DEVELOPMENT OF TOOLS FOR MANAGING THE IMPACTS ON SURFACE DUE TO CHANGING HYDROLOGICAL REGIMES SURROUNDING CLOSED UNDERGROUND COAL MINES (ECSC COAL RTD PROGRAMME, CONTRACT 7220-PR-136)

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ABSTRACT: This paper demonstrates how box model approach and FE and box mixed model approach allow to better understand and model water flows in complex mined coal measures and interactions between shallow aquifers and flooded coal measures. Benefits of these approaches are illustrated on the basis of case studies in Liège and Ruhr coal basins.

KEYWORDS: Water rebound, Box model, Mixed model, Coal mines, RFCS

RESUME : Cet article montre l'apport de l'approche de type « box model » et de la combinaison de modèles de type éléments finis et de type « box » dans la compréhension et la modélisation des écoulements dans les massifs charbonniers exploités complexes et des interactions entre les eaux minières et les aquifères adjacents. Les avantages sont illustrés à l'aide de cas d'étude choisis dans les bassins houillers de Liège et de la Ruhr

MOTS-CLEFS : Ennoyage, Modèle de type Box, Modèle mixte, Mines de charbon, RFCS

1. Introduction

Closed underground mines may induce risks for the environment and for the safety and health of the population living at the surface around the mine or nearby. Some of these risks are linked to the modification or the shut down of the mine water pumping operations leading to a groundwater rebound, they include: the pollution of underground or surface water, the flooding of zones subsided below the water table level, additional surface movements in relation with collapse of shallow mine workings or even surface heave, accelerated mine gas emissions.

These risks exist after the mine closure in the short term but especially on the long and very long term depending on the quantity and flow of water involved and the volume of the mine workings concerned.

In order to better understand the three inter-related phenomena: water rising in mining areas, stability issues relating to the flooding of shallow mine workings and surface responses to groundwater rebound, a project called "Development of tools for managing impacts due to changing hydrological regimes surrounding underground coal mines" (contract 7220-PR-136) has been performed in the framework of a research programme of the Research Fund for Coal and Steel (RFCS).

The most important tasks of this project conducted by a consortium composed of AIDE[1], Armines[2], DMT[3], University of Nottingham[4] and ISSeP[5] consisted in: back analysis of case studies, detailed

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site analysis of selected pilot sites, lab experimental works and development of modelling tools.

This paper will only focus on highlighting the work parts related to the development of numerical tools aiming at better understanding and modelling water flows in complex mined coal measures and interactions between shallow aquifers and flooded coal measures. Results related to other aspects of the project will also be presented by other authors on the occasion of Post-Mining 2005. (Shenk and Reddish, 2005), (Wadim, Hadj-Hassen, and al., 2005)

The hydraulic situation in underground coal mines is fundamentally different from the situation within an ordinary continuous aquifer system. In underground mines, drifts, adits and shafts provide practically no resistance to mine water flow and facilitate equal hydraulic heads over long distances, standard groundwater flow models are thus not suited to represent such conditions.

Recently numerical models for mine water flow and rebound have been developed on the basis of the "box model" approach. This type of approach consists in dividing the study zone in a series of boxes, each one representing a working zone drained by a network of galleries. These compartments are separated by unworked layers of rocks acting as a barrier. It is nonetheless possible that the compartments are interconnected by means of galleries or faults.

The mass conservation principle is applied to each of these compartments: the differences between inputs (pluviometric recharge, input from other compartments,…) and outputs (pumping, outflow in the waterways, export towards other compartments,…) express themselves by a variation of the water stock in the compartment and by variations of the water level, function of the porosity characterizing the compartment. The exchanges between compartments are represented by simple transfer equations (function of the load difference).

This approach has the advantage of taking into account, globally, the distinctive features of the mining system without requiring a comprehensive description and a too considerable quantity of data. At the beginning of the project, it was already used in Germany and in other countries to model flooding processes of underground coal mines (Sherwood and Younger, 1997), (Banks, 2001) but ready made models were not available on the market..

It thus appeared useful to build such a model in order to better understand the water table variations in the mined coal measures of river valleys even where the rebound process due to the shut down of the pumping operations is supposed to be ended.

On the other hand, as it was clear that when mine waters interact with other aquifers, the assumptions made in the box model approach did not allow to identify all the impacts linked with total water rebound with the requested accuracy, DMT and ISSeP, with the help of the University of Liège, decided to try to combine models based on box approach and models developed on more traditional approaches (FE and FD). This part of the project has been performed in view of forecasting the interactions between flooded mines and shallow aquifers in Ruhr area, for DMT and of identifying the potential changes in water level and flows within mined coal massif affected by drainage pattern modifications, for ISSeP and the University of Liège.

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2. Study of water table variations in the mined coal measures of the Liège coal basin by means of a box model approach

Recent experiences in the Liège coal basin showed that different mechanisms could lead to important secondary water rising. This situation can be encountered in coal basin located in valley areas. The shut down of the pumping operations induced a first water rising, the water table reaching the level of the drainage galleries emerging at the level of the river flowing in the valley. The water table remains constant as long as the gravity drainage allows the evacuation of the water volume percolating through the fissured coal measures and the mining works. If for some reasons, one part of the mining works is disconnected from the drainage galleries or if the flow in the drainage gallery itself is impeded, the water starts rising again up to a level depending on the level of new outlets. Due to this additional rising, new impacts appear such as: water emergence at the foot of the valley slopes; the loading of the alluvial aquifers, an increase of the pore-fluid pressure within the rock massif.

2.1 Analysis of the available data. Selection of a modelling approach

At the beginning of the project, scientific information on the flows within the mined coal measures of the Liège coal basin did not exist. Neither recent piezometry maps nor water budgets were available. Monitoring of the drainage galleries had been abandoned for more than 15 years. It is the reason why the first stage of the study consisted in selecting a relevant pilot site, analysing all the geological, hydrological and mine information related to this site and assessing water budgets

Detailed studies of mining plans led to locate a great number of underground works used for the drainage of carboniferous massif. The analysis of the position of all these galleries demonstrated the existence of 5 networks not directly inter-connected. Connections between these networks trough the fracturing of the rocks induced by the exploitations and trough deeper works can however not be excluded.(Fig. 1)

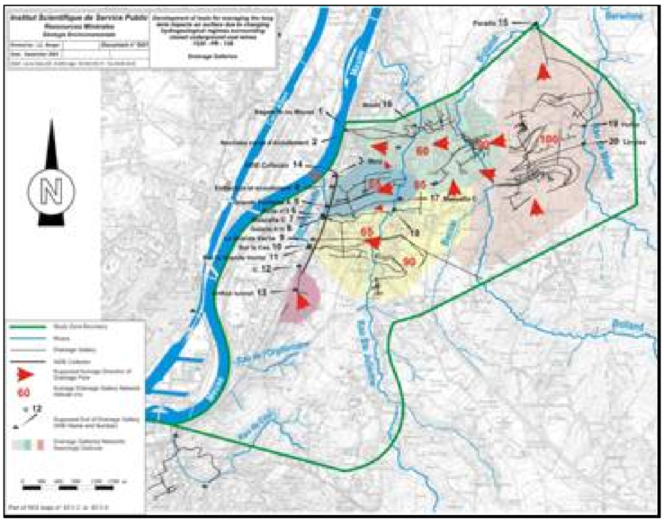

Figure 1. Liège coal basin. Identification of the 5 blocks within the pilot site.

A cross analysis of all the available information led ISSeP to consider that from the hydraulic point of view the mined coal measures are composed of different blocks with their own behaviour. Hence, conceptually, the mined coal measures above the drainage level was considered as a network of boxes connected more or less between themselves and by galleries to the surface water, recharged by rain infiltration trough overlying quaternary or strata and potential river seepage and fitted with junctions trough which water withdrawal can occur.

2.2 Selection of a modelling tool (Gardin and Brouyère, 2005)

Despite the efforts spent on the analysis of the available data, information collected on several features (connection between different mining areas, flow exchange with the areas bordering the pilot site, spatial distribution of the remaining voids, …) remained too incomplete to formulate a single conceptual model. To get round these difficulties, it was decided to try to model the phenomena with the help of a simplified box model, to compare the results obtained with the measurements supplied by monitoring campaigns and then according to the matching degree to go on with the assumptions or to assess new ones.

When a box approach is used for modelling flow, the major assumption consists in considering that from the hydraulic point of view the rock massif is composed of boxes to which a unique water level can be attributed and which are connected between themselves by a network of galleries. A situation which is very similar to the one of a network of tanks connected with pipes provided the fact that the volumes attributed to tanks correspond to the global porosity (the intrinsic porosity plus the remaining voids created by mining operations) of the boxes.

For this reason it was decided to test the EPANET program[6]which is a tool developed by EPA[7]in order to model flow in water supply networks. EPANET models water supply networks as a collection of links collected to nodes. The links represent pipes, pumps and control valves. The nodes represent junctions, tanks and reservoirs. EPANET components and the governing equations used for modelling flow according to the other variables appeared suitable for developing models based on a box model approach.

With EPANET, flow within a network is governed by two laws:

- the first one links the flow rate between two nodes (between two boxes, between a box and a drainage point,…) by the following relationship:

$$H_i - H_j = h_{ij} = A\ Q_{ij}^{\ B} \qquad (1)$$

  Where
  h_{ij} = headloss between node i dand j
  Q_{ij} = flow rate between node i and j;
  A = resistance coefficient, for the resistance coefficient;
  B = flow exponent, different values can be used for the flow exponent

- the second one expresses the water balance equation (or conservation of mass) at each node of the network.

$$\sum j = Q_{ij} - D_i \qquad (2)$$

  Where
  Q_{ij} = flow rate between node i and j;
  D_i = recharge or withdrawal rate by a pumping or injection well.

[6] http://wwww.epa.gov.ORD/NRMRL/wswrd/epanet.html
[7] Environment Protection agency. http//www.epa.gov

However, in order to yield a water table as close as possible to the reality from a box model, it is also necessary to take into account that the porosity ratio varies according to the vertical location. In EPANET it can be done by allowing storage tanks diameter which are cylindrical volumes to vary according the z coordinate. As far as its height is concerned, it is fixed by the distance between the water drainage level and the mined massif top.

In EPANET, receiving surface water is represented by reservoir elements which are supposed to be infinite external sinks of water and are characterized by hydraulic heads not affected by what happens in the network. However heads can be made to vary with time (by assigning a time pattern) in order to take into account the variations in the drainage level related to modifications in the receiving surface water regime. Recharge is modelled by junctions which are points of the network where water enters or leaves the network. They are characterized by a rate of recharge which can vary with time or which can be made dependent on a pressure gradient. Finally tanks (boxes) are connected between themselves or to receiving water by means of pipes which are characterized by their status (open, closed) and the headloss they cause.

2.3 Development, calibration and identification of the capacity of models based on EPANET program

Each of the parts of the pilot site mined coal measures drained by one of the five networks identified in the survey stage has been considered as a tank the volume of which corresponds to the global porosity of the zone. In a first stage, as the spatial distribution of the remaining void is not known accurately, the tank is represented by a simple cylinder. Its height corresponds to the distance between the drainage level (+/- 55 m) and the top of the coal measures (+/- 130 m). (Fig.2)
The model has been calibrated on the basis of both the piezometric levels and drainage flows measured by the monitoring network in service since three years and the water budgets established on the pilot site and by adjusting the resistance coefficient $A_{i,j}$ of the connections of the different boxes between themselves and with the water surface.

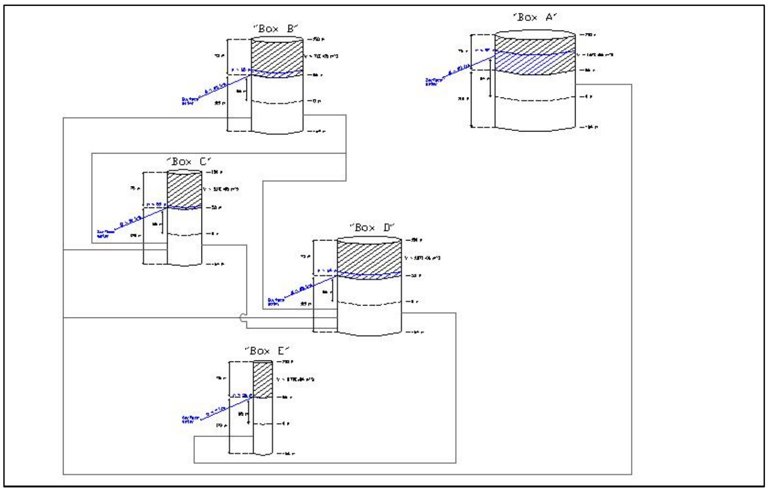

Figure 2. Liège coal basin. Conceptual model of the pilot site.

Once a good matching was reached between the measured water levels and drainage flows and those calculated reached, the model was used to simulate water rising which is supposed to have taken place after the closure of the pumping operations. Although this process was not followed up it was necessary to check that the results supplied by the model correspond to the punctual observations performed at that time. According to the model, the rebound phase lasted about three years in Box A and between one and three years in the other boxes. These results are consistent with the observations. Moreover at the end of the rebound phase, the water levels and drainage flows supplied by the model still correspond to the measures for the recharge ratio attributed to the study area.

At this stage, data are missing for validating further the model, it was thus decided to compare the results supplied by EPANET with those derived from other validated tools like MIFIM (Banks,D. 2001) Comparisons showed that the two tools give similar results.

Additional model runs demonstrated the capacity of EPANET for performing sensitivity analysis, for clarifying the role of the different parameters in the rebound processes induced by variations taking place within gravity drained coal mines and hence for identifying the risk of flow inrush according to the measures supplied by the monitoring network.

Table 1. Comparison of calculated and measured water levels and drainage flow within the five boxes of the pilot site.

Parameters	BOX A	BOX B	BOX C	BOX D	BOX E
Water level measured (m)	97,00	65,00	59,00	64,00	56,00
Water level calculated (m)	96,73	64,66	58,89	63,54	55,67
Difference	0,27	0,34	0,11	0,46	0,33
Drainage flow measured (l/s)	23,00	25,00	21,00	29,00	?
Drainage flow calculated (l/s)	20,30	24,50	19,80	25,90	2,20
Difference	2,70	0,50	0,20	4,10	

Besides these positive aspects, it has to be admitted that models developed on the basis of EPANET do not allow to represent accurately enough the water level variations in less well drained zones which does not allow to interpret correctly the piezometric map derived from the monitoring work. To reach this aim it is necessary to combine box model and more traditional approaches (see point 3.2)

3. Combining box model and traditional approach

3.1 Study of the interactions between flooded mines and shallow aquifers in Ruhr area

At the beginning of the 7220-PR-136 project, the applicability of numerical box models was already proven in predicting groundwater rebound and in simulating water management in a large section of the Ruhr coal mine district, called Emschermulde.

If the accuracy of such models allowed mining operators to define adequate pumping strategy, it was suspected that it was not sufficient for simulating the impacts of complete groundwater rebound on shallow aquifer in terms as well as of water level rising as of discharge quality of mine water.

It is the reason why DMT has proposed to assess different ways for combining box model and traditional models on a pilot site the Schwarzbach catchment area (part of the Emschermulde area). Figure 3 shows an overlay of the box-model “Emschermulde” with the Schwarzbach catchment area.

As combining both models required balancing water flow in the two models, the seepage rate from the shallow aquifers to the mine workings Q_m (in the shallow aquifer model) had to be set equal to the recharge rate of the mine workings from the shallow aquifer Q_g. (in the box model)

In the existing models of shallow aquifers in the Ruhr area the seepage of groundwater into the deeper underground was usually described by a fixed rate of seepage at the bottom of the aquifer. In the same way, recharge of groundwater into the box model at the top of the Carboniferous layer was up to now defined as a fixed recharge rate. However, in order to use combined models for assessing total water rebound, seepage and recharge rates have to be adjusted according to varying shallow aquifers and flooded mines situations. DMT proposed to make match these situations by Cauchy boundary conditions (leakage boundary condition) such as

$$Q_m = Q_g = A * k_{fv} * (h_g - \max(h_m, C_t)) / m_o \quad (3)$$

Where

Q_g = seepage rate into the deeper underground (m³/s),
A = area of seepage into the deeper underground (m²),
k_{fv} = vertical hydraulic conductivity (m/s),
h_g = groundwater level (m),
h_m = mine water level (m),
C_t = top of the Carboniferous layer (m),
m_o = thickness of the water saturated overburden (m).

From this relationship, it can be stated that mine water levels, calculated by the box model, become the leakage potentials of the FE model and the groundwater levels, calculated by the FE model, become the leakage potentials for the box model.

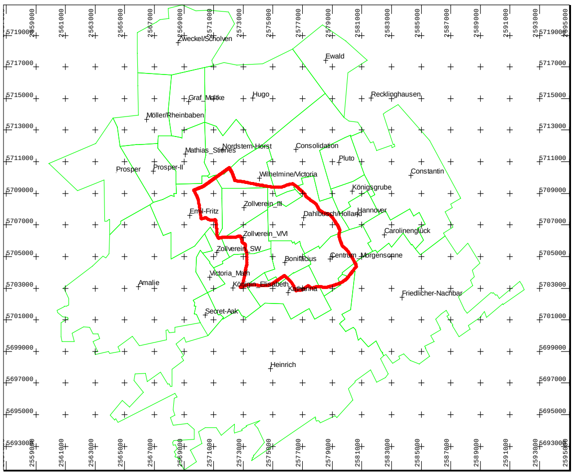

Figure 3. Projection of the Schwarzbach catchment area on the Emschermulde box model.

In the framework of the project, DMT decided to assess the two following solutions to develop an adequate coupling between box models and standard FE models:

- sequential run of the two models and adjustment via boundary conditions (batch approach);
- transformation of FE models into box models by keeping the structure of FE models (unified approach)

The objective followed in the first approach was to couple the two separate models by preserving their original status to the extent possible, using appropriate boundary conditions and exchange data files for the transfer between the models.

The principle of the model coupling by sequential run and adjustment of the boundary conditions consists in making run the two models in a sequential way using a batch process. The linear equation systems involved are normally solved in an iterative way. After each iteration sequence the necessary groundwater levels h_g, calculated by the FE groundwater model, are handed over to the box model and the mine water levels h_m, calculated by the box model, are handed over to the groundwater model.

This is done by writing each simulation result (hydraulic heads) into a specified result file, so that these data can be read by the other program. The batch process used is illustrated in the schematic flow diagram of Figure 4.

This sequential execution of both models is repeated until a certain termination condition is fulfilled (e.g. only minimal changes in mine water and groundwater levels or a maximum number of calculation steps).

Usage of this concept based on batch processes for coupling the separate models via boundary conditions depends on the possibility to execute both models in some sort of batch mode, which requires no manual user input. The two most widely spread groundwater modelling packages in Germany using the FE-method, i.e. SPRING and FEFLOW as well as the box model program offered this option.

The major work of DMT consisted in writing of programs used in the batch process (building of a element-box allocation table, procedures for adjusting the boundary conditions according to the new water levels calculated, conversion programs, graphical subroutine, program checking the termination conditions the routines for exchanging)

The validity of the approach with the Spring and Feflow programs has been controlled by checking the fact that after coupled simulations had been run leakage rates of shallow aquifer remained equal to recharge rates of the flooded mines and by comparing the water levels obtained with those supplied by the calibrated models run separately. For both cases, only slight differences were noticed.

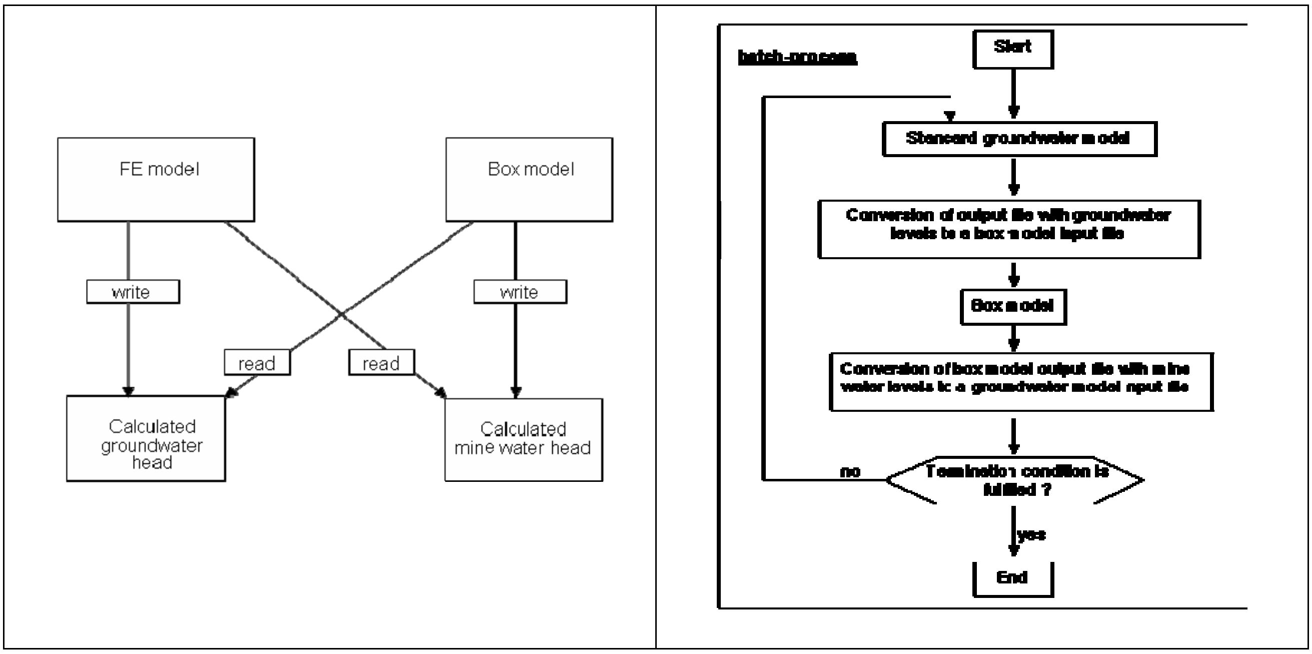

Figure 4. Schematic flow diagram of the FE-Box model coupling by batch process

For the second approach, the method chosen was to convert FE models into special box models supposed to form the uppermost layer of the existing flooded mine box models (unified model). As the boxes used in a box model approach can adopt theoretically any closed polygonal shape, they can be defined so that they correspond to cells created by FE mesh generators.

However, the main difficulties encountered when converting a FE model into a box model are caused by the different numerical approaches the programs use to solve the flow equations. The FE models discretize the simulation domain in triangular and quadrangular elements over which the differential flow equations are integrated. They are based on parameters and variables, defined for the FE's area (element parameters) and for the nodal points of the FE-grid (nodal parameters). In contrast, the volume balance method used by the box model defines all parameters and variables at the centres of the boxes and balances flow between these boxes. Therefore, transformations of nodal and element parameters of the FE-model to box-centred parameters of the box model has to be made.

Basically, two concepts for transforming a FE-grid to a box model structure could have been considered: adopting the FE-grid using each finite element as a corresponding box structure or building boxes around the nodal points

Since the first approach required the distribution of the nodal parameters over all adjacent boxes, which led to the fact that discrete and exact point information at well-defined locations (e.g. wells, rivers) would not have been represented in an adequate way any more, only the second approach was assessed further.

Building boxes around FEM nodes can be done by connecting all centres of the elements surrounding grid nodes. A special treatment has to be given to nodal points situated at the borders of the FE-grid, because they are not completely surrounded by finite elements.

Once boxes built around the nodal points of the FE-grid, nodal parameters can be easily converted into box-centred parameters. Element parameters can also readily be distributed over all corresponding boxes by using weighted values.

Box models obtained from the conversion of FE models have a much higher spatial resolution than the traditional general box model used for water mine management purposes but their overlapping with traditional box models using coarser box structure does not however cause any special difficulties, as it has been demonstrated by DMT with the Emschermulde unified model.

For the Emschermulde model, the integration of the shallow aquifer and the flooded mines models also requested to find a way for representing the seepage described by Cauchy boundary conditions between boxes of the uppermost and the lower layers. This has been solved by using special connection elements (part of the box model concept) used for the simulation of hydraulic connections between mine fields.

For each of the elements with underground seepage one special connection element with a leakage rate L was created. The lower endpoints of these connection elements were set to coincide with the top of the Carboniferous formation (C_t) so that the underground seepage rate can be correctly calculated as

$$Q_g = L^*(h_g - \max (h_m, C_t) \qquad (4)$$

The validity of the unified model has been validated on its capability to represent the present situation. Therefore the reproduction of the calibrated situations obtained separately served as an indicator.

Figure 5 shows the contour lines of the shallow aquifer (Schwarzbach) heads obtained from a unified model after conversion of the FE model compared with those supplied by the calibrated model developed on the basis of the Spring program. It can be stated that differences are very well acceptable.

Different scenarios with partially flooded mine workings including (or not) dewatering measures have been investigated. All these scenarios were considering increased pumping levels. For all scenarios the new pumping levels were chosen in a way that some mine water levels below the Schwarzbach catchment rise to elevations above the top of the Carboniferous formation and hence are affecting the seepage of groundwater into the deeper underground.

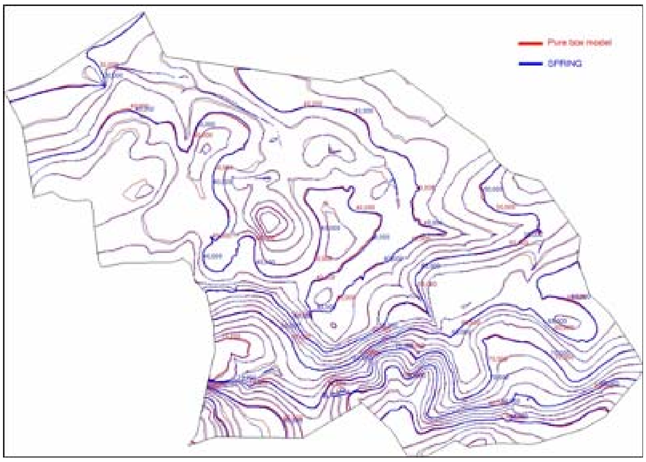

Figure 5. Schwartzbach pilot site. Comparison of groundwater contour lines of the pure box model simulating the present situation with those of the SPRING model

Simulated scenarios with high pumping levels result in elevated mine water levels in the different boxes as illustrated in Figure 6. Noticeable are the small differences in the mine water levels of the different boxes for each scenario, which are a direct consequence of all the hydraulic mine field connections assumed active at these higher water levels.

As far a the shallow aquifer is concerned, the different coupling techniques produce identical results. For this reason, only the results supplied by the batch combined approach (box model – Spring model) for scenarios where it is assumed that mine waters rise up to - 30 masl and dewatering facilities are or are not operational are presented.

Figure 7 shows that due to water rebound in mine workings the water levels of the shallow aquifer rise from values ranging from 0,25 to 2 m so that in numerous areas, the depth of the water table is not greater than 1,5 m which exposes building to ponding effects. They demonstrate also the capacity of the coupled model to simulate the impacts of dewatering measures and hence its usefulness for planning and designing the dewatering strategy to be developed in order to manage surface impacts.

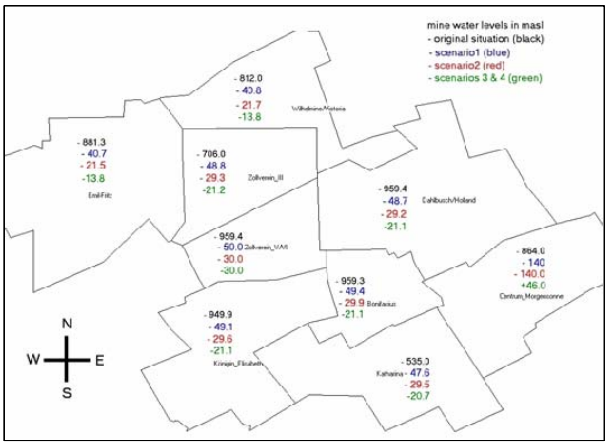

Figure 6. Schwartzbach pilot site. Mine water levels in the different boxes of the Emschermulde model according to the final pumping level

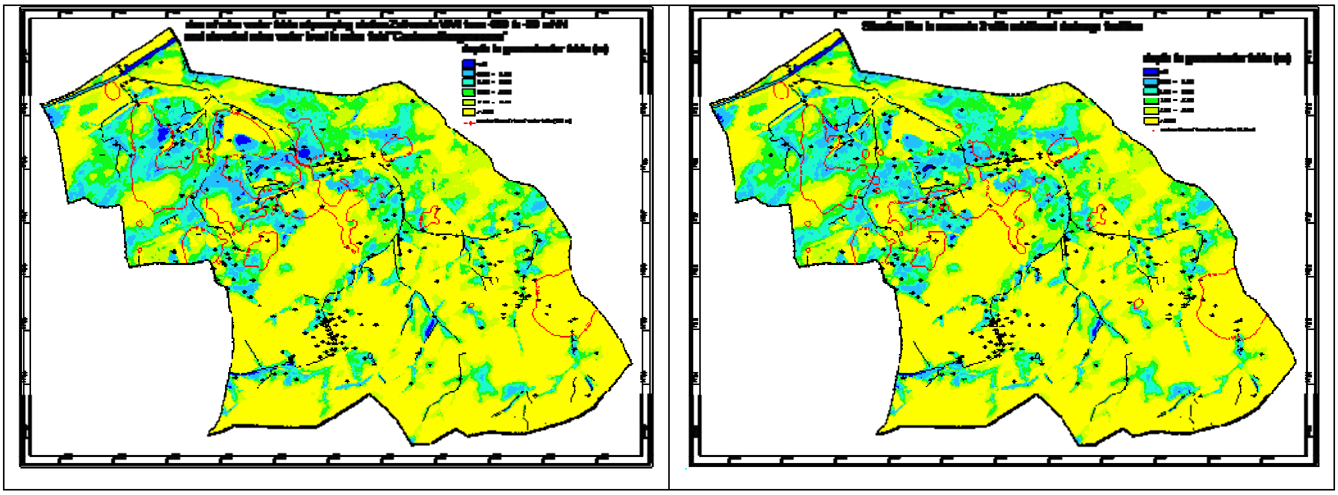

Figure 7. Schwarzbach pilot site. Depth of the water level (in red area were depth < 0,5 m) for scenario where the pumping level is fixed at -30 masl and without (left) or with (right) dewatering facilities

3.2 Study of the changes in water level and flows within mined coal massif affected by modifications in the flow pattern. Liège coal basin case study

Box model approach does not allow to represent flows in mined massive composed of a set of adjacent well and not well drained areas with the accuracy required. To achieve this aim, it is necessary to go trough a mixed approach. In the framework of the study devoted to the Liège coal basin pilot site, the mixed approach proposed consisted into using FE tools and defining, within the model, sub-domains where flow governing equations can be expressed by different mathematical relationships ranging from transfer function to more traditional differential equations.

When the sub-domains have to be considered as linear tanks, the flow governing law only comes to the relationship that expresses that the outflow varies in a linear way according to the water level in the sub-domains.

$$Qs = V_s * (\delta\theta/\delta t) = S * A_s * \delta(H-H_s)/\delta t + q \qquad (5)$$

Where

- V_s = sub-domain volume
- θ = water volumetric ratio in the sub-domain
- S = storage coefficient of the sub-domain
- H = average height in the sub-domain (dependent variable)
- H_s = average drainage level in the sub-domain
- A_s = the average surface of the sub-domain
- q = recharge/withdrawal coefficient

In the other sub-domains, the governing law is expressed as :

$$F * (\delta h/\delta t) = \nabla * (K * \nabla (H+Z)) + q \qquad (6)$$

Where

- F= generalized storage coefficient
- K = hydraulic conductivity tensor
- H = pressure potential
- Z = gravity potential
- q = recharge/withdrawal coefficient

Spatial discretization can be adapted according to the available information and thus to the mathematical (numerical) approach which can be applied. Sub-domains can even not be discretized at all and treated as a unique box. Water exchanges between each hydraulically connected sub-domain are modelled by means of internal boundary conditions defined along the interfaces.

Later on, in case more detailed information on the hydraulic behaviour of a sub-domain was collected, its model could be updated on the basis of a finer discretization and more complex flow governing laws using for spatially distributed parameters and directly integrated in the global model without requiring any modification of the other sub-domains.

In practice, these concepts are implemented in the SUFT3D program by this way:

A global mesh is generated on the overall area to be modelled (including well and non well drained areas) by means of a traditional dedicated tool (GMS). Then for sub-domains to be considered as a unique box (tank), the cells are grouped together by means of adequate criteria. In each sub-domain the nodes and elements are re numbered in order to duplicate those common to adjacent sub-domains. The equations expressing the flow governing laws are solved iteratively within each sub-domain, dedicated routines taking in charge the transfer of water volumes exchanged and boundary conditions between sub-domains interfaces.
Conceptually the pilot site will be divided into six sub-domains: one sub-domain for each of the five blocks drained by independent networks and one for the rest of the area. The first five sub-domains are presently considered as unique boxes whereas the last one is sub-divided in three layers: two for representing the overlying strata (alluvium with locally terraces, chal) and one for the coal measures. (Fig. 8)

At this stage development work of the mixed approach is still under progress and calibration and simulation processes have not started yet.

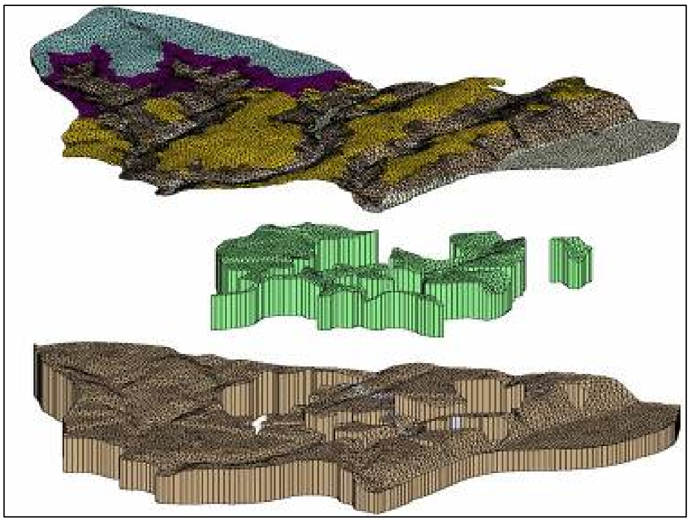

Figure 8. Liège coal basin pilot site. Mixed approach. In brown parts modelled with FE elements, in green the five parts considered as box

4. Conclusions

Once again, it has been demonstrated that the box model approach represents a satisfying method for modelling underground water rebound in mined coal measures even in special situations where water rising is caused by modifications of the gravity drainage conditions. Advantages of the EPANET software in order to implement this approach like: existence of a gravity interface, capacity of representing drainage pumping operations or the porosity variations according to the depth by adjusting the tank area have been illustrated. Moreover as it allows to model water inrush, it can be viewed as a valuable tool for predicting such phenomena.

However, when interactions between mine waters and other aquifers have to be taken into account more accurately, box model approach has to be combined with traditional approach. Three combining ways have been assessed: batch process with boundary conditions adjustment, transformation of FE models into box models in order to build a unified model, mixed approach dealing with sub domains where flow governing equations and discretization degree can be adapted according to the available data. Each of them offer potentiality for modelling complex situations.

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