University of Liege – Faculty of Applied Sciences
ArGEnCo – Architecture, Geology, Environment and Constructions
GEO³ - Geotechnologies, Hydrogeology and Geophysical Survey

Engineers facing groundwater challenges !

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UNIVERSITATEA TEHNICA DE CONSTRUCTII BUCURESTI

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A thirsty planet…

"Water is a necessary commodity to mankind and groundwater is the largest available source of fresh water" (Walton, 1963)

New developments induce new problems and … new efforts to solve them

Society is more and more demanding in quantified answers, reliable estimations, and risk assessment, … for decisions (linked to … confidence interval of answers)

→ Groundwater field measurements

→ Groundwater modelling

Groundwater modelling: equations ? not a problem !

- equations are mostly found and written …

$$R.n_e.\frac{\partial C^v}{\partial t} = \overrightarrow{div}.\left[n_e\left(D_h.\overrightarrow{grad}\,(C^v)\right) - v_e C^v)\right] + C^{v*}q' - n_e \lambda C^v R$$

Sorption-Desorption; Diffusion Dispersion; Advection; Sink-Source

$$\left(\frac{\rho_m c_m}{n_e \rho_w c_w}\right) n_e.\frac{\partial T}{\partial t} = \overrightarrow{div}.\left[n_e\left(\frac{\lambda_m}{n_e \rho_w c_w} + D\right)\overrightarrow{grad}\,T\right] - \overrightarrow{div}(n_e.v_e.T) + \frac{q'}{\rho_w c_w}$$

Thermic equilibrium; Conduction Diffusion Dispersion; Convection; Injection-Extraction of heat

(Fossoul et al., CMWR, 2010)

- how far are they properly describing the reality ?

Groundwater modelling: conceptualization/parameterization issues

- conceptual choices are never perfect
- stress factors less known than often considered
- parameters are still badly known
- scale issue
- calibration/validation, inverse modelling
- need for robustness, sensitivity analysis
- need uncertainty assessment
- CPU time /parallel processing

Groundwater modelling: solving techniques and computer efficiency

- Solving techniques have improved and are improving
  - in efficiency
  - in accuracy
  - for non-linear problems
  - for highly heterogeneous parameters/properties
  - for fractured rocks
  - Coupling with many other processes
    - Physical, biochemical processes
  - Coupling with other systems
    - Atmospheric / Climatic / Ocean models
    - Social models/systems
    - Economical models/systems

  ... Integrating !

Groundwater modelling: a few thinking

- Reductionism vs Integrationism (W.Wood, 2012)
  - Reductionism = to understand fundamental biological and physical processes by eliminating interacting effects
    - ➡ careful experimental design and choices of boundary and initial conditions
  - Integrationism = the emerging challenges of large-scale and coupled problems in soil, water, and energy
    - ➡ requiring extrapolation of well-known, small scale behaviours into larger scale models
  - numerical models has made possible the shift !
  - huge step forward to integrate the models of various water disciplines on a common platform
  - accommodate social and economic models, this aspect is definitely a work in progress

Groundwater modelling: a few thinking … on the other hand

- What is the actual role of modelling ?

  ... to assess likelihood

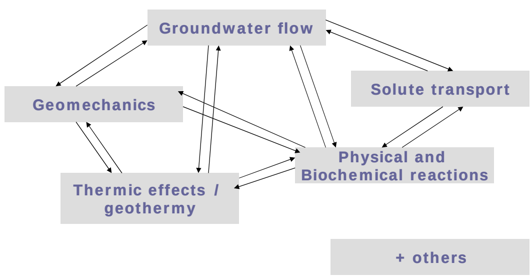
  (Doherty, 2011)

  - A) complex models can become cumbersome
    - they take too long to run
    - poor for parameter estimation and uncertainty analysis
    - but good receptacles for expert knowledge
  - B) simple models are fast and stable
    - expert knowledge may be vague or nonexistent
    - too far from the reality

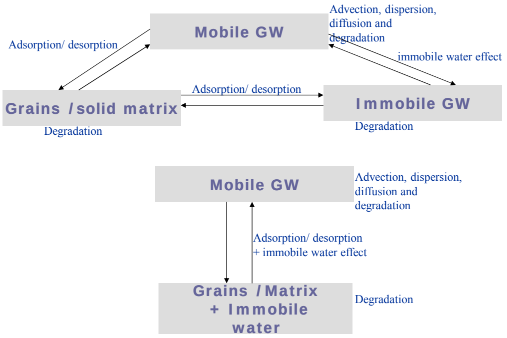
➡ optimal compromise between simplicity and complexity is needed

Groundwater modelling: coupling in the conceptual model

- Large importance of the adopted conceptual model



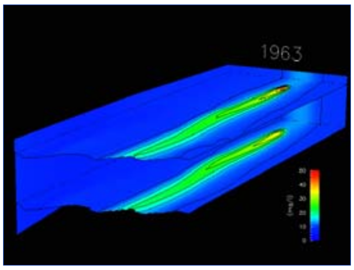
Different conceptual coupling: example for solute transport



Groundwater modelling: a few examples linked to practical questions

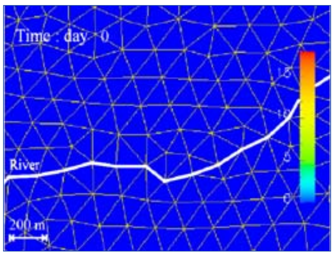
- Nitrate contamination … was it only a diffuse contamination ? Not so sure !

(P. Biver, PhD, 1993)



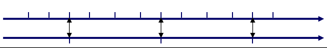
Groundwater modelling: a few examples linked to practical questions

- River – GW interactions: arrival of a pollutant in the river



advection,
dispersion,
diffusion
degradation
adsorption

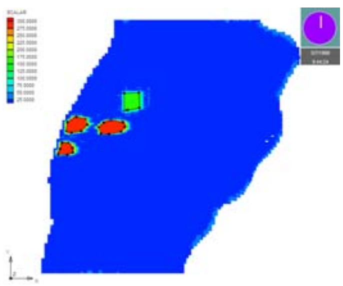
(Carabin & Dassargues, CMWR, 2000)



RM
GWM

Groundwater modelling: a few examples linked to practical questions

- River – GW interactions: arrival of a pollutant in pumping wells

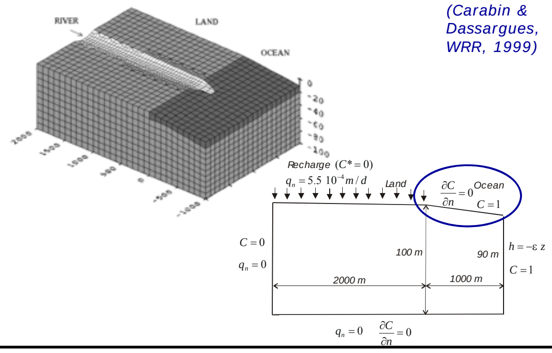


advection,
dispersion,
diffusion
degradation
adsorption

(Peeters et al., Env.Geol., 2003)

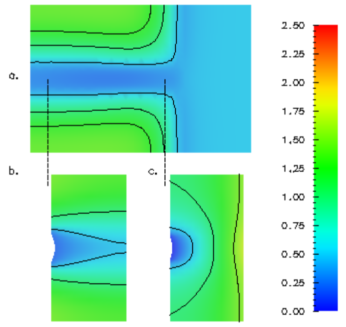
Groundwater modelling: seawater intrusion

(Carabin & Dassargues, WRR, 1999)



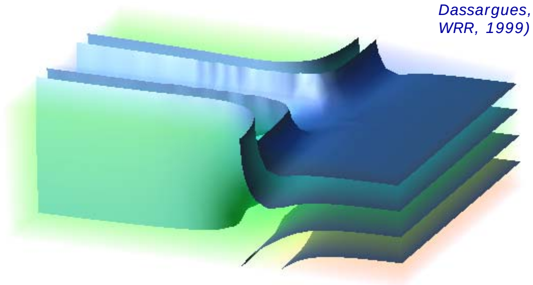
Groundwater modelling: seawater intrusion

(Carabin & Dassargues, WRR, 1999)



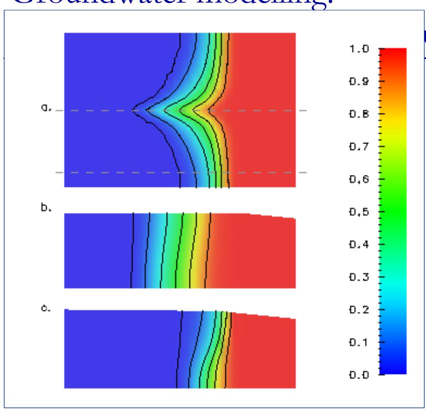
Groundwater modelling: seawater intrusion

(Carabin & Dassargues, WRR, 1999)

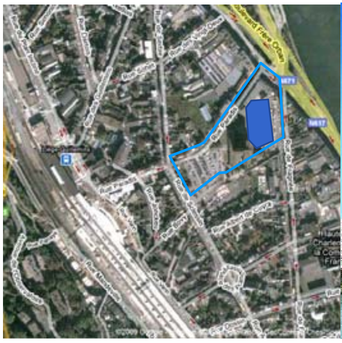


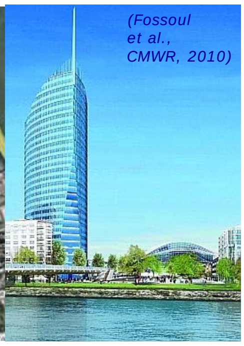
Groundwater modelling: ...usion

(Carabin & Dassargues, WRR, 1999)



Groundwater modelling: heat transport … cooling of a future office building



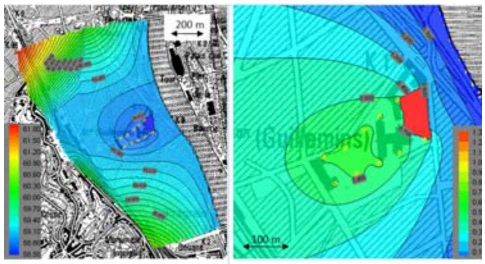


(Fossoul et al., CMWR, 2010)

Groundwater modelling: heat transport … cooling of a future office building

(Fossoul et al., CMWR, 2010)

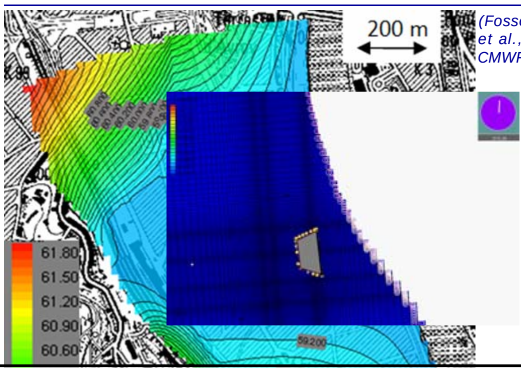
- 200 m³/h (nearly the critical value)
  - Maximum global rate for a continuous pumping



Rabattement maximal : 70 cm

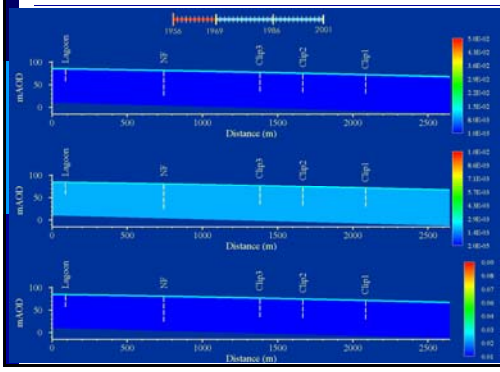
Groundwater modelling: heat transport … cooling of a future office building

(Fossoul et al., CMWR, 2010)



Groundwater modelling: 2D vertical reactive transport for a contaminated site

(B. Haerens PhD, 2004)

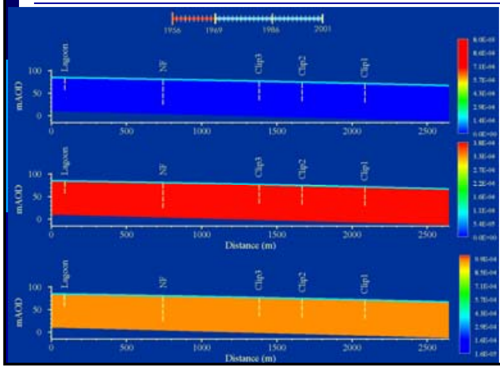


NH_4^+ (Ammonium)

Ca^{2+} (Calcium)

Cl^- (Chlorine)

Groundwater modelling: 2D vertical reactive transport for a contaminated site



(B. Haerens PhD, 2004)

C_6H_6O (Phenol)

O_2 (Dissolved Oxygen)

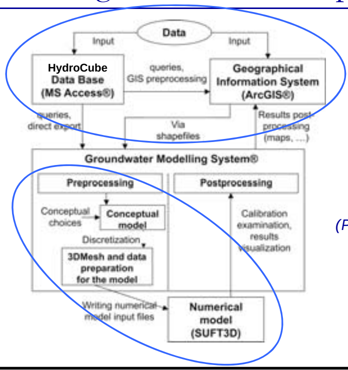
NO_3^{2-} (Nitrate)

Integrated modelling at regional scale a few thinking

"Modelling large-scale effects from small-scale influences is a delicate act" (Bear, 2011)

- Data management
- Conceptualization
- Upscaling parameters
- Calibration objectives
- Sensitivity analysis
- Range of the results

Integrated modelling at regional scale: data management and conceptualization



Data management : Database and GIS

(P.Wojda, PhD, 2009)

(Ph.Orban, PhD, 2009)

Model : Conceptualisation Equations

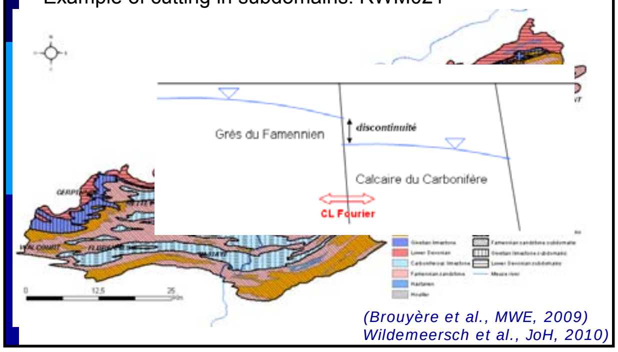
Integrated modelling at regional scale: Hybrid Finite Element Mixing Cell method

- The HFEMC method is a new and pragmatic approach which allows:
  - combining, in a single model and in a fully integrated way, different mathematical and numerical approaches
  - keeping the advantages of the spatial representation using finite element mesh
- The HFEMC method was implemented in the SUFT3D (Saturated and Unsaturated Flow and Transport in 3D) finite element code

(P.Orban, PhD, 2009)

Integrated modelling at regional scale: Hybrid Finite Element Mixing Cell method

Example of cutting in subdomains: RWM021



(Brouyère et al., MWE, 2009)
Wildemeersch et al., JoH, 2010)

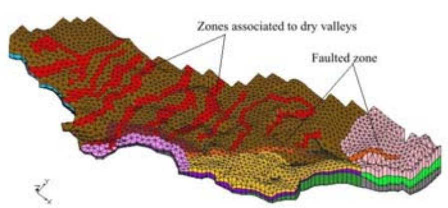
Integrated modelling at regional scale: Hybrid Finite Element Mixing Cell method

- SUFT3D: Saturated – Unsaturated Flow and Transport in 3D
  - Control volume finite element method (CVFE)
  - For large scale applications
    - Flexible discretization / meshing approach
    - Mathematical models of various (increasing) complexities for flow and transport (Hybrid Mixing Cell Finite Element approach)

		TRANSPORT		
		Simple Reservoir (Linear…)	*Distributed Mixing Model*	*Advection-dispersion*
FLOW	*Simple Reservoir (Linear…)*	OK	impossible	impossible
	Distributed Reservoir (Linear…)	OK	OK	impossible
	Flow in porous media	OK	OK	OK

(P.Orban, PhD, 2009)

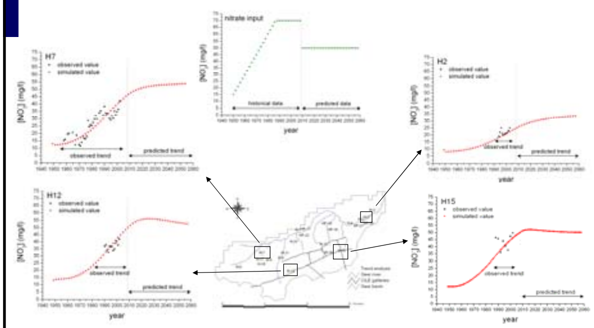
Integrated modelling at regional scale: Hybrid Finite Element Mixing Cell method



- Limit of the model similar to the limit of the hydrological basin
- Boundary conditions
- Heterogeneity of the chalk

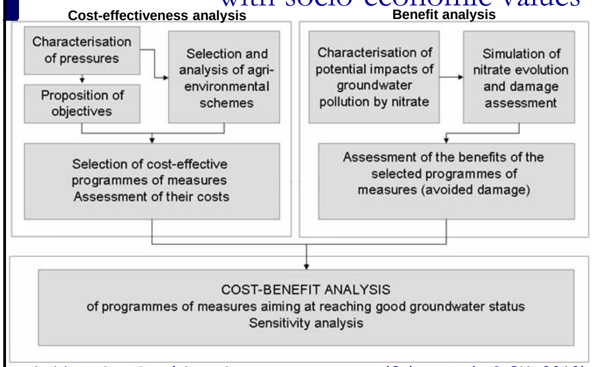
(Orban et al., JoCH, 2010)

Integrated modelling at regional scale: Hybrid Finite Element Mixing Cell method



(Orban et al., JoCH, 2010)

Integrated modelling at regional scale: with socio-economic values



(With BRGM, C. Hérivaux) *(Orban et al., JoCH, 2010)*

Integrated modelling at regional scale: with socio-economic values

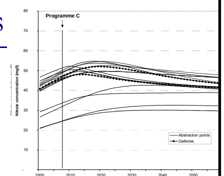
(With BRGM, C. Hérivaux)

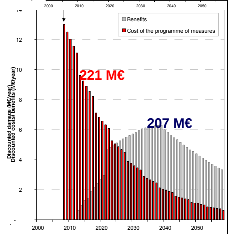
Program B (-32%) : +192 M€

Program C (-41%) : +207 M€

(Orban et al., JoCH, 2010)

	Units	Scenario 0	Scenario B	Scenario C
D^{DW}	M€	70.5	18.9	16.3
D^{SW}	M€	174.0	33.2	21.6
D^{total}	M€	244.5	52.1	37.9
B^{total}	M€	-	192.4	206.6
C	M€	-	141.0	220.6
NPV	M€	-	51.4	-14.0
D^{total}	€/household	1,343	296	217
B^{total}	€/household	-	1,047	1,126





Guidelines for large-scale groundwater flow model calibrationde with respect to end-users' expectations

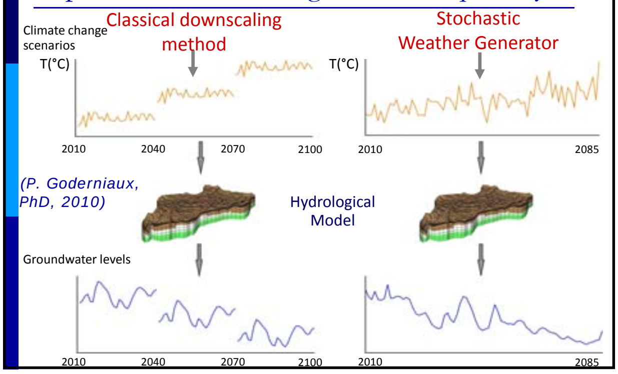
Objective of the study	Performance criteria to privilege
General evolution of base flow rates	NSE_q
Maximum value of base flow rates	PE_q
General evolution of hydraulic heads	RMS_h
Hydraulic head variations	$HHVE_h$
Hydraulic head maps	RMS_h

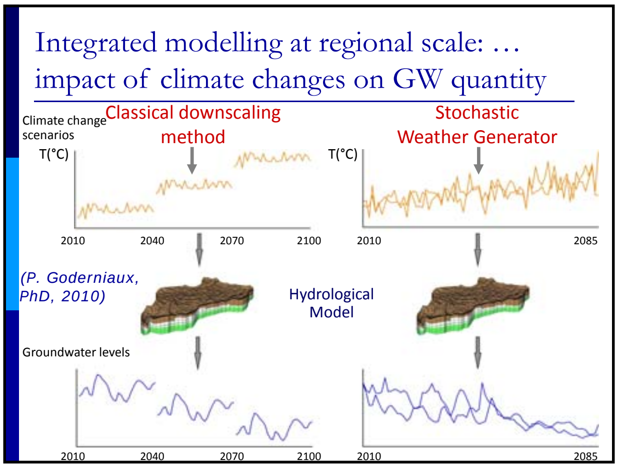
$$RMS_h = \sqrt{\frac{1}{nt} \times \sum_{t=1}^{nt} \left(h_t^{sim} - h_t^{obs}\right)^2}$$

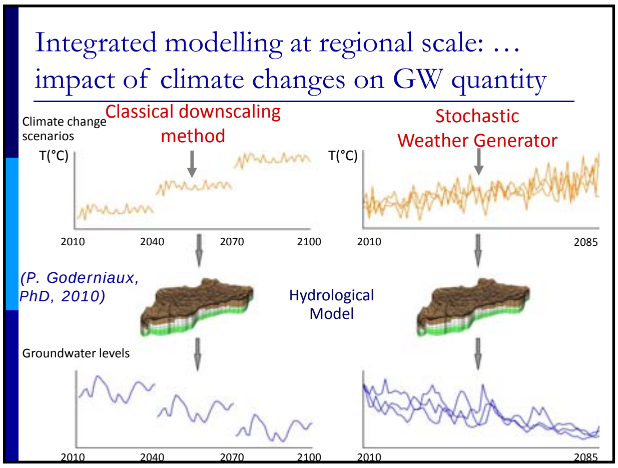
$$HHVE_h = \left(\frac{h_{max}^{sim} - h_{min}^{sim}}{h_{max}^{obs} - h_{min}^{obs}} - 1\right) \times 100$$

(S. Wildemeersch, PhD, 2012)

Integrated modelling at regional scale: … impact of climate changes on GW quantity




Integrated modelling at regional scale: …
impact of climate changes on GW quantity
Climate change scenarios
Classical downscaling method
Stochastic Weather Generator
T(°C)
2010
2040
2070
2100
2085
(P. Goderniaux, PhD, 2010)
Hydrological Model
Groundwater levels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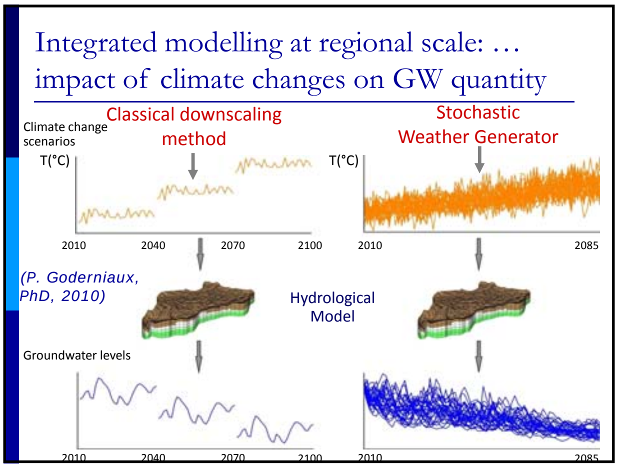
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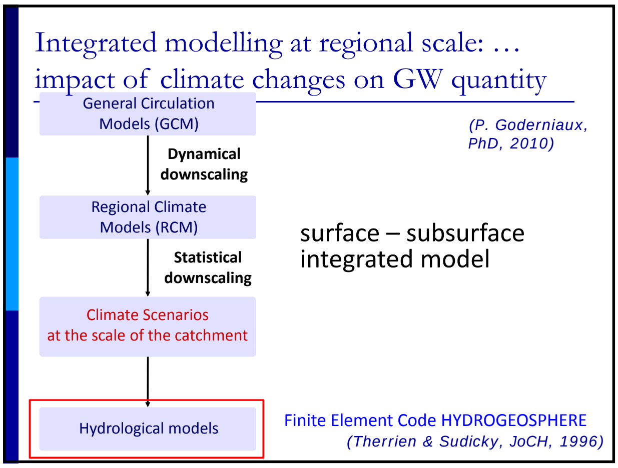
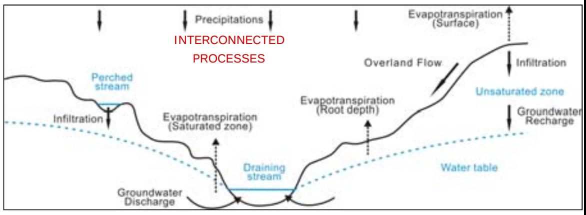

Integrated modelling at regional scale: …
impact of climate changes on GW quantity
General Circulation Models (GCM)
Dynamical downscaling
Regional Climate Models (RCM)
Statistical downscaling
Climate Scenarios at the scale of the catchment
Hydrological models
(P. Goderniaux, PhD, 2010)
surface – subsurface integrated model
Finite Element Code HYDROGEOSPHERE
(Therrien & Sudicky, JoCH, 1996)

Integrated modelling at regional scale: … impact of climate changes on GW quantity

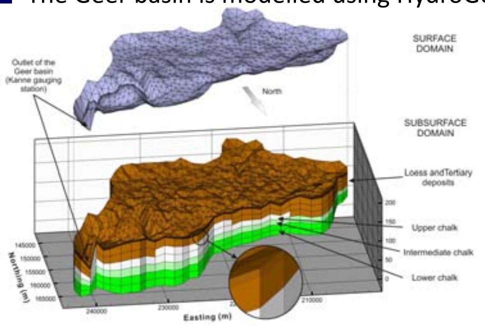


⇒ More realistic representation
Surface and subsurface data for calibration
Better representation of groundwater recharge
Crucial for climate change impact studies

(P. Goderniaux, PhD, 2010)

Integrated modelling at regional scale: … impact of climate changes on GW quantity

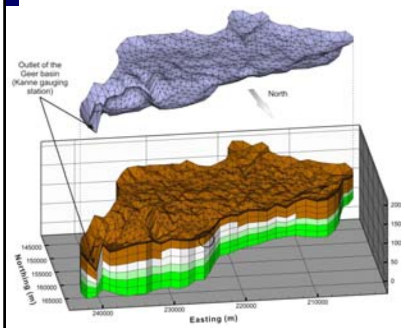
The Geer basin is modelled using HydroGeoSphere



(Goderniaux et al., JoH, 2009)

Integrated modelling at regional scale: … impact of climate changes on GW quantity

Precipitations ↓ Actual ET ↑ = f(PET, soil moisture, root & evap. Depth, LAI, canopy)
At each time step and node



SURFACE DOMAIN
2D surface water flow
(Diffusion-wave approximation of the Saint Venant equations)

↕ **Water exchanges** between nodes at **each time step**

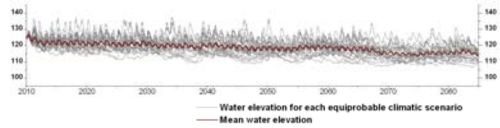
SUBSURFACE DOMAIN
3D variably-saturated flow
(Richards' equation)

(Goderniaux et al., JoH, 2009)

Climate change scenarios are applied on the Geer basin model

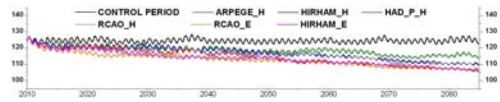
Groundwater levels

RCM : Arpege_h



MEAN groundwater levels

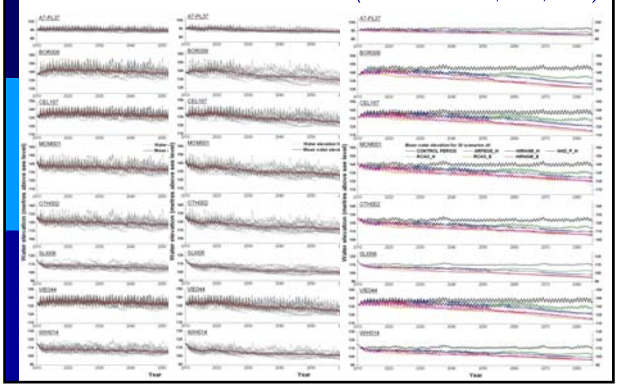
All 6 RCMs



(Goderniaux et al., WRR, 2011)

Results are achieved for all observation wells and all RCMs

(Goderniaux et al., WRR, 2011)



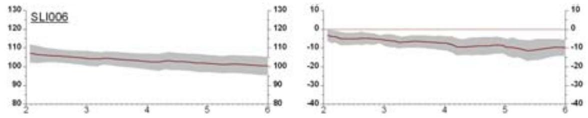
Confidence interval of the computed change in groundwater levels (h)

For the Geer basin hydrological model

- 95 % linear confidence intervals around predicted values
- Calculated over 4 years of HIRHAM_H
- Use of UCODE_2005 (USGS)

Predicted groundwater levels and 95 % confidence intervals

Change in groundwater levels and 95 % confidence intervals

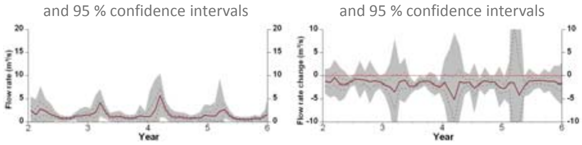


(Goderniaux et al., WRR, 2011)

Confidence interval of the computed surface flow rates

Absolute surface flow rates and 95 % confidence intervals

Change in surface flow rates and 95 % confidence intervals



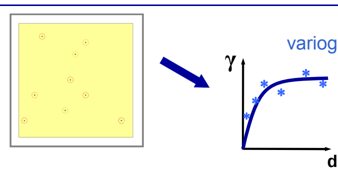
→ Uncertainty more important for winters!

(Goderniaux et al., WRR, 2011)

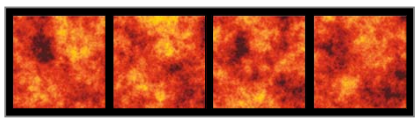
Geostatistics and groundwater modelling variogram, kriging and cond. simulation

mean value μ

variogram $\gamma(d) = f(\sigma^2, \lambda)$

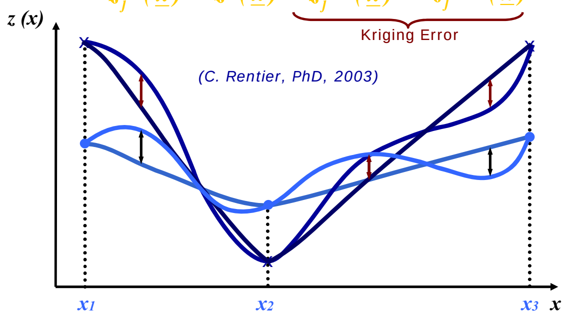


(C. Rentier, PhD, 2003)

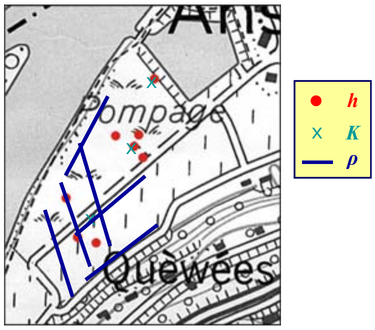


Geostatistics and groundwater modelling conditional simulation

$$z_j^{SC}(\underline{x}) = z^*(\underline{x}) + \underbrace{z_j^{SNC}(\underline{x}) - z_j^{SNC^*}(\underline{x})}_{\text{Kriging Error}}$$

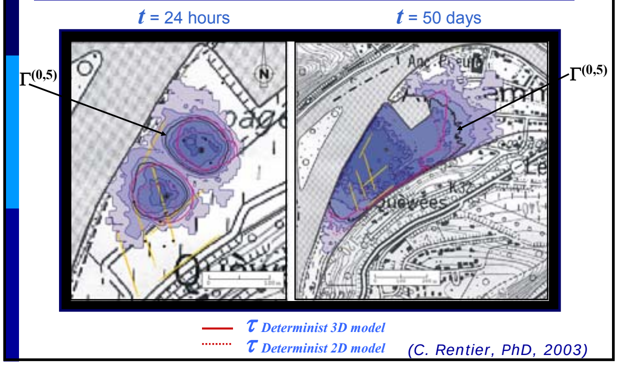


Co-conditional simulation: application for protection zone



(C. Rentier, PhD, 2003)

Co-conditional simulation: application for protection zone



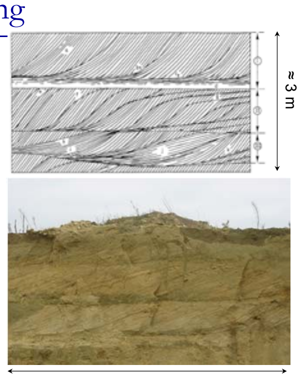
(C. Rentier, PhD, 2003)

Multiple-points geostatistics and groundwater modelling

- do not rely on variogram
- capturing structure by a 'training image'
- borrows the multiple points patterns from the training image
- still relies on the forgotten assumption of ergodicity and stationarity

(Jeff Caers, U. Stanford)

… applied here on the geological heterogeneity of Brussels Sands

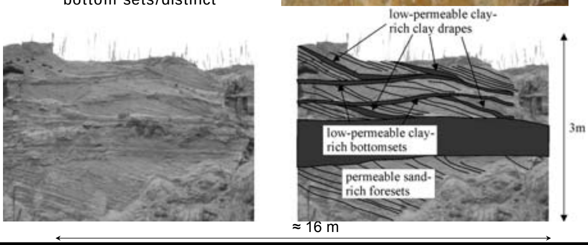


(Huysmans et al., JoH, 2008)

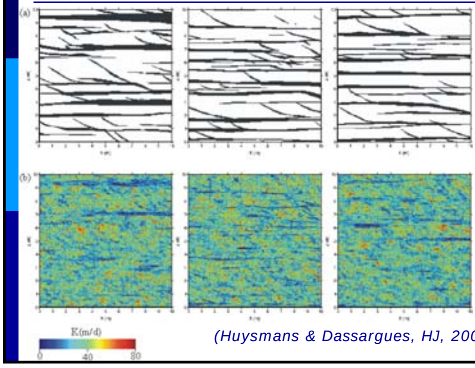
Multiple-points geostatistics and groundwater modelling

- Field observations
  - Pictures and geological sketches
  - Subjective distinction between clay-rich bottom sets/distinct

(Huysmans et al., JoH, 2008)



Multiple-point facies realizations and intrafacies permeability simulation



- 3 example facies realizations out of 150 realizations
- 3 example hydraulic conductivity realizations out of 150 realizations

(Huysmans & Dassargues, HJ, 2009)

GW vulnerability: where engineers have saved geologists and geographers

The start

- no clear definition
- relative concept
- often causes are mixed with results
  (i.e. contaminated zones are considered as vulnerable)
- multi-criteria analysis
- but with which weighting, units, objective function ?
  ➡ like an Eurovision song contest !!!!
  - hydraulic conductivity: 10 points
  - topography: 6 points
  - depth to water: 8 points

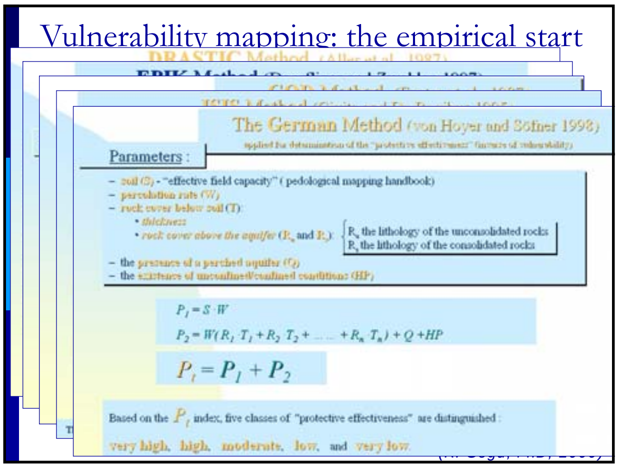
  …

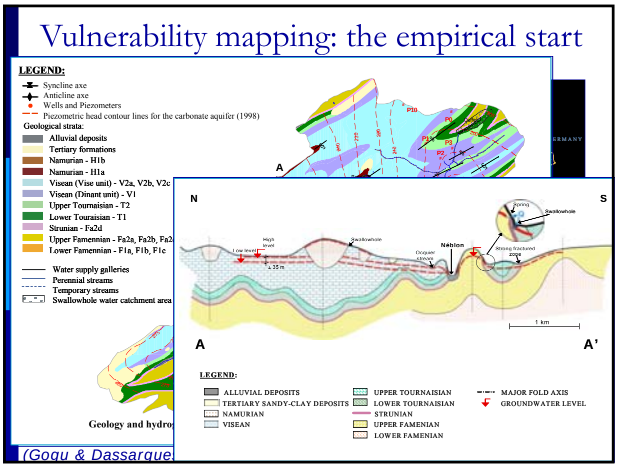
Vulnerability mapping: the empirical start

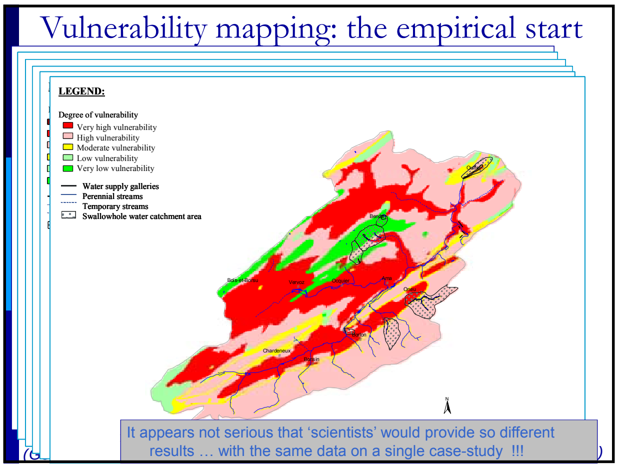
Overlay and index methods *(Gogu & Dassargues, Env. Geol., 2000)*

- estimated protective effect of the overlying layers in each pixel of the map;
- 'physical attributes' overlaid in a GIS with weighting coefficients given empirically (or conventionally);
- classification of the 'vulnerability index' values;
- nice colored maps

- DRASTIC, DRASTIC modified, SINTACS, EPIK, GOD, German method, PI, …
- Main problems
  - mixing semi-quantitative approximation of physical processes with pure empirical (local conventional) agreements;
  - not to be validated nor compared *(R. Gogu, PhD, 2000)*







GW vulnerability: more accurate definitions

… for groundwater ?

"a hierarchical process starting with intrinsic vulnerability, then progressing to specific vulnerability, and finally to risk assessment when combining with hazard (i.e. potential pollution at the surface)"

(Brouyère et al., 2001)

Risk

Specific vulnerability

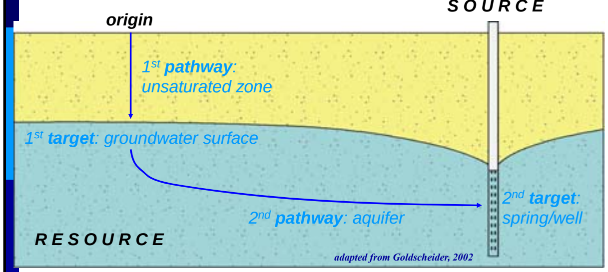
Intrinsic vulnerability: inherent geological and hydrogeological characteristics that control the impulse response of the system to a Dirac-type input of conservative contaminant

+ (bio)chemical behavior of the contaminant in the medium

+ probability of hazard + input function + mass of contaminant

Vulnerability mapping: more accurate definitions

« Origin-Pathway-Target Model »



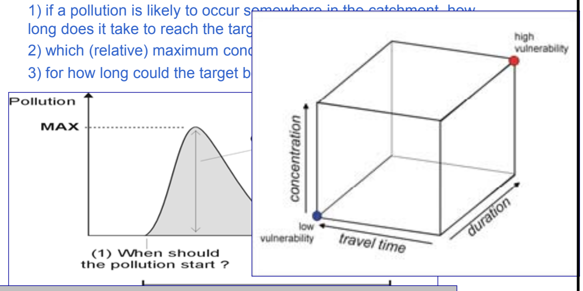
Vulnerability mapping: more "physically based"

… the potential risk of pollution for a considered target :

1) if a pollution is likely to occur somewhere in the catchment, how long does it take to reach the targ

2) which (relative) maximum conc

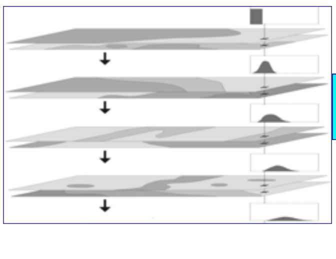
3) for how long could the target b



Still needed: … a conventional agreement on the relative importance (weighting) of each of these criteria !!!

(…re et al., 2001)

Vulnerability mapping: physically based but also feasible



$$\frac{\partial(\theta_m c)}{\partial t} = \frac{\partial}{\partial z}\left(D\frac{\partial c}{\partial z}\right) - v_e\frac{\partial c}{\partial z}$$

→ t_i

→ $C_i^* = C_i^{max}/C_0$

→ d_i

(Popescu et al., ModelCARE, 2008)

Vulnerability mapping: generalized engineering concept

In a Pressure-State-Impact causal chain,

… a generalized concept of groundwater vulnerability should reflect the easiness with which the groundwater system (the 'state') transmits pressures into impacts.

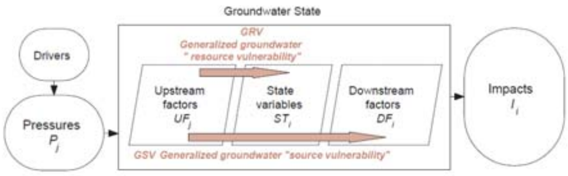
→ evaluating how a change in a given upstream factor (e.g. changes in groundwater recharge, surface contamination, etc.) has knock-on effects on downstream factors (e.g. base-flow to rivers, groundwater quality in a well, etc.)

$$S_{ij} = \frac{d(DownstreamFactor)_i}{d(UpstreamFactor)_j} = \frac{dh}{dQ}$$

= sensitivity of the i^{th} downstream factor to a change in the j^{th} upstream factor

(Dassargues et al., IAHS n°327, 2009)

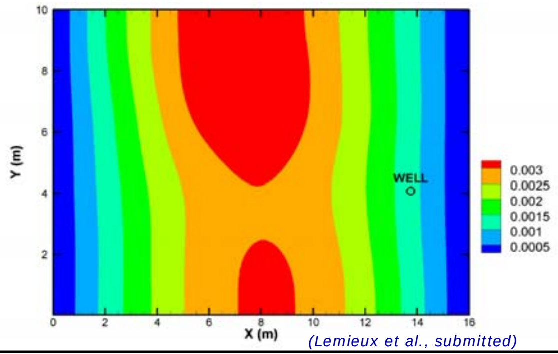
Vulnerability of Groundwater changes due to engineering involvement



- solved by a differential approach (computed with a perturbation method or by using the derivative as a primary variable)
- solved by a variational approach (adjoint operator method)

(Lemieux et al., submitted)

Vulnerability of Groundwater changes due to engineering involvement



(Lemieux et al., submitted)

Large progress …

- groundwater models grew in complexity to tackle problems previously beyond our reach (Bredehoeft, 2010)
- together with improvement of groundwater user interface (GUI) to input data and extract meaningful results
- manual calibration no longer practical so that linear and nonlinear optimizing techniques

… but the model is not an end in itself, rather a powerful tool that organizes thinking and engineering judgment

… but always many challenges in perspective

- Scale issues
- Multiple porous and permeable media in fractured/karstic media
- Numerical progress FDifferences, FElements, FVolumes, Meshless methods, …
- Efficiency for CPU time and active memory allocation and management
- Real/actual confidence intervals linked to hierarchical calibration objectives and conceptual errors
- Coupling with other processes linked to integrated approaches
- Automatic and better localized measurements
- Regional-Scale Monitoring Network for Risk-Informed Groundwater Management

STILL A LOT OF APPLIED RESEARCH AND DEVELOPPING CHALLENGES FOR ENGINEERS

Thank you to UTCB
and particularly to Prof Radu Drobot
and to all former students of the Tempus programs from 1992 to 1999
and to colleagues of the NATO SQUASH project from 2000-2004 !

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