Non-conclusive time series analyses – what can we learn on the behavior of the groundwater system? Understanding what caused the collapse of an abandoned drainage tunnel

Christophe FRIPPIAT[1], Mathieu VESCHKENS[1], Daniel PACYNA[2], Luc FUNCKEN[3]

[1]Institut Scientifique de Service Public, rue du Chéra 200, B-4000 Liège, Belgium, ch.frippiat@issep.be
[2]Service Public de Wallonie, Avenue Prince de Liège 15, B-5100 Jambes, Belgium
[3]Service Public de Wallonie, rue Côte d'Or 253, B-4000 Liège, Belgium

Abstract Time series analysis was used as an attempt to identify a potential accidental hydrogeological trigger to the collapse of an abandoned mine drainage tunnel in Belgium. Correlation, spectral and wavelet analyses were applied to piezometric data in order to characterize regional-scale hydraulic connections between groundwater bodies, but failed to provide direct insight into regional hydrogeology. No correlation between data collected in the hydrogeological unit of the collapsed area could be identified, showing that the piezometers were tapping isolated sand lenses. As a conclusion, the collapse was rather attributed to a slow increase in water pressure linked to a limited recharge.

Keywords correlation analysis, spectral analysis, wavelet analysis, barometric efficiency

Introduction

In February 2009, important ground subsidence suddenly occurred over an area of a diameter of about 50 m in the town of Saint-Vaast, near the city of La Louvière (Belgium; Fig. 1). Subsidence caused important cracks to several houses, to the sidewalks and to the road surface. A couple of days earlier, a torrent of mud erupted from the ground in a home garden near the Haine river, about 600 m south of the subsided area. It was rapidly found that an underground drainage tunnel ran at a depth of about 30 m under the subsided area and had its exit located near the eruption point of the mud torrent.

Historic documents report that the construction of the drainage tunnel started around 1747 and lasted for more than a century. Tunnel construction was heavily complicated as it had to cross wealden-facies sediments containing numerous pockets of quicksands. As tunnel construction progressed and reached such pockets, quicksands often burst into the tunnel, causing human losses and systematically filling the tunnel over significant distances. Eventually, tunnel construction was abandoned before it was connected to the mine works and used for drainage.

The likely scenario of the Saint-Vaast accident is that the drainage tunnel remained intact and water-filled over significant length portions but was plugged with debris materials near its exit. Water pressure acting on the plug eventually caused its failure, leading to a rapid emptying of the tunnel. This caused the collapse of the tunnel at one or several weak points, allowing the quicksands to flow into the tunnel and move towards its exit. The residual voids in the ground caused in turn surface subsidence.

The goal of the study is to improve the understanding of the causes of the collapse and, in particular, identify a potential accidental hydrogeological trigger to the increase in water pressure suspected in the likely scenario. The accident occurred in a region where natural groundwater flows are potentially affected by two important hydrogeological artifacts: the drawdowns at the boat lift of Strépy-Thieu and the groundwater rebound in the coal mine of

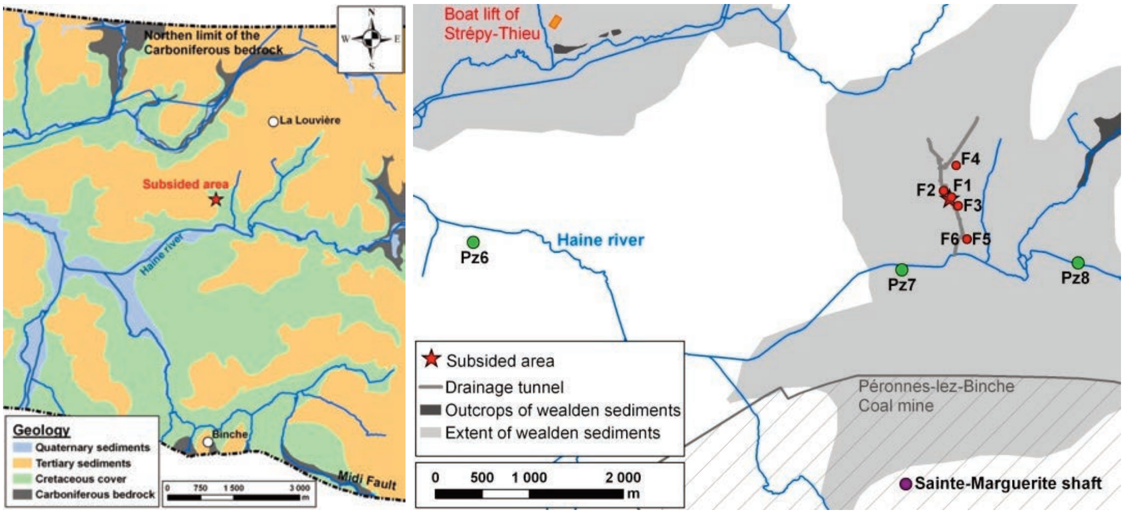

Fig. 1 *Geographic extent and geological setting of the zone of the accident. Extent of wealden-facies sediments as proposed by Marlière (1946)*

Péronnes-lez-Binche (Fig. 1). The boat lift of Strépy-Thieu is located 4.6 km northwest of Saint-Vaast. A permanent drawdown of about 28 m is maintained in the wealden-facies sediments in order to maintain the lower level of the lift dry. The coal mine of Péronnes-lez-Binche is located 3 km south of Saint-Vaast. At the time of the accident, groundwater level was rising at a rate of about 3 m/year in the Sainte-Marguerite shaft (Fig. 1) as a result of the flooding of the abandoned mine.

Considering the magnitude of these disruptions to natural groundwater flows, it was suspected that either one of those artifacts could be linked to the water pressure elevation in the wealden-facies sediments at Saint-Vaast that caused the failure of the plug in the abandoned tunnel.

Geological and hydrogeological setting

The study area is centered on the town of Saint-Vaast and extends from the Midi fault to the northern border of the Mons basin (Fig. 1). The mean surface elevation of the area is about +100 m a.s.l, ranging from about +130 m a.s.l. in the northwestern part of the zone down to about +80 m a.s.l. in its southeastern part. The regional topography is characterized by a number of small valleys and by the presence of numerous coal tips, some of them culminating at more than +200 m a.s.l.

The stratigraphic sequence is characterized by a Carboniferous basement covered with Cretaceous and Tertiary sediments. Cretaceous units consist of wealden-facies sediments, overlain by marls of Turonian age and chalks. The wealden-facies sediments are mainly distributed in kilometer-scale lenses preferentially located in local depressions of the basement. Their thickness can reach up to 50 m at Saint-Vaast. They are highly detritic sediments of various origins. They contain materials from gravel to thick clays, lignified wood debris and pockets of quicksands. Due to their high clay content, they globally behave as an aquiclude. However, the isolated pockets of sand and gravel contained in the weadlen-facies sediments are water-bearing. Turonian marls constitute a relatively continuous and impervious cover over the wealden-facies sediments. Their average thickness is in the range of 20–30 m. They act as a hydraulic barrier and confine the wealden-facies sediments. The average thickness of the chalks is 60 m but can locally reach up to 100 m. The aquifer of the chalks is the main regional aquifer. It is an unconfined aquifer that is relatively heavily tapped for drinking-water pro-

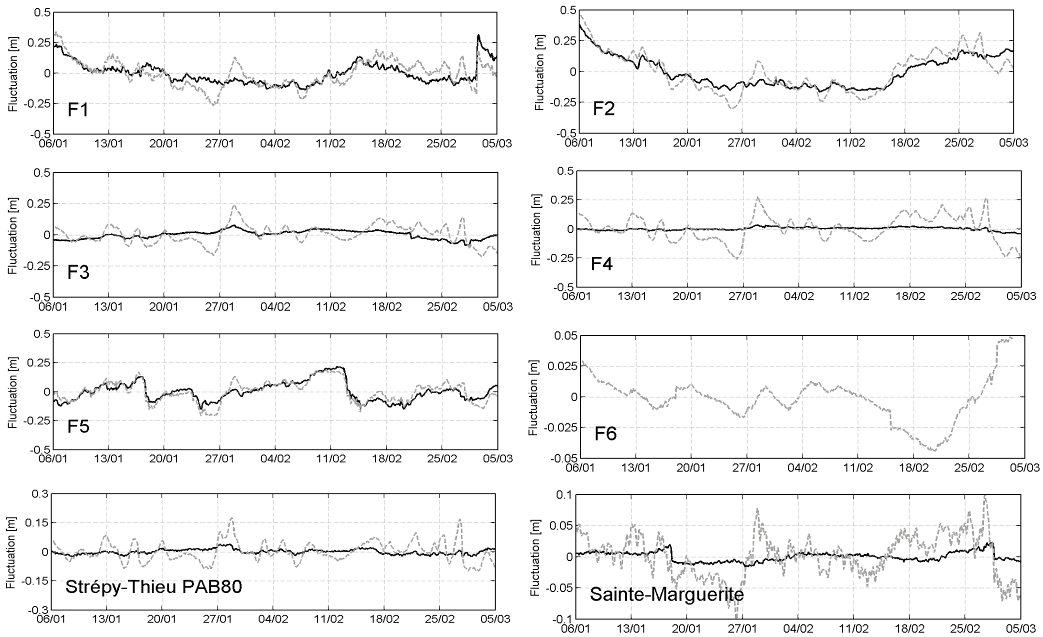

Fig. 2 *Example set of piezometric data (from January 6 to March 5, 2010). Raw data (dashed gray line) and data filtered for variations in atmospheric pressure and terrestrial attraction (black line).*

duction. Finally, tertiary sediments are mainly sands and clays.

The extent of the lenses of wealden-facies sediments at Saint-Vaast and near the boat lift of Strépy-Thieu was initially mapped by Marlière (1946; Fig. 1). Potential hydraulic connections could exist between the lens at Saint-Vaast and (i) the lens at Strépy-Thieu, as more recent log results seem to show that both lenses could be connected, (ii) the lower Carboniferous aquifer, and (iii) the upper unconfined chalk aquifer. As the wealden-facies sediment lens at Saint-Vaast is comprised between the upper clay-rich altered part of the bedrock and Turonian marls, it is expected that these hydraulic connections are of very limited magnitude. Moreover, the direct recharge area of the lens is of very limited extent (Fig. 1). All terms of the hydrogeological balance of the lens are thus expected to be relatively limited.

The initial goal of the study was to characterize hydraulic connections between aquifers at the regional scale and within the wealden-facies sediments lens at Saint-Vaast. Classical field methods based *e.g.* on pumping tests could only be used in a very limited fashion, in order to limit pressure variations in the wealden-facies sediments and avoid a new accident. Instead, correlation, spectral and wavelet analyses of piezometric data were used.

Piezometric data

Raw data

At the request of the authorities of the city of La Louvière, five piezometers (F1 to F5) were installed by the Service Public de Wallonie (the regional administration) in the wealden-facies sediments near the expected position of the abandoned tunnel (Fig. 1). Piezometric data were collected automatically using Level TROLL® probes on a 2-hour basis. As an example, detrended water levels measured between January 6 and March 5, 2010 are shown on Fig. 2. Significant correlations seem to be present, similar peaks in the raw data appearing for all five piezometers.

A sixth piezometer (F6) was installed in the shallower Cretaceous aquifer near F5 (Fig.

1), in order to gain insight into the vertical hydraulic gradient through the Turonian marls. Head difference is of the order of 9 m, yielding an ascending gradient of about 24 %. Data recorded during the example period from January 6 to March 5, 2010, are also shown on Fig. 2. Three existing piezometers tapping the chalk aquifer were identified in the vicinity of the subsided area and were also used in this study (Pz6, Pz7 and Pz8, reported on Fig. 1). Although correlation with F1 to F5 is less obvious, it seems that certain patterns also appear here.

The boat lift of Strépy-Thieu is a heavily instrumented engineering structure. Piezometric data are collected at a number of wells screened in the wealden-facies sediments, and the total discharge of the overflowing wells used to lower the water table around the basement of the lift is also continuously measured. A large number of datasets were used in this study. As an example, data recorded at well PAB80 between January 6 and March 5, 2010 is also shown on Fig. 2. A clear similarity appears with the raw data recorded at F1 to F5, seemingly supporting the assumption of a regional-scale influence of the boat lift.

Finally, a probe was also installed in the piezometer of the Sainte-Marguerite shaft, where the groundwater rebound in the mine of Péronnes-lez-Binche can be monitored. Data collected during the example time period of January 6 to March 5, 2010 are also reported on Fig. 2. Although exhibiting some high frequency fluctuation, similar peaks as in F1 to F5 also appear in the raw data collected here.

Filtering barometric and Earth tide effects

Variations in atmospheric pressure and terrestrial attraction act as distributed forces at the ground surface that can have various effects on groundwater levels, as a result of aquifer compressibility. While unconfined aquifers might not be significantly affected by such perturbations, confined aquifers will generally react to variations in atmospheric pressure and terrestrial attraction. Barometric efficiency is defined as the ratio of groundwater level fluctuations to the corresponding variations in atmospheric pressure (Batu 1998). A unit barometric efficiency expresses that the water level decreases by 1 cm when the atmospheric pressure increases by 0.98 mbar. It corresponds to a fully rigid rock matrix.

The water-bearing sand lenses in the wealden-facies sediments are confined. It was also suspected that piezometric data collected at Strépy-Thieu and in the former coal mine of Péronnes-lez-Binche could be partially influenced by such processes. The linear regression technique developed by Toll and Rasmussen (2007) was used to filter barometric and Earth tide effects. Barometric data was available at the Gosselies IRM station. Earth tide measurements were not available. Instead, a synthetic tide was generated using the software T-Soft (Van Camp and Vauterin 2005). It appears that piezometers F1 to F5 are heavily responsive to variations in atmospheric pressure. Barometric efficiencies range from 87 % for F4, 68 % for F3, 61 % for F2 and about 50 % for F1 and F5. Filtered data for the example time period of January-March 2010 are also shown on Fig. 2. There remains almost no visible fluctuation in F3 and F4. It also appears that most observed fluctuations at Strépy-Thieu are also linked to variations in atmospheric pressure. In the coal mine of Péronnes-lez-Binche, most observed mid-term fluctuations (6–24 hours) were linked to atmospheric pressure, while short-term (<6 hours) fluctuations were caused by Earth tides. The remaining jumps are of the order of one centimeter and are caused by human manipulation when performing manual checks of the measurements.

Correlation, spectral and wavelet analyses

While most visible peaks in groundwater levels were smoothed out when filtering for variations in atmospheric and terrestrial attraction, time-series analysis was conducted in order to attempt to identify correlations in the datasets. Theoretical considerations on the application of correlation, spectral and wavelet analyses to temporal data can be found *e.g.* in

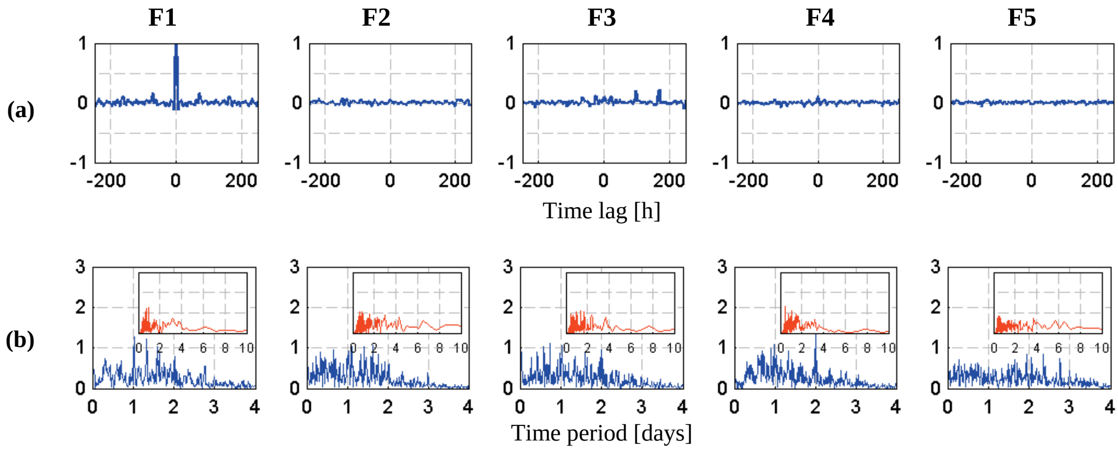

Fig. 3 *(a) Autocorrelation and cross-correlations of fluctuation rates of F1, with F1, F2, F3, F4 and F5. Data collected between November 28, 2009 and May 11, 2010. (b) Power spectral and cross-spectral densities of F1, with F1, F2, F3, F4 and F5. Densities are normalized. Densities are plotted as a function of the time period [days] (in blue) and as a function of frequency [cycle/day] (in red).*

Massei *et al.* (2006). Correlation and spectral analyses were conducted using standard Matlab® tools, and wavelet analysis was conducted using the Wavelab toolbox (Buckheit *et al.* 2005). Time series were not directly conducted on filtered piezometric data. In order to ensure data stationarity, analyses were conducted on data derivatives (*i.e.* fluctuation rates).

As an example, autocorrelation and cross-correlation functions between F1 and F2, F3, F4 and F5 are shown on Fig. 3.a. First, autocorrelation time is very small, of the order of measurement time. This indicates that fluctuations can be considered as random. Then, even though the piezometers are all screened in the wealden-facies sediments and located less than 800 m apart, no significant cross-correlation can be observed. A similar result is obtained when trying to establish correlations with data collected in the upper unconfined chalk aquifer, near the boat lift of Strépy-Thieu or in the former coal mine of Péronnes-lez-Binche. If a clear pattern appeared in the raw data, it was thus only linked to large-scale distributed forces of climatic origin simultaneously acting on all regional aquifers. Filtering for the effect of these forces removed any correlation between the time-series.

Similarly, power spectral and cross-spectral densities are shown on Fig. 3.b. The densities are plotted both as a function of the time period (in blue) and as a function of the time frequency (in red). Spectra are all relatively wide and do not exhibit any major peak. No cyclic pattern appears among the piezometer.

This led to the need to test wavelet analysis, in order to verify whether non cyclic pattern emerged in the data sets. The results are not shown here but follow the same lines: no similar type of behavior can be identified among the piezometers tapping the wealden-facies sediments and with the upper unconfined aquifer, with the aquifer at the boat lift of Strépy-Thieu or in the former coal mine of Péronnes-lez-Binche.

This is a rather disappointing result, as initial considerations and observation of raw unfiltered data led to make the assumption that regional perturbations to the groundwater system could have had an influence on water pressures within the wealden-facies sediments. Barometric effects were not directly suspected, as they affect in a much minor way unconfined aquifers and as measurements in the upper chalk aquifer (piezometer F6) seemed to show similar variations as the wealden-facies sediments aquifer. The corresponding peaks in the upper unconfined chalk aquifer were actually caused by direct recharge, a lowering of atmospheric pressure being usually accompanied by precipitations. The decreasing atmospheric pressure caused thus an increase in piezometric data in confined aquifers as a function of their barometric efficiencies, and the simultaneously-occurring precipitations caused a similar increase in the water table of the upper unconfined aquifer.

Discussion

A close examination of the boring logs of F1, F2, F3, F4 and F5 did not permit to identify any similar sequence of sand/clayey sand/sandy clay/clay. While the piezometers were all screened in sandy parts, there was thus no guarantee that they were tapping the same sand lens. Then, global trends in piezometric data (not shown here) are relatively different. Several piezometers have measured a significant decrease in water level after the accident and seem to have now stabilized. Piezometer F4 follows a very different pattern and seems to continuously increase. Piezometer F5 fluctuates much more than F1, F2, F3 and F4. A tracer test was also conducted in F1 and F2. While the flushing volume was as limited as possible (about 5 m^3), it caused a significant and persistent variation of the water level in the piezometer. The initial water level was only recovered after about 3 months. These elements allowed one to conclude that the five piezometers were tapping isolated lenses of sand, probably each of a relatively limited volume.

Hence, the wealden-facies sediments can be pictured as a series of conductive lenses embedded in a relatively impervious clay background. Recharge occurs through very limited areas and is probably extremely limited. Groundwater discharges very slowly and in very limited amounts towards the upper unconfined chalk aquifer through the Turonian marls and towards the Carboniferous aquifer and the former coal mine of Péronnes-lez-Binche through the upper altered part of the bedrock. There is no evidence of a hydraulic link with the groundwater bodies at the boat lift of Strépy-Thieu. All terms in the hydrogeological balance of the wealden-facies sediments are thus limited and it is not likely that a sudden variation in water pressure has occurred as a result of a variation in pressure in a neighbor aquifer.

Instead, the likely assumption is that water pressure slowly and gradually increased in the wealden-facies sediments, as a result of the slow and limited recharge. At some point, pressure was sufficient to overcome the mechanical resistance of the plug in the drainage tunnel, and caused its failure. This led to the sudden release of water, mud and sands. The residual voids in the wealden-facies sediments eventually resulted in the observed ground surface subsidence.

Conclusions

As an attempt to grasp a potential hydrogeological cause to the collapse of an abandoned mine drainage tunnel, time-series analysis was applied to piezometric data collected within different aquifers at a regional scale. The goal of the study was to highlight hydraulic links between aquifers and characterize the hydrogeological behavior of the wealden-facies sediments in which the tunnel was bored. Classical methods based on pumping tests or tracer tests could only be used to a limited extent in order to avoid a new accident caused by pressure variations.

The initial assumption was that either drawdowns at the boat lift of Strépy-Thieu or the groundwater rebound in a nearby abandoned coal mine caused a variation in the water pressure of the wealden-facies sediments. This hypothesis was further supported by significant correlations that were visually observed between water level fluctuations in the wealden-facies sediments and water level fluctuations in the neighbor aquifers. However, filtering barometric and Earth tide effects from piezometric data smoothed out most observed short-term fluctuations. The application of standard time series analysis techniques to filtered data failed to highlight any correlation in the data set. Correlation could not even be found between data collected in the different piezometers tapping the wealden-facies sediments at Saint-Vaast. A closer examination of available borehole logs revealed that the piezometers were probably tapping isolated more-conductive sand lenses in the wealden-facies sediments. This assumption was further supporter by the very long dissipation times that were observed after flushing one of the piezometer during a tracer test.

If a distant hydrogeological trigger was initially suspected, the final assumption is that of a very limited diffuse recharge that caused a slow and gradual increase in water pressure within the wealden-facies sediments. At some point, it is believed that the water pressure exceeded the resistance of a plug in the drainage tunnel, which failed.

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