APPLICATION OF THE HFEMC METHOD TO AN ABANDONED COALFIELD IN BELGIUM: FROM CONCEPTUALISATION TO SCENARIO SIMULATIONS

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ABSTRACT

The Hybrid Finite Element Mixing Cell (HFEMC) method is a flexible modelling technique particularly suited to mining context (Brouyère et al., 2009). The principle of this method is to subdivide the modelled zone into several subdomains and to select a specific equation, ranging from the simple linear reservoir equation to the groundwater flow in porous media equation, to model groundwater flow in each subdomain. The model can be run in transient conditions, which makes it a useful tool for managing mine closure post-issues such as groundwater rebound and water inrushes.

An application of the HFEMC method to an abandoned underground coal mine near the city of Liège (Belgium) is presented. The case study zone has been discretized taking advantage of the flexibility of the method. Then, the model has been calibrated in both steady-state and transient flow regimes based on hydraulic head and water discharge rate observations. Finally, the calibrated model has been used to run several scenarios in order to assess the impacts of possible future phenomena on the hydraulic heads and the water discharge rates. Among others, the simulation of a strong rainfall event shows a quick and strong increase in hydraulic heads in some exploited zones coupled with a strong increase in associated water discharge rates. This could lead to stability problems in the hill slopes near the exploited zones. This kind of predictions can greatly help managing and predicting mine water problems in this particularly complex mining system.

1. INTRODUCTION

Groundwater flow modelling in mining context is challenging. Classical modelling techniques solving the flow in porous media equation fail to simulate groundwater flow in large voids constituting preferential flowpaths (Rapantova et al., 2007; Younger et al., 2002; Sherwood and Younger, 1997; 1994). Another limitation on the use of classical modelling techniques in mining context is related to the lack of knowledge on hydrogeological conditions and to the scarcity of data concerning the exploited zones and their possible interconnections. Consequently, specific modelling techniques taking into account, either explicitly or implicitly, mining features have been developed. These techniques range from box model techniques (Sherwood and Younger, 1997) to physically-based and spatially-distributed techniques (Boyaud and Therrien, 2004; Younger et al., 2002; Adams and Younger, 1997), including the new HFEMC method (Brouyère et al., 2009).

The HFEMC method couples groups of mixing cells for the exploited zones with finite elements for the unexploited zone. Interactions between exploited zones and 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 using first order transfer equations between the groups of mixing cells. The HFEMC method is particularly useful to simulate mine groundwater problems such as groundwater rebound. This kind of phenomenon is essential to simulate since its consequences can be harmful (soil instability, flooding, and water inrushes (Younger et al., 2002)).

The first application of the HFEMC method focuses on an abandoned underground coal mine near the city of Liège (Belgium). The conceptual model and the calibration in steady-state conditions have already been presented (Brouyère et al., 2009). This paper presents the calibration in transient conditions, the scenario simulations performed with the calibrated model, and the conclusions and the perspectives of this first application of the HFEMC method.

2. FUNDAMENTAL PRINCIPLE OF THE HFEMC METHOD

A full presentation of the HFEMC method, including verification and illustration test cases, is proposed by Brouyère et al. (2009). The fundamental principle of the technique 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. 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.

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. 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. These by-pass flow connections can be switched on and off to simulate water inrushes.

3. CASE STUDY: AN ABANDONED UNDERGROUND COAL MINE IN BELGIUM

The abandoned underground coal mine of Cheratte is located downstream of the city of Liège (Belgium) (Figure 1). The zone of interest covers about 27 km². The altitude ranges from about 55 m in the alluvial plain of the Meuse River to 200 m in the terraces. The rivers crossing the zone are the Meuse River and three of its direct or indirect tributaries flowing mainly northward (Figure 2).

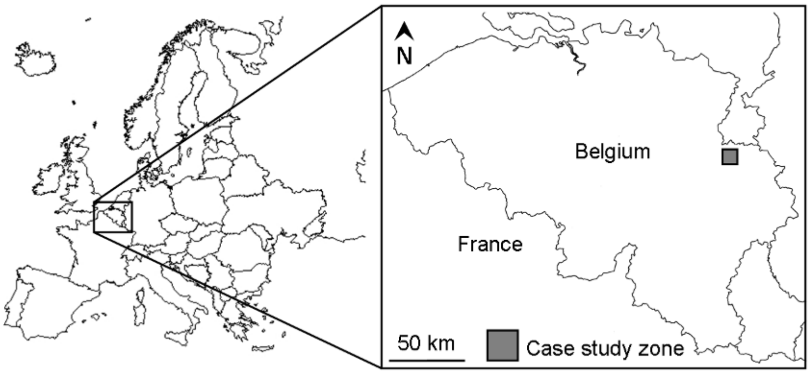

Figure 1. Location of the case study zone

The Cheratte underground coal mine is constituted of five exploited zones, *Trembleur*, *Argenteau*, *Hasard-Cheratte Nord*, *Hasard-Cheratte Sud*, and *Wandre*, each made up of a network of galleries (Figure 2). These exploited zones interact with the surface water network and with the surrounding unexploited zone.

Exploited zones are located in a faulted and folded geological formation composed of shales and silts with intercalations of sandstones, quartzites, and coal seams (Houiller Group - HOU - Upper Carboniferous). Overlying geological formations are constituted of clays and sands (Vaals formation - VAA - Cretaceous), chalk (Gulpen formation - GUL - Cretaceous), clays, silts and sands (terraces of the Meuse River - ALA - Tertiary), pebbles, sands and clays (alluvial deposits of the Meuse River - AMO - Quaternary) (Barchy and Marion, 2000) (Figure 2).

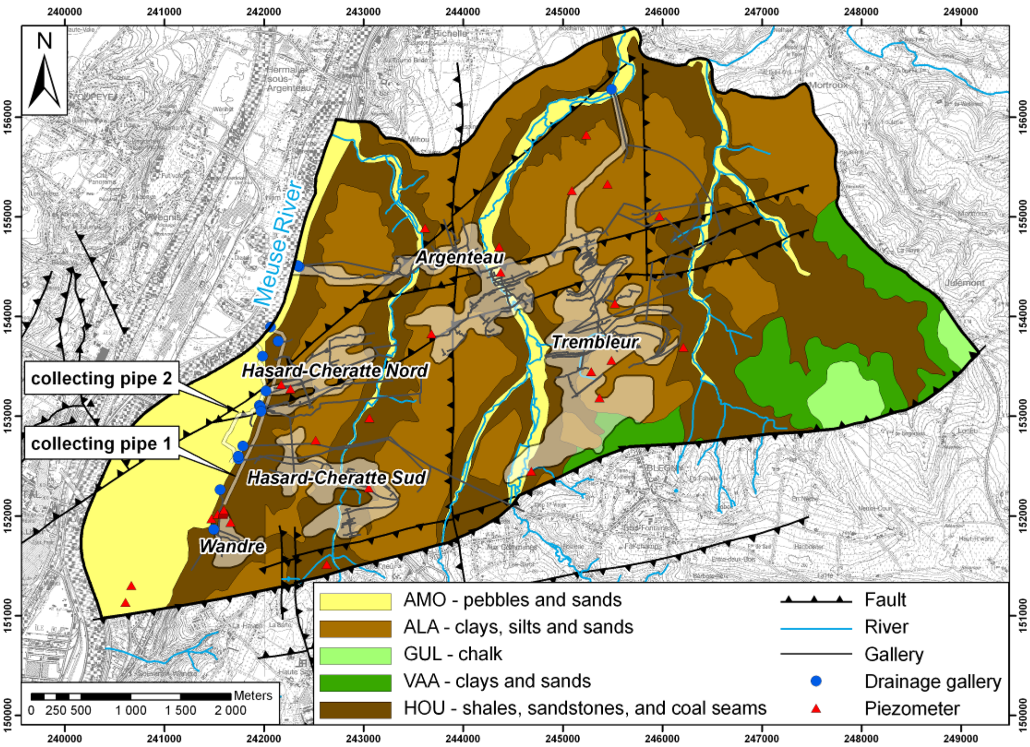

Figure 2. Geological map of the case study zone pointing out the exploited zones (adapted from Barchy and Marion (2000))

The main aquifer of the case study zone is located in the chalk of the Gulpen formation. However, local aquifers are also found in the fissured sandstones of the Houiller group and in the alluvial deposits of the Meuse River. Groundwater of this aquifer, influenced by both the dip of the Cretaceous formations and the Meuse River, flows mainly towards the northwest. However, this general trend is disturbed in the vicinity of the exploited zones where significant drawdowns are observed. As indicated by the strong correlation observed between hydraulic heads and water discharge rates (Figure 3), some of these exploited zones are probably connected through faults and unlisted mining works. As an example, the water discharge rate in the drainage gallery of *Hasard-Cheratte Sud* (E8) correlates closely with the hydraulic heads in *Argenteau* (Pz4) and *Trembleur* (Pz7) although the hydraulic head in *Hasard-Cheratte Sud* (Pz8) is almost stable. Connections must thus exist between *Hasard-Cheratte Sud* and both *Argenteau* and *Trembleur*. Hydraulic head thresholds from which groundwater within *Argenteau* and *Trembleur* is evacuated directly through the drainage gallery of *Hasard-Cheratte Sud* are estimated to 88.5 m and 102 m, respectively (Dingelstadt et al., 2007).

The Cheratte coal mine was closed in the end of the 1970s. The last pumping, maintaining the groundwater level in *Trembleur* at about -64 m, was stopped in 1982. However, the groundwater rebound was not really monitored until the installation of a monitoring network in 2003. Thanks to this monitoring network, water levels and water discharge rates measurements are now performed regularly in a series of piezometers and drainage galleries (Figure 2). Although determining a general trend using a so short time series is difficult, the groundwater rebound seems to slightly continue when looking at the hydraulic head trends in *Argenteau* (Pz4) and *Trembleur* (Pz7). However, the essential of the groundwater rebound has probably already taken place.

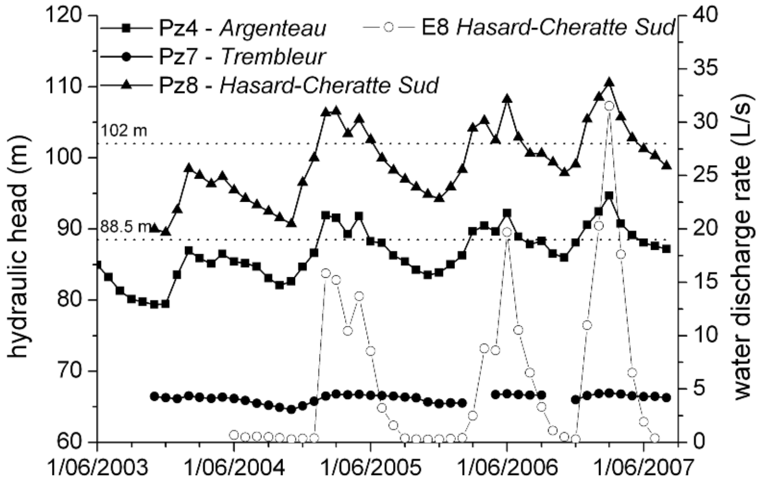

Figure 3. Correlation between hydraulic heads and water discharge rates observed in different networks of galleries (adapted from Dingelstadt et al. (2007))

4. GROUNDWATER FLOW MODELLING OF THE CHERATTE UNDERGROUND COAL MINE

Conceptual and Numerical Models

A Fourier (third-type) boundary condition is prescribed at the western external boundary of the model for considering the exchange of fluxes between the aquifer and the Meuse River. A Neumann (second-type) impervious boundary condition is prescribed at the other external boundaries assuming they correspond to groundwater divides or faults filling with clay. The top of the model corresponds to the topography and the base of the model is the -64 m plane. The corresponding mesh is composed of 3 layers, 30,443 nodes, and 40,976 elements.

The model is subdivided into eight subdomains: five corresponding to the exploited zones of *Trembleur*, *Argenteau*, *Hasard-Cheratte Nord*, *Hasard-Cheratte Sud*, and *Wandre*, two corresponding to mine water collecting pipes, and one corresponding to the adjacent and overlying unexploited zone. The internal boundary conditions between exploited and unexploited zones are defined as Fourier (third-type) *dynamic* boundary conditions in order to allow groundwater flux exchanges between them. Five drainage galleries are considered and ten by-pass flow connections between exploited zones are defined. These by-pass flow connections have been identified from previous results obtained with a box model calibrated in steady-state conditions as well as on the correlation observed between hydraulic heads and water discharge rates measurements performed in the exploited zones (Figure 3). Hydraulic head thresholds highlighted by these measurements are also taken into account. The connections *Argenteau* ↔ *Hasard-Cheratte Sud* and *Trembleur* ↔ *Hasard-Cheratte Sud* are switched on only when hydraulic heads in *Argenteau* and *Trembleur* are higher than 88.5 m and 102 m, respectively.

Calibration in Transient Conditions

Initial conditions for the calibration in transient conditions come from the calibration in steady-state condition (Brouyère et al., 2009). The calibration in transient conditions is based on both hydraulic head and water discharge rate observations performed from January 2004 to December 2005. As suggested by Hill and Tiedeman (2007) and since the prescribed recharge varies monthly (water budget with the Thorntwaite method), the observations are monthly averaged to ensure time-consistency between observed and simulated values. The calibrated parameters are the hydraulic conductivities of the geological formations, the exchange coefficients of Fourier boundary conditions, and the exchange coefficients of by-pass flow connections between exploited zones but also the specific yield and the specific storage coefficients of both exploited zones and geological formations of the unexploited zones. A list of parameters used for these transient simulations are given in Table 1. Calibrated values of hydraulic conductivities fall in the range of values estimated from pumping tests in the field (Ruthy and Dassargues, 2008). Graphical comparisons between observed and simulated values in terms of hydraulic heads and water discharge rates are presented in Figure 4 and Figure 5, respectively.

Table 1. Calibrated parameters in transient conditions

	Parameters				
Geological formations	K (m/s)	S_y (-)	S_S (m^{-1})		
HOU	5×10^{-6}	0.01	1×10^{-4}		
VAA	3×10^{-6}	0.40	1×10^{-4}		
GUL	2×10^{-5}	0.05	1×10^{-4}		
ALA	7×10^{-5}	0.50	1×10^{-4}		
AMO	7×10^{-3}	0.50	1×10^{-4}		
Exploited zones		S_y (-)	S_S (m^{-1})		
Trembleur		0.006	1×10^{-6}		
Argenteau		0.006	1×10^{-6}		
Hasard-Cheratte Nord		0.07	1×10^{-6}		
Hasard-Cheratte Sud		0.07	1×10^{-6}		
Wandre		0.07	1×10^{-6}		
External BC				α (s^{-1})	H_{ref} (m)
Trembleur - Bolland R.				2.00×10^{-8}	92
Argenteau - Meuse R.				1.50×10^{-8}	55
collecting pipe 1 - Meuse R.				1.50×10^{-7}	55
collecting pipe 2 - Meuse R.				3.00×10^{-7}	55
unexploited zone - Meuse R.				5.00×10^{-5}	55
Internal BC				α (s^{-1})	
unexploited zone - exploited zones (vertical)				1×10^{-15}	
unexploited zone - exploited zones (horizontal)				1×10^{-12}	
By-pass flow connections				α (m²/s)	
$\alpha_{Trembleur\text{-}Argenteau}$				2.15×10^{-4}	
$\alpha_{Trembleur\text{-}Hasard\text{-}Cheratte\ Nord}$				2.75×10^{-4}	
$\alpha_{Trembleur\text{-}Hasard\text{-}Cheratte\ Sud}$				3×10^{-4} if $h_{Trembleur}$>102 m	
$\alpha_{Argenteau\text{-}Hasard\text{-}Cheratte\ Nord}$				1×10^{-8}	
$\alpha_{Argenteau\text{-}Hasard\text{-}Cheratte\ Sud}$				1×10^{-4} if $h_{Argenteau}$>88.5 m	
$\alpha_{Hasard\text{-}Cheratte\ Nord\text{-}Hasard\text{-}Cheratte\ Sud}$				3.50×10^{-5}	
$\alpha_{Hasard\text{-}Cheratte\ Sud\text{-}Wandre}$				3×10^{-6}	
$\alpha_{Hasard\text{-}Cheratte\ Nord\text{-}collecting\ pipe\ 2}$				3×10^{-3}	
$\alpha_{Hasard\text{-}Cheratte\ Sud\text{-}collecting\ pipe\ 1}$				1×10^{-3}	
$\alpha_{Wandre\text{-}collecting\ pipe\ 2}$				8×10^{-4}	

K = hydraulic conductivity of the geological formations [LT^{-1}], S_y = specific yield (-), S_s = specific storage coefficient [L^{-1}], $\alpha_{i\text{-}j}$ = exchange coefficient for Fourier boundary conditions (external or internal) [T^{-1}] and by-pass flow connections [L^2T^{-1}], H_{ref} = drainage level [L]. Drainage levels have not been calibrated.

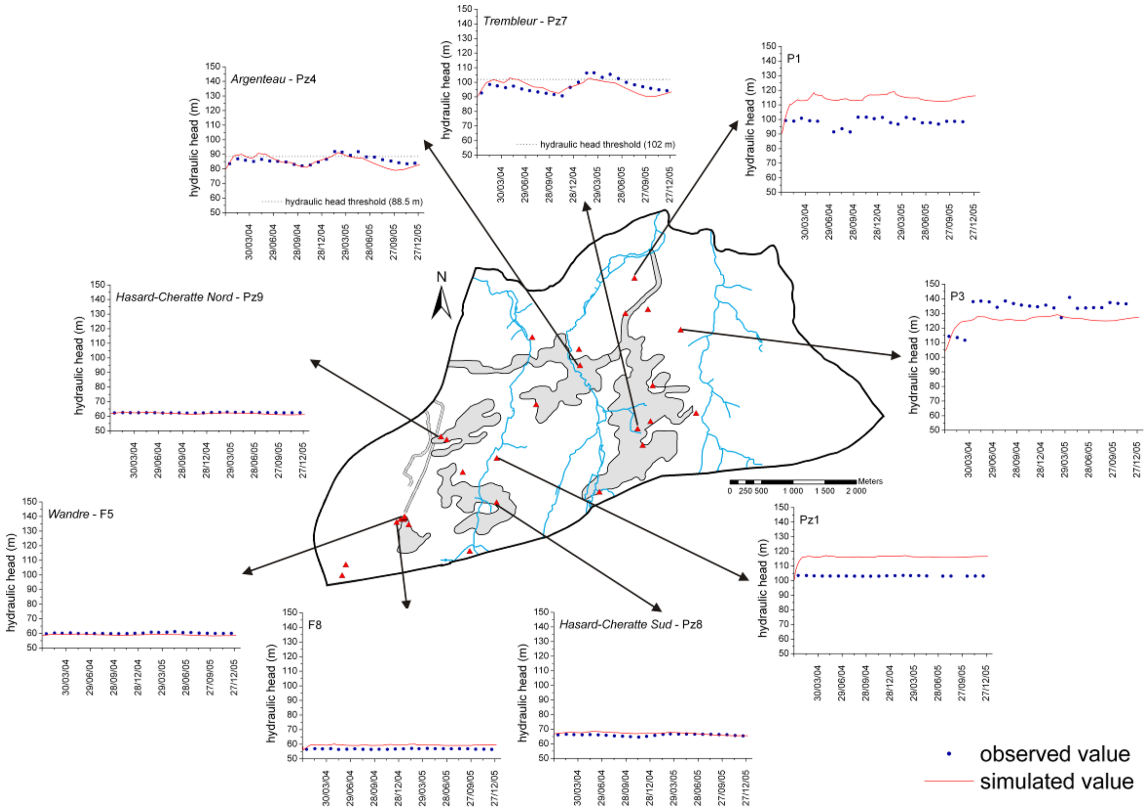

Figure 4. Comparison between observed and simulated hydraulic heads in different piezometers of the case study zone

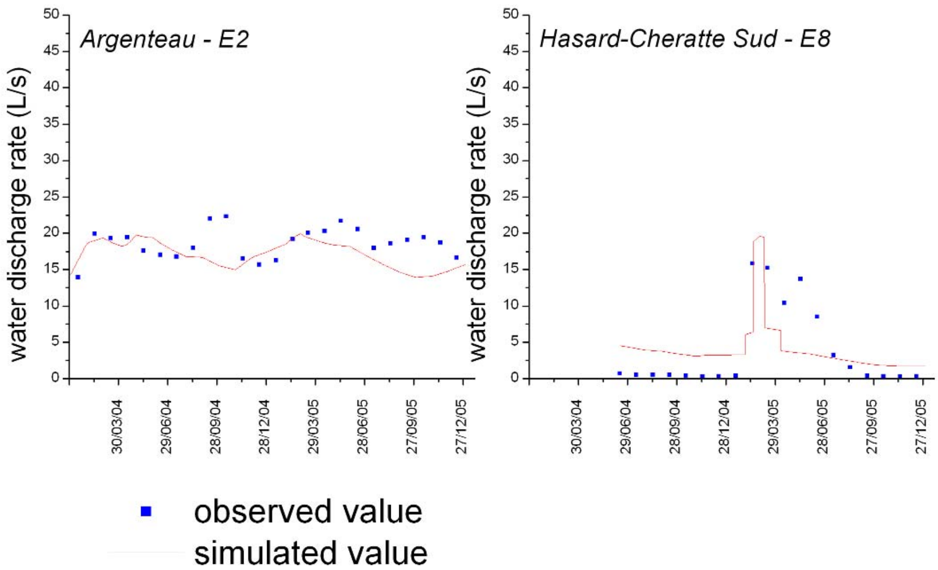

Figure 5. Comparison between observed and simulated water discharge rates

As shown in Figure 4 and Figure 5, the calibrated model is able to reproduce very satisfactorily the observed hydraulic heads and water discharge rates. These latter are directly related to the simulated hydraulic heads since they are represented by Fourier boundary conditions or by by-pass flow connections for which computed flow rates depend on the difference between hydraulic heads. Hydraulic head and simulated water discharge rate in *Argenteau* (Pz4 and E2) look thus similar. The situation is more complex for *Hasard-Cheratte Sud* (E8 and Pz8) since the simulated water discharge rate of this exploited zone is also related to the hydraulic heads in *Argenteau* (Pz4) and *Trembleur* (Pz7). Observations indicate that the hydraulic head thresholds of *Argenteau* (88.5 m) and *Trembleur* (102 m) were exceeded from February 2005 to June 2005 with a major peak in February and a minor peak in May. Accordingly, two flooding peaks are observed in the drainage gallery of *Hasard-Cheratte Sud*. The simulated hydraulic heads reproduce the major peaks observed but not the minor ones probably because of the recharge, prescribed monthly rather than daily or weekly, is somehow smoothed. Consequently, the simulated water discharge rate reproduces only the first flooding peak.

Groundwater Rebound and Very Rainy Winter Scenarios

The goal of the scenarios is to show the utility of the model for managing possible mine groundwater problems in predicting system response to unusual solicitations such as a very rainy winter.

Groundwater rebound - According to the hydraulic heads measured since 2003, the essential of the Cheratte underground coal mine groundwater rebound has probably already taken place. The goal of this scenario is to try to reproduce this past event for confirming this hypothesis.

The only data available concerning dewatering operations indicates that the last pumping was stopped in 1982. Previously, this pumping maintained the water level to -64 m in *Trembleur*. Accordingly, the first part of the simulation (5 years) is performed with a sink term withdrawing about 5000 m³/day in *Trembleur*. The second part (25 years) of the simulation was performed without any pumping. A constant recharge of 189 mm/year, equivalent to the mean annual recharge between 2003 and 2006 (water budget with the Thorntwaite method), is prescribed during the whole simulation (30 years). Simulated hydraulic heads, water discharge rates between exploited zones, and water discharge rates between exploited zones and surface waters are presented in Figure 6, and Figure 7, respectively. A negative water discharge rate means that water flows from the first exploited zone cited to the second exploited zone cited.

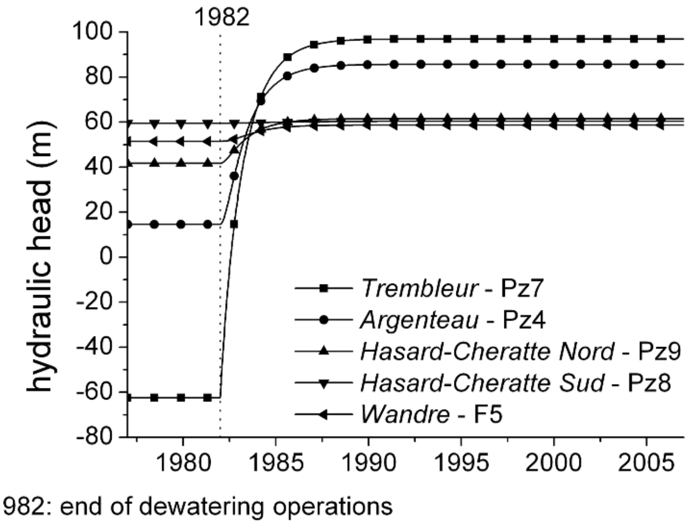

Figure 6. Groundwater rebound scenario - Simulated hydraulic heads

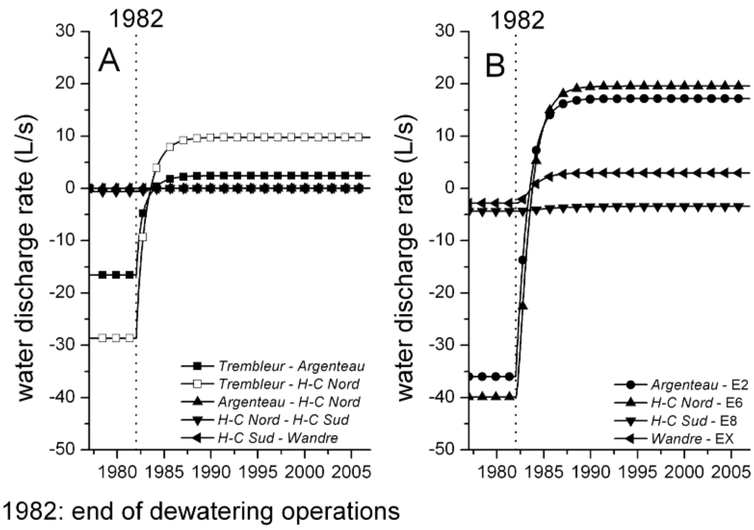

Figure 7. Groundwater rebound scenario - (A) Simulated water discharge rates between exploited zones and (B) Simulated water discharge rates between exploited zones and surface waters

As expected, the water level in *Trembleur* is -64 m during the first five years of the simulation. Through their connections with *Trembleur*, the water levels in the other exploited zones are also lowered. As highlighted by the exchanged flow rates between exploited zones, *Argenteau* and *Hasard-Cheratte Nord* are the main exploited zones which feed *Trembleur* during this period. Exchanged flow rates between the other exploited zones are limited because of their low exchange coefficients (Table 1). There is no exchanged flow rate between *Argenteau* and *Hasard-Cheratte Sud* and between *Trembleur* and *Hasard-Cheratte Sud* because the water levels are lower than the respective thresholds of 88.5 m and 102 m. Water levels in the exploited zones are also fed by the Meuse River since its water level is greater.

As soon as the pumping in *Trembleur* is stopped, the groundwater rebound takes place until the system reaches an equilibrium. The simulation indicates that the exchanged flow rates reversed after two years and that the essential of the groundwater rebound (97 %) had probably occurred after about five years.

Very rainy winter - Time variations in hydraulic heads and water discharge observed from 2003 indicate that the exploited zones react intensively and very quickly to strong rainfall events. The goal of this scenario is to predict the system response to a very rainy winter, which corresponds to period of major risk of water inrushes.

The scenario simulates a period of three years with a very rainy winter at the end of the first year simulated. The prescribed recharge varies monthly. Except for the period of this very rainy winter, the recharge rate is deduced from water balances computed between 2004 and 2006. The recharge prescribed for simulating the very rainy winter is 76 mm in December, 122 m in January, and 46 mm in February (about three times more than during an average winter). Simulated hydraulic heads in some piezometers of the case study zone, and simulated water discharge rates are shown in Figure 8 and Figure 9, respectively.

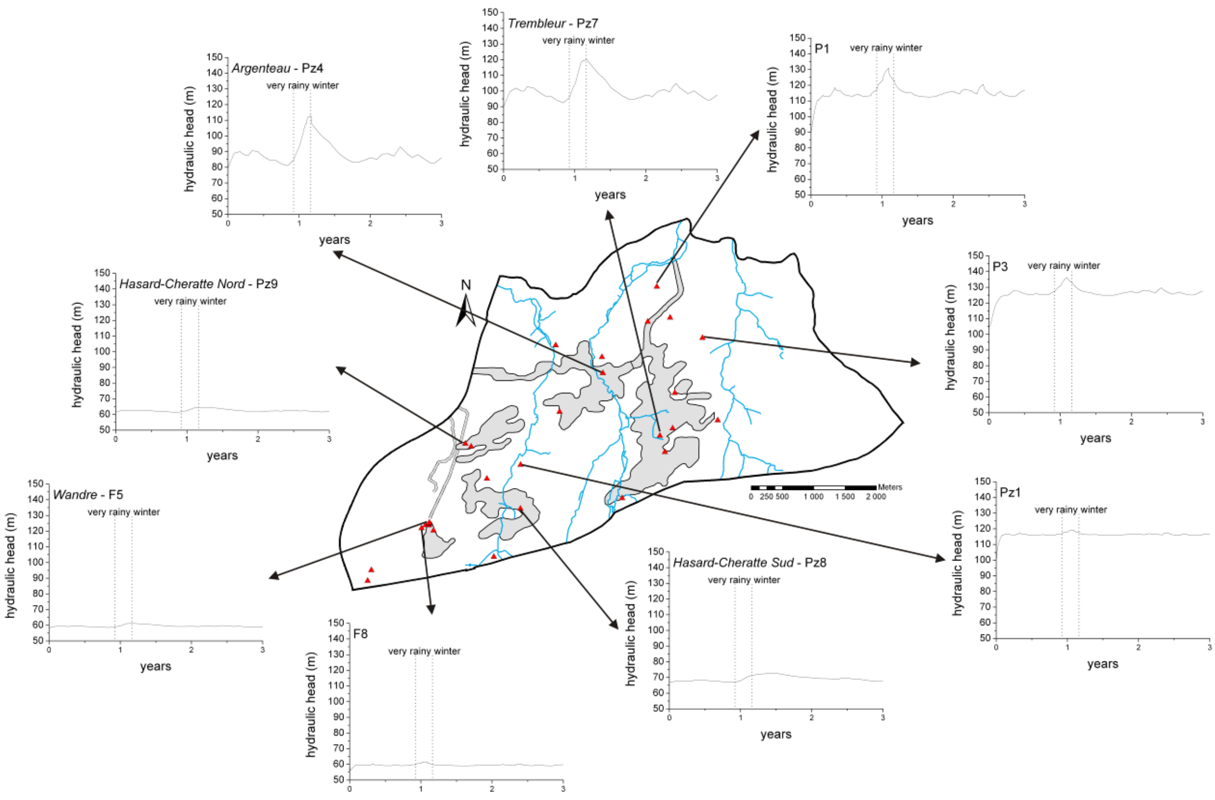

Figure 8. Very rainy winter scenario - Simulated hydraulic heads in different piezometers of the case study zone

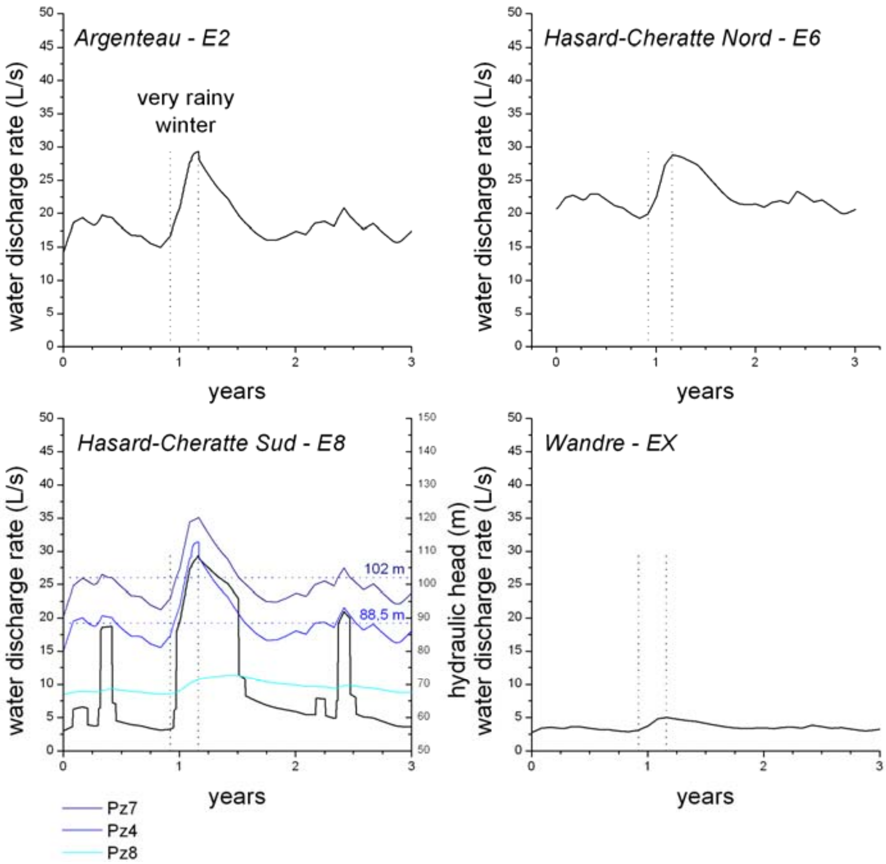

Figure 9. Very rainy winter scenario - Simulated water discharge rates

The exploited zones seem much more influenced by a strong rainfall event than the unexploited zone. It is particularly the case for *Argenteau* and *Trembleur* since their water levels increase of about 25 m in only three months. Considering the calibration period as the reference, about six months are required afterwards to return to a normal situation. The simulated water discharge rate in E2 indicates an increase of about 15 L/s in three months. The maximum computer water discharge rate is about 30 L/s. Once more, about six months are then necessary to return to a normal situation. The simulated water discharge rate in E8 is more complex since it is related to the hydraulic head thresholds of both *Argenteau* (88.5 m) and *Trembleur* (102 m). These thresholds are reached almost at the same time and they cause an almost instantaneous increase of water discharge rate of about 15 L/s. Then, the water discharge continues to increase proportionally to the simulated hydraulic heads in *Argenteau* and *Trembleur* and finally reaches a value of about 30 L/s. As long as the simulated hydraulic heads in *Argenteau* and *Trembleur* are higher than the respective thresholds, the simulated water discharge rate in E8 remains high. Consequently, the simulated water discharge rate is comprised between 20 L/s and 30 L/s for about six months. As highlighted by both the simulated hydraulic heads and water discharge rates, the other exploited zones react more slightly to the very rainy winter.

As a conclusion, this scenario shows that a very rainy winter could cause a strong increase in water levels in *Trembleur* and *Argenteau*. As a consequence, the water discharge rate in E2 and E8 could increase and remain relatively high until the water levels decrease enough. This scenario shows also that *Hasard-Cheratte Sud* is the most sensitive exploited zone. However, the model does not take into account old dewatering galleries reactivations which would modify the hydrogeology of the zone of interest and thus the system response.

5. CONCLUSIONS

The HFEMC method, developed by Brouyère et al. (2009), is a flexible modelling technique which proves to be particularly useful in mining context. Thanks to the dynamic full coupling between mixing cells for the exploited zones and classical finite elements for the unexploited zone, the method is an efficient compromise between simple box model techniques and complex physically-based and spatially-distributed techniques. Furthermore, the method is able to take into account by-pass flow connections between exploited zones.

The first application of the HFEMC method on a real case, that is the abandoned underground coal mine of Cheratte, shows very promising results. The model is calibrated in both steady-state and transient conditions based on both hydraulic heads and water discharge rates observations. Although the complex connections existing between exploited zones, sometimes depending on hydraulic head thresholds, the method is able to reproduce the time variations observed in terms of both hydraulic heads and water discharge rates. The calibrated model is then used to simulate the groundwater rebound and the system response to a very rainy winter. The first scenario indicates that the essential of the groundwater rebound had probably taken place in about five years but that the whole process had probably lasted about twelve years. The second scenario shows that a very rainy winter could cause strong hydraulic head increases in the exploited zones (particularly in *Argenteau* and *Trembleur*). Consequently, water discharge rates would strongly increase too and it could take about six months for returning to a normal situation.

As a new set of more precise observations is now available, future works will consist in improving and updating the calibration in transient conditions using an automatic parameter estimation code such as UCODE_2005 or PEST.

6. ACKNOWLEDGEMENTS

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