# Assessment of Groundwater Pollution Risks in Production Wells with RESPOND®

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## Abstract

Drinking water companies need insight into the future quality of abstracted groundwater. Activities on the surface level linked to land use mainly determine the quality of groundwater. There is fundamental uncertainty about the quality of groundwater that will be pumped in the future because measurements of groundwater quality at monitoring wells only cover a very small part of a capture zone. RESPOND® (Risk Evaluation of Soil Pollution for ProductiON of Drinking water) is a recently developed modeling instrument by which risks of groundwater pollution can be assessed. This instrument can be applied efficiently within an ArcGIS ModelBuilder environment, coupled with groundwater flow and transport models in which dilution, retardation and attenuation are taken into account. RESPOND® facilitates the identification of effective risk-reducing measures such as changing land use in the capture zone or selection of additional monitoring sites.


## Introduction

Kiwa Water Research is the Dutch research and knowledge institute for drinking water, wastewater and related ecological and environmental aspects. Kiwa has been conducting the Joint Research Programme of the Dutch Water Sector (BTO) for more than thirty years on behalf of the Netherlands' water supply companies. GIS-technology has been used since 1989 to support the integration of our fields of knowledge (hydrology, ecology, process technology and distribution technology) into innovative concepts and tools.

In The Netherlands 70 % of the drinking water comes from groundwater sources. Drinking water companies need insight in the future quality of abstracted groundwater. Activities on the surface level, linked to land-use, mainly determine the quality of groundwater. The rising pressure on scarce space in densely populated areas such as The Netherlands causes a continuing increase of potentially harmful activities in groundwater capture zones (Figure 1). Monitoring networks are installed to track possible groundwater-pollutions in an early stage. However, the use of monitoring networks can not reveal all risks of groundwater pollution. Because of dynamic changes in land use and the relative inaccessibility of aquifers there is fundamental uncertainty considering the quality of groundwater and consequently of the future quality of extracted groundwater for drinking water production (raw water). Therefore, drinking-water companies need appropriate methods to quantify the risks of groundwater pollution.


Figure 1. Water sources in The Netherlands and present urbanisation.

RESPOND® (Risk Evaluation of Soil Pollution for ProductiON of Drinking water) is a recently developed modeling instrument by which risks of groundwater pollution can be assessed. In this method, we use "soft knowledge' (prior information/expert knowledge) on probabilities of the occurrence of pollutions as a function of present and historical land use.

Instead of modelling the transport of groundwater solutes, the transport of risks is modelled. As a result, a consistent prognosis of risk-scores for the raw water per substance (Pesticides, volatile aromatics, heavy metals etc.) is calculated. Thanks to the formalised and consistent approach, risk predictions of different wells can be compared and prioritization for further research and risk-reducing measures are possible. These measures may vary from additional monitoring to the placement of additional treatment capacity.

As the method is based on explicit criteria and decision rules it can be applied efficiently within a GIS environment, coupled to MODFLOW, MT3d and other transport models. Changes of the perceived importance of specific contaminants or of estimates of the probabilities that particular types of land-use related pollution may occur can be taken into account in the risk prognosis in a quick and cost-effective way.

Assessment of uncertainties in the results is possible by carrying out multiple simulations for different combinations of model parameters. A proper validation is not considered possible because risks are even more difficult to validate than manifest properties.

In this paper the concepts, tools and applications of RESPOND® will be presented and discussed Special attention is given to the use of ArcGIS and ModelBuilder tools.

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# RESPOND® concepts

## Multi barrier approach

In RESPOND® a so called multi barrier approach for the risk assessment is applied. We have distinguished three barrriers (figure 2):

1) Risk load on surface
2) Risk reduction during transport
3) Risk reduction during drinking water purification

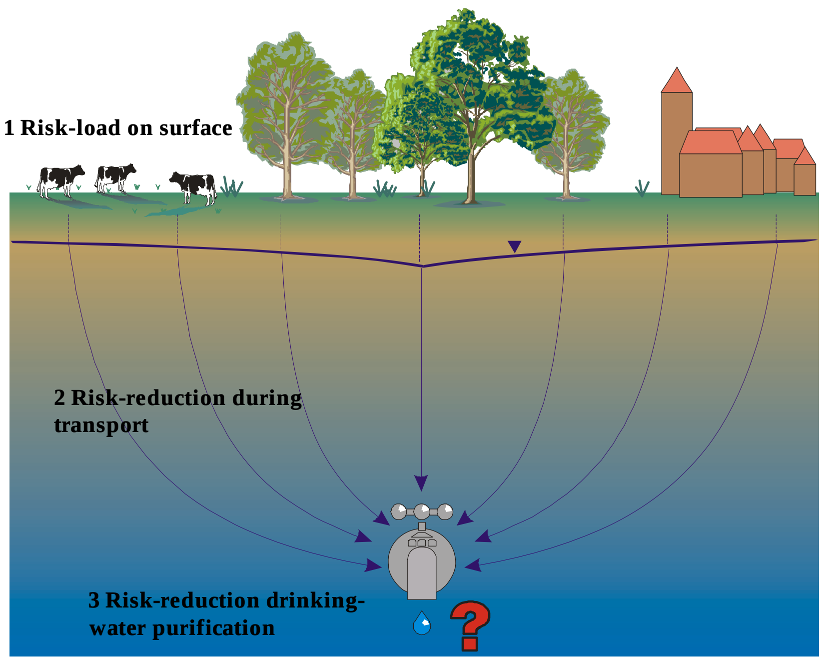


Figure 2. Quantifying risks for drinkingwater pollution on three levels.

This paper is focussed on the risks of groundwater pollution for the quality of raw water, extracted by production wells.

## Risk load on surface

The total load of risks on the surface is imposed both by point pollution and non-point pollution sources. Point pollution sources may either be known (manifest) or potential. The relationship between a certain type of land use, a time period and the probability of a point pollution source is not known very well. Therefore, risk scores for point-pollution sources are estimated by expert judgement.

Risk scores (on a relative sale from 0-10) for 31 types of land use (see table 1) and for 9 substance groups (see table 2) have been assigned by a group of experts (Laeven, 1999). In more recent research (Vink, 2006) also microbiological risk indices have been added to RESPOND®. With this latest extension also the risks imposed by leaking sewage pipes and septic ranks can be assessed. See appendix I For a complete list of all substances and microbiological parameters.

Table 1. RESPOND® land use codes.

| Number | Group | Subgroup |
|---|---|---|
| 1 | Nature | Water |
| 2 | | Heath |
| 3 | | Forest |
| 4 | Agriculture | Intensive-high |
| 5 | | Intensive-low |
| 6 | | Extensive |
| 7 | Cattle | Intensive |
| 8 | | Extensive/biological |
| 9 | Other | Horticulture |
| 10 | | Orchard |
| 11 | | Estate |
| 12 | | Campsite |
| 13 | | Garden |
| 14 | Residential | Dense-old |
| 15 | | Dense-new |
| 16 | | Scattered-old |
| 17 | | Scattered-new |
| 18 | | Bungalowpark |
| 19 | Trade/service | Offices/schools |
| 20 | | Trade building |
| 21 | Public green facility | Cemetary |
| 22 | | Public park |
| 23 | | Outdoor sports facility |
| 24 | Industrial | High level |
| 25 | | Low level |
| 26 | Infrastructure | Road |
| 27 | | Parking lot |
| 28 | | Water course |
| 29 | | Harbour |
| 30 | | Railroad |
| 31 | | Railroad yard |

Table 2. RESPOND® groups of chemical substances.

| | **Substance group** |
|---|---|
| 1 | Nutriënts |
| 2 | Salts |
| 3 | Acids |
| 4 | Heavy metals |
| 5 | Disinfectants |
| 6 | Pesticides |
| 7 | Volatile aromats |
| 8 | Halogenated hydrocarbons |
| 9 | Other hydrocarbons |

The potential risk for groundwater pollution on the surface differs per type of land use and over time. For example a forest will be less a risk (considering pesticides) compared to an area with arable farming. Per type of land use an assessment is made to quantify the development of the risks (on a scale from 0 to 10) on potential groundwater pollution over time (see figure 3).

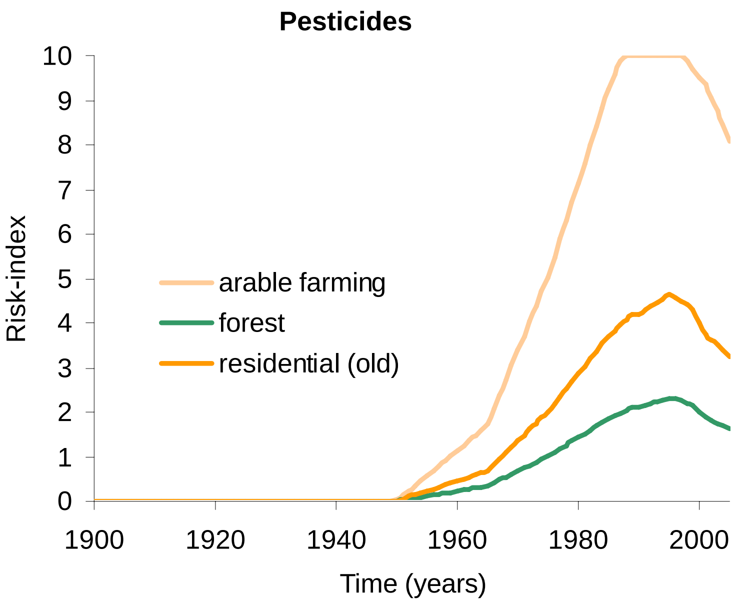


Figure 3. Risk index for pesticides over time and for different types of land use.

If historical data of land use is available, or may be assumed, risk-index maps for certain substances and time periods may be derived (see figure 4). A risk-index map library contains maps for each year and each substance. Maps from this library may serve as input to groundwater transport models.

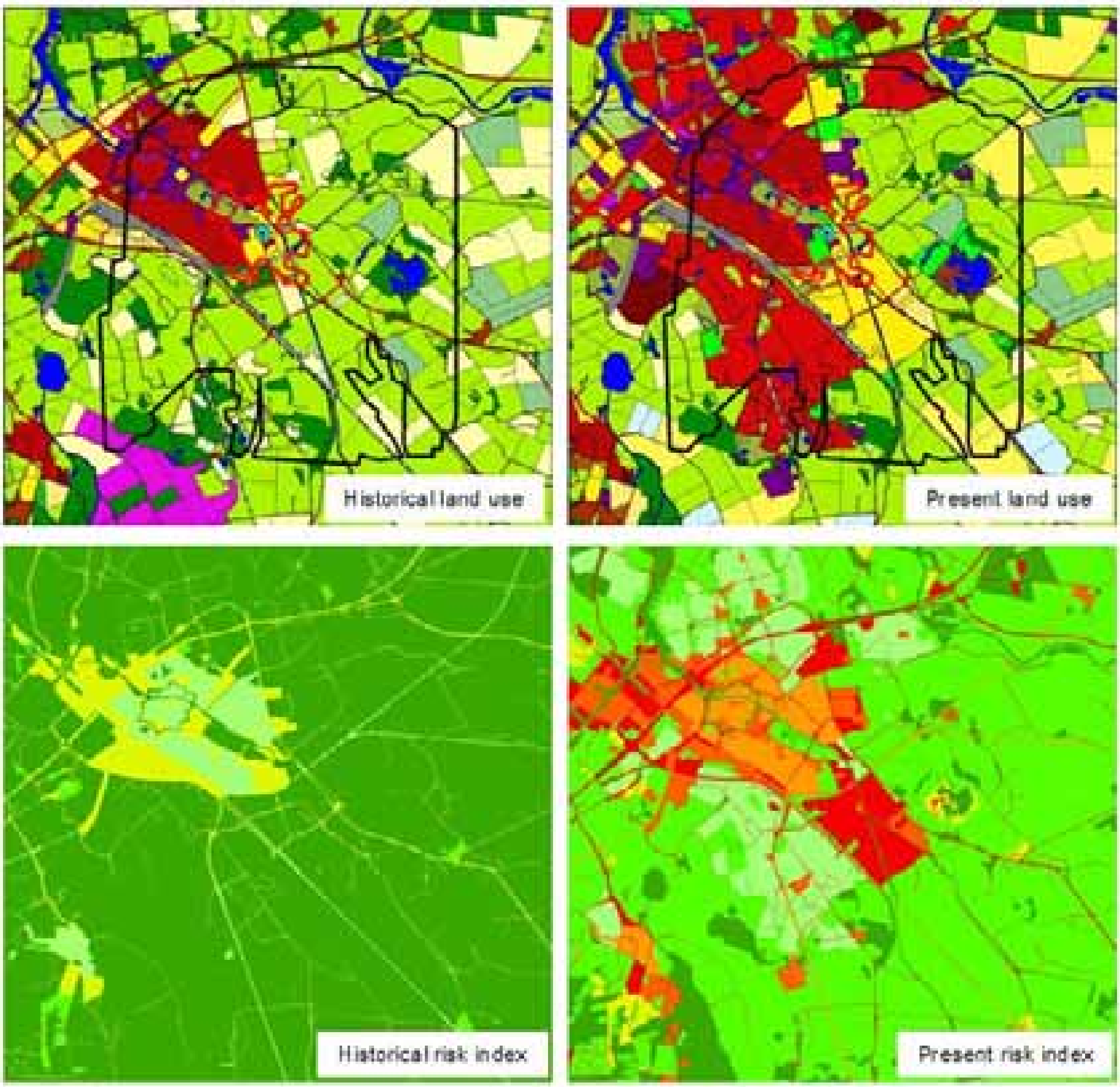


Figure 4. Increasing urbanisation and intensification of agriculture in groundwater capture zones causes an increasing risk of contaminated drinking-water wells

## Risk reduction during transport

Instead of modelling the transport of groundwater solutes, the transport of risks is modeled. The risks are defined as relative probabilities of pollution, caused by a certain type of land use occuring in a certain period of time, weighted for potential impact. The transport is simulated with flux-based (MT3d) or flowpath-based models. Risk reducing processes like dilution, retardation and attenuation are taken into account just like in modelling the transport of dissolved pollutants. As a result, a consistent prognosis of risk-scores for the raw water per pollutant or group of pollutants (Pesticides, heavy metals etc.) can be calculated, see figures 5 and 6.

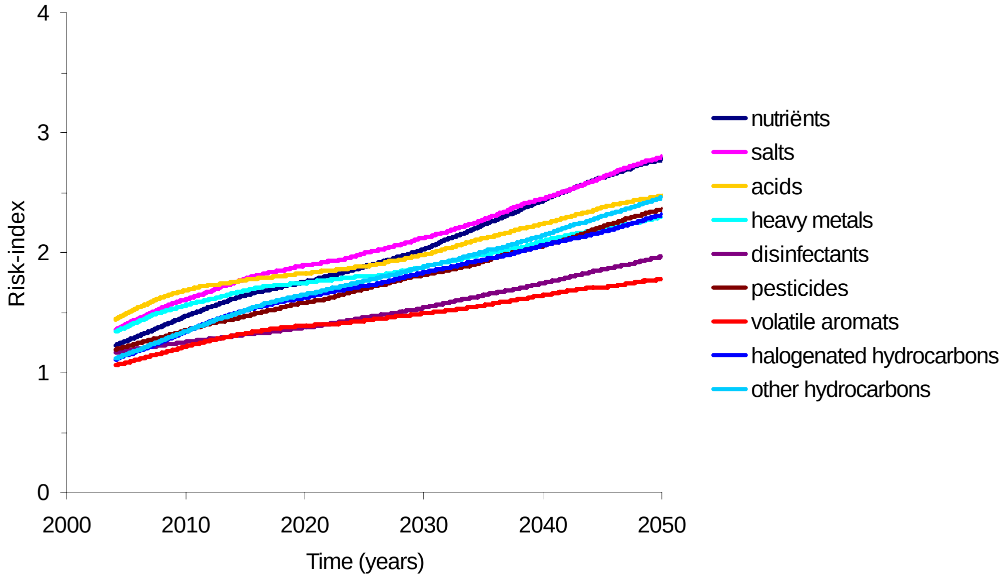


Figure 5. Prognosis of raw water risk-scores in an urbanized area.

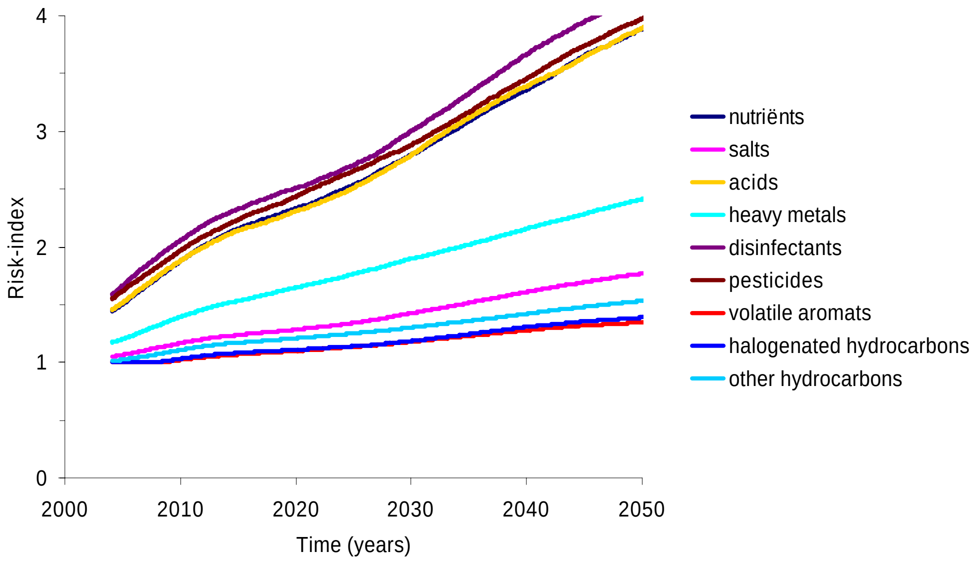


Figure 6. Prognosis of raw water risk-scores in a rural area.

To quantify the risk reducing effect of transport in the soil, aquitards and aquifers, 20 guiding substances have been selected (at least one for each substance group, see appendix I). If applicable the physical or chemical processes of sorption, 1$^{st}$ order decay and Redox reactions have been accounted for.

The degree to which these processes occur depend on five subsurface chatacteristics:

1) Percentage of organic matter;
2) Redox potential;
3) pH;
4) CEC (Cation Exchange Capacity);
5) CaCO3 content.

These five characteristics can be derived from borehole data by applying a set of decision rules. In the Netherlands often a dense network of these borehole data is available, so the results can be interpolated in three dimensions. Figure 7 shows an example of this 3D hydrochemical mapping of pH in a pilot study area in the Netherlands.

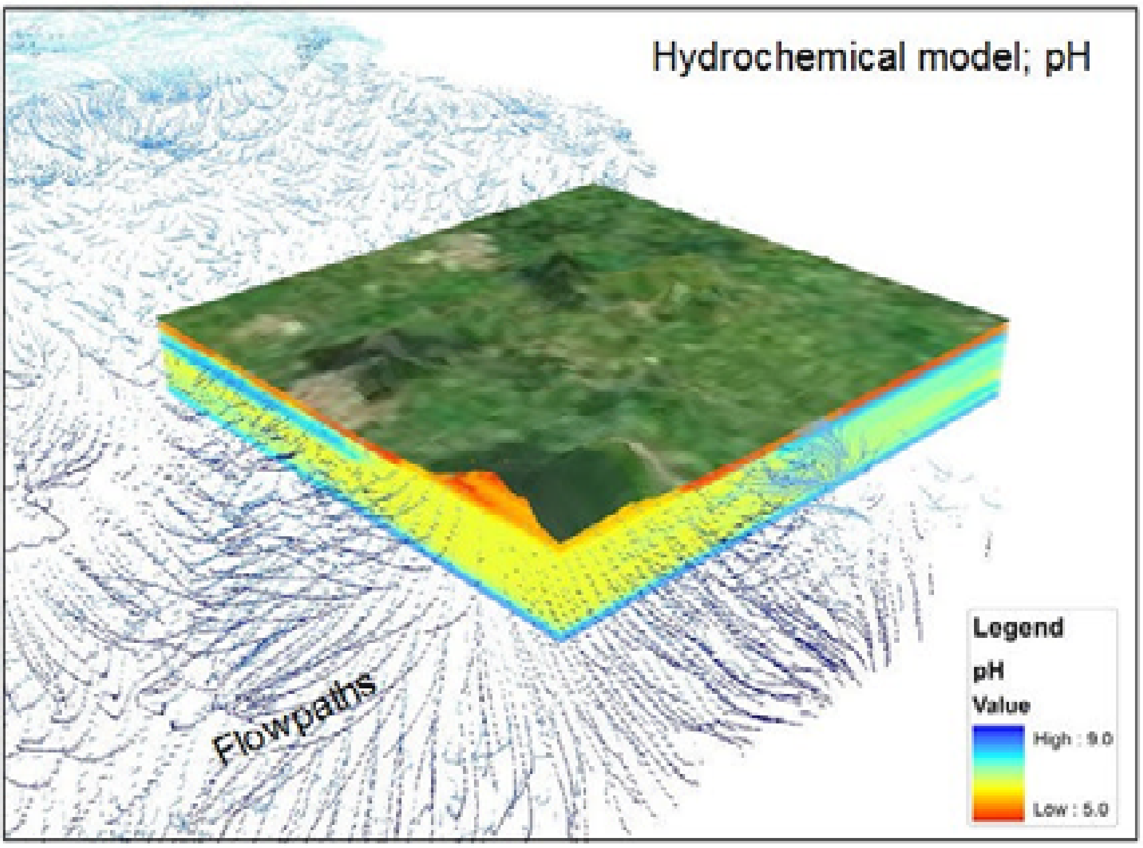


Figure 7. Hydrochemical mapping of pH in the subsoil and flowpaths from MODPATH have been visualised in ArcScene.

The transport is simulated with flux-based (MT3d) or flowpath-based (e.g. Soilpath) models. Microbiological risks are calculated with a flowpath-based model.

## Risk reduction during drinking water purification

Eventually the type of raw water treatment plays an important role in the remaining risks after treatment. Also the concentration of pollutants in the raw water is an important factor. A set of decision rules have been designed to assess the risk reducing effect of the various treatment facilities. Because European and Dutch guidelines dictate that a good quality of groundwater must be achieved and maintained in the future, this final step in the multi barrier approach is not accounted for in most practical applications of RESPOND® .

## Possible applications of RESPOND®

There are a number of possible practical applications. The first pilot studies with RESPOND® are currently undertaken for two dutch water companies, Vitens and WML. Vitens plans to incorporate these methods and tools in their scheme of groundwater source management, protection and monitoring. In the near future RESPOND® will play a role in the communication between water companies and provinces, mainly for land use planning purposes. A water company may also use this approach for the planning of water sources and capacities as to determine which configuration of sources will result in a minimum risk of poor raw water quality. A number of possible applications are listed in table 3.

Table 3. Examples of Questions wich may be solved by RESPOND®.

| | |
|---|---|
| 1 | How does the prognosis of raw water quality change if the landuse of parcel A changes from agricultural (cattle grazing) to urban (light industry)? |
| 2 | Which parcel location for the development of an industrial facility imposes the lowest risk for the raw water quality in production well B? |
| 3 | What is the prognosis of substance X in the raw water of production well C? |
| 4 | What does the vulnerability map for substance Y around production well D reveal? |
| 5 | Which substances are a high risk for production well E? |
| 6 | What are the consequences for the raw water risks if the capacity of production well F decreases by 50%. |
| 7 | Prioritise all production wells for substance Z in 2010? |
| 8 | Which production well shows the highest/lowest vulnerability to changes in capacity? |

# RESPOND® tools

## General overview

RESPOND® consists of a set of loosely coupled tools both in and outside the ArcGIS environment. Wherever possible we use standard software available like MODFLOW or MT3d. Our own developments focus mainly on the flowpath approach, conversion software and GIS tools. Depending on specific project needs the applicable tools are selected. The development and coupling of some of these tools is still in progress and undertaken by separate experts. Eventually all the tools will be enabled to interact coordinated from a user interface in the ModelBuilder environment. A brief description of the tools is given below, see also figure 8 for an illustration.

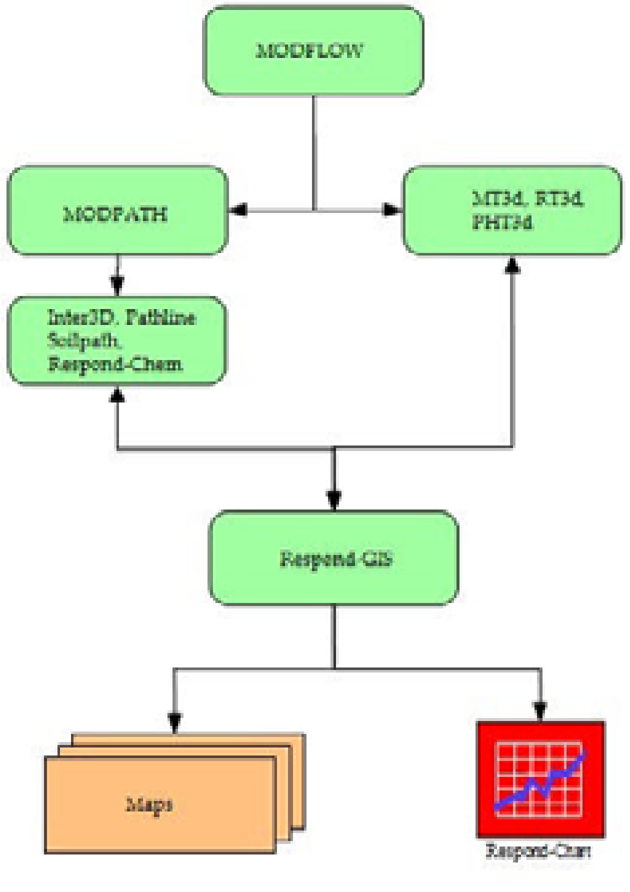


Figure 8. RESPOND® tools and process flow.

### MODFLOW

Modular three-dimensional finite-difference ground-water flow model (USGS).

**MODPATH**

A particle-tracking postprocessor model for MODFLOW (USGS).

**MT3d, RT3d and PHT3D**

Widely used (USGS and others) tools to model transport and chemical reaction of solutes. These models are based on fluxes between 3D cells. Concentrations or risk scores from various pollution sources will be mixed and the results in each production well will not be traceable to a single parcel.

**Inter3D**

Interpolates borehole data to a 3D file with estimates of pH, CEC, CaO3, Redox and Organic content of the aquifer or aquitard.

**Pathline**

Converts Modpath x,y,z,t output to a polyline shapefile and an accompanying point shapefile with starting points of the flowpaths, Adds Q(debiet) to each flowpath.

**Soilpath**

Adds the appropriate values of CEC, pH, OS and Redox to each section of the flowpath. Soilpath may be used instead of MT3d in those cases were pollution risks from single parcels need to be traced.

**RESPOND®-Chem**

Calculates the net loads after sorption and 1$^{st}$ order decay. Contains a library of substances and reaction coefficients.

**RESPOND®-Chart**

Generates Excell charts with prognosis of raw-water risk scores.

**RESPOND®-GIS**

A set of ModelBuilder tools for data analysis and pre and post processing, a standard mxd file with specially designed layout of data frames and some simple VBA scripts for data and zoom synchronisation. These components are illustrated more thoroughly in the next paragraphs.

## ArcGIS and ModelBuilder tools

In our research work the development of software**,** as such**,** is rarely a separate goal. New software has to prove its functionality immediately. This means also that the capacity for software development is rather limited. So the introduction of ModelBuilder and Python scripting techniques in ArcGIS 9 proved to be very usefull.

Our strategy in developing tools has always been to extend, and not to limit, the functionality of the ‘out of the box’ software. Protecting the user from GIS functionality is bad practice; especially if end-users are highly qualified and are always requiring more functionality (Raterman, 2004).

For RESPOND we need a number of flexible and interoperable model tools based on separate user-friendly modules. Again the functionallity offered by ModelBuilder suits this need very well. A module may be prototyped in minutes, litterally.

Another challenge is to organize our work within an ArcMap session in such a way that it facilitates the operation of the tools. The concept of **data frames** has been used to organize input and output to the modules. Figure 9 illustrates how the model RESPOND® is set up within an ArcMap document.

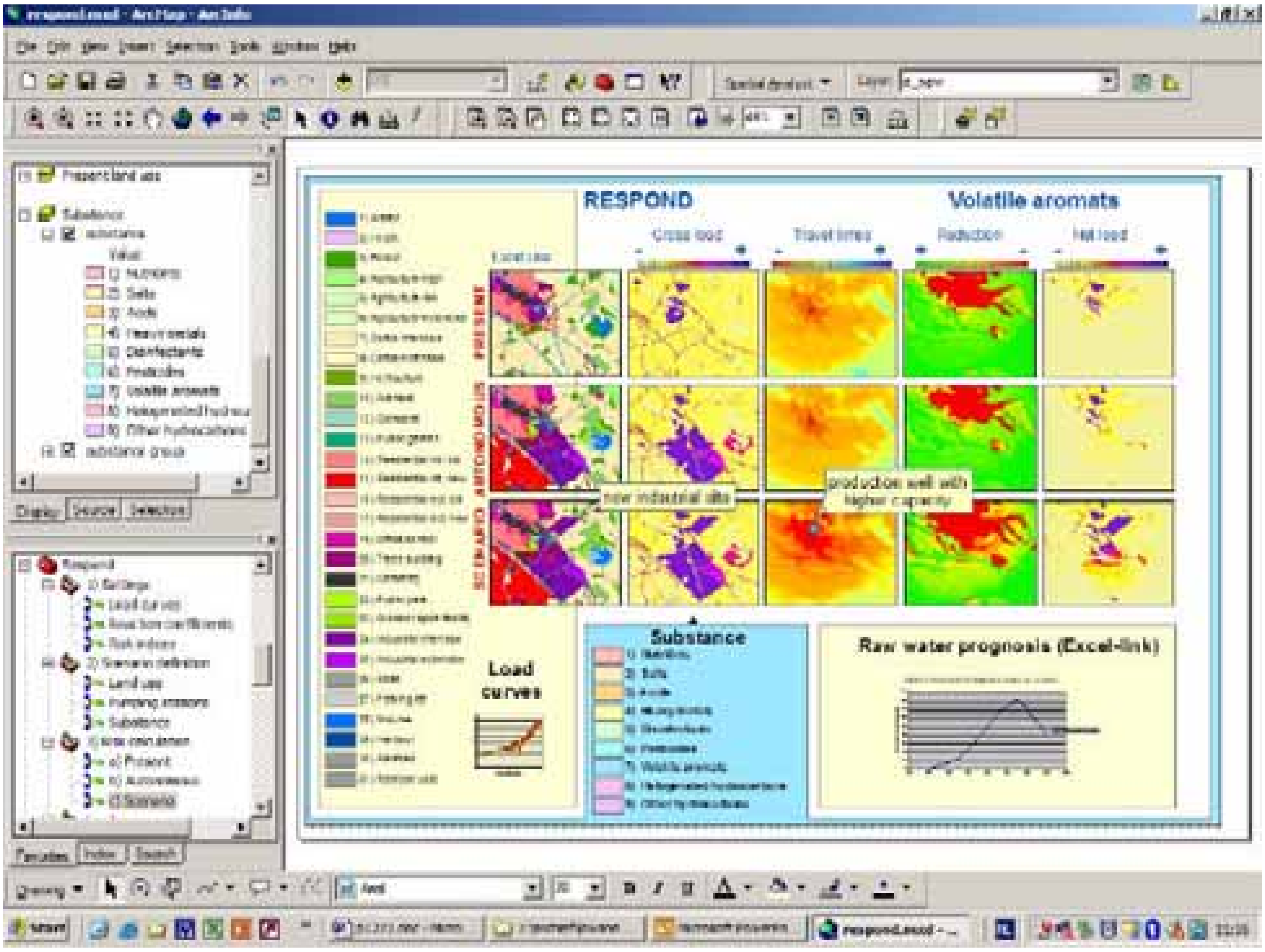


Figure 9. ArcMap document with special RESPOND® layout and ModelBuilder tools (lowerleft window).

The ArcMap document contains the input and output of the present situation, the autonomous development and a specific scenario. The autonomous development shows what will happen under currently planned land use management and production capacity, with a forecast of e.g. 15 years. The scenario shows the risk assessment for a new land use plan in the same time frame. These three situations (present, autonomous and scenario) are organized in three rows of data frames. Per situation five maps are shown in data frame columns; land use pattern (1), gross risk load (2), travel times to production well (3), the effect of transport reduction (4) and the net riks load (5). Note in the example above how these parameters reflect the change in land use and production well capacity; higher gross risk load of volatile aromats, less reduction during transport caused by decreased travel times and thus a higher net risk load in the choosen year. To see the raw water prognosis for the total transport period (e.g. 25 years) the results of the RESPOND®-Chem module in Excel can be accessed through the link “Raw water prognosis”. The ModelBuilder tools work in such a way that the geoprocessing results are always overwritten and the results are not added automatically (see figure 10). The tools interact with input and output based on a common data model. The results, mostly GRID files, reside in a standard directory on a network drive. Within the data frames standard layers are present, connected to the results of the ModelBuilder tools. After the tool has been run, the connection to the data-source needs to be reastablished, therefore a VBA macro has been developped and made accessible through a button in a custom toolbar. Another macro is available to synchronise zoom levels for all data frames.

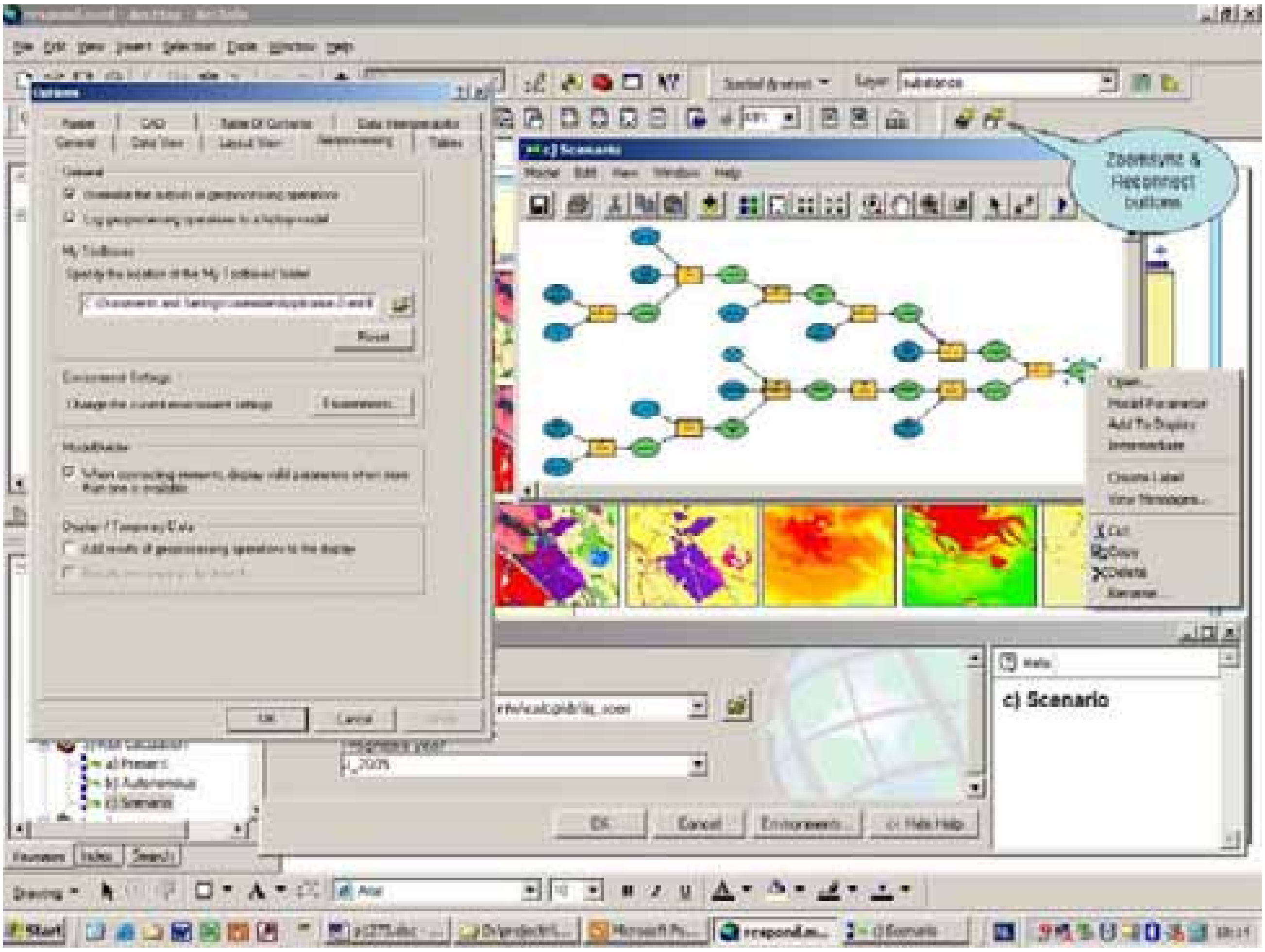


Figure 10. ModelBuilder and essential settings in ArcMap 9.1.

The RESPOND® ModelBuilder tools are grouped in three functional toolset levels; Settings (1), Scenario definition (2) and Risk calculation (3). The settings toolset is designed for the hydrologist or hydrochemist and may be used to alter load curves, reaction coefficients and risk indices. With the Scenario definition toolset the user can choose an alternative land use map for the study area, a different production capacity and the substances of interest in the study area. From the Risk calculation toolset the processes can be started. Most scenarios require MODFLOW and MT3d (or Soilpath) to run. The tools to streamline these processes are still under development.

Other specific ModelBuilder tools for RESPOND® are designed to:

1) Combine Land use maps of different detail and/or period;
2) Link land use to risk indices and extracting risk maps per substance per year;
3) Summarise risk indices for a certain period of time for input in MT3d;
4) Extract risk indices at the starting point of each flowpath;
5) Link the results of transport/reduction calculations to land use parcel map;
6) Visualize 3D geochemical model of the subsurface;

Further development of these and other tools are undertaken in the course of a number of pilot studies, carried out together with dutch water companies.

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# Conclusions

RESPOND® is a helpful tool for land planning and development by quantifying the relations between land use and raw water quality. The risks for drinking water production can be minimized by optimization of the land use in the capture zone

RESPOND® enables a formalized and consistent approach, risk predictions of different wells can be compared and prioritization of further research and risk-reducing measures are possible. These measures may vary from additional monitoring to the placement of additional treatment capacity.

As the RESPOND® method is based on explicit criteria and decision rules it can be applied efficiently within a GIS environment, coupled to Modflow and MT3d. Changes in the perceived importance of risks on land use related pollution, can be taken into account in a quick and cost-effective way.

ArcMap, ModelBuilder and VBA may be used efficiently to achieve a good modular design and implementation of the required tools and user interfaces.

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# Appendix I

List of guiding substances selected for risk calculations with RESPOND®.

| Number | Group | Guiding substance | Process 1 | Process 2 |
|---|---|---|---|---|
| 1 | Nutrients | Nitrate | Redox | - |
| 2 | Acids | Sulfate | Redox | - |
| 3 | Heavy metals | Nickel | Sorption | - |
| 4 | Heavy metals | Cadmium | Sorption | - |
| 5 | Pesticides | Dicamba | Sorption | 1st order decay |
| 6 | Pesticides | 2,4-D | Sorption | 1st order decay |
| 7 | Pesticides | MCPA/MCPP | Sorption | 1st order decay |
| 8 | Pesticides | Bentazon | Sorption | 1st order decay |
| 9 | Pesticides | Bromacil | Sorption | 1st order decay |
| 10 | Pesticides | Dichlobenil, BAM | Sorption | 1st order decay |
| 11 | Pesticides | Diuron | Sorption | 1st order decay |
| 12 | Pesticides | Simazin+metabolites | Sorption | 1st order decay |
| 13 | Pesticides | Glyfosate (AMPA) | Sorption | 1st order decay |
| 14 | Volatile aromats | Benzene | Sorption | 1st order decay |
| 15 | Volatile aromats | Toluene | Sorption | 1st order decay |
| 16 | Volatile aromats | Ethylbenzene | Sorption | 1st order decay |
| 17 | Volatile aromats | Xylene | Sorption | 1st order decay |
| 18 | Solvents | Tri | Sorption | 1st order decay |
| 19 | Solvents | Tetra | Sorption | 1st order decay |
| 20 | Other hydrocarbons | MTBE | - | - |
| 21 | Pathogenic organisms | Viruses | Removal unsaturated | saturated zone |
| 22 | Pathogenic organisms | Bacteria | Removal unsaturated | saturated zone |
| 23 | Pathogenic organisms | Spores | Removal unsaturated | saturated zone |
| 24 | Pathogenic organisms | Protozoa | Removal unsaturated | saturated zone |

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