



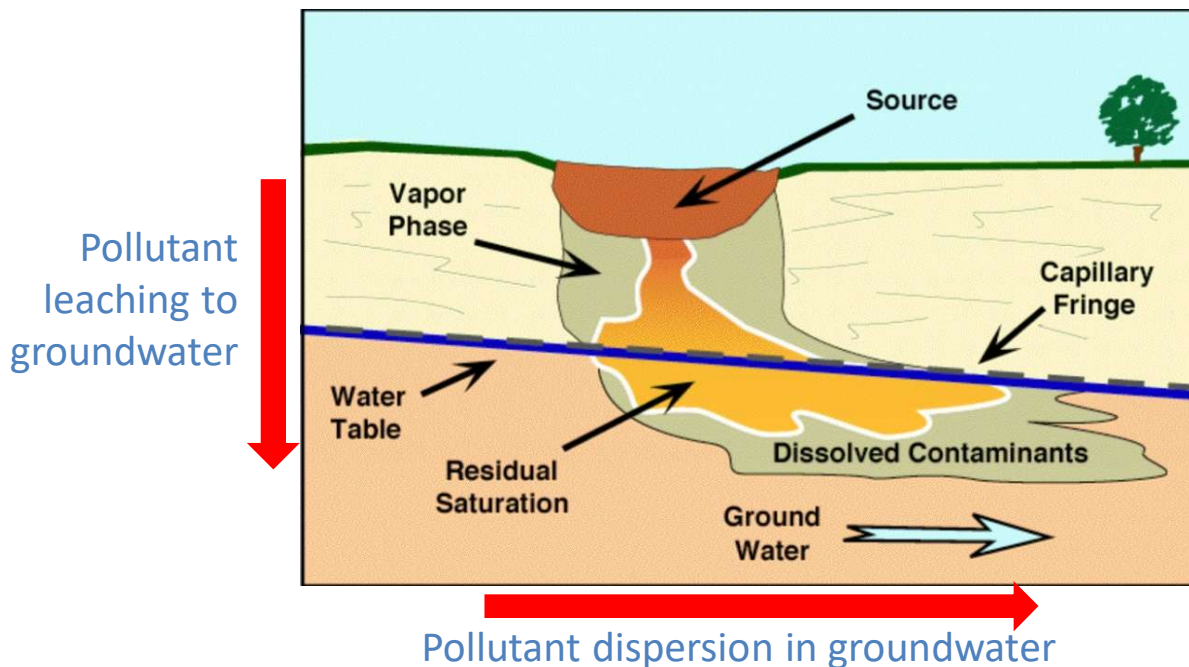
**A new semi-analytical solution for groundwater
pollution risk assessment:
Integrating mass fluxes and degradation by-products**

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Contextualization : the soil decree in the Walloon region of Belgium

In risk assessment studies, groundwater can be considered as :

- **A receptor** (as a resource) : risk of pollutant leaching from the vadose zone
- **A pathway**, i.e. exposure route to downgradient receptors

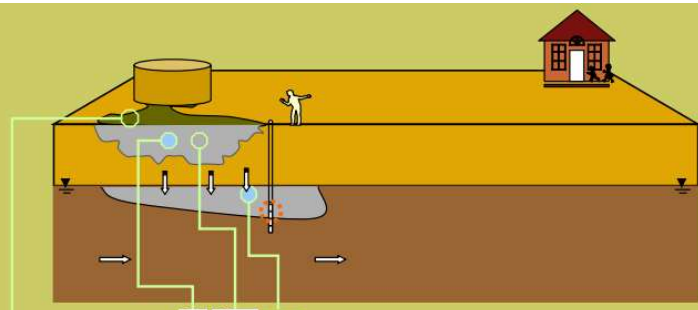


➔ Focus here on risk of groundwater resource degradation

Source image : http://wpage.unina.it/giutosca/mesocosmo/index_en.html

RA leaching and dispersion « disconnected » and incompatible ...

- VS_N : seuil de concentration pour le sol garantissant le respect à long terme du critère $VS_{(nappe)}$ compte tenu des risques de migration des polluants
- F_v : fraction contaminée de la zone non saturée (= 1 par défaut)
- K_{sw} : (inverse du) coefficient de partition sol-eau ($K_{sw} = 1/K_d^*$)
- FD : facteur de dilution (= 30 par défaut)



$$VS_N = \frac{FD}{K_{sw} \times F_v} \times VS_{(nappe)}$$

Based on Connor (1996, 1997) Connor et al., 1996,

$$FD = 1 + \frac{d_{zm} \times K \times \nabla H}{I \times L}$$

The more permeable is the aquifer, the less it is at risk ...!!!

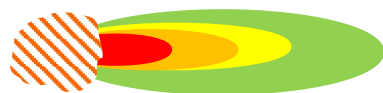
By their design, the two modules do not really fit together: C_{out} leaching \neq C_{in} dispersion
 → A question of mass-balance ...

Leaching : C_{soil} compared with VS_N
 VS_N defined based on VS_{nappe} using dilution factors
 VS_{nappe} comes from drinking water standards (GW threshold value)

Dispersion : $C < VS_{nappe}$ at the border of the land parcel in a time frame < 100 years

The « Dilution Factor Paradox » that makes « good » aquifers less protected than « poor » ones ...

Low-K Aquifer : Low GW Fluxes → less extended, more concentrated plumes

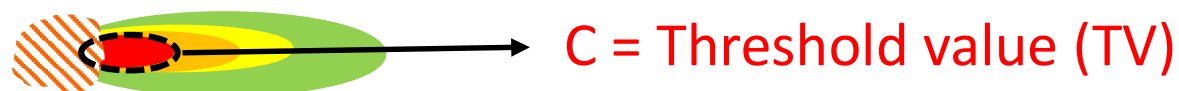


High-K Aquifer : High GW Fluxes → more diluted but also more extended plumes



The « Dilution Factor Paradox » that makes good aquifers less protected than poor ones ...

Low-K Aquifer : Low GW Fluxes → less extended, more concentrated plumes



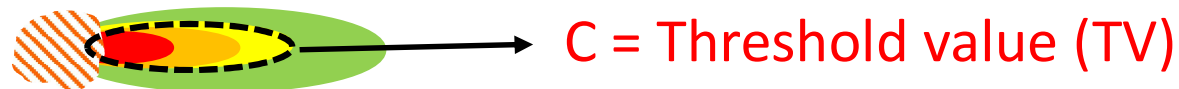
High-K Aquifer : High GW Fluxes → more diluted but also more extended plumes



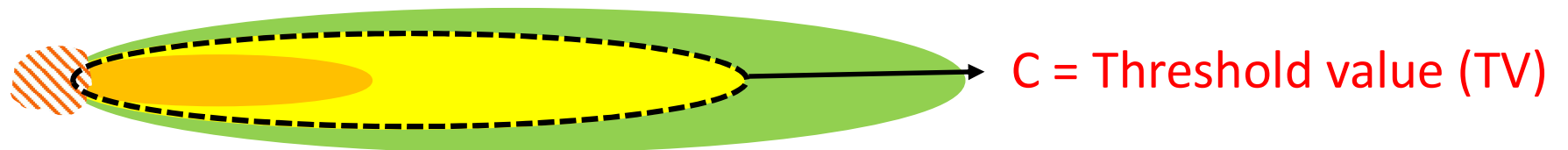
→ If TV corresponds to red and above, groundwater is more degraded in the first case because dilution is enough in the 2nd ...

The « Dilution Factor Paradox » that makes good aquifers less protected than poor ones ...

Low-K Aquifer : Low GW Fluxes → less extended, more concentrated plumes



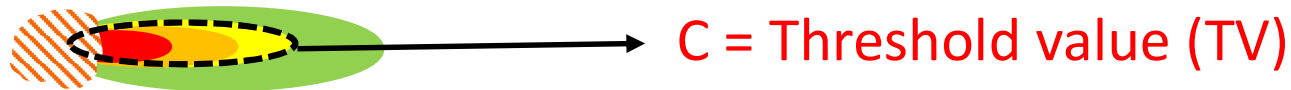
High-K Aquifer : High GW Fluxes → more diluted but also more extended plumes



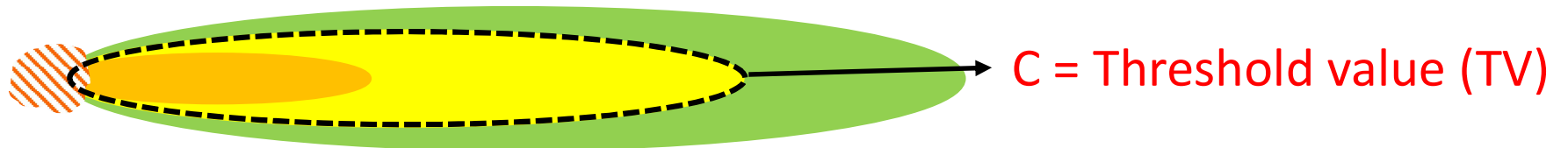
➔ If TV corresponds to yellow and above, the volume of degraded GW is more important in the 2nd case, even if concentrations are lower !

Revised framework for flux-based groundwater pollution risk assessment

Low-K Aquifer : Low GW Fluxes → less extended, more concentrated plumes



High-K Aquifer : High GW Fluxes → more diluted but also more extended plumes



Volume of degraded groundwater larger in case 2 **because the mass flux is larger!**

→ Risk analysis be based on a maximum acceptable degraded volume of groundwater above threshold ... (Walloon Region of Belgium : 5000 m³)

Adapted FBRA Tool : a new analytical solution to compute pollutant leaching and dispersion through groundwater

Minimal requirements :

- Capability to **calculate the volume of groundwater polluted above threshold** value
- Combination of leaching and dispersion processes through the **continuity of mass discharge at the vadose zone – saturated zone interface** (mass conservation)

Bonus capabilities :

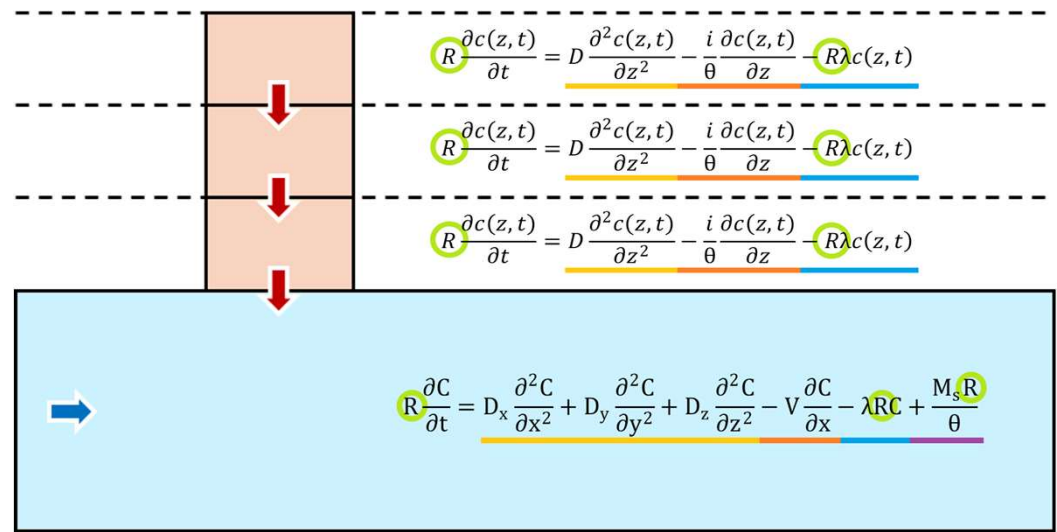
- Dealing with **various types of pollution scenarios** (source strength, continuous versus step input, pollutant leaching from a contaminated soil ...)
- Dealing with **mother (precursors) and degradation products** across a given chain of degradation

Adapted FBRA Tools : a new analytical solution to compute pollutant leaching to and dispersion through groundwater ...

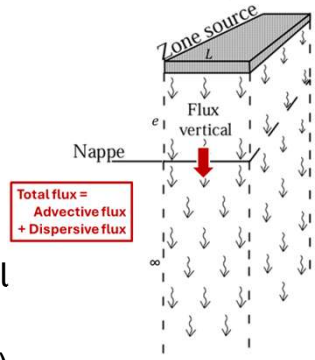
Conceptual model

- Advection
- Dispersion
- Decay
- Adsorption
- Source term

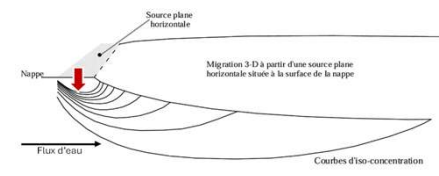
$$P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow P_4 \rightarrow \dots$$



- **Vadose zone:**
 - Infinite-length column
 - Vertical 1D transport
- **Injection of pollutant:**
 - soil initially polluted
 - Mass flux injection at top of model
- **Results:**
 - Concentration (function of **z** and **t**)
 - **Mass flux** at a depth **e** (function of **t**)



- **Aquifer:**
 - 1D horizontal permanent flow
 - 3D transport
- **Injection of pollutant:**
 - **Mass flux** injection on a rectangular horizontal surface
- **Results:**
 - Concentration (function of **x**, **y**, **z** and **t**)

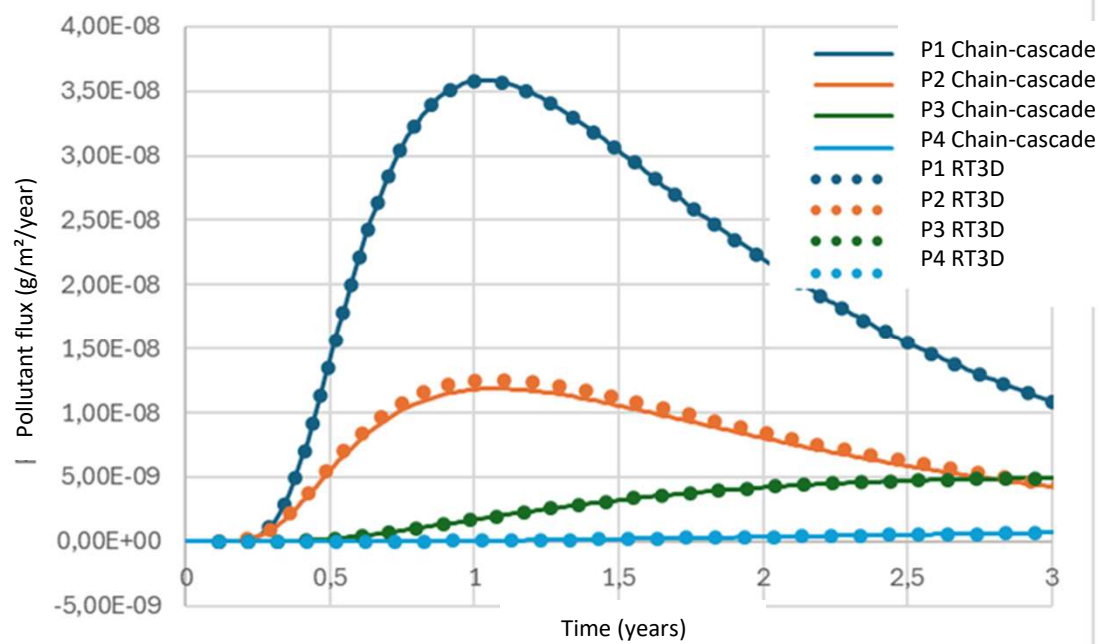


Adapted FBRA Tools : a new analytical solution to compute pollutant leaching to and dispersion through groundwater ...

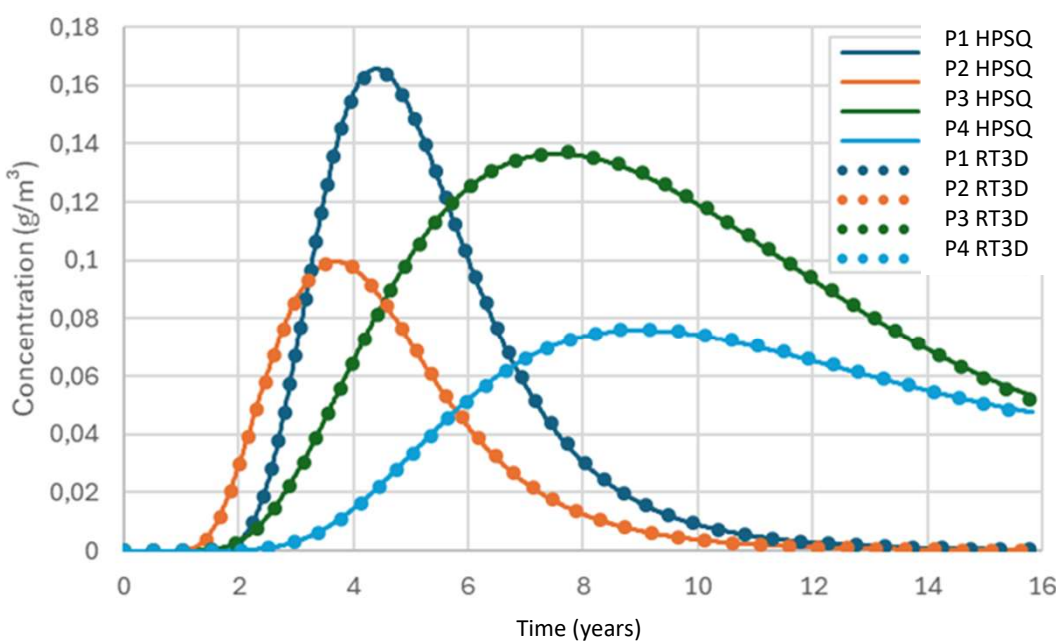
Validation of the analytical solution

Two months step discharge of pollutant P1 and its degradation

Mass flux at bottom of the unsaturated zone



Concentration in the aquifer at a point downgradient the source



Welcome to discuss in front of our poster !

A new analytical solution for groundwater pollution risk assessment integrating mass fluxes and degradation by-products

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1. Conventional method

- Calculation of a concentration in the aquifer below the source with a dilution factor.
- Calculation of 3D transport in the aquifer from a vertical rectangular surface at this concentration.
- Criteria $c < 1\%$ at the border of the cadastral parcel for 100 years.

$$C_p = C_s \frac{K_{eff}}{FD}$$

$$FD = 1 + \frac{2.303 C_p}{C_s} \frac{K_{eff}}{K_{eff} - 1}$$

2. New criteria and tools requirements

The Walloon region would like to base its new risk analysis criterion on a maximum acceptable soil volume of 5000m³ whose pollutant concentration in water exceeds a threshold.

Minimal requirements:

- Capability to calculate the volume of groundwater polluted above threshold value.
- Combination of leaching and dispersion processes through the continuity of mass discharge at the vadose zone – saturated zone interface (mass conservation).

Bonus capabilities:

- Dealing with various types of pollution scenarios (source strength, continuous versus step input, pollutant leaching from a contaminated soil, ...).
- Dealing with mother (precursors) and degradation products across a given chain of degradation.

3. Leaching

Vadose zone:

- Infinite-length column
- Vertical 1D transport

Injection of pollutant:

- soil initially polluted
- Mass flux injection at top of model

Results:

- Concentration (function of z and t)
- Mass flux at a depth z (function of t)

4. Dispersion

Aquifer:

- 1D horizontal permanent flow
- 3D transport

Injection of pollutant:

- Mass flux injection on a rectangular horizontal surface

Results:

- Concentration (function of x, y, z and t)

5. Conceptual model

Multi-component (degradation products)

$$P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow P_4 \rightarrow \dots$$

Multi-layer in vadose zone (degradation products)

6. New analytical solutions

Inspired from ...

- BRGM MISP (Guyonnet 2008) : combined leaching – dispersion approach
- CHAUN (Van Genuchten 1985) framework for mother – daughter reaction pathways
- AFSU GW vulnerability method (Popescu et al 2004) : 1D cascading based transport model across successive layers on CXTHT (Van Genuchten 1981, Toride et al. 1995)
- Sahya (1987) analytical solution: mono-component 3D transport
- Quezada 2004: description of Laplace transform method to add mother – daughter reaction pathways
- Wang et al. 2012: method to add non-zero initial concentration in an analytical solution

7. First results

Example of plume obtained by this approach

8. Numerical validation

Comparison of a multi-component simulation with Modflow-RT3D numerical simulation (for continuous pollutant injection flux for 2 months)

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