Physically-based groundwater vulnerability assessment : from concepts to objective mathematical formulations and applications

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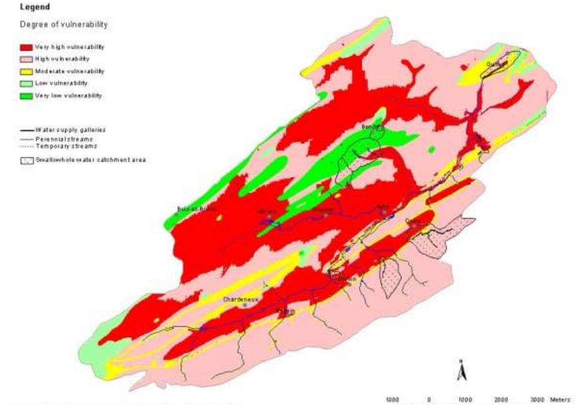
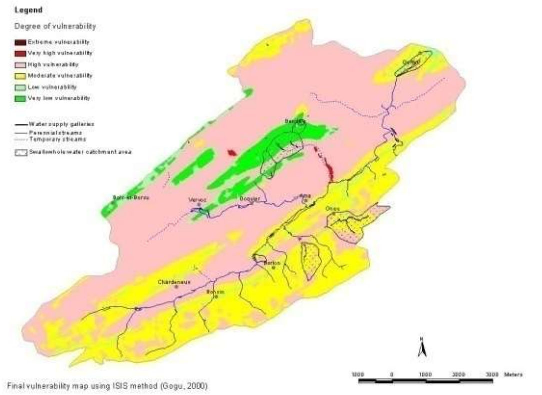
There is a common agreement, in groundwater vulnerability (GWV) mapping, to state that **red** means **vulnerable** and **green** means **not vulnerable**…

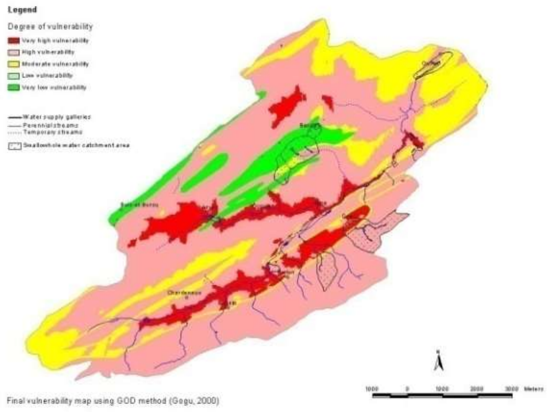
German method



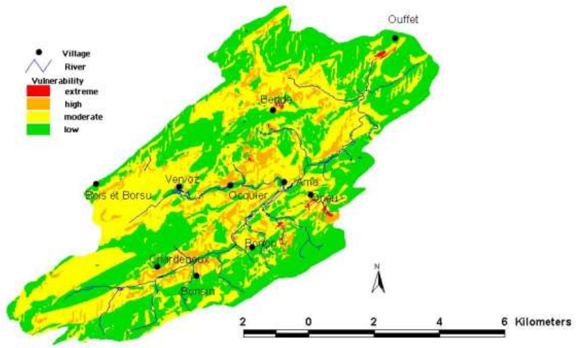
ISIS method



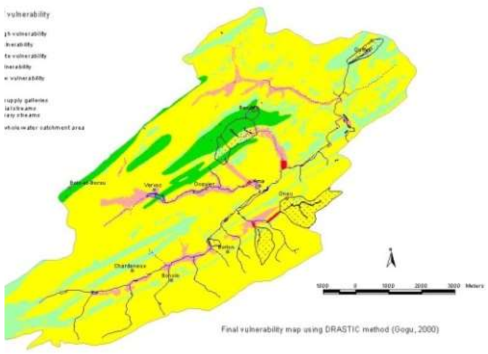
GOD method



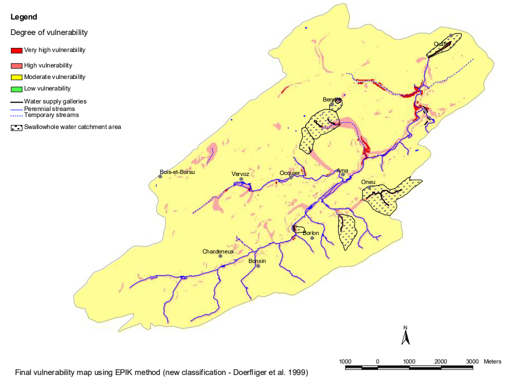
PI method



DRASTIC method



EPIK method



cf. Gogu and Dassargues 2000

However … what does "**vulnerable**" mean in these maps?

Our research efforts on GWV assessment are scientifically sound; however they are often hardly translated into efficient tools for GW managers

Clarify and agree on what is meant by groundwater vulnerability

why is this pixel red and this one green?
→ Define clear criteria and indicators of GWV assessment

Groundwater contamination is a key issue but there are other aspects to be considered

Groundwater quantity issues : overexploitation, influence on the good status of surface water bodies

Reconciliation between GWV mapping concepts and modelling concepts

Models are efficient to calculate the GWV indicator maps and GWV indicators maps are efficient in translating modelling results into decision making tools

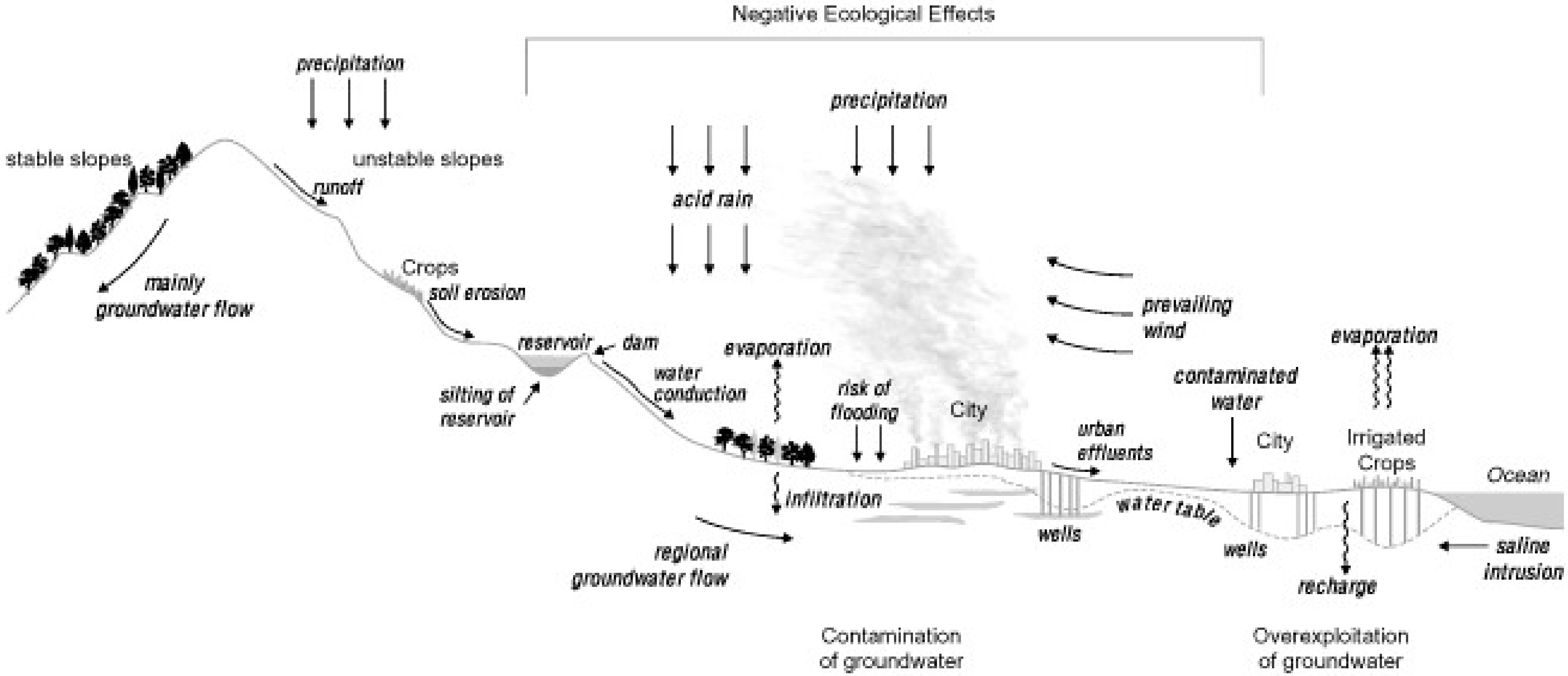
Outline

1. A general framework for groundwater vulnerability assessment

2. Examples of applications to groundwater quality and quantity issues

3. Some conclusions and perspectives

Groundwater is vulnerable because it is affected by pressures with negative impacts on the <u>resource</u>, on its <u>natural functions</u> and on <u>our use / dependence of it</u>

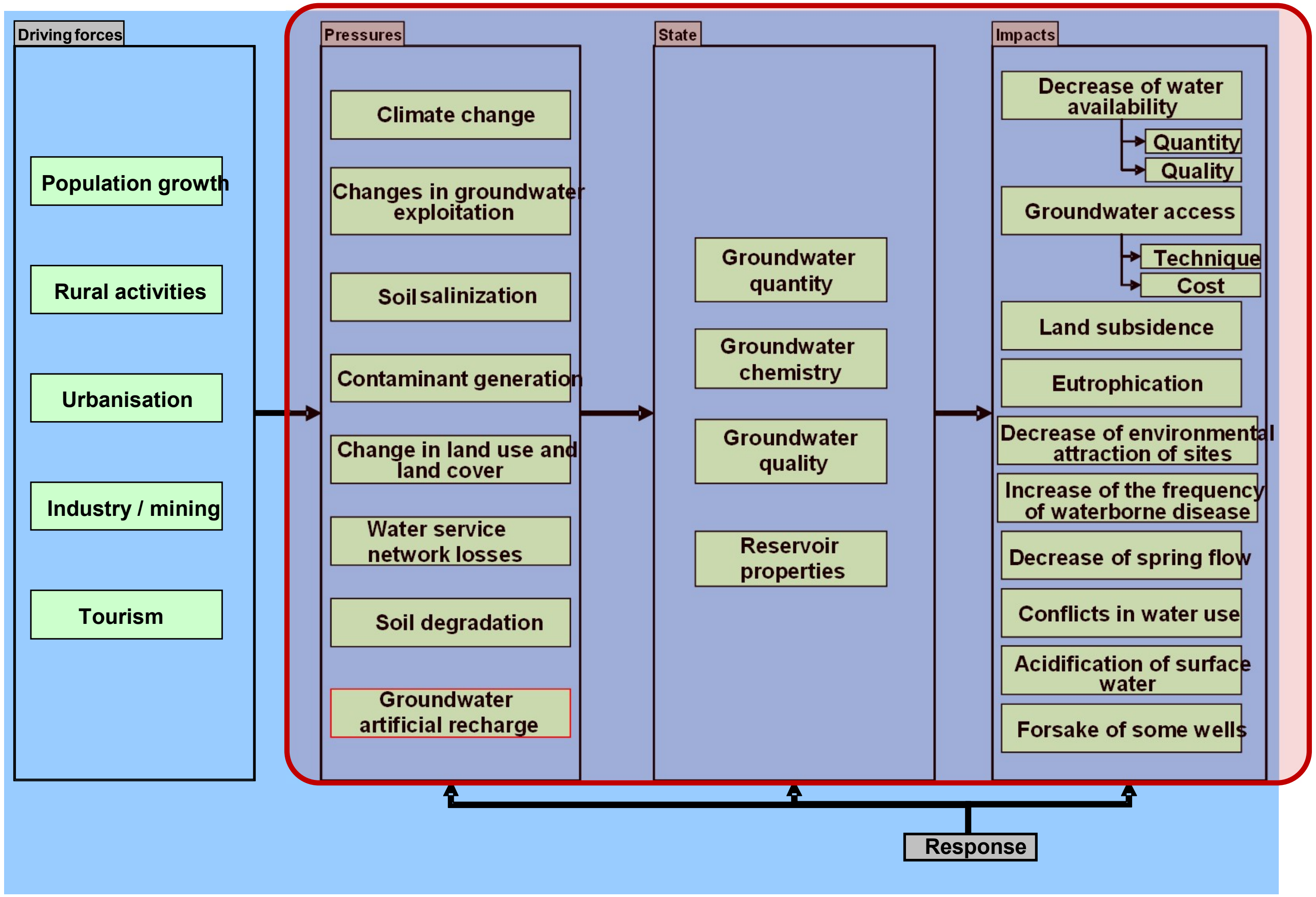


Source : Anton 1993, *Hydrol. Proc*

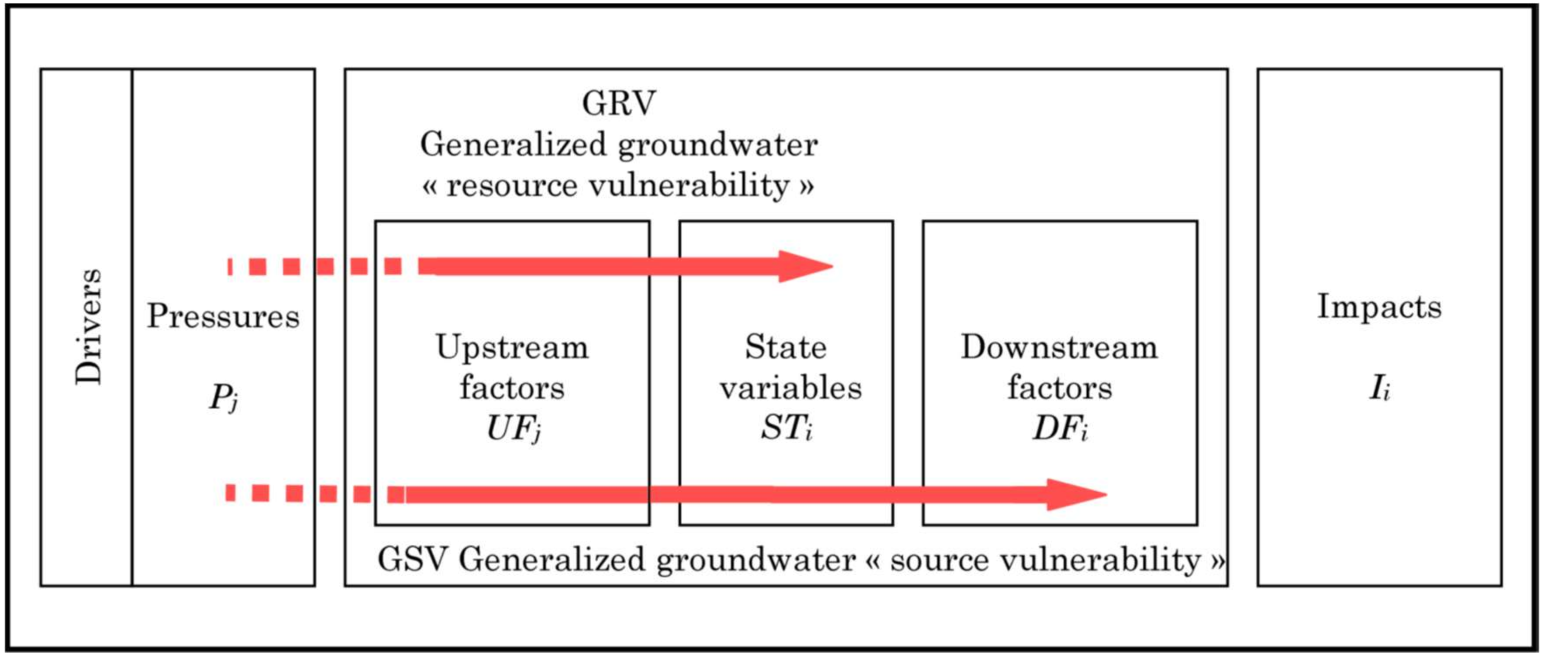
Groundwater is vulnerable because it is affected by pressures with negative impacts on the resource, on its natural functions and on our use / dependence of it

DPSIR causal chain, EEA (Kristensen 2004)

If we apply this to groundwater …



Groundwater is the "conveyor belt" between pressures and impacts



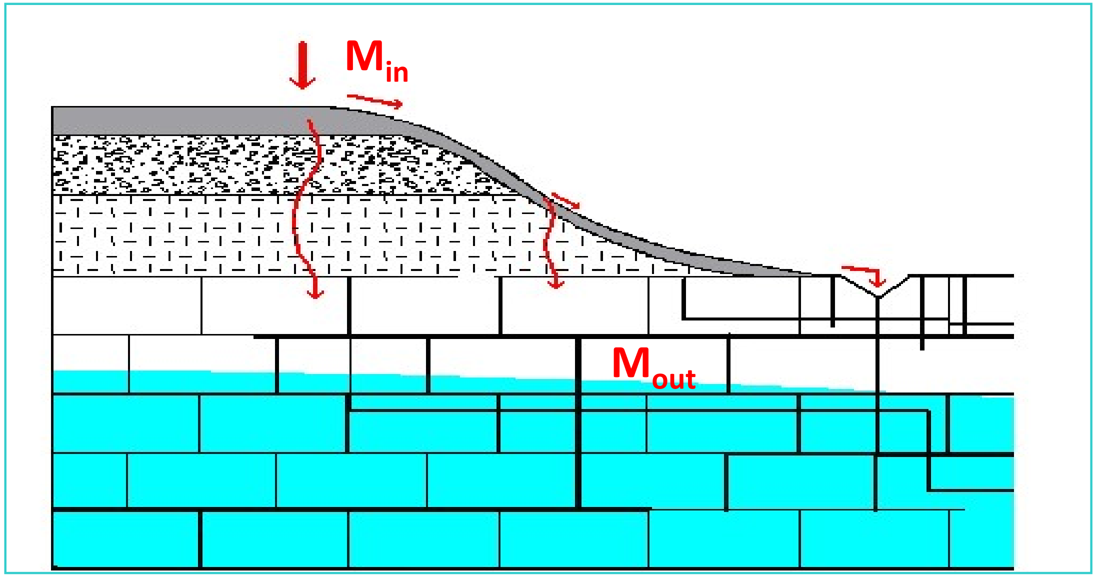
Upstream factor : physical component in relation with pressures (e.g. groundwater recharge)
Downstream factor : physical component in relation with impacts (e.g. base flow to river, hydraulic head in wetland…)

The more the conveyor is "efficient", the more groundwater is vulnerable

On the contrary, groundwater is less vulnerable if it contributes to delay, attenuate or dissipate the expected impacts

Illustration 1 : groundwater **intrinsic vulnerability** to pollution (Apsù method)
Upstream factor : source of contaminant (e.g. nitrate manure in the basin)
Downstream factor : groundwater contamination (e.g. NO3 in groundwater)

When a pollution event occurs somewhere, groundwater is not vulnerable if the contaminant never reaches the groundwater table



- M_{in} = quantity of pollutant released at the soil surface
- M_{out} = quantity of pollutant reaching the groundwater table

On the contrary, groundwater is more vulnerable if

- the infiltration of contaminant is high
- the attenuation of contaminant in the unsaturated zone is low

The most relevant GWV indicator is the relative quantity of pollutant reaching the GW table : GWVI = M_{out} / M_{in}

Controlling processes : runoff/infiltration, sorption, chemical reactions

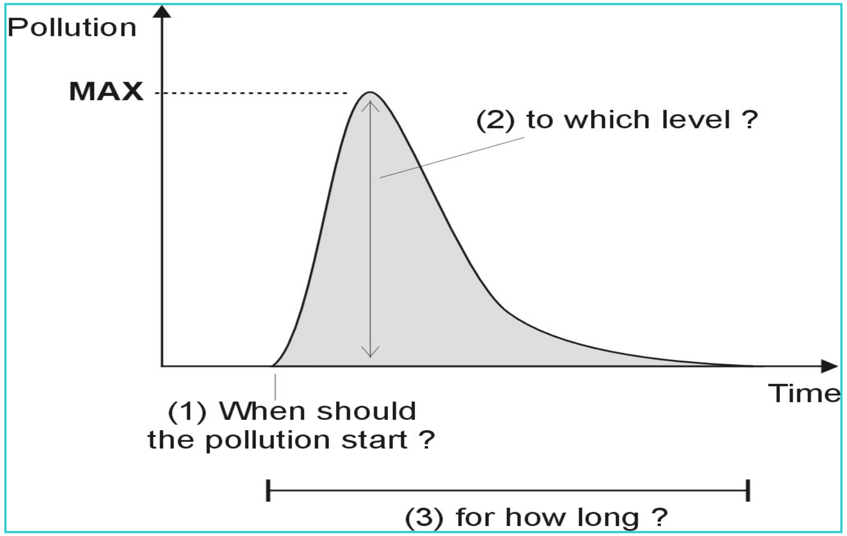
GW Intrinsic Vulnerability Assessment : only geological and hydrogeological factors, independently of the specific behaviour of pollutants

No sorption, no degradation, so … no attenuation (except runoff)

GWVI = 1 in all cases, which is not so useful from the point of view of the decision maker!

In this case, two options

- Forget about intrinsic GW vulnerability assessment
- Think about and use physical descriptors other than M_{out}/M_{in}



Physical descriptors of a (conservative) pollution event (Brouyère et al. 2001)

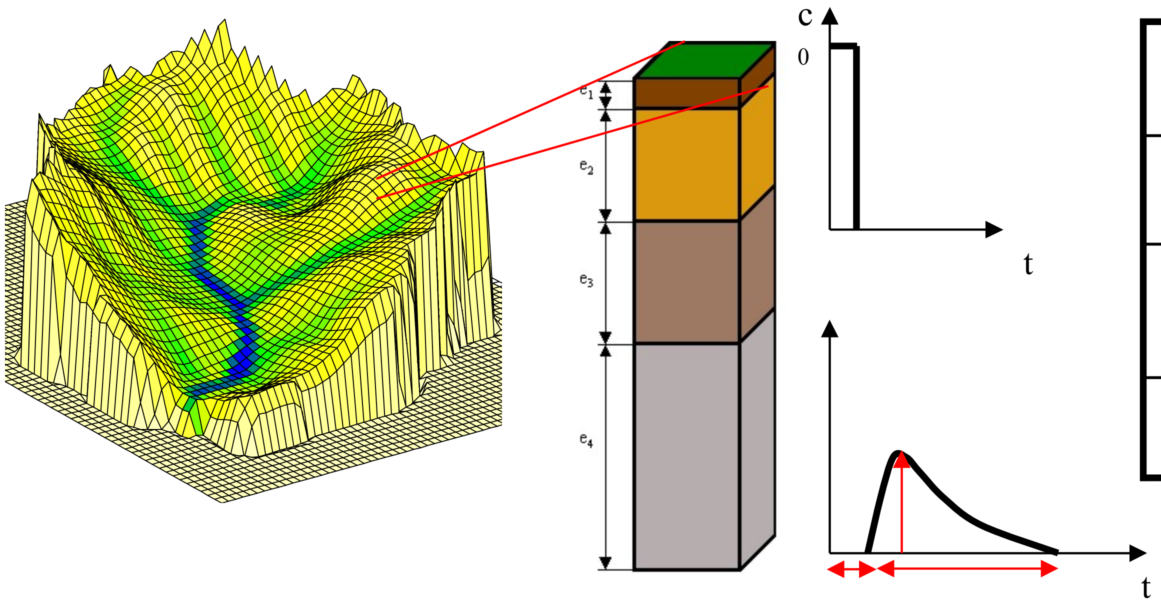
- Travel time to groundwater
- Concentration level at the groundwater table
- Duration of the pollution event

Apsù method for groundwater intrinsic vulnerability assessment

(Popescu et al. 2004)

Physically based approach dealing with

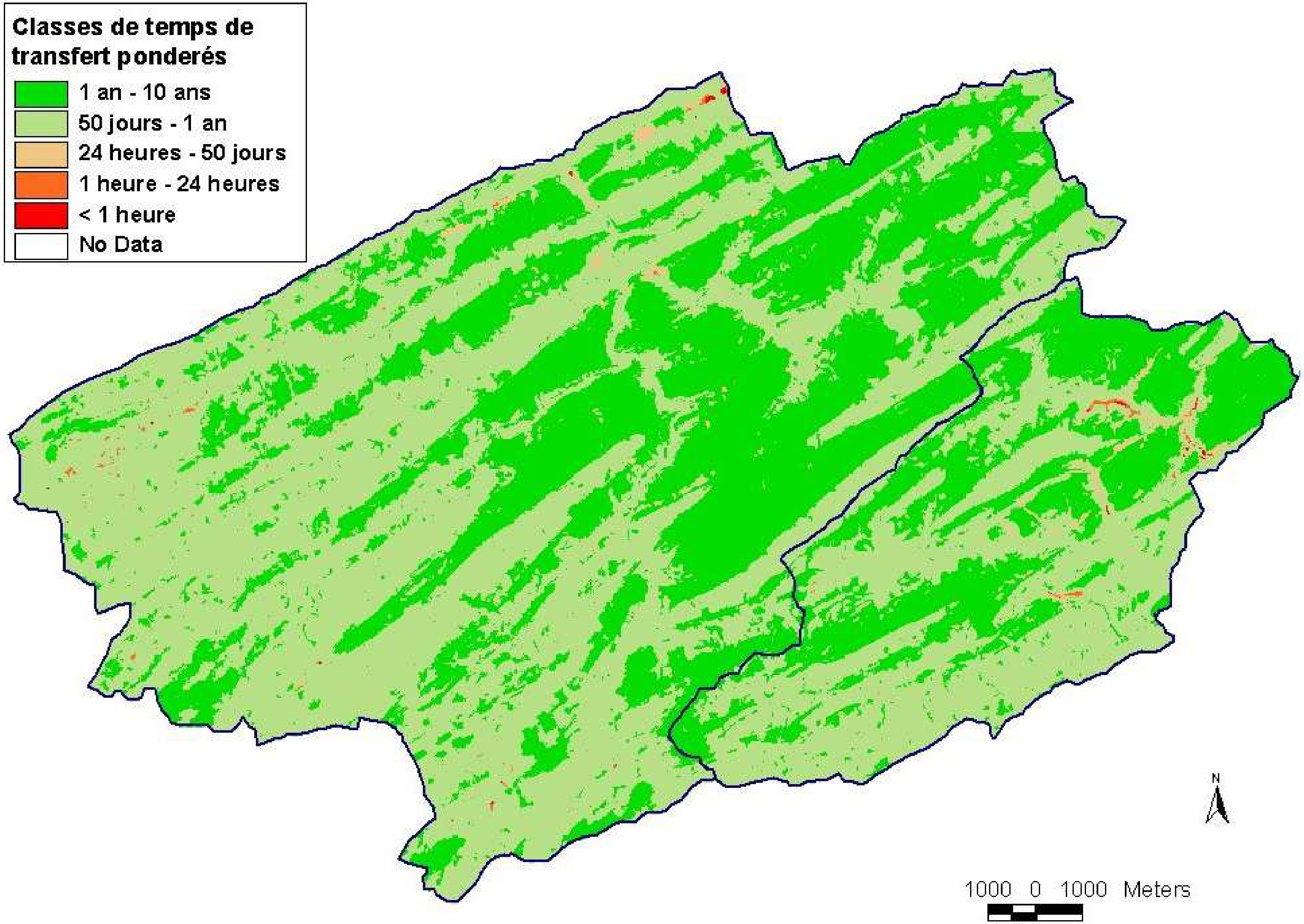
- Direct and lateral infiltration of pollutants (dangerousness of land surface)
- 1D vertical transport of contaminants from land surface to groundwater table (protective capacity of the unsaturated zone)
- Physical criteria (advective-dispersive minimal travel time, maximal concentration, duration)



Degree of vulnerability	**High**	**Moderate**	**Low**
min travel time	short e.g, : 24 h	medium e.g.: 50 d	long
Concentration level / attenuation	high	medium	low
duration	long	medium	short

Application to the limestone – sandstone Hoyoux-Néblon basin in Belgium

Minimal travel time criteria, weighted according to direct and lateral infiltration conditions



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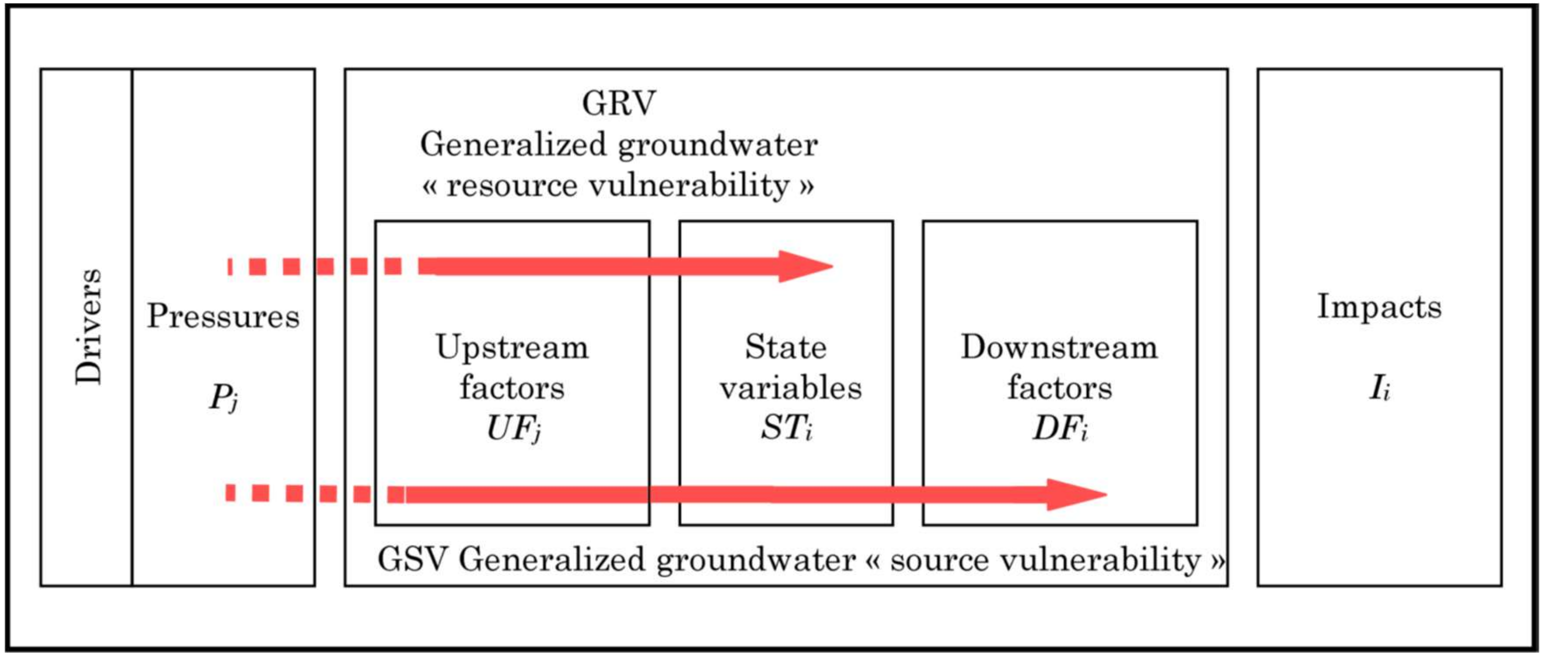

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Illustration 2 : **groundwater quantity vulnerability** using sensitivity methods
Upstream factor : pumping rate Qw or GW recharge ..
Downstream factor : piezometric levels in the aquifer, baseflow to river…

GW vulnerability is related to the sensitivity of the downstream factor to changes in the upstream factor and a "distance to damage state"

$$V = f\left(S_{ij}, D_w\right) = S_{ij} \cdot \left| W / W_0 \right|$$

From Luers et al. 2004

Source sensitivity

$$S_{ij}^{GS} = \frac{\partial DF_i}{\partial UF_j}$$

Resource sensitivity

$$S_{ij}^{GR} = \frac{\partial ST_i}{\partial UF_j}$$

V	Vulnerability
S	Sensitivity
D_w	Threshold
W	Current state
W_0	Damaged state

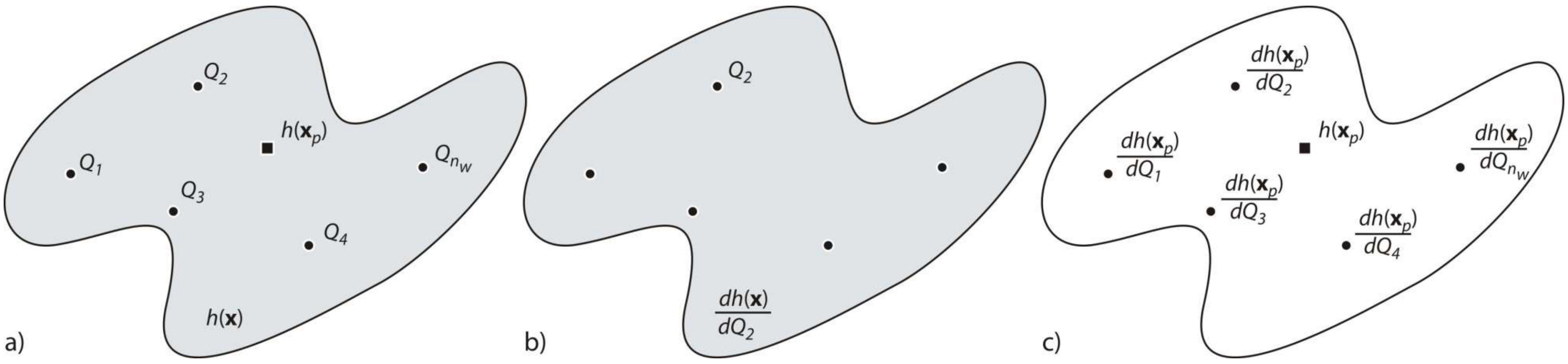
UF	Upstream factor
DF	Downstream factor
ST	GW resource state

Details in Lemieux et al., submitted to Ground Water, July 2012

Sensitivity coefficients can be obtained using a groundwater flow model with different methods

- Sensitivity of the groundwater resource system to one parameter (stress factor)
  → **Perturbation method** or **Sensitivity equation method**
- Sensitivity of selected locations in the aquifer to various stress factors
  → **Adjoint operator method**

Example : Sensitivity of groundwater levels (*h*) to pumping (Q)

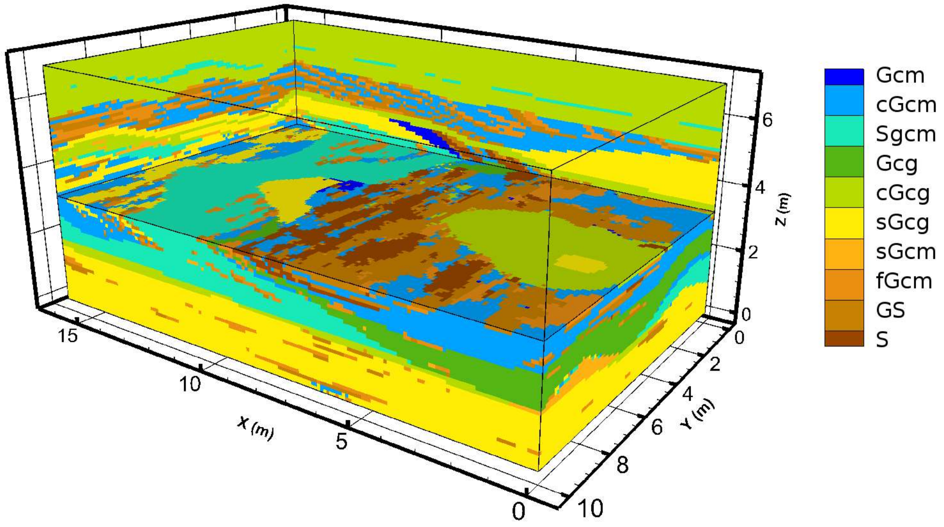


Example : the Herten high-resolution fluvio-glacial aquifer analog

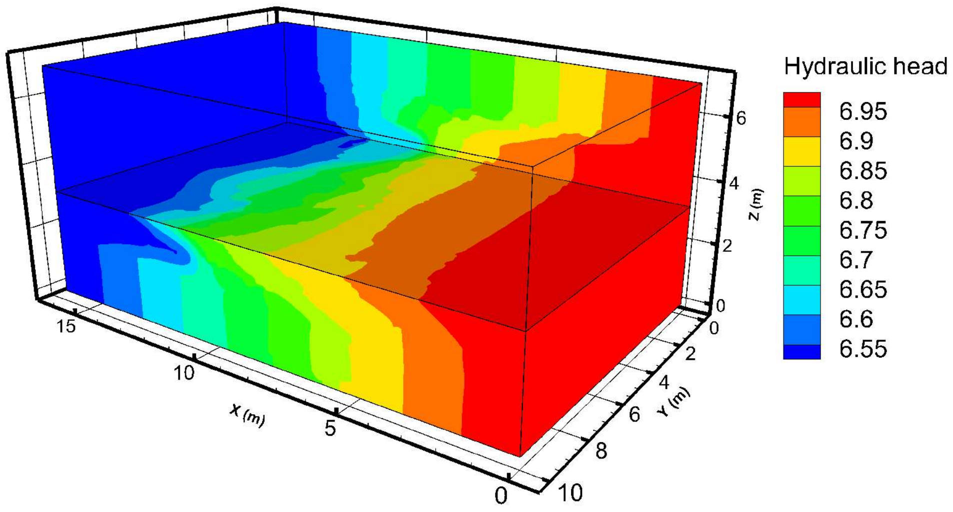
Comunian et al. 2011, Bayer et al. 20122

Developed with control volume finite element model HydroGeoSphere (*Therrien et al. 2006*), 1.119.000 10-cm elements

downscaled reconstructed hydro-facies

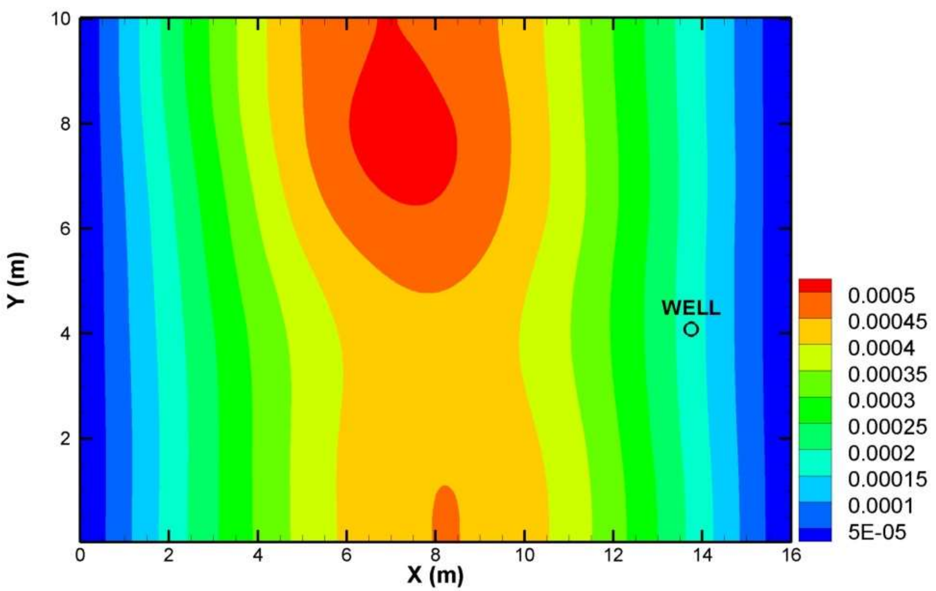


Computed hydraulic heads

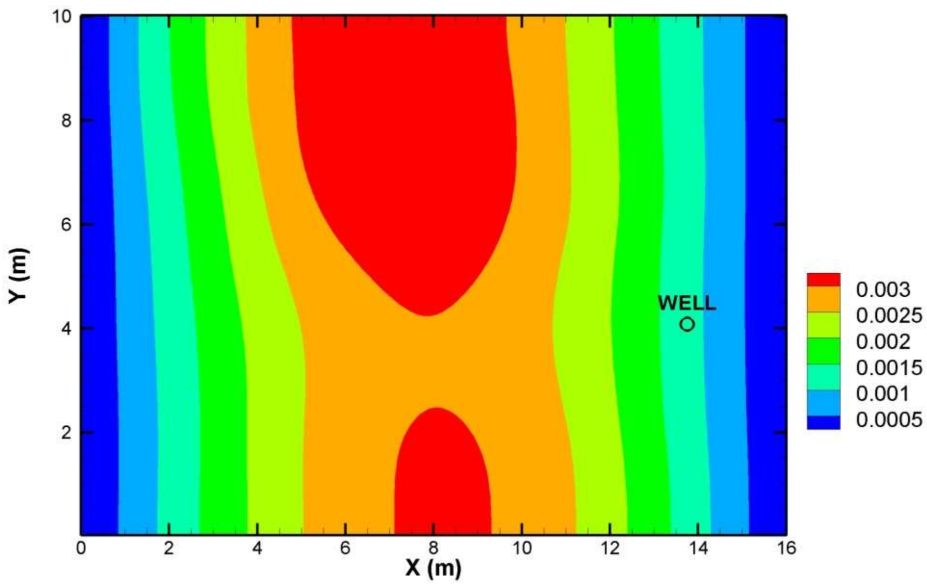


Sensitivity / vulnerability of hydraulic head at a specific location (e.g. an observation well) to an elemental surface change in groundwater recharge

Sensitivity map



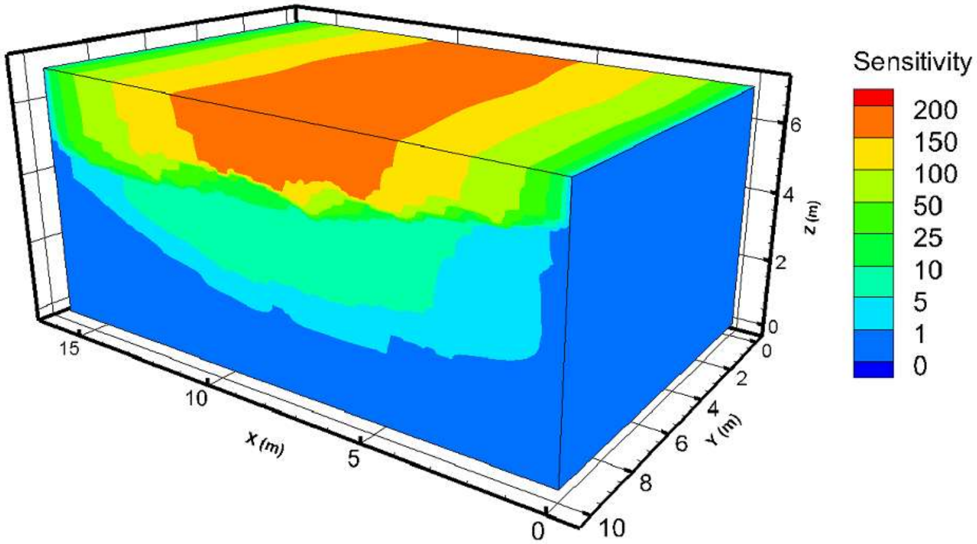
Vulnerability map
(damage state : hmin = 6m)



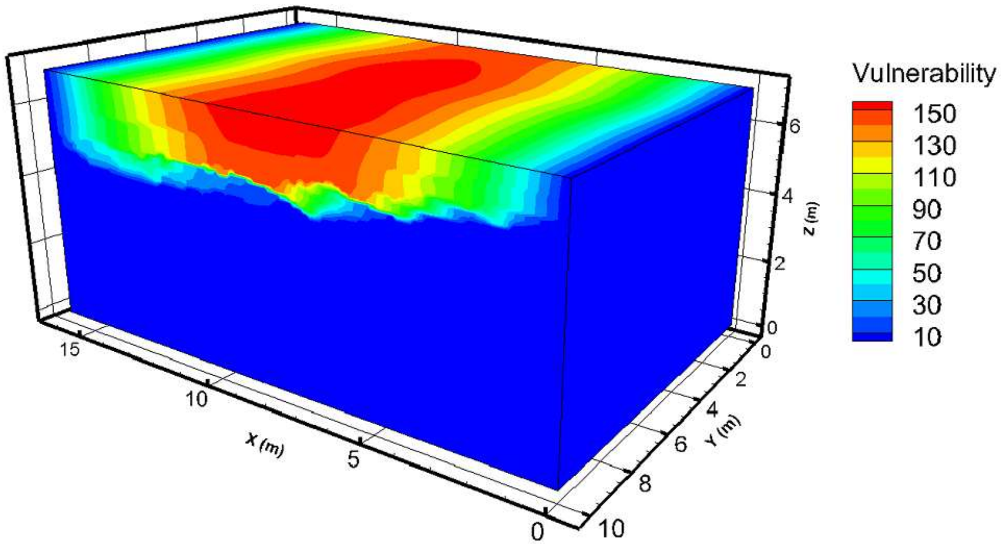
Because of the heterogeneity of the aquifer, the most sensitive area are not directly above the observation well

Sensitivity / vulnerability of hydraulic heads in the whole aquifer to a change in overall groundwater recharge

Sensitivity map



Vulnerability map
(damage state : current h - 2m)



Deeper part of the aquifer less sensitive / vulnerable because of low hydraulic conductivity facies located half-depth

Conclusions & Perspectives

It does not matter how complex are the processes controlling GW vulnerability and the models behind provided that the results are delivered in a practical manner to GW managers and decision makers

To deliver those results, GWV indicators are efficient candidate if they are meaningful and easy to understand, i.e. clearly reflecting the physics of flow and transport in the subsurface

Using physical metrics as GWV criteria and indicators is essential

They give a clear sense to the red and green colours, they facilitate the identification of key parameters and field investigations for GWV assessment and they are easily combined with models

The physically-based concepts presented here can be applied, developed and adapted to any kind of pressure-state-impact causal chain dealing with groundwater and to multi-relational problems

Groundwater vulnerability for reactive contaminants, to sea water intrusion, evaluation of mitigation measures (e.g. artificial recharge), integrated water resources management …

Thank you for your attention!

Acknowledgement

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Further reading

Popescu, I. C., Gardin, N., Brouyère, S., & Dassargues, A. (2008). Groundwater vulnerability assessment using physically based modelling: from challenges to pragmatic solutions. In Calibration and Reliability in Groundwater Modelling: Credibility in Modelling (pp. 83-88). Wallingford, UK: IAHS Press., http://hdl.handle.net/2268/3595

Brouyère, S., Jeannin, P.-Y., Dassargues, A., Goldscheider, N., Popescu, I. C., Sauter, M., Vadillo, I., & Zwahlen, F. (2001). Evaluation and validation of vulnerability concepts using a physically based approach. Mémoire des Sciences et Techniques de l'Environnement, 13, 67-72. http://hdl.handle.net/2268/2806

Lemieux J.-M., Beaujean J., Gardin N., Dassargues A., Therrien R., Brouyère S., Physically-based groundwater vulnerability assessment using sensitivity analys methods, submitted to Ground Water, July 2012.