



Long-Term Time-Series Analysis to Understand Groundwater Flow in Abandoned Subsurface Mines with Application to a Coalfield in Liège, Belgium

B. Ronchi¹ · F. Stassen¹ · J.-P. Drevet¹ · C. C. Fripiat¹ · J.-L. Berger¹ · C. Dingelstadt¹ · M. Veschkens¹

Received: 20 October 2016 / Accepted: 12 March 2018 / Published online: 15 March 2018
© Springer-Verlag GmbH Germany, part of Springer Nature 2018

Abstract

Complex underground flow processes can occur in flooded mine workings. As the groundwater rebounds, outbreaks, flooding, and slope stability problems can occur where hydraulic pressures build up in less drained areas. A time-series statistical analysis was conducted to understand how exploited areas in an abandoned coalfield were connected and to calculate groundwater response times to rain events by spatially and temporally correlating piezometric levels and discharge rates. Ten years of flow rate and water level data were statistically analyzed for an abandoned coalfield in Liège (Belgium). Then, the results were compared to results from physically-based simulations (a 3D groundwater flow model) based on data from the first 2 years of monitoring. The statistical approach gives qualitative indications on the interconnections between the different areas of the coalfield, as well as on the storage capacity/transmissivity of the aquifer. Improved understanding of this hydrogeological behavior can be used to prevent post-mining accidents and assess the associated risks.

Keywords Post-mining monitoring · Quickflow · Baseflow · Correlation

Introduction

Groundwater rebound starts as soon as the extensive pumping required during mining stops, and continues until water pressure within the mine equilibrates with regional aquifers or when the mine water table reaches a point of discharge. Consequently, stress redistribution occurs underground, potentially inducing flooding and/or stability problems in the surrounding area (Wolkersdorfer 2008). If a discharge point malfunctions (e.g. due to the collapse of a drainage adit), water pressure can build up and eventually cause an outbreak, with potential human losses and high impacts to surrounding buildings and infrastructure. Monitoring flow rates in drainage adits and water levels in piezometers is one way to detect the potential occurrence of outbreaks in

time, as they occur when a build-up of hydraulic head is observed without any corresponding increase in downstream discharge rates (Mayes and Jarvis 2012).

The porosity of a mined area is composed of the intrinsic rock matrix porosity as well as mining-induced fractures and voids, i.e. shafts, inclines, adits, galleries, and stopes. As a result, complex flow processes can occur in flooded mine workings, and monitored flow rates and water levels can be difficult to interpret. Nevertheless, understanding how pressure anomalies spread in these systems is key to risk management in these areas. The main question addressed in this study is how to estimate the response time to a pressure anomaly. Response times to recharge events are linked to the storage capacity of the hydrogeological system, which influences how fast groundwater pressure pulses propagate through an abandoned coalfield. Indeed, fast pulse propagation is observed as recharge events are drained in a short period of time by quick flow processes (e.g. Padilla and Pulido-Bosch 1995) in systems characterized by low storage capacity. In contrast, base flow is the dominant process controlling water release in systems with a high storage capacity (e.g. Larocque et al. 1998). Time-series analysis is commonly used to highlight specific features within karstic systems (Mayaud et al. 2014; Panagopoulos and Lambrakis

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s10230-018-0528-y>) contains supplementary material, which is available to authorized users.

✉ B. Ronchi
b.ronchi@issep.be

¹ ISSeP, Institut Scientifique du Service Public, Cellule Risque
Sous-sol, Rue du Chéra 200, 4000 Liège, Belgium

2006). Due to the presence of cavities and rubble zones, hydraulics within mine workings and karst systems behave similarly (Burbey et al. 2000). Therefore, the use of time-series analysis should be a low-cost way to characterize flow processes in underground mines (Sahu et al. 2009). Different statistical techniques applied to rain data, water levels, and discharge hydrographs are used to characterize storage capacity and identify hydraulic connections in such systems (e.g. Larocque et al. 1998; Padilla and Pulido-Bosch 1995; Panagopoulos and Lambrakis 2006).

Rain peak attenuation (input data) by the system is calculated with the gain function, which is commonly used in spectral analysis (Padilla and Pulido-Bosch 1995). To detect if water fluxes are influenced by short or long-term processes (e.g. rain events vs seasonal recharge) in a defined location, the auto-correlation function of each time series is estimated. Cross-correlation functions give an estimation of the pressure-pulse transfer times between input and output data. When calculated between piezometric levels and/or discharge adits, it allows connections to be characterized between different locations within the mine workings. This analysis is performed *at different time scales*. Long-term time-series analysis (1 year or more) provides average properties of the aquifer. In contrast, time-series analysis of a single rain event allows one to evaluate if the aquifer behavior varies depending on hydrological conditions within the system (Mayaud et al. 2014).

This study presents how time series analysis can be used as a risk management tool to help understand how groundwater pressure propagates in an abandoned coalfield. It shows how methods used in karstic systems can be translated to other hydraulic systems with large cavities and channels, e.g. underground exploited zones. It aims at understanding hydraulic connectivity within mined zones and identifying transfer times of groundwater to surface water through spatial and temporal correlation relationships between piezometric levels and discharge rates monitored over a 10 year period in an abandoned coalfield in Belgium. The results of this statistical approach allowed the evaluation of the conceptual model used in a 3D groundwater flow model (Wildemeersch et al. 2010), based on data from the first 2 years of monitoring, and assess the spatial and temporal variability as well as the storage capacity/transmissivity of the aquifer.

Study Area and Available Data

The studied area is located in eastern Belgium, in the Liège Coal Basin. It spans 27 km², including the villages of Wandre and Cheratte. Elevation varies from ca 55 m in the alluvial plain of the Meuse River to 200 m on the plateau. The Meuse River and three of its tributaries cross the study area and flow mainly northward (Fig. 1a). The temperate climate

is characterized by annual rainfall amounts between 650 and 1000 mm, with an estimated annual evapotranspiration ranging between 420 and 550 mm (Veschkens et al. 2014).

Coal was extracted from the Houiller Group, composed of Carboniferous (e.g. Serpukhovian, Bashkirian and Moscovian) shales and siltites, alternating with sandstone and quartzite layers (Fig. 1b). This aquiclude has a generally low natural permeability, mostly associated with fractures in the sandstone layers associated with folding and faulting of the geological units. However, intense mining activities have significantly affected the permeability of the rock formations. The residual mine voids and the associated fractured and rubble zones behave as an unconfined aquifer, called a mine-aquifer system in this study. On the plateau, in the eastern and southern parts of the study area, the Houiller Group is covered by Cretaceous formations (Fig. 1b); the aquitard constitutes glauconite-rich clays and sands of the Campanian Vaals Formation and a perched unconfined aquifer consisting of the Gulpen Formation's Campanian and Maastrichtian chalks. Finally, an aquifer composed of Tertiary alluvium (clays, sands, and stony loams) covers the terraces, while Quaternary alluvial sand and gravel are deposited in the valley (Fig. 1b). Groundwater generally flows to the NW, following the dip of the Gulpen Formation, except in the mined areas (Dingelstadt et al. 2007; Ruthy and Dassargues 2008).

Mining stopped in the late 1970s. Outbreak, flooding, and stability risks are greatest near the drainage adits that discharge to the Meuse valley, so this study was focused on mine maps above the level of the Meuse River (55 m). At these altitudes, a maximum of five coal seams (Fig. 1) and a total length of about 80 km of galleries were reported (Dingelstadt et al. 2007). Residual mine voids at or above this level have been estimated at about 1.8×10^6 m³ (Veschkens et al. 2005).

On February 27th, 2002, the abandoned colliery and surrounding houses suddenly flooded due to an outbreak from the main access tunnel to the mine. No casualties were reported but material damage was relatively important. The accident was caused by the collapse of a drainage adit. Pressure built up in the adit until it exceeded the mechanical resistance of the plug, which caused the sudden release of large amounts of debris, mud, and water. This accident raised awareness on the specific risks associated with groundwater fluxes through the mines in the area. Consequently, a monitoring network was set up in the area to prevent another occurrence of such an event. Previous studies on the piezometric data of this study area confirmed that the groundwater rebound stopped before monitoring started (Ronchi et al. 2016; Wildemeersch et al. 2010).

The groundwater monitoring network consists of nine piezometers that has been progressively installed since 2003. All piezometers are screened in the Carboniferous shales in the mine-aquifer system. According to the

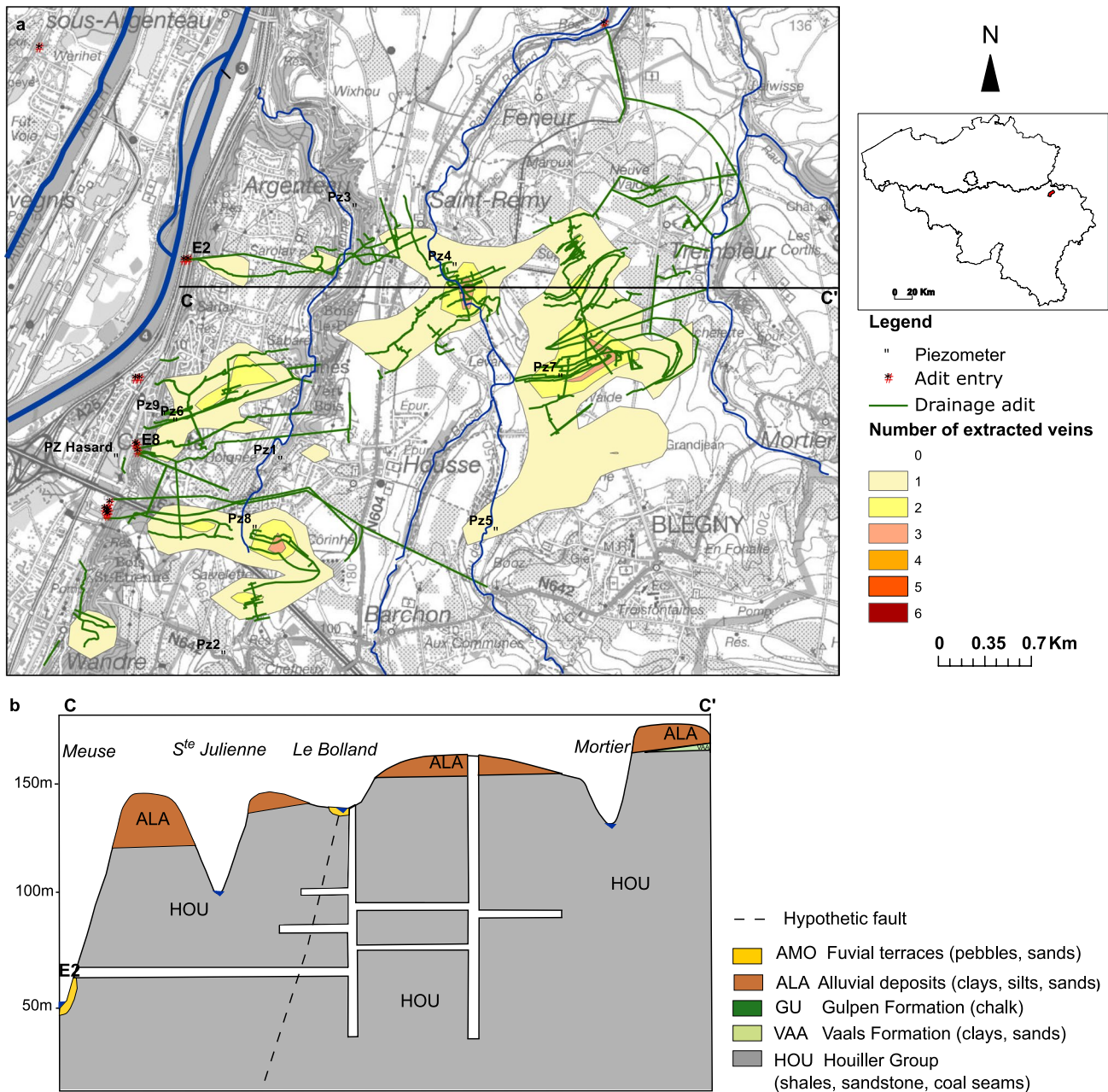


Fig. 1 **a** Location of the study area, mining plans of the exploitations located above the level of the Meuse River (55 m) and monitoring network (map extracted from IGN maps 42/3 and 42/2; mining data:

SPW). **b** West-east oriented geological profile (from point C to C' on **a**) including a schematic representation of the shafts and galleries in the exploited zone

direction of river flow (from south to north), piezometers Pz2, Pz8, Pz1, and Pz3 are located along the river La Julienne and piezometers Pz5 and Pz4 along the river Le Bolland (Fig. 1). Pz1, Pz2, and Pz3 are located in unexploited zones, in contrast to the other piezometers (Fig. 1). Based on the density and outline of the mine workings (Fig. 1), the likelihood of hydraulic connections between the workings around Pz4, Pz7, and E2, and those around Pz6, Pz9, and E8 was expected to be high.

Pumping tests conducted in piezometers Pz2, Pz4, Pz6, Pz7, and Pz8 indicated hydraulic conductivities between 2.5×10^{-8} to $1.4 \times 10^{-6} \text{ m s}^{-1}$ and specific yields between 9×10^{-4} and 5×10^{-3} . Higher hydraulic conductivities (1.1×10^{-6} to $4.8 \times 10^{-5} \text{ m s}^{-1}$) and lower specific yields (1×10^{-7} to 5×10^{-6}) were estimated in piezometer Pz1 (Gardin et al. 2005).

Three piezometers (Pz1, Pz2, and Pz3) were monitored for only 3 years, while the other six (Pz4–9) were monitored

for much longer (10 years—see Supplementary Table 1). Groundwater depths were either manually measured on a monthly basis or monitored hourly with pressure sensors (pressiometric probes). Stream levels were monitored behind weirs with rectangular and triangular notches installed in two channels (E2 and E8) in the valley (Fig. 1) using pressure sensors (pressiometric probes); these were used to calculate hourly discharges (Fig. 2).

Groundwater levels and discharge peaks typically occur in January while minima are generally observed in November (Fig. 2). Groundwater levels observed in Pz1, Pz2, and Pz3 ranged from 2 m above and below the topographic level of the nearby river La Julienne, which likely drains the Houiller group at those locations. At measurement point Pz3, water pressures are even artesian. In the other piezometers located near rivers (Pz4, Pz5, Pz8), average groundwater levels were at least 20 m lower than river levels, making direct groundwater inflow into the closest rivers less likely around these piezometers. The amplitude of groundwater level variations differs largely from one location to another (Supplementary Fig. 1). Centered groundwater levels were computed by subtracting the mean value over the whole time series. Groundwater levels in Pz1, Pz2, Pz8, and Pz9 were very stable compared to groundwater levels in Pz5 and Pz7 (Supplementary Fig. 1).

Application of Statistical Methods

The *timeSeries* package in *R* was used for all of the statistical methods presented in this paper. Theoretical explanations of these statistical methods can be found in Cowpertwait and Metcalfe (2009). Piezometers Pz1, Pz2, and Pz3 were not considered in the statistical analysis as these piezometers were monitored over much shorter time periods than the other piezometers. To study the hydrology of the Wandre-Cheratte mine complex, univariate and/or bivariate statistical methods were applied to the precipitation, discharge, and groundwater level time series.

Daily averages of hourly data were calculated to clean up time series for gaps and allow working with daily data. To fill in local gaps when pressure transducers were down, linear interpolation of the manually-measured levels were used. Univariate analysis is applied to the long-term data groundwater and discharge data with auto-correlation analysis (Table 1). Bivariate analysis included gain function calculations on long-term data as well as cross-correlation computations on long-term and single-event data (Table 1). Long-term analysis includes data measured over the whole monitoring period, from 2003 until 2014. For the analysis of single events, 21 peak events were manually selected based on a visual examination of the time series of Pz4, Pz7, E8 and E2 between January 2008 and October 2014 (Fig. 2).

The data used for each event was selected at the start of a peak until the end of the latest peak observed in one of the measurement points. For some events, no data was available due to technical issues at one of the measurement points. Consequently, the analysis could not be performed for all 21 events for all measurement points.

Gain Function

The response of the aquifer to rainfall time series was analyzed in the spectral domain using *gain functions*. Gain functions allow the assessment of rainfall attenuation as an input signal in the system in the frequency domain. Evapotranspiration is not considered in this analysis. Actually, some quick-flow processes could be neglected during summer by using evapotranspiration estimates, since the uncertainty of these estimations is important for this complex mine system. Two characteristic values of the gain function give insight into the behavior of the system. First, a gain value equal to 1 corresponds to the threshold between amplification and attenuation of the input signal. The frequency at which the gain function equals 1 is considered to be representative of the time period needed to return to base flow conditions after an impulse perturbation. Second, if the gain function reaches a value of 0.4 at high frequency, the corresponding period is considered as representative of quick-flow duration through the system. Although this value is somewhat arbitrarily chosen, it has been shown to be effective/adequate in the studies of Padilla and Pulido-Bosch (1995) and Panagopoulos and Lambrakis (2006). In this study case, a gain function value of 0.4 corresponded to relatively low frequencies (i.e. long time periods), implying that quick-flow could be a limited process in this system (Fig. 3). Shorter periods (<20 days) were only observed in groundwater levels at Pz5, suggesting that quick-flow may take place there (QF in Fig. 3). Periods corresponding to the base flow duration are also shorter at Pz5, implying limited storage capacities of the system at these locations. In contrast, Pz6 and Pz8 were characterized by longer periods of base flow duration (BF in Fig. 3) and thus, by larger storage capacity. At Pz9 and Pz7, the gain function did not reach a value of 1. Interpretation in terms of base flow response is therefore limited for these locations (Fig. 3).

The shortest estimated durations for quick-flow and base flow in the drainage adits were for E8, though the durations for Pz5 are comparable. The estimated durations for E2 were a bit longer and similar to the estimates for Pz4.

Correlation Function

Spatio-temporal pulse propagation through the system was analyzed with correlation functions in the time domain, and were calculated for the time-derivatives of the daily

Fig. 2 Groundwater levels (above), discharges (middle) and rain data (below) monitored between 2004 and 2014. Grey and yellow shaded areas represent selected single events for cross-correlation analysis

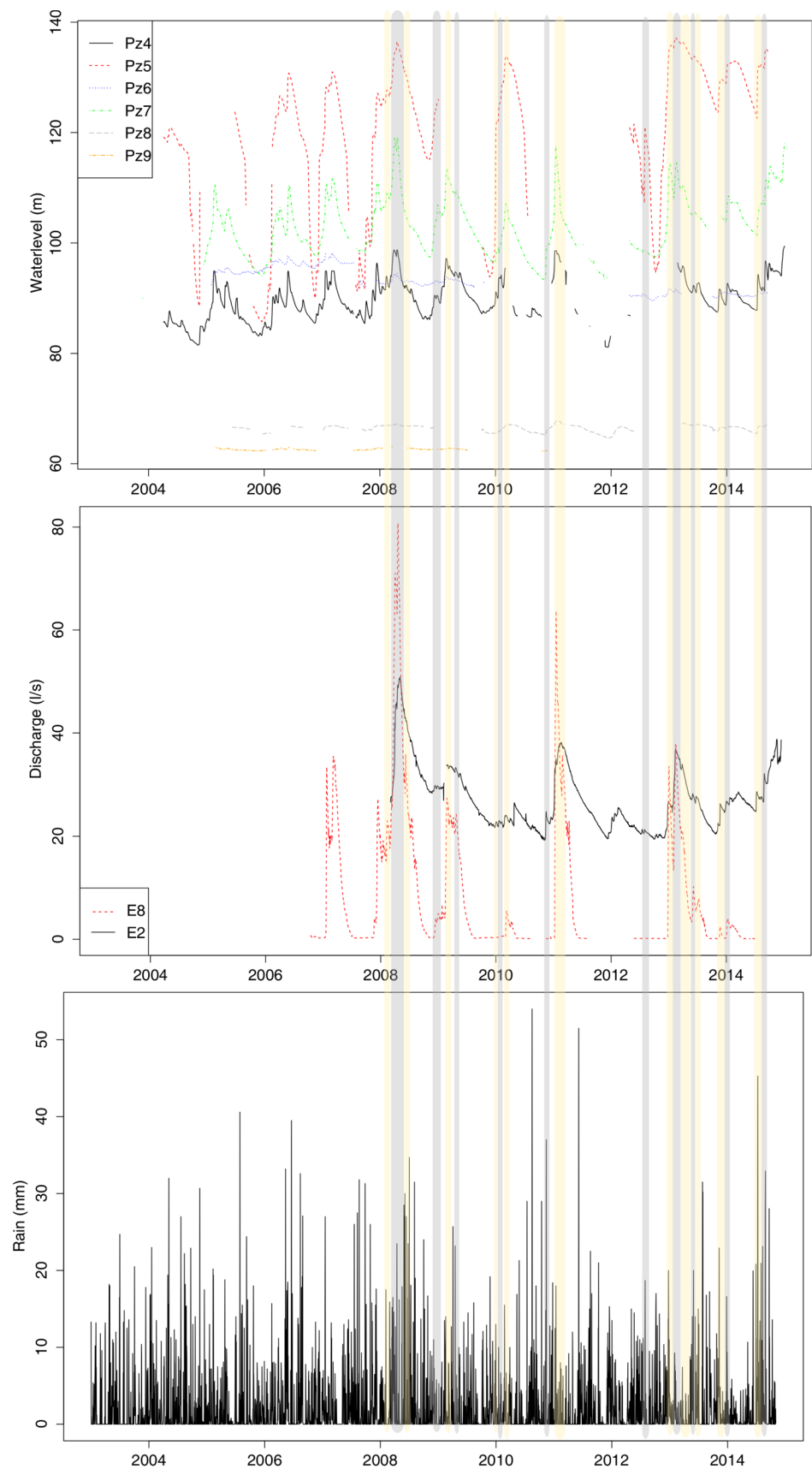


Table 1 Synthesis detailing the data type and time scale used for each statistical method

| | Univariate | | Bivariate | |
|------|------------|--|-----------|-----------|
| | ACF | | CCF | |
| | Long term | | Long term | Event |
| | | | | |
| Pz4 | × | | × | × |
| Pz5 | × | | × | |
| Pz6 | × | | × | |
| Pz7 | × | | × | × |
| Pz8 | × | | × | |
| Pz9 | × | | × | |
| E2 | × | | × | × |
| E8 | × | | × | × |
| Rain | | | | Input fct |

ACF auto-correlation function, CCF cross-correlation function, GAF gain function

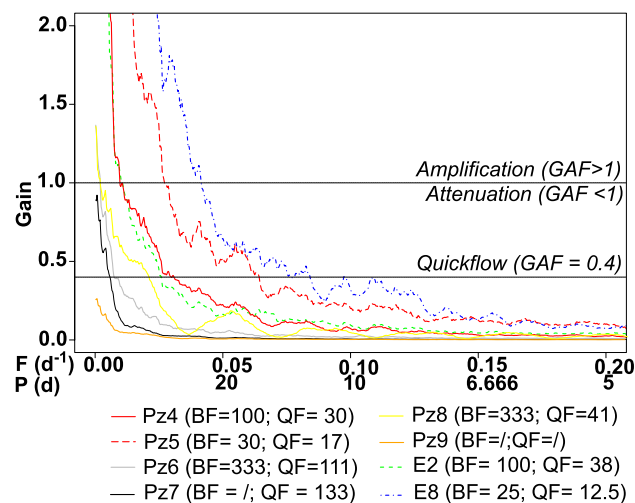


Fig. 3 Gain function from spectral analysis where rain data is considered as input data. Periods (in days) corresponding to a gain function value of 1 (for base flow, BF) and 0.4 (for quick-flow, QF) are indicated in the legend

groundwater levels and discharges. Indeed, correlation analysis requires at least weakly stationary data. Such assumptions cannot be met if the data exhibits a trend, where first-order derivatives have been shown to exhibit stationarity. As a result, discussions and conclusions on spatial and temporal correlations are related to the rates at which groundwater levels and discharges change. Correlation analysis considering rainfall data as an input signal for the mine complex is not presented in this paper, as we considered that the recharge mechanisms in this study area are too complex to be directly linked with rainfall or throughfall (calculated with the Thornthwaite equation),

since no clear correlations between rainfall (or throughfall) and discharge and piezometric data could be highlighted.

Auto-correlation functions (ACF) were calculated to identify reactive areas in the mine workings. Memory effects of each data series are characterized by a decorrelation lag time, computed as the time to reach an auto-correlation value of 0.2 (Kovačič 2010; Larocque et al. 1998). A long decorrelation time (a slowly decreasing ACF slope and thus long memory effect) can be due to seasonal recharge (Sahu et al. 2009), or to a poorly interconnected hydraulic system with a major groundwater stock. In contrast, a small decorrelation time (a steep ACF slope and thus short memory effect) is typically observed in systems reactive to single events, like an active, interconnected hydraulic network without important groundwater reserves. Bimodal systems will present a sharp drop during the first days, corresponding to quick-flow processes, and a gentle slope afterwards due to base flow processes (Panagopoulos and Lambrakis 2006).

Auto-correlation functions show different patterns based on the measurement locations. However, all decorrelation times were found to be less than 10 days (Fig. 4). The mine-aquifer system is thus characterized by a rather low storage capacity and quickly propagated pressure-pulses. The highest decorrelation times (d.t. in Fig. 4) occurred at piezometers Pz7 and Pz8, in the more heavily exploited areas with their higher storage capacities.

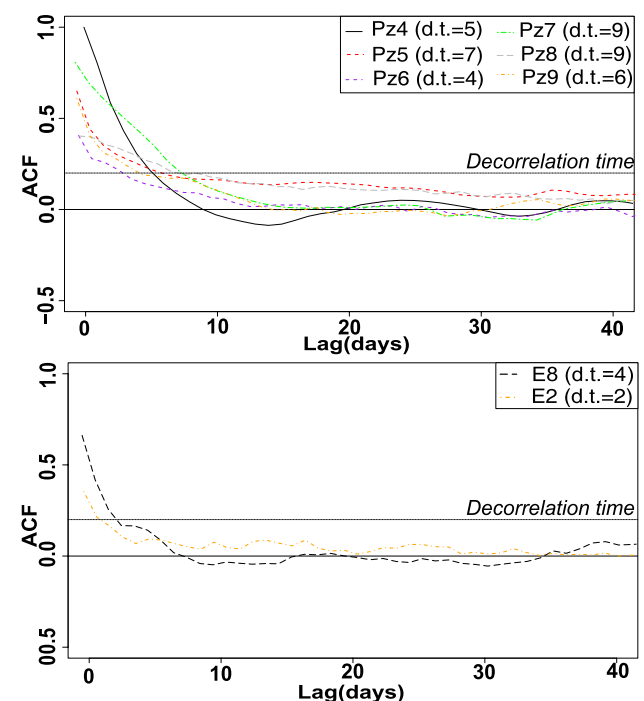


Fig. 4 Autocorrelation functions of the piezometers and drainage adits. Decorrelation times are indicated by “d.t.” in days in the legend

Cross-correlations were calculated between discharges and groundwater levels measured at different locations to quantify signal delays between data series. With this analysis, responses to recharge events are studied to understand: (1) pressure pulse transfer times through the mine aquifer system (expressed by the time lag in Table 2), and (2) the degree of connectivity between different locations (expressed by the correlation coefficient in Table 2). Signal delay is defined as the time lag corresponding to the maximum correlation observed between two time series. According to the principle of causality, the sign of the delay depends on the order in which the variables are used to calculate the correlation and on the direction of the pressure pulse transfer. A positive time delay will be observed if a pressure pulse is transferred from the first variable to the second, while a negative delay is observed if the transfer is in the opposite direction or if peaks of each time series are related to external processes. Cross-correlations were calculated between: data variations over the entire monitoring period (2003–2014), and at the scale of single events, in piezometers Pz4 and Pz7, and discharge adits E2 and E8.

A long term analysis allows an understanding of the global behavior of the mine-aquifer system, in base flow conditions as well as during recharge events. However, as seasonal base flow variations can average results, occasional connections in specific peak flow conditions may be missed. Therefore, we combined our long-term analysis with an analysis of the time scale of single events. This allows an understanding of the short-term response of the mine-aquifer system by considering specific initial conditions before the

peak flow. In karstic systems, long response times of gently sloping cross-correlograms are associated with an important storage capacity and a low degree of karstification. In contrast, short response times are characteristic of well-developed karst aquifers (Kovačič 2010; Padilla and Pulido-Bosch 1995). In this case study, correlation functions similar to functions described for poorly developed karst system would correspond to poorly connected exploited zones or poorly exploited zones, while characteristics of a developed karst aquifer should be observed in intensively exploited zones (open galleries).

Maximum cross-correlation coefficients (*ccf* in Table 2) for the long-term analysis (2003–2014) were generally reached for a zero or one day delay (time lag 0 or 1 days in Table 2). Pressure-pulses measured in Pz4 and Pz7 correlate highly with each other (*ccf* > 0.5—in italic font in Table 2) while intermediate *ccf* values (0.3–0.5) were calculated between Pz4/Pz7 and the other piezometers. The lowest *ccf* values (< 0.3) were calculated between Pz5, Pz8, and Pz9, suggesting connections between these areas are limited, or nonexistent.

Very low *ccf* values were calculated between E2 and the piezometers. In contrast, the drainage adit E8 correlates well with piezometers Pz4 and Pz7 (> 0.5—in italic font in Table 2). However, correlation coefficients calculated between Pz5, Pz8, and Pz9 on one hand, and E8 on the other hand, were also low (< 0.3 in Table 2). For correlations calculated between all piezometers and E8, the wide distribution of time lags (Fig. 5) proves that response times can vary considerably.

Table 2 Maximum cross-correlations coefficients (*ccf*—above) between time series measured on the long term (2003–2014) and corresponding time lags in days (*d*—under)

| | Pz5 | Pz6 | Pz7 | Pz8 | Pz9 | E2 | E8 |
|------------|------|------|-------------|------|------|-----------|-------------|
| <i>ccf</i> | | | | | | | |
| Pz4 | 0.46 | 0.49 | <i>0.65</i> | 0.38 | 0.32 | 0.09 | <i>0.51</i> |
| Pz5 | | 0.22 | 0.33 | 0.24 | 0.2 | 0.22 | 0.17 |
| Pz6 | | | 0.41 | 0.33 | 0.39 | <u>ns</u> | 0.46 |
| Pz7 | | | | 0.38 | 0.36 | 0.05 | <i>0.66</i> |
| Pz8 | | | | | 0.26 | 0.11 | 0.27 |
| Pz9 | | | | | | <u>ns</u> | 0.23 |
| E2 | | | | | | | <u>ns</u> |
| <i>d</i> | | | | | | | |
| Pz4 | 0 | 0 | – 1 | 0 | – 3 | – 19 | – 1 |
| Pz5 | | 0 | – 1 | – 1 | – 2 | – 36 | – 1 |
| Pz6 | | | 0 | 0 | – 1 | <u>ns</u> | 0 |
| Pz7 | | | | 0 | – 1 | 1 | 0 |
| Pz8 | | | | | – 1 | 10 | 0 |
| Pz9 | | | | | | <u>ns</u> | 0 |
| E2 | | | | | | | <u>ns</u> |

All italic figures are related to coefficients > 0.5. The underlined symbol “ns” stands for not significant values. Positive time lags stand for an impulse passing first by the location indicated by the line, and then by the column (while negative time lags are calculated when the impulse is first detected in the location indicated by the column)

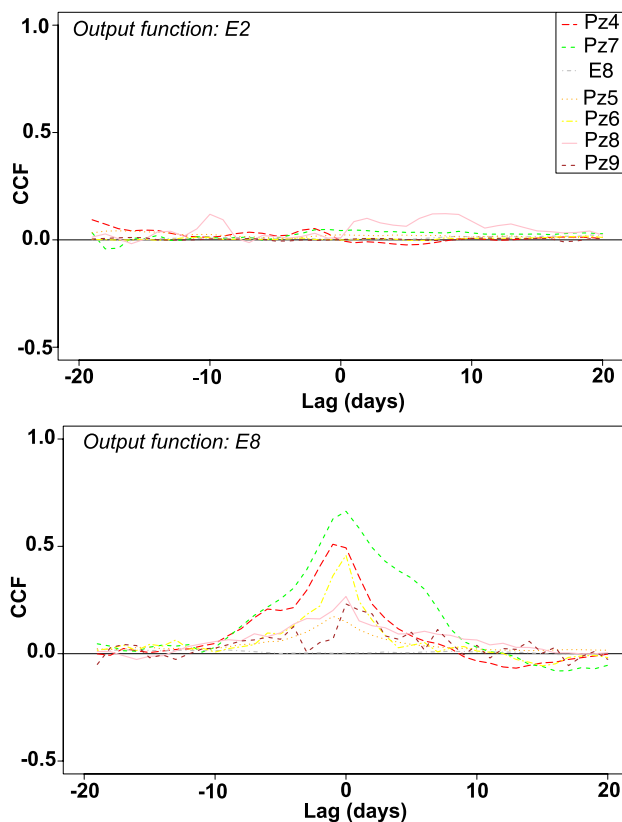


Fig. 5 Cross-correlation functions calculated between the piezometers and the drainage adits E2 (above) and E8 (below). The positive time lags mean the peak is first detected in the piezometer and later in the adit, while negative lags mean is the opposite

Results for single events vary considerably from one event to another if we compare the obtained maxima and minima for each type of correlation (Table 3). The highest cross-correlation coefficients were calculated between Pz4 and Pz7, with median and average time lags of respectively 1 and 2 days (Table 3).

Average and median maximal correlation coefficients between changes in discharges and groundwater levels exceed 0.6 for average time lags between 0 and 2 days. Higher correlation coefficients for shorter time lags were calculated between the piezometers and E8, compared to E2. However, negative time lags were calculated for several events, in which peak flow was first observed at the drainage adit, and later in the piezometers. In those cases, an intermediate quick flow provides the primary source for the peak flow observed in the drainage adit and an attenuated peak in the groundwater arrives later at the drainage adit. Duration of the pressure pulse transfer from the piezometer to the drainage adit is not calculated for those events in this study. Therefore specific base flow separation methods should be applied to each discharge

Table 3 Median, average, minimum and maximum cross-correlations coefficients (*ccf*—above) and corresponding time lags (*d*—below) for each rain event

| | PZ4 PZ7 | PZ4 E2 | PZ7 E2 | PZ4 E8 | PZ7 E8 |
|------------------------|-------------|-------------|-------------|---------------|---------------|
| n sign | 14 | 14 | 17 | 13 | 15 |
| n non sign | 1 | 1 | 4 | 3 | 2 |
| <i>ccf</i> | | | | | |
| Median | 0.79 | 0.68 | 0.63 | 0.72 | 0.67 |
| Average | 0.77 | 0.61 | 0.63 | 0.71 | 0.69 |
| Min | 0.56 | − 0.6 | 0.38 | 0.42 | 0.43 |
| Max | 0.94 | 0.91 | 0.79 | 0.93 | 0.94 |
| Time lags (<i>d</i>) | | | | | |
| Median | 1 | 2 | 2 | − 1 | 0 |
| Average | 2.14 | 1.21 | 2.94 | − 2.14 | − 0.41 |
| Min | 0 | − 11 | − 3 | − 9 | − 7 |
| Max | 13 | 17 | 16 | 3 | 5 |

All bold values correspond to cross-correlation coefficients (*ccf*) higher than 0.5 and their related time lags

Positive time lags stand for an impulse passing first by the location indicated by the first line, and then by the second line (while negative time lags are calculated when the impulse is first detected in the location indicated by the second line). The next two lines give the number of analyzed events with significant results (n sign) and with non-significant results (n non sign)

peak to simulate the contribution of the different sources (intermediate flow vs groundwater flow).

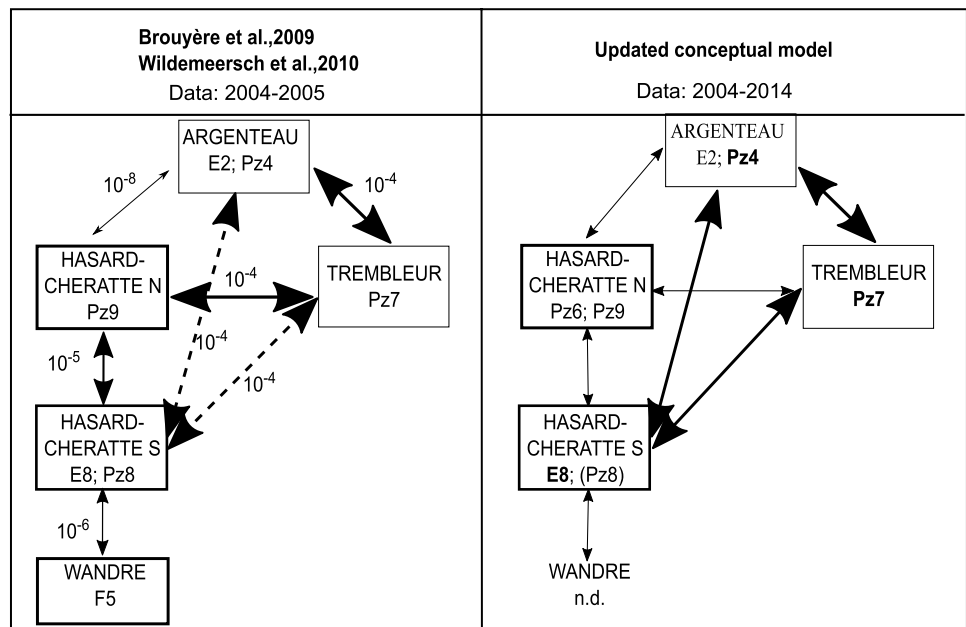
Discussion

Conceptual Model of the Cheratte Coalfield

This statistical study provides new insights into the mined system's hydraulic connections, which allows the conceptual model of the Cheratte coalfield suggested by Brouyère et al. (2009) to be updated. This physically-based numerical model, which was calibrated using two years of data (January 2004–December 2005; Wildemeersch et al. 2010) subdivided the mined system into five reservoirs, all connected to each other, except for the Wandre reservoir (Fig. 6). This last reservoir was only connected to one reservoir in the Brouyère et al. (2009) model, and since it was not expected to actively contribute to the discharge in these adits, it was never equipped with piezometers or included in the monitoring network. As no data was collected there over the 10 year period, this reservoir was not considered in this study.

According to the model of Brouyère et al. (2009), connections with the highest exchange coefficients were identified between the Argenteau (E2, Pz4), Trembleur (Pz5, Pz7), and Hasard–Cheratte Sud (E8, Pz8) reservoirs. The important connections between these reservoirs were confirmed

Fig. 6 Conceptual models of the abandoned coal field in Liège used in the existing numerical model (left) of Brouyère et al. (2009) and updated according to the findings of this study (right). The boxes represent the different reservoirs; the thickness of their frame: storage capacities; arrows: connections between reservoirs, dotted arrows: conditional connections between reservoirs; thickness of the arrows: importance of the connection; figures: exchange coefficients for by-pass flow connections (m^2/s)



by our analysis. After 10 years of measurements, the most important groundwater level variations were still observed in these more heavily mined areas (Pz4, Pz5, and Pz7—Fig. 1). Even though the galleries located near Pz4 (Argenteau) and Pz7 (Trembleur) were not directly connected (Fig. 1), pressure-pulses were clearly transferred between these two locations and to the drainage adit E8 (Hasard–Cheratte Sud), according to the cross-correlation functions (Fig. 4; Table 2). Unknown mine workings, mined coal seams, faults, and fractures probably connect these sites (Brouyère et al. 2009). Moreover, the higher number of exploited coal seams and galleries (Fig. 1) probably provides larger empty volumes around Pz7, and thus high storage capacity, as deduced from the calculated decorrelation times (Fig. 4). These large storage capacities are not favorable to quick-flow processes, as indicated by the gain function (Fig. 3). No quick-flow occurs in Pz4 and Pz7, in contrast to E8 (Fig. 3). However, the cross-correlation functions calculated for specific events (Table 3) proved pressure pulses causing quick-flow in E8 probably originate, at least in part, from Pz4 and Pz7 during some rain events. As this high correlation was not observed for each event, the connections of the Pz4 and Pz7 areas with E8 may only be active under specific hydrological conditions. In the first suggested conceptual model, discharge peaks at E8 were thus only expected when groundwater levels exceed threshold levels in Pz4 and Pz7 (respectively 88.5 and 102 m; Brouyère et al. 2009; Dinkelstadt et al. 2007). Consequently, low correlation coefficients between piezometers Pz4 and Pz7 and discharges at adit E8 would be expected when groundwater levels were below these threshold levels. However correlation coefficient values do not show any dependency on groundwater

levels at the beginning of recharge events (Fig. 7). In other words, connections between the Argenteau, Trembleur, and Hasard–Cheratte Sud reservoirs can also be active below these threshold groundwater levels, even though initial conditions causing quick flow remain difficult to identify. Therefore, the updated conceptual model considers these connections to be more regularly active (dotted arrows replaced by plain arrows in Fig. 6).

Based on the mining maps (Fig. 1), the workings near Pz5 were also expected to be connected to the workings near Pz4 and Pz7. However lower maximum cross-correlation coefficients (Table 2) were calculated for Pz5. This lower

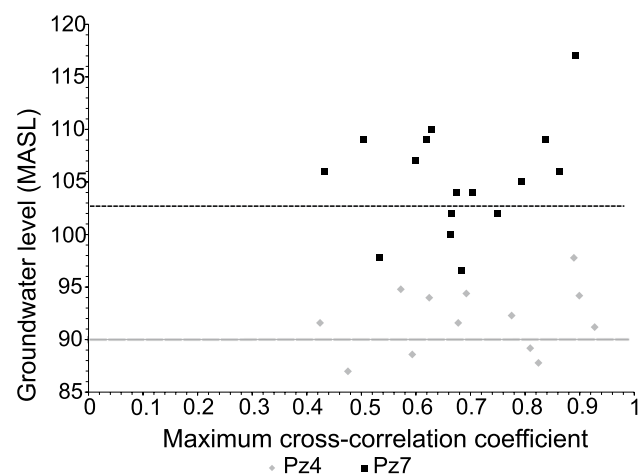


Fig. 7 Maximum cross-correlation (dot size) calculated between E8 and Pz 4 (black) and Pz7 (gray) in function of groundwater level and the beginning of the rain event. Lines represent the threshold levels of Pz 4 (black) and Pz7 (gray)

connectivity can probably be attributed to less coal having been extracted near Pz5 (Fig. 1). The large variations of piezometric levels observed in Pz5 (Fig. 2) are related to quick-flow processes, according to the gain function (Fig. 3).

Connections with Hasard–Cheratte Nord were rather low in Brouyère et al. (2009), except for Trembleur. These limited connections were confirmed by the limited groundwater level variations and low correlation coefficients calculated for Pz6 and Pz9. In Pz9, variations were as low as in zones (Pz1, Pz2, Pz3) where groundwater flow occurs in areas unaffected by mining (Supplementary Fig. 1).

Pz6 is located in an area with large storage capacities (Fig. 3), which is less influenced by surrounding pressure. This was proven by low groundwater level variations (Supplementary Fig. 1) combined with low cross-correlation coefficients (Table 2). Interconnections between this area and the other measurement locations are very limited. Consequently, we suggest updating the existing conceptual model by diminishing the importance of the connection between Trembleur and Hasard–Cheratte Nord. The large storage capacity of the reservoir is kept in the updated model (symbolized by a thick frame in Fig. 6).

The highest specific yields (symbolized by a thick frame line in Fig. 6) were attributed to Hasard–Cheratte Nord and Hasard–Cheratte Sud in the numerical model. This was confirmed by the time series analysis, as Pz6 and Pz8, respectively located in Hasard–Cheratte Nord and Sud, had large storage capacities, according to their gain function.

Within the described reservoirs, some piezometric levels and/or discharge adit of the same reservoir do not seem to behave similarly. The connections described above do not involve Pz8 and E2, for instance, respectively located in Hasard–Cheratte Sud, and Argenteau. Data measured in Pz8 do not correlate with other data. Its gain function suggests it is probably located in an area with larger storage capacities (symbolized by the thick frame of Hasard–Cheratte in Fig. 6), which can buffer pressure-pulse transfer. Like Pz7, this area is characterized by a high number of exploited coal seams (Fig. 1).

Despite the presence of galleries connecting the workings around Pz4 to E2 (Fig. 1), interconnections between the studied piezometric levels and E2 are limited as long-term cross-correlation coefficients are low (Fig. 5). This drainage adit, located in the northern part of the study area (Fig. 1), is probably not draining directly from our study area during base flow conditions. Pressure-pulses during single events are, however, rapidly drained by quick-flow processes in this gallery. This was proven by the low decorrelation time (Fig. 4) and high cross-correlation coefficients calculated at event scale (Table 3). Nevertheless, this process was not observed for all events. This probably explains why quick flow did not appear as an important process in the gain function analysis (Fig. 3). This discussion highlights that the

reservoir description should be treated with caution as some variability is observed between measurement points of the same reservoir (E2 vs Pz4; Pz8 vs E8).

Application of Time-Series Analysis to Mine Workings

The methods used are presented briefly as the aim of the paper was to present a step-by-step approach to apply these complementary analyses. First, the gain function was used to differentiate short and long period processes in data series that vary at different frequencies (rainfall vs piezometric and discharge variations). Then, storage capacities around each measurement point are evaluated with a univariate method (auto-correlation functions) where connections between different parts of the mines are highlighted with a bivariate method (cross-correlation function). Applying this method to the whole dataset first is recommended to provide information about the “average” aquifer behavior/properties (Panagopoulos and Lambrakis 2006). However, since the influence of seasonal variation in base flow averages the results, occasional connections, specific to peak flow conditions are only highlighted when the same analysis is applied at the event scale (Bailly-Comte et al. 2008; Mayaud et al. 2014). Nonetheless, the detection of all potential connections in the system is important for risk management purposes, since it can help localize inundation hazard areas. Above all, the results differed for one event to another, proving that the behavior of the mine aquifer system varies temporarily and is a dynamic non-linear system. This step-by-step methodology is therefore recommended for aquifers that diverge from Darcy law and present an appreciable quick-flow component relative to base flow. Indeed, karst and mine aquifer systems both present preferential flow through a void network that dominates the hydraulic behaviour.

Result Implementation for Risk Management

Detecting connections and understanding the duration and flow path of pressure pulses through the mine workings are essential for risk management. Our statistical analysis allows the efficient evaluation of the current monitoring system and indicates how to interpret the data from different measurements points in real time. For instance, highly connected measurement points (e.g. Pz4, Pz7, and E8) need to be directly compared for interpretation. Data from points that are only connected with the mine system under certain conditions (e.g. E2) should be used with caution. For those points, comparison with other measurement points is only possible when these conditions are fulfilled. In the case of E2, only data from peak flows should be considered (Table 3) for comparison with other points. Analyzing base flow at that point is, however, impossible with the current

monitoring network (Fig. 5). This illustrates how a statistical analysis highlights the limitations of the existing monitoring system.

The conclusions of the statistical study should also consider mapping hazardous areas (inundations, collapses) and designing remediation measures where an anomaly is detected. Detecting all possible connections is important. A concrete example can be given for the discharges at E8, which are controlled by impulse transfers from Pz4 and Pz7 (as proven by the cross-correlation analysis). If data evolution differs between these specific locations during future monitoring, investigations should be performed to know why pressure is not being transferred in the usual way. If a hypothetical pressure build-up is observed in Pz4 and/or Pz7, but not in E8, further investigations should be conducted to identify if the pressure is building up somewhere or if it is being transferred and released via another pathway. The first other pathway that should be studied is the release of pressure at E2. Discharges at adit E2 should therefore be carefully analyzed, as this adit can drain the area around Pz4 and Pz7 during recharge events. If no discharge rise is observed at E2 either, different measures, both adits should be investigated to find the location of any plug. Measures to gently drain the pressure build up behind the plug should then be designed to prevent an outbreak. If no plug is found, measures to remove large volumes of water should be developed and implemented to the protect population living near the adit.

Conclusion

This study showed that time series analysis performed on a long-term database is not only an efficient low-cost tool to improve the understanding of groundwater fluxes through karst systems but can also be used for other complex subsurface systems, such as mine aquifer systems. First, the gain function allows one to detect areas of the mine with high storage capacities and those affected by quick-flow processes by analyzing the attenuation of the rainfall signal. The autocorrelation function highlights areas that are sensitive to pressure pulse transfers through the mine workings. Finally, the cross-correlation function helps one to understand the interconnections between different zones and the reactivity of the water table at different locations in the mine. The results show that information gathered from the exploitation maps above the drainage level (Fig. 1) are not sufficient to understand the hydraulic connections between different exploited zones. The statistical approach highlights connections between measuring points that are not connected by galleries (e.g. Pz4–Pz7–E8) and shows that old galleries do not always transfer hydraulic pressures nowadays (i.e. Pz4–E2 and Pz9–E8).

Moreover, our study proved that considering different time scales (10 year vs event time scale) provides complementary information and new insights on active flux processes in mine workings. The long-term data reveals interconnections during base flow conditions and gives indications on relative storage capacities. Complementary information is gathered from the event-scale analysis, which gives more indications on the occurrence of quick flow responses and the variability in connection times. Indeed, results of cross-correlation analysis differ from one event to another and reveal intermittent connections. This proves the necessity of combining single event analysis with an analysis of the entire dataset. The proposed step-by-step methodology presented in this paper is therefore recommended for aquifers with unknown geometries of conduits, which diverge from Darcy's law and present an appreciable quick-flow component, like karst systems and mine workings.

Our time series analysis could not, however, detect clear correlations between rainfall and the measured piezometric levels and discharges. It also failed to detect which peculiar hydraulic conditions were needed to connect the areas near Pz4 and Pz7 with the drainage adits. Moreover, calculating the duration of pressure pulse transfers between piezometers and drainage adits was not possible when important quick-flow processes took place. Other aquifer characterization techniques should thus be used to complete the interpretation of flow processes and aquifer properties. At this site, the existing numerical model (based on only the first 2 years of data) can be updated with the findings of this statistical approach. An updated model would allow one to study the recharge processes in the mine workings and to test a new hypothesis concerning the factors controlling the connections between the areas near Pz4 and Pz7 with the drainage adits. Base flow separation methods would also provide more information on the importance of quick-flow processes.

Acknowledgements This study was funded by Service Public de Wallonie (SPW/DGO3/DRIGM) as a recurrent annual research contract (Subvention ISSeP “Après-mine”). We thank the reviewers for their constructive suggestions.

References

- Ahu P, López DL, Stoertz MW (2009) Using time series analysis of coal mine hydrographs to estimate mine storage, retention time, and mine-pool interconnection. *Mine Water Environ* 28:194–205
- Bailly-Comte V, Jourde H, Roesch A, Pistre S, Batiot-Guilhe C (2008) Time series analyses for karst/river interactions assessment: case of the Coulazou river (southern France). *J Hydrol* 349:98–114
- Brouyère S, Orban P, Wildemeersch S, Couturier J, Gardin N, Darsargues A (2009) The hybrid finite element mixing cell method: a new flexible method for modelling mine ground water problems. *Mine Water Environ* 28:102–114

- Burbey TJ, Younos T, Anderson ET (2000) Hydrologic analysis of discharge sustainability from an abandoned underground coal mine. *J Am Water Resour As* 36:1161–1172
- Cowpertwait PSP, Metcalfe AV (2009) *Introductory Time Series with R, Use R!* Springer, New York City. <https://doi.org/10.1007/978-0-387-88698-5>
- Dingelstadt C, Drevet J-P, Veschkens M, Flamion B (2007) Etude des conséquences de l'après-mine en particulier sur la gestion des eaux souterraines et des risques—Mission 2006. Institut Scientifique du Service Public, Liège (**unpubl; in French**)
- Gardin N, Brouyère S, Dassargues A (2005) Modélisation de la remontée des niveaux piézométriques dans les massifs affectés des travaux miniers dans l'ancien bassin charbonnier liégeois—site pilote de Cheratte. Université de Liège, Liège (**unpubl; in French**)
- Kovačič G (2010) Hydrogeological study of the Malenščica karst spring (SW Slovenia) by means of a time series analysis. *Acta Carsologica* 39:201–215
- Lafare AEA, Peach DW, Hughes AG (2015) Use of seasonal trend decomposition to understand groundwater behaviour in the Permo-Triassic sandstone aquifer, Eden Valley, UK. *Hydrogeol J* 24(1):141–158
- Larocque M, Mangin A, Razack M, Banton O (1998) Contribution of correlation and spectral analyses to the regional study of a large karst aquifer (Charente, France). *J Hydrol* 205:217–231
- Mayaud C, Wagner T, Benischke R, Birk S (2014) Single event time series analysis in a binary karst catchment evaluated using a groundwater model (Lurbach system, Austria). *J Hydrol* 511:628–639
- Mayes WM, Jarvis AP (2012) Prioritisation of abandoned non-coal mine impacts on the environment. XIII. Hazards and risk management at abandoned non-coal mine sites. Environment Agency Science report SC030136/R2, Bristol
- Padilla A, Pulido-Bosch A (1995) Study of hydrographs of karstic aquifers by means of correlation and cross-spectral analysis. *J Hydrol* 168:73–89
- Panagopoulos G, Lambrakis N (2006) The contribution of time series analysis to the study of the hydrodynamic characteristics of the karst systems: Application on two typical karst aquifers of Greece (Trifilia, Almyros Crete). *J Hydrol* 329:368–376
- Ronchi B, Fripiat C, Drevet J-P, Veschkens M, Pacyna D (2016) Assessing post-mining risks in the long term: ten years of hydrological monitoring in Liège (Belgium). In: Drebenstedt C, Paul M (eds) *Proc, IMWA 2016—mining meets water—conflicts and solutions*, Freiberg, pp 736–739
- Ruthy I, Dassargues A (2008) Carte hydrogéologique de Dalhem—Herve 42/3–4, 1/25.000: Notice explicative. Service Public de Wallonie DGRNE, Namur, Belgique (**French**)
- Veschkens M, Unland W, Kories H (2005) Development tools for managing the impacts on surface due to changing hydrological regimes surrounding closed underground coal mines. In: *Proc. Post-mining 2005*, Nancy, France
- Veschkens M, Drevet J-P, Dingelstadt C (2014) Remontées des nappes dans les anciens travaux miniers et activités de démergement—mesures et surveillance. In: Dassargues A, Walraevens K (eds) *Aquifères et Eaux Souterraines en Belgique*, Ghent
- Wildemeersch S, Brouyère S, Orban P, Couturier J, Dingelstadt C, Veschkens M, Dassargues A (2010) Application of the hybrid finite element mixing cell method to an abandoned coalfield in Belgium. *J Hydrol* 392:188–200
- Wolkersdorfer C (2008) Water management at abandoned flooded underground mines: fundamentals, tracer tests, modelling, water treatment. Springer