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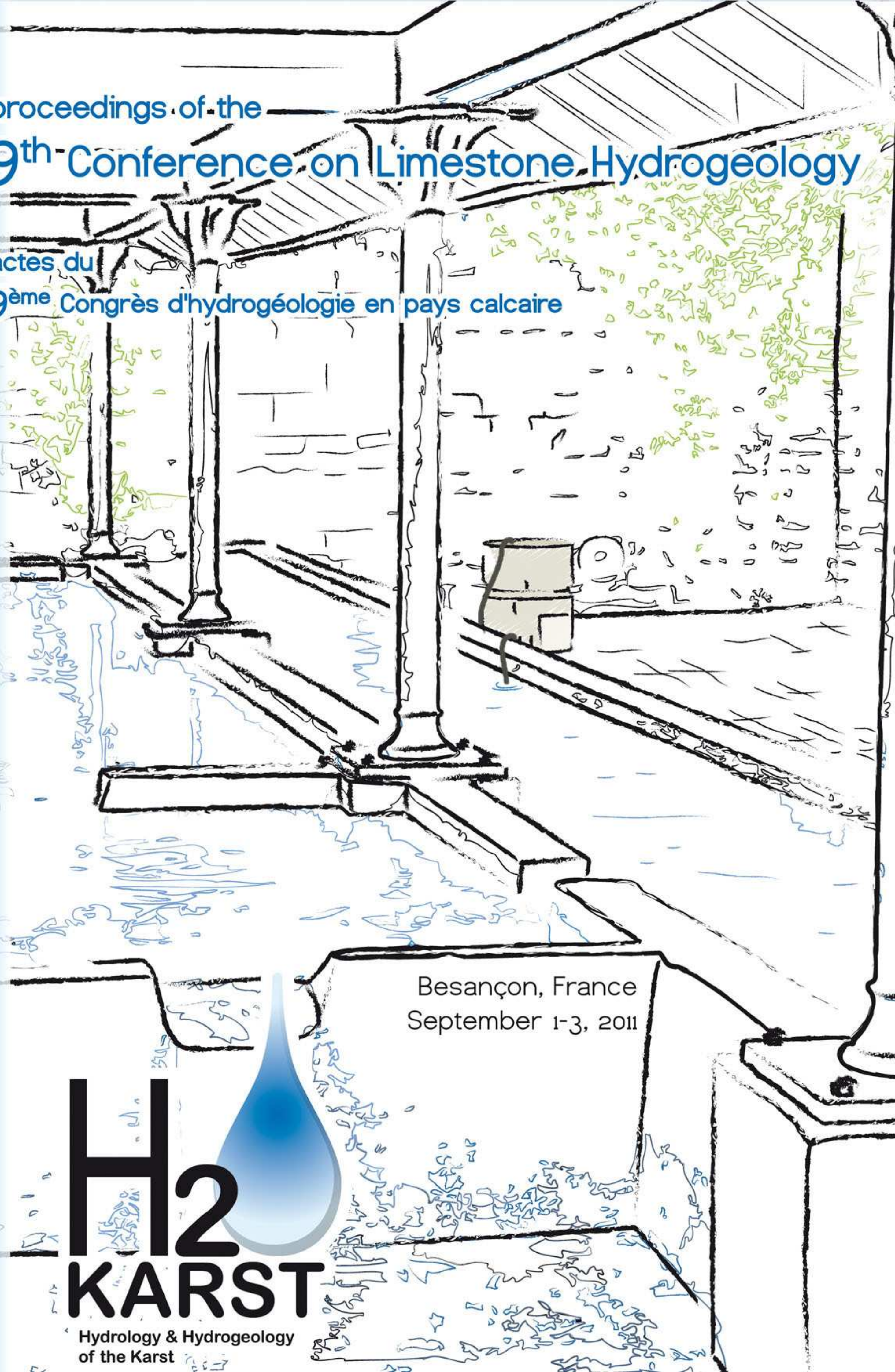

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H2 KARST
Hydrology & Hydrogeology of the Karst

Catherine Bertrand, Nicolas Carry, Jacques Mudry,
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9th conference on limestone hydrogeology

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The Hybrid Finite-Element Mixing-Cell method: a candidate for modelling groundwater flow and transport in karst systems

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Abstract

Groundwater flow and contaminant transport modelling in karst systems remains a challenge because of the complexity of the geology made of caves, voids, conduits of various sizes and forms and interacting matrix. Such heterogeneous structures cause complex hydraulic conditions for groundwater flow and transport processes. Despite the progresses in field investigation techniques and experiments, detailed knowledge and characterization of the karst system geometry and connectivity remains inaccessible and pragmatic modelling approaches have to be used.

Groundwater models of different complexities have been developed for karst systems, ranging from transfer functions and linear reservoir models to spatially distributed models. Here, a new flexible modelling approach, the Hybrid Finite-Element Mixing-Cell method (HFEMC), has been developed that allows combining in a single model, and in a fully interacting way, different mathematical approaches of various complexities for groundwater modelling in complex environments. This includes linear reservoirs, distributed reservoirs, groundwater flow in variably saturated equivalent porous media, with possibilities to consider by-pass flows along preferential flow paths, internal boundary conditions between the karstic features and the surrounding rock mass matrix background and drainage by surface waters. This method has been implemented in the groundwater flow and solute transport numerical code SUFT3D.

The objective of this communication is to present the modelling concepts and to discuss the potentials and advantages of the HFEMC method for modelling groundwater flow in karst systems over existing more classical modelling approaches. The discussion is supported by illustrative "synthetic" examples representative of karst systems and a real modelling application to the case of groundwater rebound and water inrush in a closed underground coal mine which presents a very similar geometrical and hydrological context to a karst, with cavities, drains and interacting rock mass.

1. Introduction

Caves, voids, and conduits of various sizes interacting with the surrounding matrix are key features governing groundwater flow in both karstic and mining context. Consequently, groundwater flow modelling in such complex environments is challenging. Classical modelling techniques solving the flow in porous media equation fail to simulate groundwater flow in large voids constituting preferential flowpaths (SHERWOOD & YOUNGER 1994; YOUNGER *et al.*, 2002; RAPANTOVA *et al.*, 2007). Another limitation on the use of classical modelling techniques in karst is related to the lack of knowledge on hydrogeological conditions and to the scarcity of data concerning the most karstified zones and their possible interconnections.

A series of specific modelling techniques taking into account, either explicitly or implicitly, mining features have been developed in the mining context. These techniques range from box model techniques (SHERWOOD & YOUNGER, 1997) to physically-based and spatially-distributed techniques (ADAMS & YOUNGER, 1997; YOUNGER *et al.*, 2002; BOYAUD & THERRIEN, 2004), including the new Hybrid Finite Element Mixing-Cell (HFEMC) method (BROUYÈRE *et al.*, 2009). Considering geometry and hydrology, karstic and mining systems can be considered as relatively similar. So, these techniques, and particularly the HFEMC method, are likely to be used for modelling karst aquifers. A karst system is indeed composed of an intricated network of voids creating a high water storage capacity and interconnected conduits assuring a global conductivity. These features can be considered as very similar to those found in intensively mined rock massifs with an intricated network of galleries and exploited zones.

The HFEMC method couples groups of mixing cells for the exploited zones with finite elements for the unexploited zone. The interactions between the exploited zones and the unexploited zone are considered using internal boundary conditions defined at the interfaces between the groups of mixing cells and the finite element mesh. Another feature of this technique lies in its ability to simulate by-pass flows between exploited zones or karstified zones using first order transfer equations between the groups of mixing cells. These features could be particularly useful in complex karstic systems in contact with more continuous and porous aquifers.

A short presentation of the concepts of the HFEMC method is given. Concise information is given on how the method was applied on a series of test cases and on a case study of an abandoned coal mine in Belgium. Then, perspectives concerning the use of the HFEMC method in karstic context are proposed.

2. Main principles of the HFEMC method

A full presentation of the HFEMC method, including verification and illustration test cases, is proposed by BROUYÈRE *et al.* (2009) and WILDEMEERSCH *et al.* (2010). The fundamental principle of the technique in mining context is to subdivide the modelled zone into exploited and unexploited zones. The exploited zones are discretised by groups of mixing cells and modelled using linear reservoirs characterised by a mean water level (Eq. 1a). The unexploited zone is discretised by finite elements providing spatially-distributed hydraulic heads obtained through the finite element solution of the groundwater flow equation in porous media (Eq. 1b). Choosing different equations for the exploited and unexploited zones is motivated by the different level of knowledge of hydrogeological conditions in each of them. The exploited zones are often poorly hydrogeologically characterised compared with the unexploited zone. Furthermore, the groundwater flow in porous media equation is no more valid in the large voids of the exploited zones.

$$Q_{LR} = S_{LR}\, A_{LR,upper}\, \frac{\partial H_{LR}}{\partial t} = -\alpha_{LR}\, A_{LR,exc} \left(H_{LR} - H_{ref}\right) + Q \tag{1a}$$

$$F \frac{\partial h}{\partial t} = \underline{\nabla}\left(\underline{\underline{K}}\, \underline{\nabla}(h+z)\right) + q \tag{1b}$$

where Q_{LR} = flow rate entering or leaving the linear reservoir [L³T^{-1}], S_{LR} = storage of the linear reservoir [-], $A_{LR,upper}$ = area of the upper face of the linear reservoir [L²], H_{LR} = mean hydraulic head in the linear reservoir [L], α_{LR} = exchange coefficient of the linear reservoir [T^{-1}], $A_{LR,exc}$ = area of the exchange face of the linear reservoir [L²], H_{ref} = drainage level of the linear reservoir [L], Q = source/sink term [L³T^{-1}], F = specific storage coefficient of the porous medium [L^{-1}], h = pressure potential [L], $\underline{\underline{K}}$ = hydraulic conductivity tensor [LT^{-1}], z = gravity potential [L], and q = source/sink term by unit volume [T^{-1}].

The interactions between exploited and unexploited zones are considered via internal boundary conditions defined at the interfaces between the groups of mixing cells and the finite elements. Three types of internal boundary are available: Dirichlet (first-type) *dynamic* boundary condition (Eq. 2a), Neumann (second-type) *impervious* boundary condition (2b), and Fourier (third-type) *dynamic* boundary condition (2c). The term *dynamic* is used for underlining that the hydraulic heads used in these boundary conditions are variable with time and remain unknonws of the problem.

$$h_{SD,i}(x,y,z,t) = h_{SD,j}(x,y,z,t) \tag{2a}$$

$$\frac{h(x,y,z,t)}{\partial n} = 0 \tag{2b}$$

$$Q_{SD,i-SD,j} = \alpha_{FBC}\, A_{exc} \left(h_{SD,j}(x,y,z,t) - h_{SD,i}(x,y,z,t)\right) \tag{2c}$$

where $h_{SD,i}$ = the hydraulic head in sub-domain *i* [L], $h_{SD,j}$ = the hydraulic head in sub-domain *j* [L], $Q_{SD,i-SD,j}$ = exchanged flow between sub-domains *i* and *j* through the third-type of *internal* boundary condition [L^{3}T^{-1}], α_{FBC} = exchange coefficient for the third type of *internal* boundary condition [T^{-1}], and A_{exc} = the exchange area for the third type of *internal* boundary condition [L^2].

The term α_{FBC} is function of the hydraulic conductivity on both sides of the interface between interacting subdomains. This term is estimated during the calibration process.

The interactions between the exploited zones themselves, that is by-pass flow connections through old mining works such as shafts or galleries, are modelled using a first-order transfer equation (Eq. 3). These by-pass flow connections can be switched on and off to simulate water inrushes.

$$Q_{SD,i-SD,j} = \alpha_{BF} \left(h_{SD,j}(x,y,z,t) - h_{SD,i}(x,y,z,t)\right) \tag{3}$$

The exchange coefficient α_{BF} (L²T^{-1}) is related to the head losses along preferential flow paths. A general schema of the HFEMC method is proposed in Figure 1.

3. Test cases results and case study

A series of synthetic examples were developed and modelled using the SUFT3D code for checking the implementation of the HFEMC method. The first two test cases were used to verify the numerical implementation of the HFEMC method through a comparison with available analytical solutions. The third and fourth examples illustrated the flexibility and potential of the proposed method for modelling mine water problems.

The first test was about the subdivision into sub-domains and the use of internal boundary conditions. Analytical solution and simulated results were identical. The second verification test case focused on the simple linear equation in transient regime. Analytical and simulated results were also identical (BROUYÈRE *et al.,* 2009).

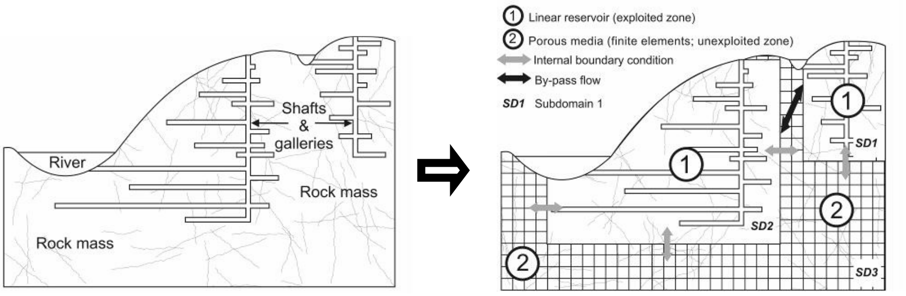
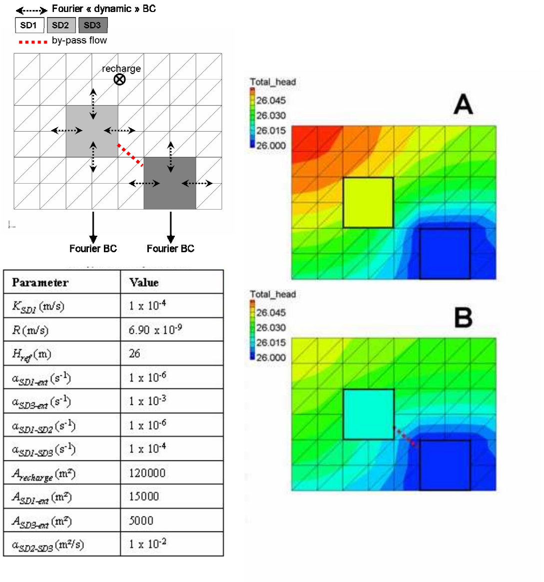


Figure 1: General schema of the HFEMC method showing the subdivision of the modelled zone into sub-domains and the choice of one groundwater flow equation for each of them.

A third test case was performed to illustrate the capacity of the HFEMC method to model by-pass flows between different mined zones. A schematic representation of the modelled example is given in Fig. 2. The mesh was divided into three sub-domains. The first sub-domain (SD1) corresponds to the unexploited rock mass, modelled using classical finite elements. The two others (SD2 and SD3) represent exploited zones modelled as linear reservoirs. These two mined zones were assumed to be connected by an old gallery constituting a preferential flowpath which was modelled using a first-order transfer equation. Third-type *dynamic* boundary conditions (internal boundary conditions) were prescribed at the interfaces between the rock mass (SD1) and the two exploited zones (SD2 and SD3). A third type external boundary condition was also prescribed at the external lateral faces of SD3 and at the south external lateral faces of SD1, to account for natural drainage of the mined system to surface water. Other external boundaries of SD1 were considered as impervious. A constant recharge was prescribed on the upper faces of the entire mesh. The model was run in steady-state conditions with parameters given in Figure 2.



Parameter	**Value**
K_{SD1} (m/s)	1×10^{-4}
R (m/s)	6.90×10^{-9}
H_{ref} (m)	26
$\alpha_{SD1\text{-}ext}$ (s^{-1})	1×10^{-6}
$\alpha_{SD3\text{-}ext}$ (s^{-1})	1×10^{-3}
$\alpha_{SD1\text{-}SD2}$ (s^{-1})	1×10^{-6}
$\alpha_{SD1\text{-}SD3}$ (s^{-1})	1×10^{-4}
$A_{recharge}$ (m^2)	120000
$A_{SD1\text{-}ext}$ (m^2)	15000
$A_{SD3\text{-}ext}$ (m^2)	5000
$\alpha_{SD2\text{-}SD3}$ (m^2/s)	1×10^{-2}

Figure 2: Discretisation and boundary conditions, parameters, and simulated hydraulic heads (in meters) (A) without by-pass flow between SD2 and SD3 and (B) with by-pass flow between SD2 and SD3

Figure 2A shows simulated hydraulic heads for the entire mesh without by-pass flow between the two exploited zones (SD2 and SD3), i.e. assuming that the first order transfer coefficient between these two zones is equal to zero. Fig. 2B shows the same simulation but considering by-pass flow between SD2 and SD3. The simulated mean water level in SD2 is higher in the first case than in the second case. Indeed, in the absence of by-pass flow between SD2 and SD3, SD2 is only drained through the low-permeability rock mass around. At the same time, resulting groundwater levels in SD1 are also higher because of the less efficient drainage capacity of the mined system. With by-pass flow between SD2 and SD3, SD2 is still drained through the rock mass around but also through the direct connection with SD3. The outflow of groundwater is thus facilitated and groundwater levels are depleted throughout the mined system. The simulated mean water level in SD3 is the same in both cases as it is governed by the exchange coefficient of the third-type external boundary condition. A fourth test case was performed with success (BROUYÈRE *et al.*, 2009) to check the capacity of the HFEMC method to model water inrushes (sudden water outflows).

The method was then applied to a real case as detailed in the publication of WILDEMEERSCH *et al.* (2010). It consists in an old coal field with many galleries, geological faults and unknown mine workings. The global discretisation is shown in Figure 3.

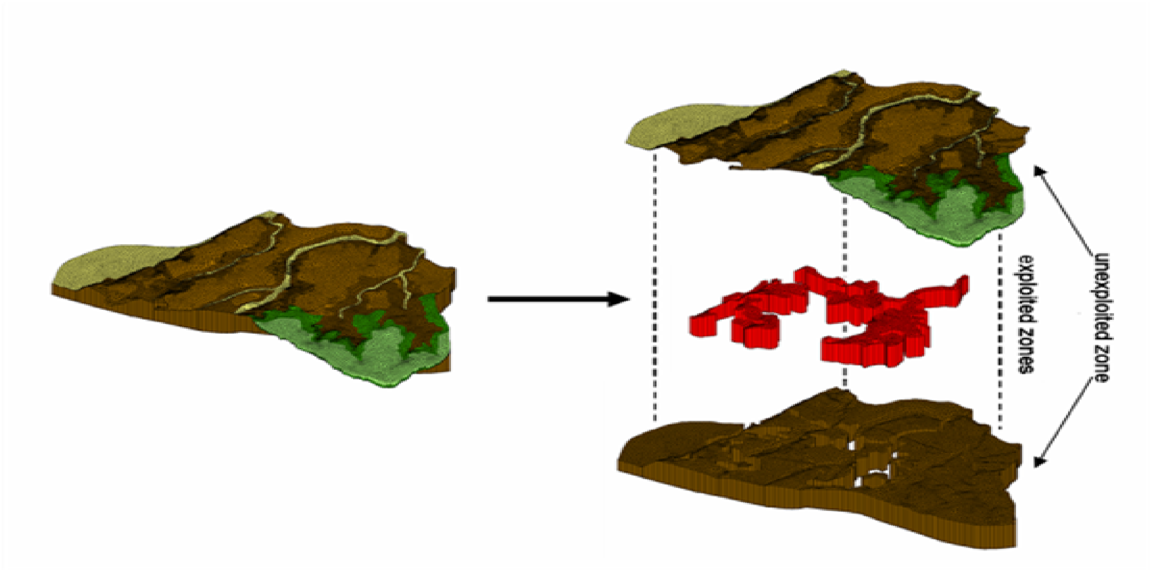


Figure 3: Discretisation showing 5 mixing cells for old unknown working zones (in red) and the three layers of finite elements. Interconnections between the mixing cells are not shown (for more details see Wildemeersch et al. 2010).

4. Conclusions

The Hybrid Finite Element Mixing Cell (HFEMC) method is a new flexible method that has been developed and validated for the simulation of groundwater flows in complex underground mined systems. The method couples a simplified approach (linear reservoir equation) for the exploited zones, most often poorly hydrogeologically characterised, with a classical approach (flow in porous media) for the adjacent and overlying unexploited zones.

This method offers advantages and potentials over existing more classical modelling techniques for simulating groundwater flow in karstic environments. As shown in the test cases and in the old underground coal mine case study, complex systems made of cavities, voids, and conduits, so very similar to karst systems, can be simulated successfully with this tool. The tool is ready: tests with actual karst sytems will be performed in the next months.

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