10
porosity	0,48	0,48
mixing depth, plough depth [m]	0,3	0,05

Table 10 Characteristics of arable land and pasture on clay soil

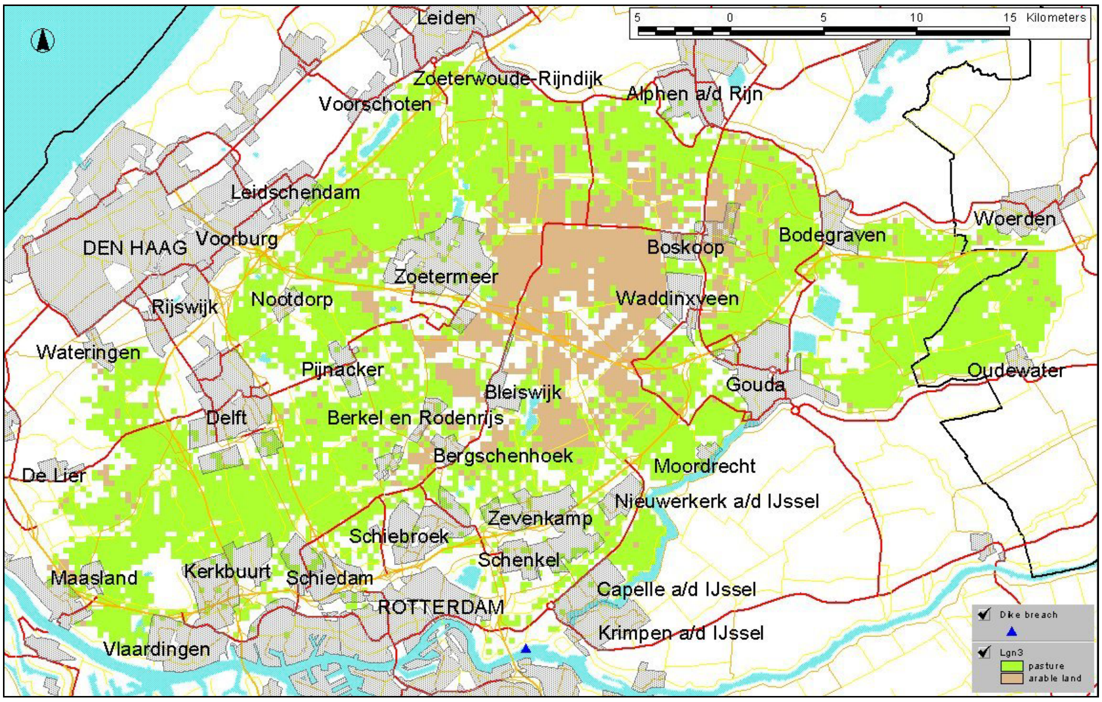

Figure 37 Distribution of arable land and pasture in the flooded area (source: LGN3 Alterra, based on Landsat TM images from 1995)

The original subsoil will contain background concentrations of heavy metals. Values for Zn and Cd are shown in Table 11 (values are adapted for Dutch standard soil type)

compound	arable land	pasture
Cd	0,28	0,5
Zn	93	102

Table 11 Generalized background concentrations in Dutch clay soils [$mg.kg^{-1}$], converted to a standard soil composition (Van Dijk et al., 1998)

Using the data of Table 10 in the equations above yields the values of $m_{subsoil}$ as shown in Table 12. Combining this data with the values in Table 11 gives total (background) weights per m^2 of Zn and Cd in the layer that is mixed with the deposited material, cf. Table 12.

parameter	Arable land	Pasture
$m_{subsoil}$ (kg.m^{-2})	409.72	71.34
Background mass Zn in mixing layer (g.m^{-2})	38.1	7.28
Background mass Cd in mixing layer (g.m^{-2})	0.115	0.03567

Table 12 relevant data for mixing layer of subsoil

Given the maximum deposition values for Zn and Cd of about 7 g.m^{-2} and 25 mg.m^{-2} respectively, the Zn and Cd concentrations in arable land were found to rise, due to the flood, with ca. 20%. For pasture, concentrations will double roughly. Figure 38 and Figure 39 show the resulting concentrations for Cd and Zn for arable land and pasture, located within the modelling area.

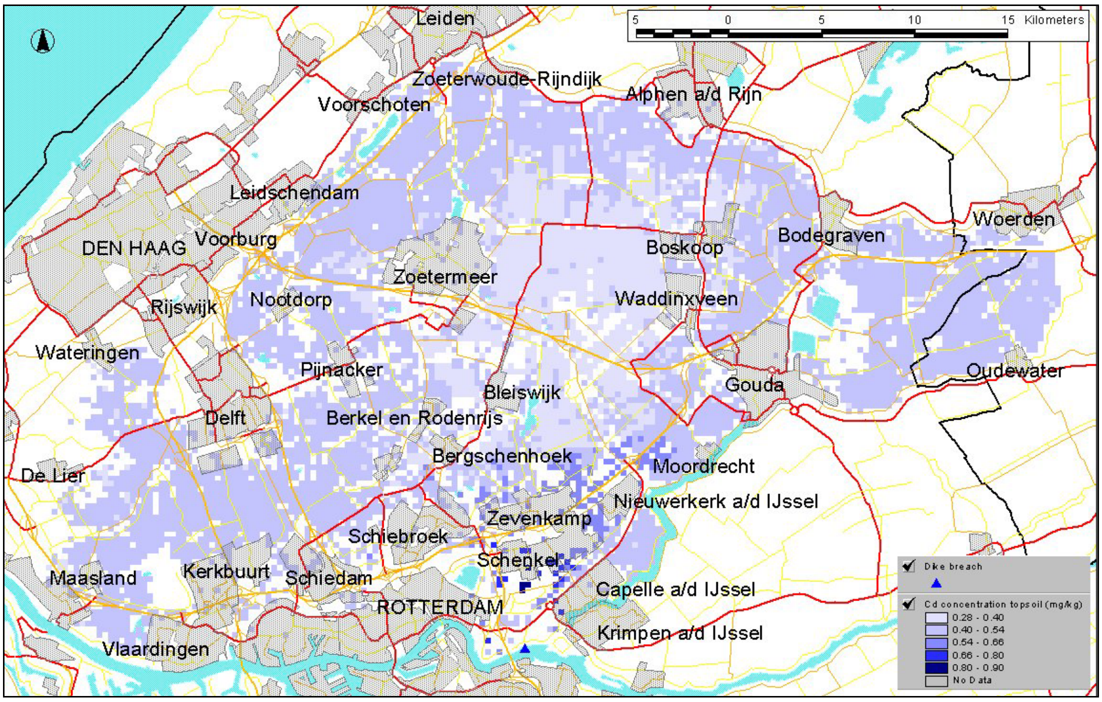

Figure 38 Cd concentrations after mixing with the top soil [mg/kg] as calculated with the ERA model.

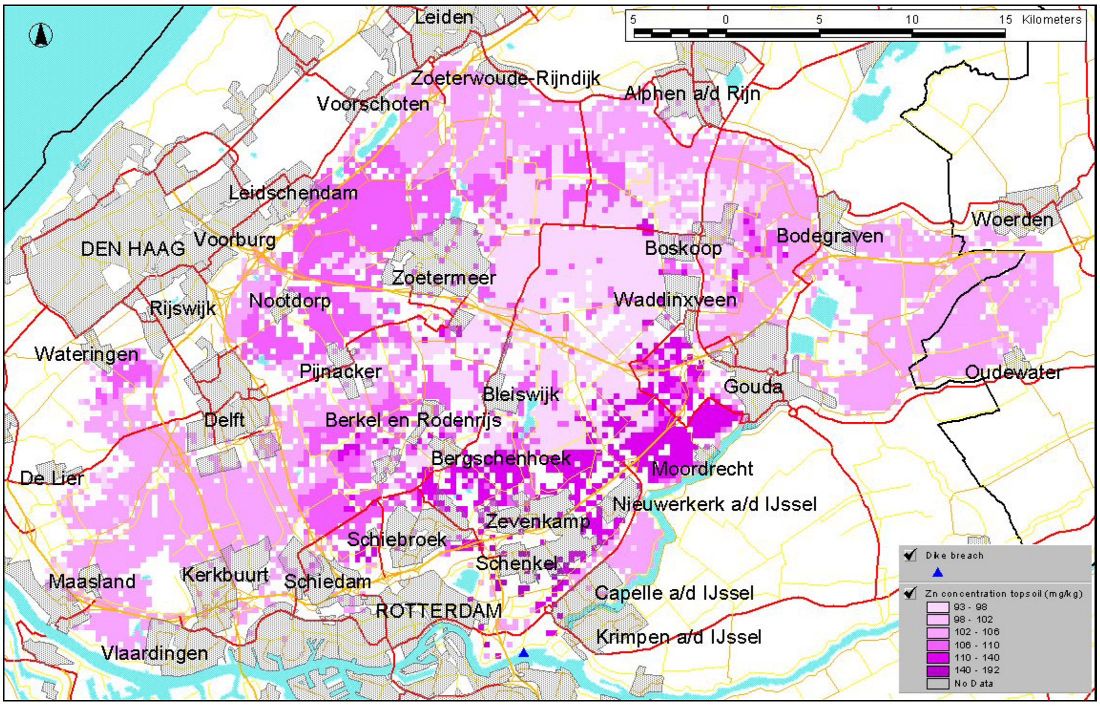

Figure 39 Zn concentrations after mixing with the topsoil [mg/kg] as calculated with the ERA model.

4.9 Phosphates

The deposition of phosphates after 10 days of flooding is shown in Figure 40 and Figure 41, for both release criteria. Regardless the location where the sedimentation occurs, the rates of sedimentation are similar. Therefore it is concluded that, for both release criteria, the deposition is mainly caused by phosphates entering the area with the river water. In reality, much more phosphates will be released from manure, applied on arable land than the model output suggests. However, due to the abovementioned problems with the model concept of DELWAQ with respect to adsorbed substances, the release of these phosphates into the flooding waters is substantially underestimated. This is due to the fact that the release criterion of a water flow velocity of 0.25 m/s is only met in a limited area (see also Figure 10) and for a limited number of modelling time steps.

Despite the fact that the results will be an underestimation, P-deposition is quite high with values up to 250 kg/ha. It is Dutch policy to tolerate a phosphate surplus of 20 $kg.ha^{-1}.yr^{-1}$ at the highest (the so-called MINAS legislation). However, as a result of the flood, the degree of phosphate saturation will not increase significantly. Still, these results severely underestimate the release of phosphates within the area. Further research at this point is required.

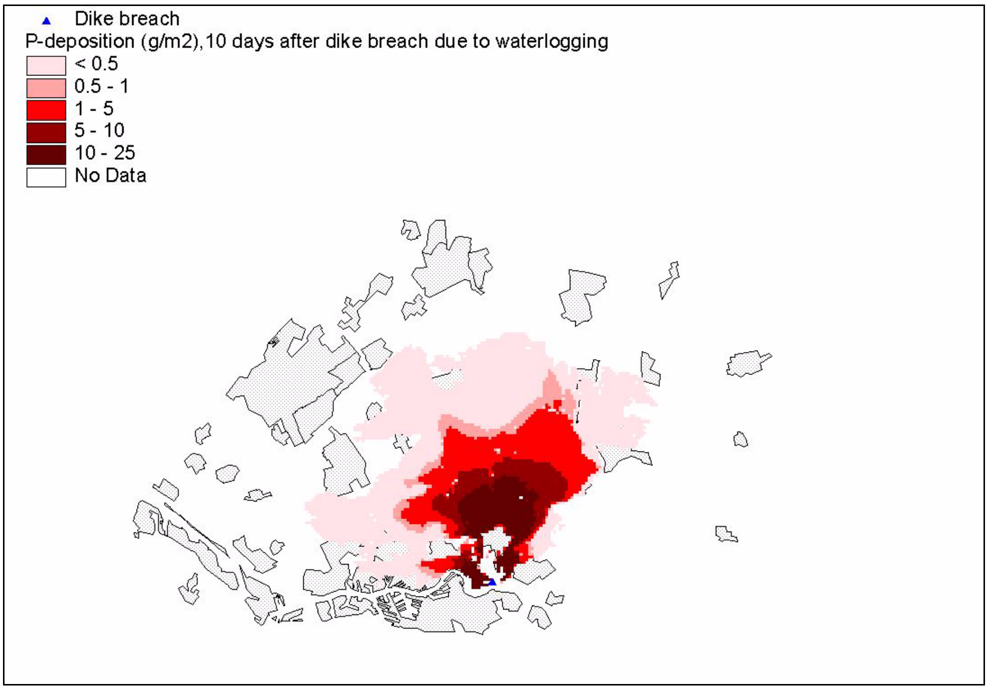

Figure 40 Concentrations of Phosphate, released following the 'h'-criterion, ten days after the dike breach, as calculated with the DELWAQ model

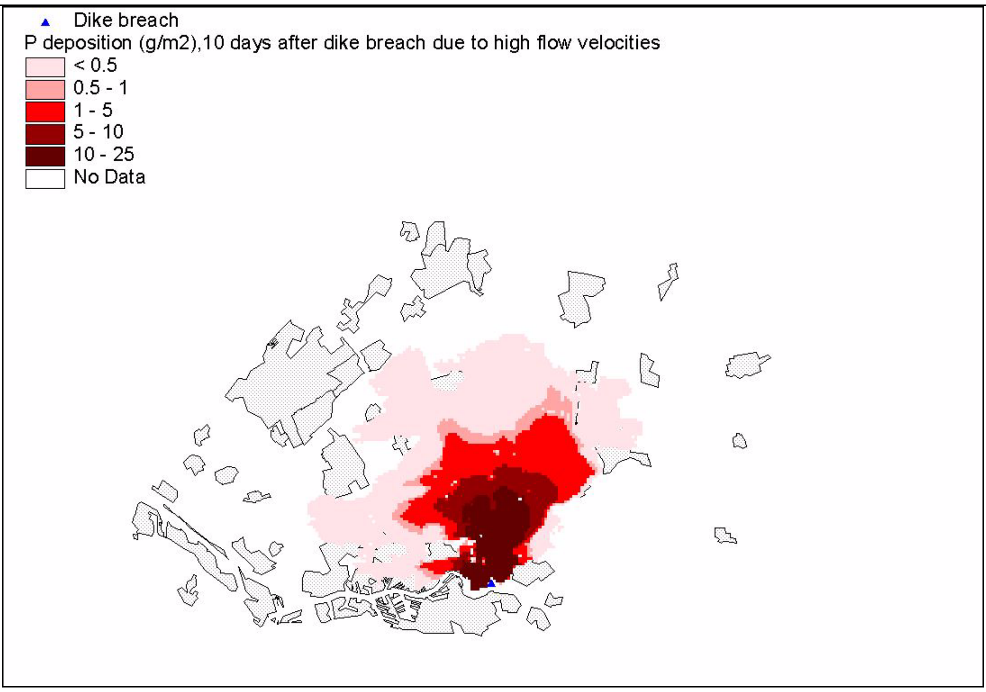

Figure 41 Concentrations of phosphate, released following the 'v'-criterion, ten days after the dike breach, as calculated with the DELWAQ model

4.10 Pesticides and herbicides

Concentrations of pesticides, 2 and 10 days after the dike breach are shown in Figure 42 and Figure 43. In the simulations, pesticides are only released due to high water levels. The conditions for high velocities are not met. Despite the decay, one can see a rise in concentration from less than 0.01 $mg.l^{-1}$ after 2 days, to maximum values of 3 $mg.l^{-1}$ after 10 days. This is caused by the fact that companies with larger stocks of pesticides are located further away from the breach. The group of pesticides is being modelled as one single group. However, in reality this group consists of many agents with various decay rates and various ecological risks. Components with a concentration exceeding 0.1 $mg.l^{-1}$ always cause an ecological risk. This concentration is also the maximum concentration which is allowed in drinking water. Still, concentrations as low as 0.01 $\mu g.l^{-1}$ may be toxic. Fortunately, components which are toxic at low concentrations generally have higher decay rates. Herbicides usually have low decay rates but are only toxic in relatively high concentrations (approximately 0.1 $mg.l^{-1}$). Hence, it was established that concentrations of herbicides and pesticides may cause a substantial risk, particularly if one realises that the grid-size of the model is 250×250m, so that concentrations may be much higher locally. Reversely, the concentrations will decrease substantially by decay in the six months or so period with stagnant water after the breach is closed.

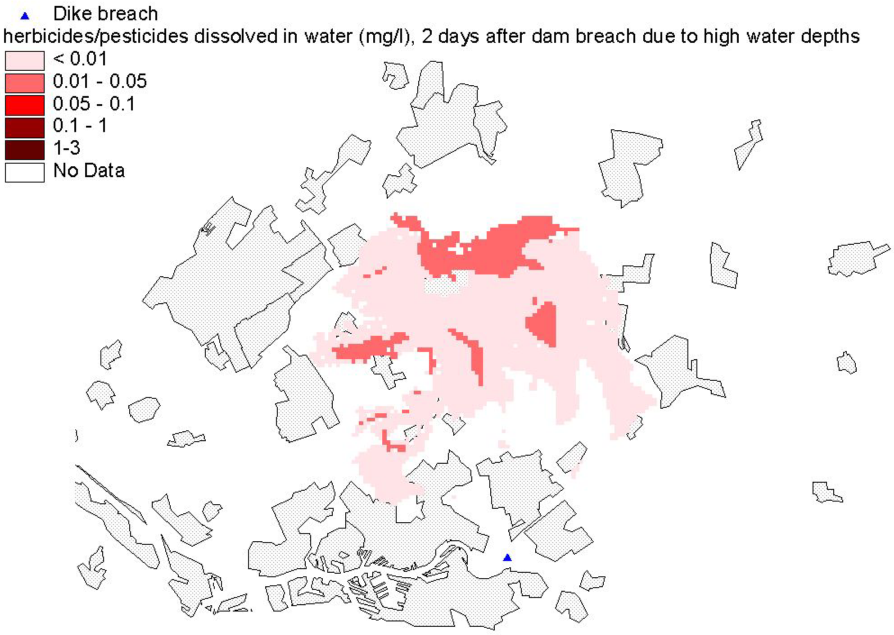

Figure 42 Concentrations of pesticides, released following the 'h'-criterion, two days after the dike breach

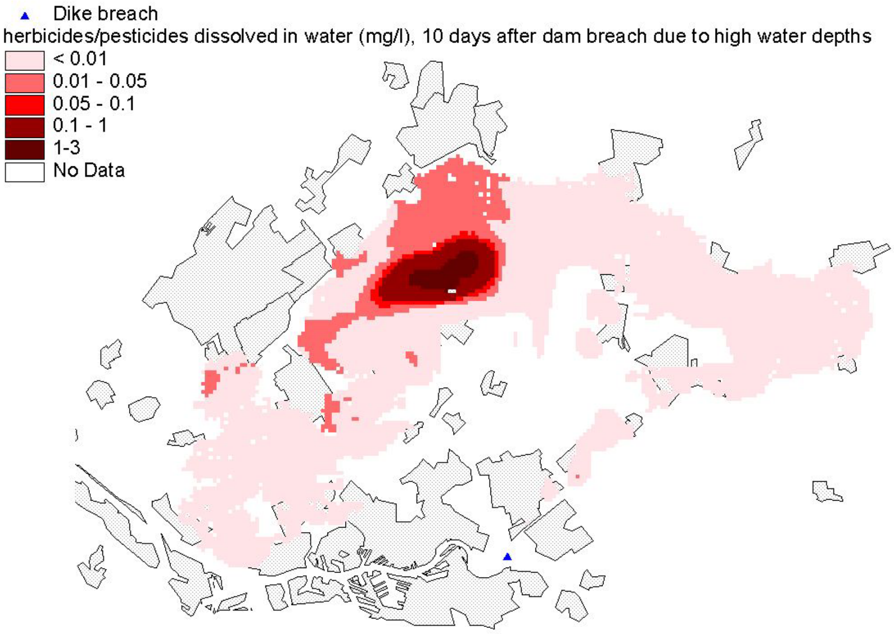

Figure 43 Concentrations of pesticides, released following the 'h'-criterion, ten days after the dike breach

5 Assessment of damage from the environmental impacts

5.1 Introduction

In the previous chapter, the simulation results are reported as concentrations of the modelled compounds in the water and quantities in deposited sediments. In this chapter, the effects of such concentrations on receptors (people and ecosystems) are discussed as well as potential remediation costs. It is important to realise that, during the simulations, the solubility values of many compounds in water may be exceeded. For instance, immediately after collapse of a large storage tank, large volumes of contaminants are released. This may be a layer of oil, floating on the water, or a DNAPL layer moving over the ground surface. This type of contamination is likely to be a major threat to flora, fauna and humans, living close to collapsing tanks. It may also result in pollution of (underground) piping systems like those used for municipal drinking water, which is difficult to remove (see also paragraph 2.5.2)

5.2 The impact of flooding waters on the environment

5.2.1 Effect of contaminants in water

In Table 13, typical concentrations, as reported in Chapter 4, are shown for pollutants that are not adsorbed to soil particles yet subject to natural attenuation processes. Reference values and background concentrations in the Rhine River are included for comparison. Intervention values are derived from Dutch soil remediation legislation. If living organisms come in contact with water loaded with concentrations of pollutants in excess of the intervention values, their functionality may be seriously affected.

Compound code	Compound name	typical concentration in simulations (mg/l)	Present in Rhine water (mg/l)	Reference value (mg/l)
2	Benzene	5	0.000209	0.05 (Dutch Intervention value)
3	Micro-organisms	(Large increase)	0	
7	PER	1	0.000266	0.04 (Dutch Intervention value)
10	Pesticides	3	0	0.1 (standard for drinking water)

Table 13 Typical concentrations found in flood waters as simulated in this project, compared with values found in Rhine water and reference values

In the simulations, it is shown that the water during the flood will contain amounts of benzene, PER (DNAPL) and pesticides well in excess of the reference values tabulated here. These compounds appear to be washed away to the borders of the flooded area, where they tend to accumulate. Clearly, one should be careful with the intake of drinking water during this time. In the modelled 'Krimpen' area, flood water is likely to remain present for possibly half a year, which would be the time required to pump the water out, using all available pumping capacity. During this period most components are likely to decay naturally, probably to sub toxic levels.

Micro-organisms may remain a cause of concern for longer periods of time because of their growth. Effects can only be expressed in qualitative terms as a proper modelling algorithm was not available in the model. Important parameters that should be included in such an algorithm are temperature (season) and effects of the failures of water treatment installations during and after the flood. the importance of the latter was clearly demonstrated in the literate study on recent floods in Europe (cf. Chapter 2). The growth and its effect are also dependent on the type of micro-organisms. It is likely that algae growth may occur. This may cause oxygen depletion and lead to growth of toxic organisms like blue algae. At this moment it is not possible to quantify these effects. During the Elbe flood in Germany, oxygen depletion recorded frequently, whereby all life in the water was affected,. fish in particular.

5.2.2 Effects of contamination in the sediment

The deposition of polluted sediment may cause health risks and adverse effects on ecosystems. Human risks may occur when contact is made with polluted sediment. According to Van Bruggen et al. (1995), the most important routes of contact are:

1. Intake of sediment via consumption of crops;
2. intake of sediment via hand-mouth contact;
3. skin contact with polluted sediment;
4. intake of sediment (dust) via wind dispersion;
5. consumption of polluted drinking water;
6. consumption of crops, cultivated on polluted sediment;
7. consumption of meat and dairy products from cattle, raised on polluted pastures.

Contact routes one to five are of most importance in the period immediately after the flood and during the removal of sediment from the flooded area. Avoiding direct contact with sediment, avoiding the consumption of crops coated with sediment and avoiding drinking water from wells in the flooded area, will reduce most of the risks.

Effects of contact routes six and seven will emerge only after longer periods of time and could possibly reduce the land use potential for agriculture. To evaluate possible human and ecological risks it is significant to investigate the extent of the concentration increase in the topsoil after a flood in these areas and compare results with soil standards. Again useful standards can be derived from Dutch soil remediation legislation. For the relevant components, Dutch Intervention and Target values are shown in Table 14. Target values represent concentrations that should not be exceeded if full functionality of organisms in contact with the soil is to be guaranteed. Soil concentrations calculated during the modelling exercise are shown also in Table 14. Most of the soil is polluted at concentrations between the Dutch Target value and Intervention value. In Chapter 4, it was shown that the concentrations modelled were almost exclusively the result from material brought in by the river Rhine. This was partly the result of shortcomings of the model, which resulted in an underestimation of the release of land based material. Therefore, contact with the sediment (after water is pumped out of the flooded area) could have some adverse health effects, particularly if there is a risk of intake.

Components	In sediment (model simulations)	Dutch Intervention value for standard soil	Dutch Target value for standard soil
PAK10	50 mg/kg	40 mg/kg dry matter (d.m.)	1 mg/kg d.m
PCB	0.1 mg/kg	1 mg/kg d.m.	0.02 mg/kg
Mineral Oil	2 g/kg	5 g/kg d.m.	0.05 g/kg d.m.
Zn	0.6 g/kg	0.72 g/kg d.m.	0.14 g/kg d.m.
Cd	2.5 mg/kg	25 mg/kg d.m.	0.8 mg/kg d.m

Table 14 High concentrations in sediment after flood compared with Dutch standards

For rural areas, the results are probably best evaluated by comparing the soil concentrations with agricultural land use requirements, rather than the Dutch Intervention and Target values. These requirements were outlined by the Dutch Agricultural Counselling Committee (LAC) and defined in the 'LAC-alert values' If such LAC-values are exceeded, the suitability of the soil for agricultural purposes should be (re-)assessed. For Zn and Cd, the LAC-values are presented in Table 15. For comparison, the table also contains the mean quality of suspended sediment in the river Rhine over the period 1992-2000.

compound	arable land	pasture (cattle)	Mean quality of suspended sediment in the river Rhine (mg/kg sediment)
Cd	0,5	3	1,8
Zn	350	350	467

Table 15 LAC-alert values [mg/kg] for arable land and pasture on clay soil (values are converted to a 'Dutch standard' soil composition), as well as the quality of suspended sediment in the river Rhine over the period 1992-2000

Table 15 shows that Cd- and Zn-concentrations in the sediment layer exceed LAC-alert values for arable land. For pasture, only Zn exceeds the LAC-alert value. Mixing the sediment layer with the underlying topsoil reduces concentrations to values below LAC-values (see Figure 38 and Figure 39). These findings indicate that regular agricultural activities, in which top layers of soil are mixed, may eliminate possible risks in arable and pasture land, and hence the exposure risks through routes 6 and 7 mentioned above.

This conclusion is however based on a simple model, using global soil characteristics, just a few chemical compounds and only considering the river Rhine as a source of pollution. Local variations in soil characteristics, variation of concentrations in suspended river sediment and the proper inclusion of a wider range of chemicals from land sources in the flooded area might increase the amount of resulting chemical concentrations in the soil and therefore the likelihood of health risks.

5.2.3 Clean-up costs

According to Dutch regulations, all pollution must be removed. The regulations prescribe that all contamination which occurred after 1987 has to be cleaned up. Assuming that this regulation is applicable in case of flooding, a first estimation of cleanup costs can be done.

In Chapter 4, the total amount of sediment deposited in the area is estimated as 388 million kg, which is equivalent to approximately 0.23 million m^3. Sediment thickness will vary (see paragraph 4.1.1) but will often be only a few mm. As it is difficult to remove layers less than 10cm thick, this could mean that a total volume of 10 million m^3 would have to be disposed of as contaminated soil. With typical soil remediation costs of €35-55 /m^3 this would amount to total cleaning costs of €350-550M.

This scenario is not very likely, though. In the flooded area, 15% is urban area and 85% is agriculture land. As outlined above, mixing with underlying soil is likely to take place in agricultural land, apart perhaps from locations with thicker accumulations of sediment. In urban areas, material deposited on hard-covered areas could be collected. This may be cumbersome (and thus expensive) in cases when the sediment has entered areas that are difficult to access. Nonetheless a more realistic cost assessment could be that only about 30% (15% from the urban areas and say another 15% from rural areas) of the sediment would be disposed of as polluted soil. Clean-up costs per m^3 might be higher than stated above (say double). This would result in estimated cleanup costs of about € 80M.

Before such a cleanup is undertaken, detailed soil analyses will probably be carried out. Given the scale of the flooding event a risk analysis could be used to prioritise soil remediation efforts. Such a technique could be based on the risk analysis technique currently used in soil contamination problems, where soil pollution is divided in three different risk categories: immediate humane risks, immediate ecological risks and risks of spreading of contamination; the latter leading to risks in the longer term. In the regulations, these risks are linked to the urgency of clean-up.
After the risk analysis, clean-up costs will be calculated for the locations where an immediate risk exists. In addition, an overview will be made of the consequences for those areas where contamination is not removed. Possible consequences are loss of live, loss of multi-functionality of land, loss of ecological values, drinking water problems and more.

5.3 The physical impact of flooding waters on agricultural fields

In addition to the many impacts on the environment caused by the migration of pollutants, the mere physical effects of flood waters on agricultural fields has been taken into consideration as well. So far however, in The Netherlands no appreciable research has been devoted to the assessment of damage to agriculture due to flooding events. The knowledge and expertise, required to quantify this type of damage is obviously inadequate for the simple reason that research into crop damage in The Netherlands has always been associated with the creation of optimal boundary conditions for agricultural production. Even so, Van der Bolt and Kok (2000) have attempted to develop a protocol to quantify damage due to flooding events. The lack of real data, associated with flooding events, is a substantial handicap where verification of the results of any damage assessment procedure comes into play.

Physical Processes

Flooding damage on agricultural fields is largely related to the following physical processes:

Inundation. The most important source of damage to crops, occurring with shallow groundwater tables as well as with flooding, is strongly decreased aeration of the root zone. Root systems of crops will die as the uptake of oxygen is severely restricted. The physical processes which cause this type of damage are well defined, yet quantification of this type of damage is difficult as the values of the associated parameters are not very well known. A rule of thumb, applied in The Netherlands, is that any crop will die after 72 hours of continuous inundation. This rule is based upon practical experience.

Deterioration of soil structure. Due to surfacial soil clogging, air entry into the soil surface is restricted as long as the soil surface remains saturated, even after the flood waters have receded. The associated processes are known in a qualitative manner only.

Salt. Most agricultural crops will not tolerate high salt concentrations of flooding waters. The associated physical processes are well known.

Other processes. Flooding may cause other unwanted processes, such as:

- leaching of nutrients from agricultural fields to vulnerable, adjacent lands like nature areas;
- infiltration of flood waters, loaded with pollutants, into the soil;
- deposition of sediment which contains adsorbed pollutants, e.g. heavy metals;
- deposition of sediment on crops, rendering them unsaleable;
- damage to, or decay of harvestable crops.

It is important to assess flood damage for various types of land use (Van der Most and Van der Bolt, 1999). Taking the potential damage per hectare as a starting point, e.g. average yields in agriculture and horticulture, the following land use categories are defined and investigated: grassland, arable land, high-grade agriculture and -horticulture, greenhouse agriculture, urban areas (residential, industrial and special objects) and nature.

Having investigated the state of art of knowledge concerning flood damage, Van der Bolt and Kok (2000) have developed a method for calculating this type of damage in agriculture due to short, extreme precipitation events, both on arable land and on grassland. This damage has been modelled for three groups of crops and for seven soil types. The parameters that were used are provisional nature due to the fact that this method is still being developed. On arable land, the primary process analysed is the saturation of the upper soil strata with water due to extremely shallow groundwater tables. The associated damage is related to the so-called critical groundwater table. This damage is maximum as soon as the groundwater table has coincided with the soil surface (‘ponding’) for at least 72 hours. It is assumed that, in such cases, any additional inundation will not induce additional damage.

In addition, an assessment has been made of the damage which is the result of a reduction of trafficability and soil tillage. As data for arable land were not available, damage parameters for arable land were based upon damage calculated for grassland on sandy soil (Postma, 1992). The parameter values have been corrected for soil types other than sand and for crops other than grass. The flood damage functions for grass-, and arable land contain coefficients that are seasonally dependent. As a result, inundation of grassland during the winter season will not induce any damage. The calculated damages appear to be realistic yet cannot be verified due to a lack of reliable data.

Investigations into, and assessments of flood damage in The Netherlands are scarce. Flood damage due to excessive precipitation in September and October 1998 has been estimated to be as high as €427M, following the associated insurance companies, and experts of the Dutch Ministry of Agriculture. Approximately 85% of the damage had occurred in agriculture, cf. Table 16.

In this study, flood damage to crops was assessed by multiplying flooded areas with average crop yields, cf. Table 17.

Category	Estimated damage (M€)	
	Sept 1998	Oct 1998
Crop damage in agriculture	135.0	91.0
Other damage in agriculture	4.2	3.0
Other businesses	1.8	13.0
Local authorities	3.5	8.8
Private properties	1.1	1.1
Corporations and churches	1.2	0.2

Table 16 Estimated flood damages due to excessive precipitation events in September and October 1998 in The Netherlands. After Van der Bolt and Kok (2000)

crops - breeding	typical yield (kg/ha)	marketable value (€/kg)	Produce (€/ha)
Grass	75 000		900
Field crops average			3 600
corn	50 000		900
winter wheat	8 600	0.14	1 200
summer barley	6 000	0.14	900
other cereals	5 800	0.15	900
seed potato	36 000	0.21	7 700
edible potato	48 000	0.09	4 500
farina potato	45 000	0.05	2 250
sugar beets	56 000	0.05	2 800
horticulture			18 000
fruit-growing			11 500
arboriculture			29 500
flower bulbs			28.500

Table 17 Average yields of crops. After Van der Bolt en Kok (2000)

Glasshouse horticulture is the only type of agriculture for which damage assessment functions due to flooding have been established ($HKV_{\text{lijn in water}}$ and Oranjewoud, 1999). In these assessments, which were made for the Hoogheemraadschap of Delfland; damage is linked to the depth of inundation in that damage is at its maximum for at least 0,5m inundation depth. The damage may also be linked to the inundation period (Van der Bolt en Kok, 2000). For short term flooding events, i.e. less than three days, the damage is assessed to be 50%, whereas for longer periods the damage will be 100%, in line with analyses made for agricultural and horticultural crops. The figures are calculated as gross losses / area (i.e. ha), or as losses for an entire object, for three categories of crops: pot- and bedplants, cut flowers, horticultural crops and vegetables, cf. Table 18.

Crop	gross produce (€/ha)
pot- and bed-plants	275 000
cut flowers	230 000
vegetables	185 000
glasshouse horticulture, average	225 000

Table 18 Average yields of glasshouse crops. After Van der Bolt en Kok (2000).

In Table 19, inundation depth data are specified for the major categories of crops that were cultivated in the area when the flooding occurred. Assuming that the damage to the crops caused by the inundation of the agricultural fields is 100% as soon as the duration of the flooding has exceeded a period of 72 hours, which is the case at all agricultural fields in this simulation, the damage was calculated by multiplying the produce (€/ha) with the associated acreage (ha), yielding a total damage due to flooding of M€853 (worst case scenario) cf. Table 20.

Crop	25×25m cells (6.25 ha)	area (ha)	area (%)	min water layer (m)	max water layer (m)	water layer range (m)	average water layer
grass	5 775	36 094	71.4	0.01	5.72	5.71	1.75
other crops[3]	629	3 931	7.8	0.01	5.45	5.44	2.56
glasshouse horticulture	559	3 494	6.9	0.01	5.63	5.62	2.35
cereals	383	2 394	4.7	0.01	5.47	5.46	3.32
potato	321	2 006	4.0	0.01	5.27	5.26	3.41
maize	226	1 413	2.8	0.03	5.47	5.44	2.14
sugar beets	183	1 144	2.3	0.03	5.29	5.26	3.30
orchard	16	100	0.2	0.08	5.06	4.98	2.92

Table 19 Cultivated crops, associated inundated areas and water layer heights in rural areas in the 'Krimpen' case

crop	area (ha)	produce (€/ha)	damage due to flooding (M€)
grass	36 094	900	32
glasshouse horticulture	3 494	225 000	786
cereals	2 394	900	21
potato (edible)	2 006	4 500	9
corn	1 413	900	1
sugar beets	1 144	2 800	3
orchard	100	11 500	1
Totals	46 645		853

Table 20 Estimated maximum crop damage in agriculture, regardless of water layer height

[3] In this region, mainly arboriculture and horticulture in the open.

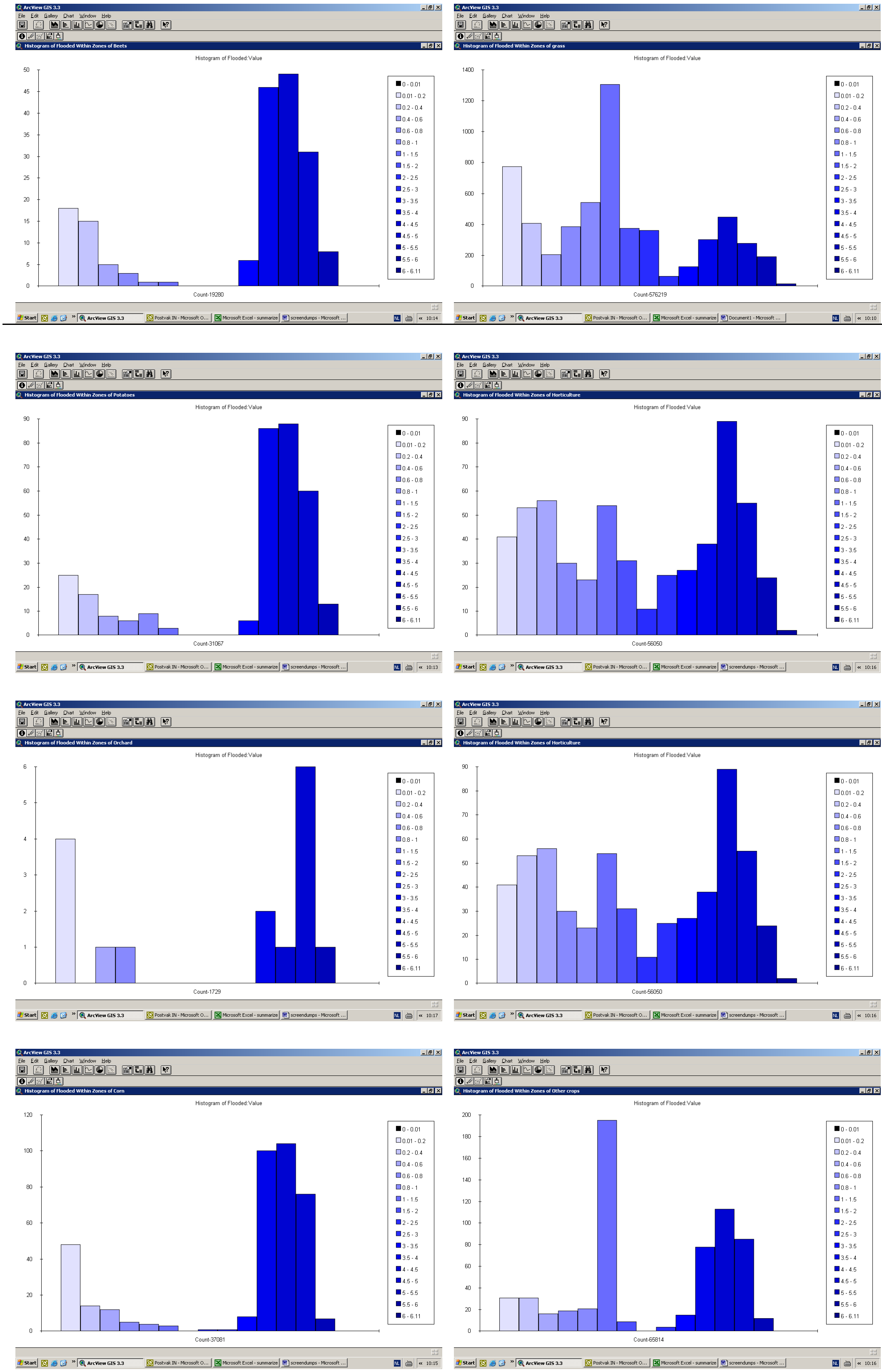

Figure 44 Gross view of inundation depth (horizontal axis) and frequency of occurrence, for eight different crops or agricultural land use. Generally spoken, the inundation depth focuses around two dominant values; the lower ones below 2m and the higher ones ranging from 2-6m, depending on the depth of the soil surface below MSL of the polders concerned

6 Conclusions

6.1 Introduction

The objective of this study was to assess the possible environmental consequences of pollutants entering a flooded area with the incoming water and release of pollutants as a direct or indirect result of the flooding. This has been done by developing a conceptual framework and testing this framework on a simulated major flood, following a literature search.

The first part of the study, an extensive literature search, revealed that studies on chemical hazards due to flooding and inundation are quite scarce. Reporting is dominated by immediate and very obvious effects like casualties, damage to buildings / infrastructure and the impact on the economy. Relevant information from this literature study was used in the second part of the study, in which a breach of a river dike near the city of *Krimpen aan de Lek,* was a model case for the study of environmental effects.

In the second part of the study, a conceptual framework was defined, based on the sequence of events during flooding, the so-called *chain reaction*: after a dike breach the flood water will reach source objects (with pollutants) that may fail and release their contents (initiating mechanism). Next the floodwater will disperse the material (dispersion mechanism), which subsequently may reach a target (person, ecosystem) that may be adversely affected (consequence mechanism). A distinction was made between water-soluble pollutants, which will be removed with the water being pumped out, and sediment-bound pollutants, which will stay behind. Also, sediment itself is a factor causing damage as is the water layer.

Several elements that are important for the study of environmental effects of flooding are well studied, but all in separate scientific fields. Sediment transport is a well-studied engineering science; many models can simulate floods and other models can predict environmental hazards. An integrated model capable of predicting environmental effects of flooding was not available. Such a model had to be developed during the project from readily available modules. Of course such a prototype product is compromised in various ways:

- The modelling capabilities for the release of toxic agents from leaking / collapsing structures were very limited. This caused underestimation of released products further away from the breach;
- sedimentation could not be modelled independently of release;
- the adsorption / desorption behaviour could not be modelled;
- a very coarse modelling grid (250×250m) may have obscured relevant local details, leading to a conservative assessment of concentrations of suspended solids and dilution rates;
- the fate of some components, in particular micro-organisms could not be modelled.

In addition, various modules required input data, like strengths of industrial structures and types and volumes of chemicals, which do not exist or were difficult to obtain, that is, within the time frame of the project. Therefore, many decisions had to be taken on the basis of expert judgement, in an attempt to simulate rather severe, yet realistic, scenarios. The conclusions drawn should be interpreted with this in mind.

6.2 Discussion and conclusions

The water soluble compounds BTEX, PER, TRI and pesticides (non-adsorbing compounds) will be washed towards downstream boundaries of the flooded area, i.e. to areas where the water becomes more or less stagnant. During the ten day modelling period, typical concentrations of these compounds were found to be in excess of legal limits, i.e. standards for drinking water and groundwater target values. However, as these components are subject to natural attenuation processes like biodegradation and evaporation, these concentrations are expected to decrease to sub toxic levels during the period that the floodwater is assessed to remain in the area (six months typically). During the flood, high concentrations of dangerous micro-organisms and algae may develop as well. Effects of toxic concentrations of water soluble compounds on the receiving surface waters and micro-organisms have not been quantified yet.

Components that will adsorb to soil particles and -aggregates, e.g. PAHs, PCBs, (cyclo)alkanes, Zn, Cd, Phosphates, concentrations, found in the incoming Rhine water will cause pollution exceeding Dutch soil remediation standards. Land based sources may contribute significantly, particularly from oil type products of which large volumes are available (cf. Table 4). Many oil products are stored in large tanks above ground level, in underground storage tanks of petrol stations or as dispersed sources in cars. Of these sources, cars are probably the most vulnerable and their contribution could very well be the most significant. However, the exact contribution to the total contamination of these sources could only be assessed roughly during the time period of the project due to the conceptual limitations of the current version of the Delwaq model.

If the polluted sediment would have to be disposed of as contaminated soil, clean-up costs are estimated between €80M and €550M. The high value would be the result of the removal and clean up of 10cm of topsoil from all areas covered with sediment. The lower value could be achieved if only areas from which sediment can be collected, were cleaned up, and if contaminated sediment were mixed with unpolluted topsoil in agricultural areas. The consequences of such solutions should be assessed beforehand.

Until date, only the effects on agriculture and nature / ecology caused by physical impact of flooding were taken into account. In some earlier studies, some effort had been made to quantify the effects of the polluted riverine sediment. This study clearly shows that the ‘chain reactions’ during the flood, causing the release of contaminants that are stockpiled in the area itself must be taken into account as well.

The cost of production loss in agriculture due to physical damage by the water in the simulated case study is calculated to be €853M at maximum. This high figure is mainly due to the substantial acreage of glasshouse horticulture.

The release of pesticides in the flooding water is modelled as a point source. The grid size of the model is 250×250m, hence concentrations are ‘diluted’ upon migration into the environment. This is the case for all point sources. It is expected that pesticide concentrations in the floodwaters will exceed legal values in the vicinity of the farms yet subsequent dilution is quite substantial. Concentrations, expressed in µg/litre will be required to make a judgement. In The Netherlands, the concentration of pesticides leaching into the groundwater should not exceed 0.1 µg/litre. The influx of water + pesticide into the groundwater body is a source of concern, notably if groundwater is being used for other purposes, e.g. the production of drinking water.

As far as the modelling concept is concerned, the Delwaq model is more advanced than the ERA model. Still, the simulation results of both models are comparable, although the DELWAQ model should give more accurate results. The ERA model is easier to use. An important finding is that it is crucial to include local sources of pollution while modelling advection of substances that are adsorbed to suspended material, since local sources hold substantial amounts of polluting material that can be deposited in the flooded area. Further development of both sedimentation models is under way. So far, the ERA model has been used for modelling environmental effects of emergency retention areas. The additional effects of small sources located in the flooded area such as cars are not included in those impact studies. The results of our study show that this will lead to an underestimation of the effects.

In summary, this study shows that flooding may have a considerable environmental impact on the receiving environment. On agriculture, because of physical damage to crops and installations, and due to toxic sediments on agricultural fields. On nature areas, because of deposition of phosphates and toxic materials in sediments. On people, because of toxic concentrations of chemicals in the floodwaters, growth of micro-organisms and algae that may cause diseases, and because of the deposition of polluted sediments in sensitive areas like playgrounds and gardens. The effect of deposition of sediment by itself is an important factor as they may cause damage to subways and sewage systems. In conclusion, it is justified to state that the environmental impact of flooding is very likely to be substantial. Hence, in order to be comprehensive, damage to the environment cannot be ignored in any assessment of the effects of a flooding event.

7 Recommendations for further research

In this study into the environmental consequences of a release of pollutants as a result of flooding it was clearly shown that there is a significant risk of environmental damage due to chemicals used and stored on land. For a more detailed assessment of these effects, in particular as compared to casualties and economic losses, a follow-up study is recommended to enhance the understanding of these effects, in order develop improved strategies for policy makers to decrease such damage, including possible long term effects. Several aspects will need particular attention in such a study. While innovative in its capacity to simulate various hydraulic and chemical processes with an integrated model, this model was a prototype and drastically needs to be upgraded in conceptual terms, viz.:

- separate modules should be implemented for the release and sedimentation of toxic agents;
- more toxic agents should be included in the modelling process;
- component-specific behaviour should be introduced; this would apply to the release, sedimentation and decay of pollutants and the growth of micro-organisms;
- modules for multi-phase flow should be included, e.g. in order to model the behaviour of oil and DNAPL;
- the spatial resolution should be enhanced.

Other aspects that should receive more attention in the future are:

- The failure of water treatment facilities should be included;
- more accurate data should be obtained on toxic substances, stockpiled in the flooding-prone area;
- improved analyses should be carried out of the structural integrity of various installations, in particular for those containing oil type products, so that multiple, more realistic release criteria can be selected.

It is obvious that results, to be obtained from improved future model studies should be validated with real data. For this purpose, contacts with research institutes and authorities involved in the 2002 ‘Elbe’ flood have been established recently.

Given the scale of a flooding event and the potential remediation costs, there is clearly a need for a proper risk assessment technique, in which both the necessity and the urgency of clean-up of contaminated sediment can be determined. This will pave the way for a balanced assessment of the relative importance of the environmental, economic an health effects. Such an assessment is essential for local and regional authorities, and other decision makers, to take adequate and cost-effective measures to reduce the adverse effects of flooding.

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General Appendix: Delft Cluster Research Programme Information

This publication is a result of the Delft Cluster research-program 1999-2002 (ICES-KIS-II), that consists of 7 research themes:
►Soil and structures, ►Risks due to flooding, ►Coast and river , ►Urban infrastructure, ►Subsurface management, ►Integrated water resources management, ►Knowledge management.

This publication is part of:

Research Theme	:	Risk of Flooding		
Baseproject name	:	Flood consequences and acceptability		
Project name	:	Flood consequences		
Projectleader/Institute		Prof. A.C.W.M. Vrouwenvelder	Projectleader/Institute	
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		Twente University		
		Alterra		
		CSO		
		Delphiro		
Total Project-budget	:	€ 450.000		
Number of involved PhD-students	:	2		
Number of involved PostDocs	:	0		

Delft Cluster is an open knowledge network of five Delft-based institutes for long-term fundamental strategic research focussed on the sustainable development of densely populated delta areas.

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