Modelling the Hydrological Processes in a Catchment and Analysis for the Distributed Predictions Using a Physically Distributed Model

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ABSTRACT

Application of the distributed hydrological models has been increased noticeably in the past few years. This was encouraged by the rapid development of the processors capabilities, which helped to speed up the consuming simulation time. This paper presents the application of the fully distributed physically-based MIKE SHE model to a mid-size catchment. The model was applied to the river Jeker basin, situated in the loamy belt region of Belgium. A 600 m grid size conceptual model was built to model the 465 km² area of the catchment. The landscape is rolling, and the soils are varying from sandy-loam to clay-loam. The soils are deep, and the phreatic aquifer is at a depth of 4 to 50 m below the surface. The daily data of a continuous period of 6 years were used for the calibration and validation. The distributed model was calibrated and validated using a split-sample (SS) test and a multi-site (MS) test.
A set of well-known performance indices was used to quantify the model performance. The results show that the model is considered to be a good physical representative for the whole catchment, however additional and more accurate data may improve the predictions especially with ground water levels. The model showed better results with SS test than the MS test.

KEY WORDS: distributed code, hydrological model, model performance, MIKE SHE

INTRODUCTION

A general model of rainfall-runoff process requires representations of the interacting surface and subsurface processes. An outline of the physics underlying such a description was first published by Freez and Harlan (1969), although the individual process descriptions had all been established well before then. Most physically-based models today are still based on the Freeze and Harlan "blueprint", and many are, in fact, simplifications of that blueprint (Beven, 2000).

Physically-based distributed hydrological model codes have been developed from a need to analyze and solve specific hydrological problems often required in multi-objective and multi-decision management investigations. These problems may differ in type and scale, but have usually one thing in common, namely that in order to obtain a useful outcome of the modeling exercise, variations in state-variables over space and time need to be considered

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and realistic representations of internal flow processes have to be computed (Storm and Refsgaard, 1996).

In the past few years several papers have reported success in applying the MIKE SHE distributed hydrological model. In a similar study (Feyen et al., 2000) have conducted similar study in Belgium on the application of MIKE SHE on an adjacent catchment to this one studied here using 600 m grid size and concluded that the model is capable of simulating an integrated state variable like the discharge with relative accuracy, but that the distributed results show large variance. Refsgaard et al. (1992) have applied the SHE model to number of catchments in India and discussed its applicability there using 2 km grid size. Refsgaard (1997) investigated the effect of using different grid sizes namely 1000 m, 2000 m and 4000 m on the model performance and concluded that changing the grid size requires recalibration of parameters and possibly reformulation of some model components. Xevi et al. (1997) have performed a sensitivity analysis of the MIKE SHE model using a catchment in Germany; the study demonstrated that the results are sensitive to grid size.

Some authors tend to critique the use of distributed models. Their main concern is the many parameters that can be altered during the calibration phase. Beven (1989, 1996) considers models, which are usually claimed to be distributed physically-based, as in fact being lumped conceptual models, just with more parameters. According to Beven (1996) a key characteristic of the distributed model is that "the problem of over parameterization is consequently greater". In response, Refsgaard and Storm (1996) emphasize that a rigorous parameterization procedure is crucial in order to avoid methodological problems in the subsequent phases of model calibration and validation.

CODE DISCRIPTION

MIKE SHE is a comprehensive deterministic, distributed and physically-based modeling system for the simulation of all major hydrological processes occurring in the land phase of the hydrological cycle. It simulates water flow, water quality and sediment transport (Refsgaard and Storm, 1995). The model is based on the SHE (Système Hydrologique Européen) modelling concept (Abbott et al., 1986). It was developed to model the spatial distribution of basin parameters, hydro-meteorological inputs and hydrological response in 3 dimensional forms. This means that it represents the basin horizontally by an orthogonal grid network and it uses a vertical column at each horizontal grid square, each of them is characterized by several parameters and variables, thus the model has obvious large amount of input data. This implies that the MIKE SHE needs more requirements with regard to parameterization, calibration and validation procedures. MIKE SHE encompasses a number of components describing the flow within different parts of the hydrological cycle. They can be combined depending on the scope of the study (DHI, 1999). The hydrological processes are modeled by finite difference representations of the partial differential equations for the conservation of mass, momentum and energy in addition to some empirical equations. The major flow components (processes) of the hydrological cycle represented by the model are: saturated zone flow, unsaturated zone flow, evapotranspiration, and overland channel flow.

STUDY AREA

The Jeker catchment (465 km^2) situated in the mid-east part of Belgium (Figure 1) was chosen for the model application. It lies on the linguistic border between the two major communities in Belgium, partly in the Flemish and the Walloon regions. Eight different soil types, according to the legend on the Belgian soil map, were defined. The dominant soil type is loam, which occupies 86 % of the basin area. The land use is mainly non-irrigated arable land, which occupy 70 % of the total catchment area and 17% of the basin area is occupied by discontinuous urban fabric. The landscape is rolling and the original DTM resolution is 30 m x 30 m. The topography of the area varies from 59 m in the north to 200 m in the south. The actual geological formation consists of the following six geological layers ranked from top to bottom: the Limon or Quaternary layer (mainly silt and clay where the alluvium appear along the river path), the Sables Tertiaires or Sandy Tongerian layer, the Conglomerat à Silex or the Conglomerate Flint layer, the fractured Cretaceous Chalk layer, the Hard Ground layer (which is 1 m thick dividing the chalk layer into old and new formations), and finally the compacted Cretaceous Chalk layer. The catchment is characterized by its two man-made galleries, which are located in an average depth of 50 m below the ground surface in the compacted cretaceous chalk layer and extends for 14 and 26 km long over the catchment with 1 m diameter. The galleries are used mainly to extract drinking water by gravity.

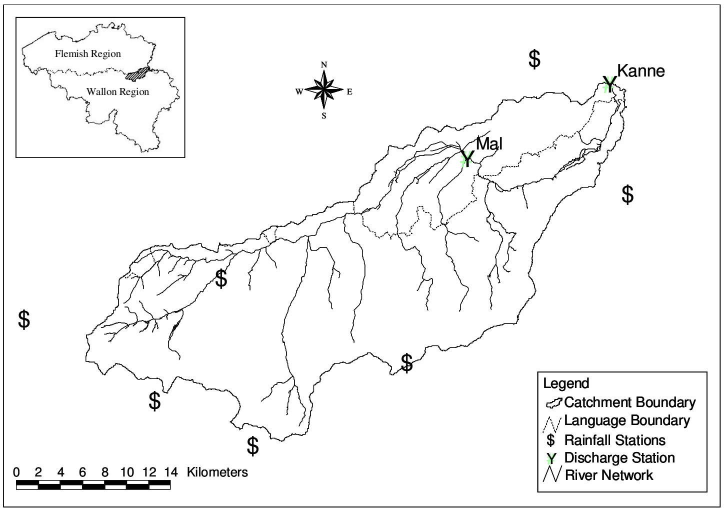

FIGURE 1: Location of the study area, river network and discharge and rainfall stations

CALIBRATION & VALIDATION

Prior to the calibration all the data layers (land use, soil… etc) required to run the model were prepared in a GIS environment and transformed into MIKE SHE format. The transformation was done with programs written in PERL language (Schwartz, 1997). In addition to the river discharge calibration, the model was calibrated against set of potential head observations scattered throughout the catchment. In order to obtain a successful calibration for distributed models such as MIKE SHE the number of parameters and possible combinations should be restricted. In this study the following conditions were applied: the chosen measured field data were assumed reliable; the boundary conditions (In-out flux) were considered constant potential head along the south border of the catchment (Due to prior knowledge that there is a constant influx of water coming from south of the catchment) and were assumed impermeable elsewhere; parameter intervals (minimum and maximum values were used) and parameters of great uncertainty were kept constant and not distributed.

The available topography resolution was 30 x 30 m and in order to achieve the chosen resolution of 600 x 600 m a previous study was carried out (Abu El-Nasr et al., 2000) to examine the effect of the interpolation technique, which is used for the up-scaling method of the original topography and concluded that aggregating the original data using a two-step aggregation procedure from 30 x 30 m to 60 x 60 m and then to 600 x 600 m using GIS technique was appropriate to apply.

The calibration was focused on following three parameters; the first parameter is the drainage level being a hypothetical level to define the intermediate flow; the second parameter was the time constant, which determines the height of the peaks and the tailing of the recessions on the river discharge. The calibration yielded the following values for the drainage level and the time constant -0.40 m and was $9.6e^{-8}s^{-1}$ respectively. The third parameter is the vertical and horizontal hydraulic conductivity for the saturated zone, which influenced by the type of the geological layers available in the basin. The hydraulic conductivity was calibrated in a distributed way, depending on the different specifications of the geological layers, the most significant effect came from the Cretaceous Chalk layer by its two branches; the fractured and the compacted. The compacted layer was characterized by the great influence of the two galleries, which lies inside it, beside most of the abstraction wells. This was taken care of by introducing different zones of hydraulic conductivities around the area of the galleries influence. Assuming a constant abstraction along the galleries path assembled the abstraction of the galleries. The pre-defined six geological layers were reduced to three computational layers in the model structure by adding the similar layers together, this was mainly to avoid numerical instability and to reduce the problems arising from the sparse distribution and the small thickness of some of the small geological layers that slow down the computational process as a consequence of its interaction with the ground water levels. To avoid wasting some of the available time series in warming up the model, a spatially distributed initial conditions were introduced for the average ground water levels on the whole catchment, this was based on the available time series for some observation wells in and around the catchment. The validation of MIKE SHE was carried out in two steps: (1) a typical split-sample technique was applied on the outlet discharge station (Kanne) and to a set of ground-water observation wells scattered throughout the catchment, (2) a multi-site (Refsgaard, 1997) validation test was applied, which compromise validation on an internal station (Mal), in addition to several wells spread in the catchment, those data have not been used during the calibration process.

PERFORMANCE CRITERIA

Different performance criteria were utilized to perform the analysis and to control the calibration process. This includes; agreement between simulated and observed daily river flow at the different discharge stations; agreement between observed and simulated water levels at several observation wells scattered throughout the catchment and quantitative evaluation for the river flow discharge by set of statistical performance indices (Nash and Sutcliffe, 1970; Loague and Green, 1991; Gupta et al., 1998; Xevi et al., 1997; Legates and McCabe, 1999, Feyen et al., 1999) being: Relative Root Mean Square Error (RRMSE), Mean

Absolute Error (ABSERR), Coefficient of Determination (CD), Modeling Efficiency (EF) and Goodness of Fit (R^2).

RESULTS & DISCUSIONS

A historical time series of continuous data (i.e. discharge, rainfall…etc) for six years were utilized split into three years for calibration and three years for validation. The calibration period extends from 1/6/1986 - 1/5/1989 and the validation period was 1/6/1989 - 1/5/1992. Seven rainfall measuring stations scattered around the catchment were used. An outlet discharge station at the downstream end of the catchment together with eight observation wells were used to calibrate and validate the river discharge and water levels simulations with the SS test. An internal discharge station and four observation wells, which were not used during the calibration and used only for the validation of the MS test. Figure 2 shows the topography and river network as used by the model with a resolution of 600 x 600 m in addition to the spatial distribution of all the observation wells, which were used in the calibration and validation.

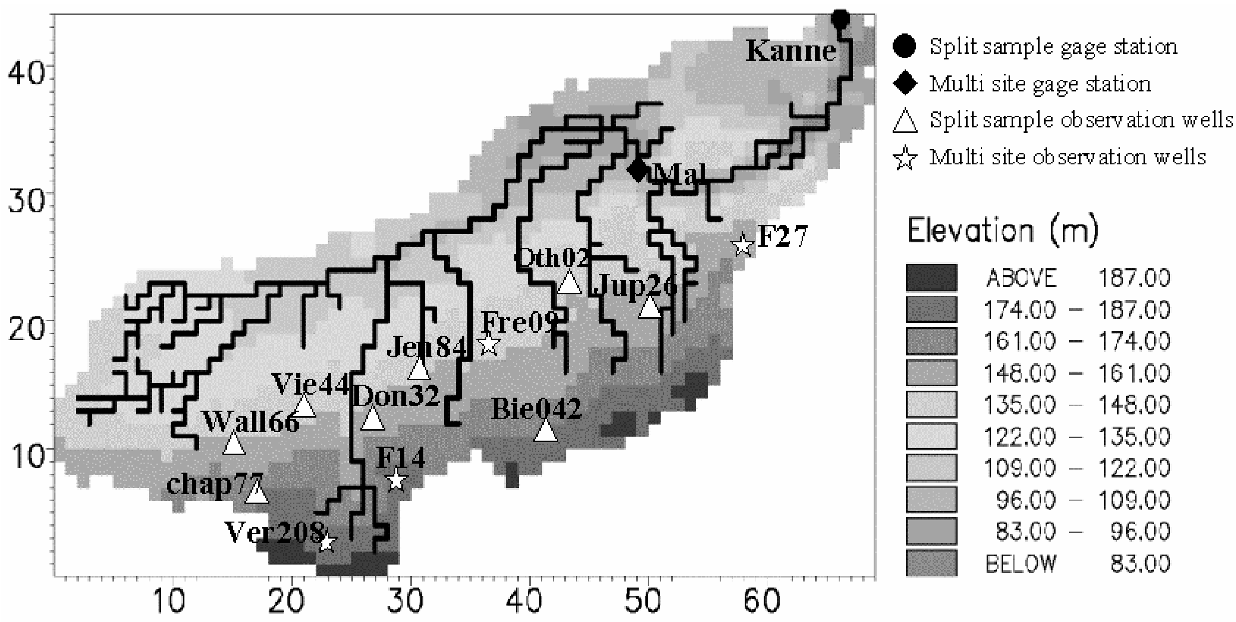

FIGURE 2: Topography, river network and location of gage stations and observation wells

Figure 3 shows the three years of calibration and validation periods respectively for the river discharge at the main discharge station. The model tends to underestimate the base flow during the calibration and in general to underestimate the moderate peaks.

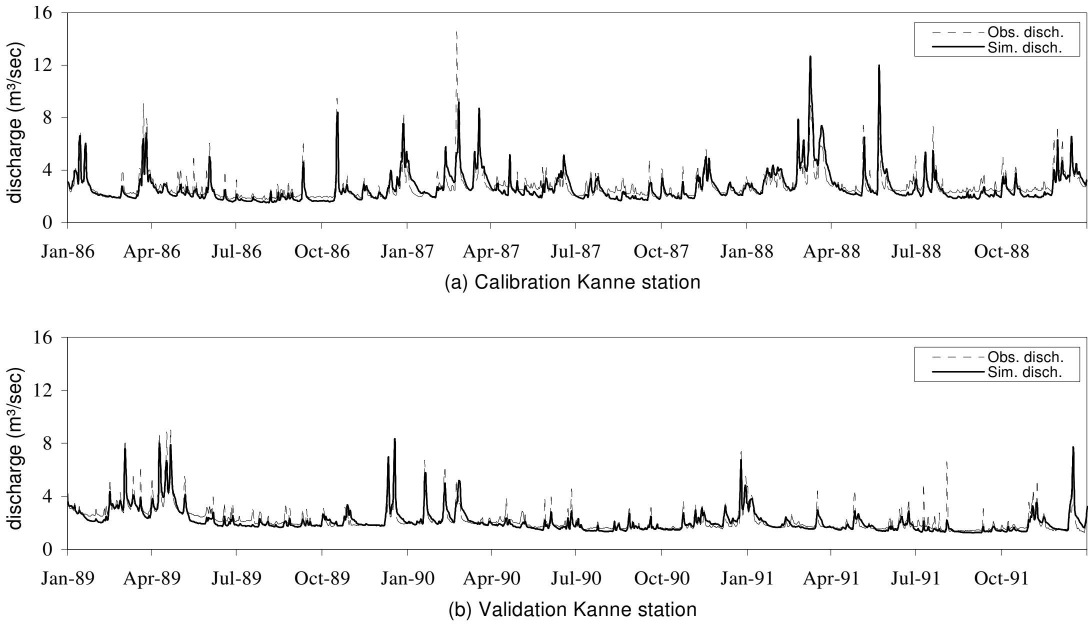

FIGURE 3: Observed and simulated river flow at the main gage station (Kanne) (a) calibration and (b) validation

Figure 4 shows the validation at the internal gage station Mal that was not used during the calibration. It should be realized that the measured values of the stream flow are not reliable in some periods of the year especially around April, as it tends to have a dramatic increase during the recession period whereas it should decrease. This can have a direct effect on the accuracy of model prediction and is more pronounced in the statistical indices values for this station (table 1).

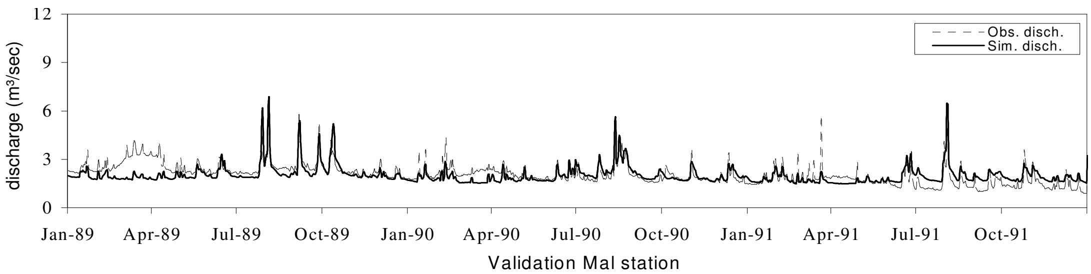

FIGURE 4: Observed and simulated river flow at the internal gage station (Mal)

The flow in the lower aquifer (chalk layer) proved to have big impact on the basin water balance as a result of the high hydro-geological complexity, which characterizes the Jeker catchment due to the existence of two main galleries, the model was hardly able to generate the water levels in the observation wells and to reproduce the annual water cycle, which can be realized every 3 years. However the model proved to produce better results with the wells included in the calibration (SS test) than with those used in the validation only (MS test). Out of 48 observation wells only 12 were reliable and used in this study. Figures 5 and 6 show the results of comparing the observed and simulated water levels in the observation wells that were used in the split sample and multi site tests, respectively. Figure 5 shows the calibration and validation together in one graph, while figure 6 shows the validation period only, which in this case was considered as the whole six years to take account for the annual water cycle. All the wells are located in the chalk layer by its two divisions compacted and fractured.

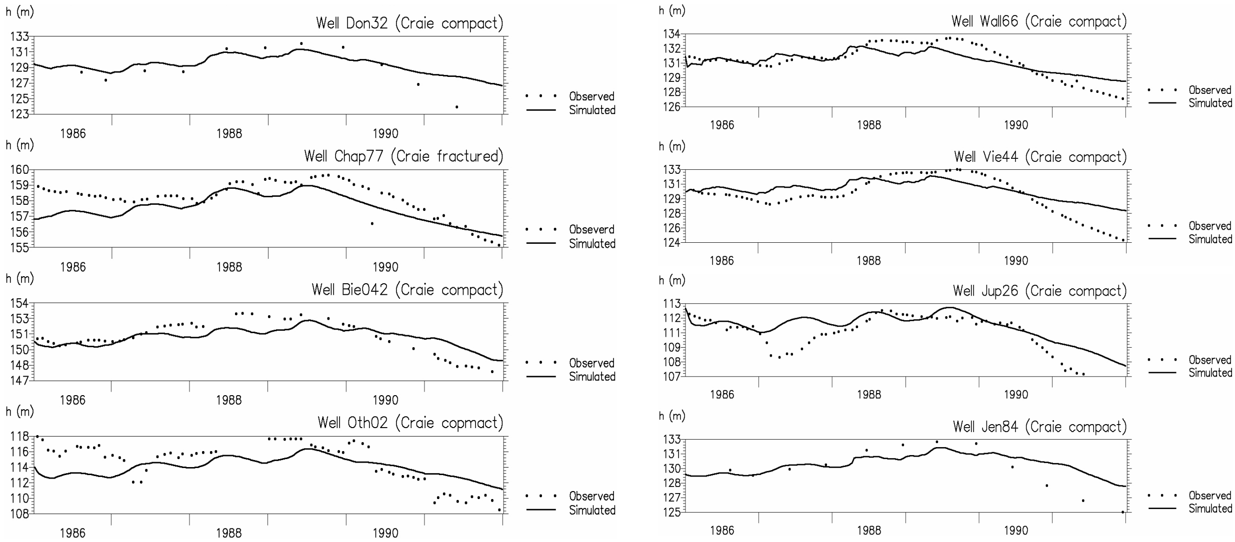

FIGURE 5: Observed and simulated piezometric levels in the observation wells used in SS test

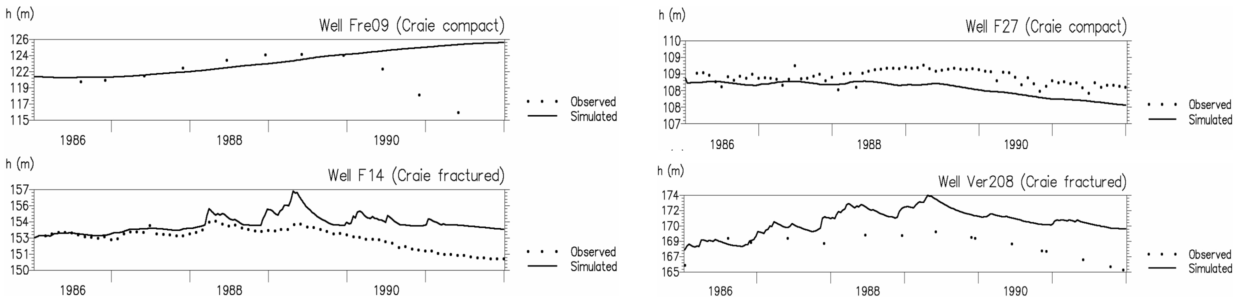

FIGURE 6: Observed and simulated piezometric levels in the observation wells used in MS test

The model was able to simulate the water levels during the split-sample test with a margin of error of few meters the fluctuation of the predicted water levels were more or less following the fluctuation in the measured ones, however there was some delay in the model response. The water levels in two of the wells (namely Ver208 and F14), which were included in the multi-site test and located near the river, tend to be influenced by the variation of the water levels in the river. This is clear in their tendency to have more fluctuation than the other wells.

The statistical performance indices (Table 1) were calculated for the calibration and validation periods of the river flow at the main outlet station and for the validation period of the internal station. Better results are characterized when RRMSE and MAE closes to zero, R^2, CD and EF values closes to unity.

TABLE 1: Statistical performance indices

	RRMSE	ABSERR	CD	EF	R^2
SS calibration Kanne	0.244	0.434	0.810	0.607	0.691
SS validation Kanne	0.204	0.296	1.088	0.764	0.782
MS validation Mal	0.252	0.388	1.321	0.351	0.413

The overall results from the goodness-of-fit statistics (Table 1) and plots (Figure 2) for the river flow prediction in the SS test, during the calibration and validation period, reveals that the model performs better in the validation period. This improvement can be explained, as the model was able to predict the base flow during the validation better than during the calibration.

CONCLUSIONS

The performance of the MIKE SHE model was tested using a qualitative (graphical) and quantitative (statistical) assessment. The analysis, both the graphical and statistical approach, revealed that the model was able to model the catchment in acceptable result. The overall results from the goodness-of-fit statistics and the hydrograph plots shows that the model was able to simulate the river flow at the main outlet of the catchment during the SS test in acceptable accuracy, however less accurate result was obtained at the internal discharge station during the MS test. The same conclusion can be drawn for the piezometric heads. Using a multi-site validation test in addition to the traditional split-sample test proved to give more credibility and confidence in the model predictions. It can also give an indication on how would the model predict other variables that were not accounted for during the original calibration. A general conclusion can be drawn that the model is considered to be a good physical representative of the whole catchment, however additional and more accurate data may improve the predictions especially with ground water levels, which were mostly unreliable.

Among other challenges that are facing the future of the distributed models is the distributed predictions, is it myth or reality? This is a difficult task as normally the distributed input are in different scale than the distributed output, more research to evaluate the effective grid size can help to eliminate this problem. Another problem which has been discussed by many authors is the over parameterization of the model due to the distributed and physically-based nature of the model, resulting in more inputs and model parameters, which in turn result in more uncertainty in the prediction. Nevertheless the need for such models is not questionable.

ACKNOWLEDGEMENTS

This study was made possible by a research grant of the OSTC (Belgian Federal Office for Scientific, Technical and Cultural Affairs) and the Water Department of the Flemish administration AMINAL. The authors would like to thank the following administrations for making available the hydrological time series: the Water Department of AMINAL, DIHO, OC-GIS Vlaanderen, the Royal Meteorological Institute, the National Geographic Institute, the Department of Natural Resources and Energy, the Laboratory of Hydrogeology and the Institute of Soil and Water Management both of the K.U.Leuven; the Belgian Geological Survey, Le Ministère de la Region Wallone, Direction Générale Des Resources Naturelles et de l'Environment, Division d'Eau, Service des Eaux Souterraines, and the Centre d'Environment of the Université de Liège.

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