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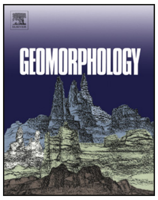

ERT, GPR, InSAR, and tracer tests to characterize karst aquifer systems under urban areas: The case of Quebec City

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ABSTRACT

Urban infrastructures built over karst settings may be at risk of collapse due to hydro-chemical erosion of underlying rock structures. In such settings, mapping cave networks and monitoring ground stability is important to assure civil safety and guide future infrastructure development decisions. However, no technique can directly and comprehensively map these hydrogeological features and monitor their stability. The most reliable method to map a cave network is through speleological exploration, which is not always possible due to restrictions, narrow corridors/passages, or high water levels. Borehole drilling is expensive and is often only performed where the presence of karsts is suggested by other techniques. Numerous indirect and cost-effective methods exist to map a karst flow system, such as geophysics, geodesy, and tracer tests. This paper presents the outcomes from a challenging application in Quebec City, Canada, where a multidisciplinary approach was designed to better understand the groundwater dynamics and cave paths.

Two tracer tests in groundwater flowing through the cave system indicated that water flows along an approximately straight path from the sinking stream to the spring. It also suggests the presence of a parallel flow path close to the one already partially mapped. This observation was confirmed by combining Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) techniques, and ultimately by observing voids in several boreholes drilled close to the main cave path. Lowering the water levels at the suspected infiltration zone and inside the karst, the infiltration cracks were identified and the hydraulic link between them was confirmed. In fact, almost no infiltration occurs into the karst system when the water level at the sinking stream drops below a threshold level. Finally, SAR interferometry (InSAR) using RADARSAT-2 images detected movements on few buildings located over a backfilled sinkhole intercepted by the karst system and confirmed the stability of the rest of the karst area. The knowledge of the flow system described in this paper is used by policy makers to assure civil security of this densely populated area.

1. Introduction

Karst aquifer systems are present throughout the world and represent 10% to 20% of Earth's surface area (Ford and Williams, 2013). Their large distribution ensures that they are regularly found under urban settings. The construction of infrastructure above karst aquifer systems, where voids frequently occur, poses major issues for civil engineering and public safety (Beck, 1984, 2002; Waltham et al., 2005; Del Prete et al., 2010). Such aquifers often have complex structures limiting their characterization. The development of voids and preferential groundwater flow paths follow various controlling factors and is difficult to predict (Chalikakis et al., 2011). No singular approach exists to map, understand, and monitor the behavior of karst systems because of their varying water saturation, depth, and shape. Consequently, complex and multidisciplinary studies involving a combination of techniques are often required to assess the associated risks to urban infrastructure.

In urban settings, geophysical methods such as seismic reflection, Electrical Resistivity Tomography (ERT) methods, and low-frequency Ground Penetrating Radar (GPR) work reasonably well (dos Reis Júnior et al., 2015). Satellite imagery interpretation by Interfrometric Synthetic Aperture Radar (InSAR) techniques are promising to detect infrastructure motion related to the erosion of underlying caves, as the abundance of hard and angular structures guarantee a high density of targets reflecting the emitted electromagnetic signal. Finally, groundwater tracer tests often

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reveal useful information regarding the groundwater flow path and dynamics.

Seismic reflection is based on the propagation of mechanical waves and specifically the body waves *P* and *S* into the ground. The method implies emitting elastic waves and monitoring their reflection over time with receivers (geophones) located at the surface. Several studies using seismic waves have helped detection of karst-related anomalies following the analysis of the propagation velocity of *P* and *S* waves (Belfer et al., 1998; Hoover, 2003; Parker, 2002). Recent developments in high-resolution seismic reflection have led to applications in urban areas (Krawczyk et al., 2013). For example, Di Fiore et al. (2013) presented its use to detect caves in Italy.

Electrical Resistivity Tomography (ERT) consists in emitting a DC current between two electrodes and measuring the difference of electric potential between two other electrodes (Roth et al., 1999; Rubin and Hubbard, 2005). The difference of electric potential *V* is interpreted using the relation between the intensity of the injected current *I*, the resistivity *R* of the ground (in Ohms), and *V*. Parameter *V* is influenced by the spatial distribution of electrical resistivity and electrode positioning at the surface. Inversion algorithms are used to assess the spatial distribution of resistivity in the ground that explains the measured electrical potential. Several types of inversions exist, and the most often used is the regularized least-squares method (Rubin and Hubbard, 2005). Ultimately, the method provides a two-dimensional section or profile of the ground resistivity and allows for the detection of anomalies such as voids which are extremely resistive.

Ground Penetrating Radar (GPR) is an ElectroMagnetic (EM) technique consisting of emitting an EM pulse into the ground within the radio frequency range (10–1000 MHz). A part of the signal is eventually back-reflected to a receiver antenna close to the emitting one when it encounters contrasts of electrical permittivity. Typically, the antenna pair is moved at the surface, and the reflected signal is constantly recorded. A measurement of EM wave intensity reflection in function of time and space is obtained. The conversion from time to depth is performed by fitting hyperbolas on the diffracted signal (Rubin and Hubbard, 2005). Typically, GPR surveys are performed along profiles. If multiple profiles are acquired in a spatially dense pattern, a 3D cube of GPR traces can be produced. It allows following the continuity of karstic channels when observed over multiple subsequent parallel 2D profiles. The technique is used by civil engineers to map underground structures. It is very sensitive to pipes and other shallow artefacts that may limit its depth of penetration and renders its interpretation complex in urban or highly heterogeneous environments.

Synthetic Aperture Radar interferometry (InSAR) is a fast-developing technique efficient to monitor ground movement (e.g., Castellazzi et al., 2016, 2017). It consists in interpreting the phase shifts between several identical EM wave signals (1–10 GHz) sent by a Synthetic Aperture Radar (SAR) satellite from the same orbital position and at different times (Massonnet and Feigl, 1998; Ferretti et al., 2001; Berardino et al., 2002). The phase shifts not related to ground motion are estimated and subtracted. Ultimately, ground displacement over time and along the satellite Line Of Sight (LOS) angle is inferred. On one hand, using InSAR as an early warning tool assumes the occurrence of precursory movements before collapse. On the other hand, identifying and mapping sinkhole collapse with InSAR is limited by our ability to convert the phase shifts into LOS distance change (solving 'the phase ambiguity') for sudden and nonlinear movements. Indeed, phase-to-displacement inversion algorithms usually rely on analysing the progressive component of phase shifts in time and/or space. In the case of sinkhole collapse, the phase difference is expected to be largely nonlinear in time and space (sudden movement over a limited area).

Despite its main limitations, several authors successfully used InSAR to detect karst-related ground movements or to observe the potential occurrence of precursory signs before collapse. Recent studies demonstrated the utility of InSAR for sinkhole detection and monitoring in natural settings (Gutiérrez et al., 2011; Atzori et al., 2015; Galve et al., 2015), in mining environments (Rucker et al., 2013), and in urban/built environments (Yerro et al., 2014). Intrieri et al. (2015) successfully used Ground-Based InSAR (GB-InSAR, which uses the same principle as InSAR on a fixed ground-based system) for early-warning of sinkhole collapse in Italy, pointing out the remaining potential offered by space-borne InSAR toward such applications.

Groundwater tracing techniques consist in adding a given mass of a traceable substance at the sinking stream and monitoring its arrival at one or several downstream springs or flow conduits. The transport times and the tracer mass balance are used to infer the occurrence of active conduits, their water flow rates, and the hydrodynamic links between the sinking stream and the springs. Kass and Behrens (1998) and Goldscheider et al. (2008) provide a complete description of the available tracers, their related applications, and the advantages and drawbacks of each. Among them, salts (which dissolve into cations and anions) and fluorescent dyes are the most used. The latter has the advantage of being visually observable and precisely quantifiable on site and in real time.

Recently, several authors performed case studies illustrating the value of combining techniques in order to improve the understanding of these complex aquifer systems. In a case study in Spain, Carbonel et al. (2014) described a multidisciplinary approach that includes a stereoscopic interpretation of aerial photos, the creation of a Digital Elevation Model (DEM) from a LIght Detection And Ranging (LIDAR) survey, a combination of GPR and ERT, InSAR, and linear excavations (exploration trenches). The authors note the importance of the geomorphological model to help with field work planning and result interpretations and to propose adapted risk mitigation measures. Lollino et al. (2015) suggested the following workflow to map and monitor caves: map geological features and define stratigraphy, interpret aerial photos and perform SAR interferometry (InSAR), drill boreholes, apply the available geophysical methods (including pilot tests to identify the right techniques), analyze water level variations, map hydraulic conductivity, estimate groundwater flow rate and direction, and identify recharge (sinking stream) and discharge (springs) areas. In another case study in Italy, Zini et al. (2015) used vertical borehole data, geotechnical surveys, GPR and seismic reflection, and hydrogeological and geochemical field investigations. They conclude that the multidisciplinary approach was essential to produce a reliable hydrogeological model, which was impossible using one method alone. Galvão et al. (2015) classified a karst system into five zones of risk according to the geological and hydrological conditions. The classification was based upon the analysis of aerial photos, the lithological profiles from boreholes, the optical inspection of boreholes with downhole camera, and a geological map.

The approach proposed in this study is inspired by previous multidisciplinary works (Cooper and Calow, 1998; Carbonel et al., 2014; Lollino et al., 2015; Zini et al., 2015) and involves a selection of techniques relevant in urban settings. It includes InSAR to detect ground movement, seismic reflection, a combined GPR/ERT survey to detect voids and cave, the drilling of boreholes on anomalies detected through geophysical methods, a hydrodynamic test with field monitoring of water level changes at the inflow/outflow of the system and inside the caves, and groundwater tracer tests to assess the spatial hydrodynamics of the aquifer system.

2. Study area

In spring 2013, a sinkhole appeared in the backyard of an apartment building in Quebec City, Canada, leading to the evacuation of four neighbouring buildings. Some of them showed signs of past ground movements, such as cracks on walls. The instability occurred over a ~6-m-thick and heterogeneous sediment backfill. Sediments were used there to fill a ~100-m-wide hole that appeared by collapse of a void created by hydrochemical erosion within the karst system and/or by the exploitation of a quarry (the history of the site is not entirely known). We assumed that the saturated portion of the backfill erodes