Tracer tests, hydrochemical and microbiological investigations as a basis for groundwater protection in a remote tropical mountainous karst area, Vietnam

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Abstract The Tam Duong karst area in NW Vietnam is among the poorest and remotest regions in the country. The local population largely depends on water from two main karst springs. Due to agricultural activity and untreated domestic wastewaters, the spring water is often microbiologically contaminated. In order to provide a scientific basis for groundwater protection in the area, different field methods have been applied including hydrogeological framework investigations, tracer tests, and hydrochemical and microbiological sampling and analyses. All methods had to be adapted to the conditions of a poor and remote area. These adaptations included, amongst other measures, the use of a portable microbiological water_testing kit and the involvement of the local population in the sampling campaign. The tracer tests showed simple and direct connections between two important swallow holes and the two main springs, and made it possible to determine the linear groundwater flow velocities, which are extremely high (up to 875 m/h). The hydrochemical and microbiological data confirmed the strong impact of the streams sinking into the swallow holes on the spring water quality. Future groundwater source protection strategies should consequently focus on the reduction of polluting activities near the sinking streams and within their catchment areas.

Resumen El área kárstica Tam Duong al noroeste de Vietnam se encuentra entre las más pobres y remotas del país. La población local depende fuertemente del agua de dos manantiales kársticos principales. El agua del manantial se contamina frecuentemente con microbios por la extensa actividad agrícola y la descarga de aguas residuales domésticas sin ningún tratamiento. Para aportar bases científicas en la protección del agua subterránea del área se han aplicado diferentes métodos de campo incluyendo investigaciones del marco hidrogeológico, pruebas con trazadores, muestreo y análisis microbiológico e hidroquímico. Todos los métodos tuvieron que adaptarse a las condiciones pobres y remotas del área. Estas adaptaciones incluye, entre otras medidas, el uso de un kit manual de evaluación microbiológica del agua y el involucramiento de la población local en la campaña de muestreo. Las pruebas con trazadores mostraron una conexión directa y simple entre dos pozos someros importantes y los dos manantiales principales, haciendo posible determinar las velocidades lineares de flujo de agua subterránea las cuales fueron bastante altas (hasta 875 m/h). Los datos hidroquímicos y microbiológicos confirman el impacto fuerte de los arroyos hundidos en los pozos someros y en la calidad de agua del manantial. Las estrategias futuras de protección de agua subterránea deberían por lo tanto enfocarse en la reducción de actividades contaminantes cerca de los arroyos hundidos y dentro de sus áreas de drenaje.

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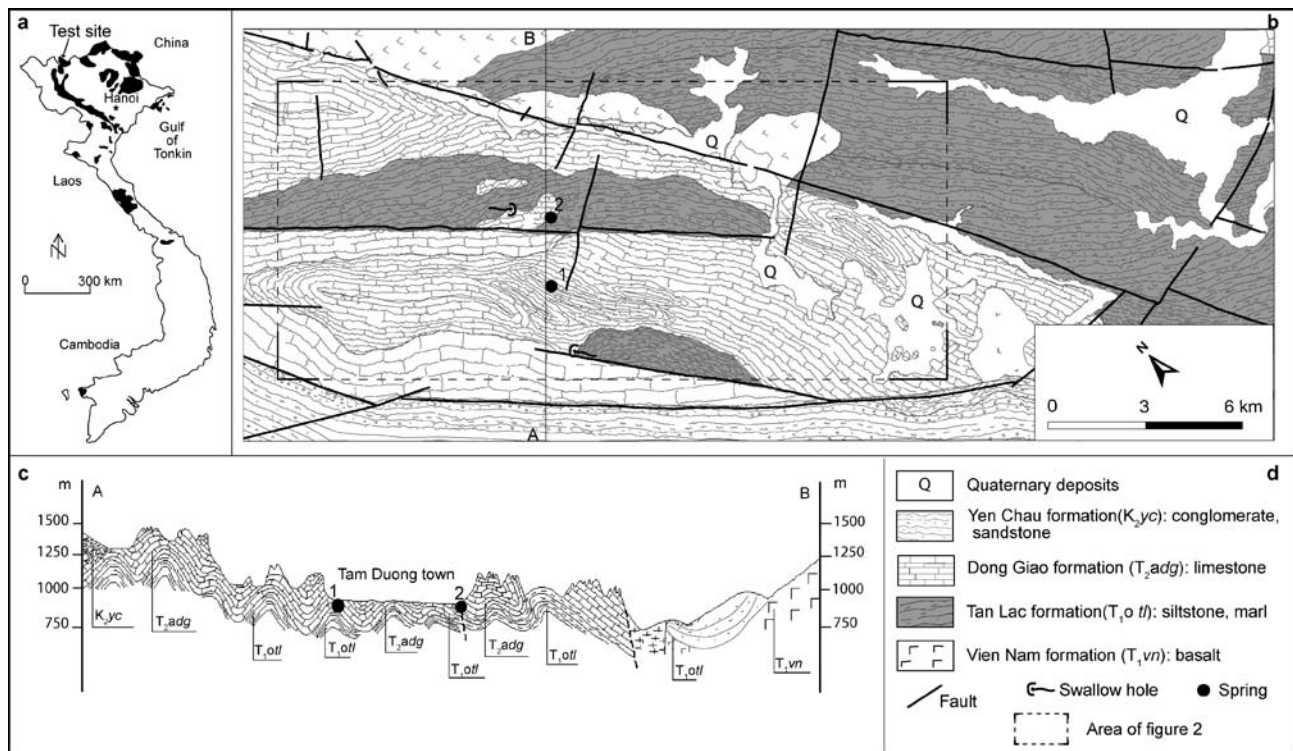e-mail: nico.goldscheider@unine.ch

Résumé La zone karstique de Tam Duong, au NO du Vietnam, fait partie des régions les plus pauvres et les plus reculées du pays. La population locale est largement dépendante de l'eau provenant de deux principales sources karstiques. En raison de la variété des activités agricoles et des eaux usées domestiques non traitées, l'eau de source subit souvent une contamination microbiologique. Afin de fournir une base scientifique pour la protection de l'eau souterraine dans cette zone, différentes méthodes de terrain ont été appliquées comprenant des investigations de base en hydrogéologie, des essais de traçage ainsi qu'un échantillonnage et des analyses hydrochimiques et microbiologiques. Toutes ces méthodes ont dû être adaptées aux conditions de cette zone pauvre et reculée. Ces adaptations ont inclus, parmi d'autres mesures, l'utilisation d'un kit portatif pour la microbiologie de l'eau et la participation de la population locale à la campagne d'échantillonnage. Les essais de traçage ont montré les connections simples et directes entre deux importantes pertes et les deux sources

Fig. 1 **a** Map of Vietnam with carbonate (karst) areas in black and location of the test site. **b** Geological map of the Tam Duong area with location of the two most important swallow holes and springs; the *dashed rectangle* indicates the location of the maps in Figs. 2 and 3. **c** Geological cross-section with location of springs 1 and 2. **d** Legend of the map and section. Modified according to VIBEKAP (2003)

principales, et ils ont rendu possible la détermination des vitesses d'écoulement de l'eau souterraine, qui sont extrêmement élevées (jusqu'à 875 m/h). Les données hydrochimiques et microbiologiques ont confirmé le fort impact des cours d'eau plongeant dans les pertes sur la qualité de l'eau de source. En conséquence, les futures stratégies de protection de l'eau souterraine devraient se concentrer sur la réduction des activités polluantes à proximité des ruisseaux qui s'infiltrent et à l'intérieur du bassin versant.

Introduction

Carbonate rocks cover about 215,000 km^2 or 10% of the land surface of mainland Southeast Asia including some of the world's most spectacular tropical karst landscapes (Mouret 2004). Many of these karst areas hold important groundwater resources that are used as drinking water, for agriculture and industry. At the same time, karst aquifers are vulnerable to contamination resulting from human activity. Contaminants can easily reach the groundwater through thin soils or via swallow holes, and are rapidly transported over large distances in the conduit network (Vesper et al. 2001). Microbial pathogens are often the most problematic

contaminants (Auckenthaler and Huggenberger 2003; Dussart-Baptista et al. 2003). Karst groundwater thus needs special protection. Tracer tests, hydrochemical and microbiological investigations are suitable methods for providing a scientific basis for the development of sustainable groundwater protection schemes (Bakalowicz 2005; Drew and Hötzl 1999).

The application of these techniques requires considerable financial, logistic and technical efforts including spring water monitoring and sampling, cooling and transport of the samples, and sophisticated analyses in microbiological and hydrochemical laboratories. In rich countries, these facilities are usually available. In developing countries and remote areas, however, such investigations are a challenge and require special methodological adaptations.

The Tam Duong karst area in NW Vietnam is among the poorest and remotest regions in the country (Fig. 1). It takes more than one day to get from Hanoi to the test site. The local population largely depends on water from karst springs, which is also used for irrigation, fishponds and a tea factory. Some years ago, Tam Duong used to be a small town with roughly 5,000 inhabitants. At the beginning of 2004, the provincial government decided to split up the existing province into two new provinces and proposed that Tam Duong should be the capital of the newly created Lai Chau province. Since then, many people have been moving to the town and there is construction work all around. At the end of 2004, about

10,000 people were living in Tam Duong, and the town is continuing to grow. This means that both the freshwater demand and the land-use pressure are increasing.

The study presented in this paper is aimed at providing a scientific basis for groundwater protection in the Tam Duong area, and at better understanding the variability of microbial and hydrochemical water quality in tropical karst aquifer systems. The study was prepared within the framework of cooperation between the Research Institute of Geology and Mineral Resources (RIGMR) in Hanoi and the Centre for Hydrogeology at the University of Neuchâtel (CHYN) in Switzerland. It was the first detailed hydrogeological study in the region and included field-work in summer 2004 and subsequent laboratory work at the CHYN. The applied methods include hydrogeological mapping, hydrochemical and microbiological sampling and analyses, and a multi-tracer test. The methodology had to be adapted to the condition of a poor and remote tropical area. The local population helped with the sampling during the tracer test and thus contributed to the success of this study.

In recent years, several karst areas in Northern Vietnam have been studied within the framework of the Vietnam-ese-Belgian Karst Project (VIBEKAP), which includes speleological, geomorphological and hydrological investigations, remote sensing, geographic information systems (GIS), flooding prediction and other aspects and methods (Liu et al. 2004; Nguyet et al. 2004a; Tam et al. 2001, 2004, 2005; Hung et al. 2002). Previous activities in the Tam Duong area focused on speleological investigations, because Vietnam's deepest cave, the 600-m-deep Cong Nuoc cave, is located in the area (Dusar et al. 1994; BVSE 2002; VIBEKAP 2003).

Test site description and framework investigations

Geographical and climatic overview

The test site belongs to a large karst region in NW Vietnam that extends from the Chinese border towards the Gulf of Tonkin and covers about 8,200 km^2 (Tuyet 1998). Tam Duong town is located in a NW–SE tending valley at an altitude of 800 m. The steep conical hills at both sides of the valley, up to 1,400 m in altitude, also belong to the test site (Fig. 1).

The climate is tropical humid with an annual precipitation of 2,600 mm, most of which falls during the rainy season from May to October. The average annual air temperature is 20°C with a maximum in July to August and a minimum in December to January (weather station Tam Duong, 1996–2000, personal communication).

Geological framework

The mountain ranges in NW Vietnam were essentially formed during the Indian-Eurasian collision since the Eocene and can be considered as a prolongation of the Himalayans. East of the main collision zone, crustal blocks escaped along strike-slip faults in an easterly direction. As the Indian plate progressed northwards, these faults often changed from left to right lateral movement; there was also temporal and spatial change from extension to compression (Tapponier et al. 1986). Northwest Vietnam is thus characterised by NW–SE tending faults, fold belts, and pull-apart basins. The faults cut the crust into slices that are difficult to connect due to important displacements. The Red River Fault, one of the major tectonic features in SE Asia, runs through NW Vietnam, adjacent to the Tam Duong area (Tri et al. 1977).

The studied area is formed of Triassic to Cretaceous sedimentary rocks. The Early Triassic Tan Lac formation is 300–600 m thick and predominantly consists of marl. The most prominent rocks are the 300–800-m-thick limestones of the Middle Triassic Dong Giao formation. The conglomerates and sandstones of the Cretaceous Yen Chau formation form the SW margin of the test site. To the NE, there is fault contact to the Vien Nam formation, mainly consisting of basalt. Shallow Quaternary gravel, sand and clay deposits locally cover the valleys. Structurally, the region is characterised by NW–SE tending folds. Most folds are entirely formed of Dong Giao limestone. The underlying marls are exposed along two large anticlines. Two main fault directions can be observed in the area: NW–SE and NE–SW, resulting from paleo- and neo-tectonic activity (My 1978; Thu and Ban 1996). There is important mineralisation in the sedimentary sequence, consisting of fluorite, barite and others. High contents of rare earth elements (REE) were found in these mineral deposits (Japanese Mining Project 2002).

Karst development and basic hydrogeological characteristics

The Dong Giao limestone is intensively karstified, and the test site represents a typical tropical tower karst landscape. The towers have the form of steep conical hills, which are often aligned and form peak clusters or isolated towers (Tuyet 1998). The 600-m-deep Cong Nuoc cave and many other caves are located in the area (Dusar et al. 1994; BVSE 2002). There are many dolines, some of which act as swallow holes. In most parts of the area, the karstified rocks are covered by shallow loamy soils and overgrown by vegetation. Epikarst development can be observed in road exposures and in quarries.

Hydrogeologically, the area is characterised by a thick karst aquifer (Dong Giao limestone) on top of a regional aquiclude (Tan Lac marl). Within the test site, the marls are exposed along the cores of two anticlines. Northeast of the main fault limiting the karst area, wide parts of the land surface consist of marls overlying basaltic rocks. These zones drain by surface runoff, while the limestone areas generally drain underground. Quaternary deposits are thin and restricted to small areas, and play no significant role for the regional hydrogeology.
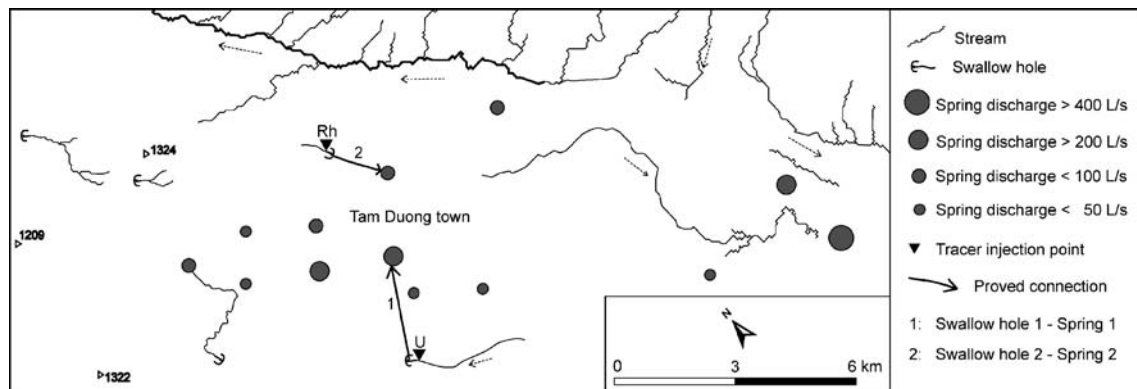
Fig. 2 Surface waters, springs and swallow holes in the study area. The tracer injection points and the underground connections proved by the tracer tests are also shown. For location of the map see Fig. 1b

Surface waters, springs and swallow holes

Most surface waters in the Tam Duong area flow over non-carbonate rocks (compare Figs. 1 and 2). The largest river developed on Tan Lac marl and Vien Nam basalt and flows parallel to the fault that forms the NE limit of the karst area. Surface streams often sink into swallow holes when they reach the karst area. These swallow holes are located at faults and/or near the contact between non-carbonate and karstified carbonate rocks. Most springs in the area discharge from the Dong Giao karst aquifer.

The study presented in this paper mainly focused on two karst springs (Dau Nguon Sin Ho and Nha May Che), which are simply named spring 1 and spring 2. During the observation period in summer 2004, the water level at both springs was manually recorded on a daily basis. At spring 1, the discharge was measured at intervals using the salt-dilution method (Käss 1998). For practical reasons, such measurements were not possible at spring 2. The discharge at this spring was thus estimated on the basis of channel width, water level and flow velocity. At the other springs in the area, the discharge was estimated and/or measured occasionally using different methods. The water level and discharge data presented in this paper only apply for the observation period; much higher and lower values are expected to occur during different hydrological conditions.

Spring 1 is situated at the SW margin of the Tam Duong Valley Basin at an altitude of 850 m. It is used as a drinking water source for a part of the town. Geologically, it is located near the axis of an anticline, where the aquifer thickness is reduced. During the observation period, the discharge varied between about 200 and 400 L/s. Spring 2 is located at the same altitude on the other side of the valley, near a major fault and close to the contact of marl and limestone. The observed flow rate ranges between 50 and 100 L/s. Spring 2 is used as a drinking water source for the town and for a nearby tea factory.

Hydrogeological and speleological observations already indicated that the two springs are connected to two swallow holes, a hypothesis that was later confirmed by tracer tests (see below). Swallow hole 1 (Nung Nang) is located 3.0 km SW of spring 1, and swallow hole 2 (Suoi Thau) is 1.75 km NW of spring 2, both at an altitude of 1,000 m. The catchment areas of the two sinking streams consist of marl, which is exposed in the cores of two anticlines. The two swallow holes are located near the
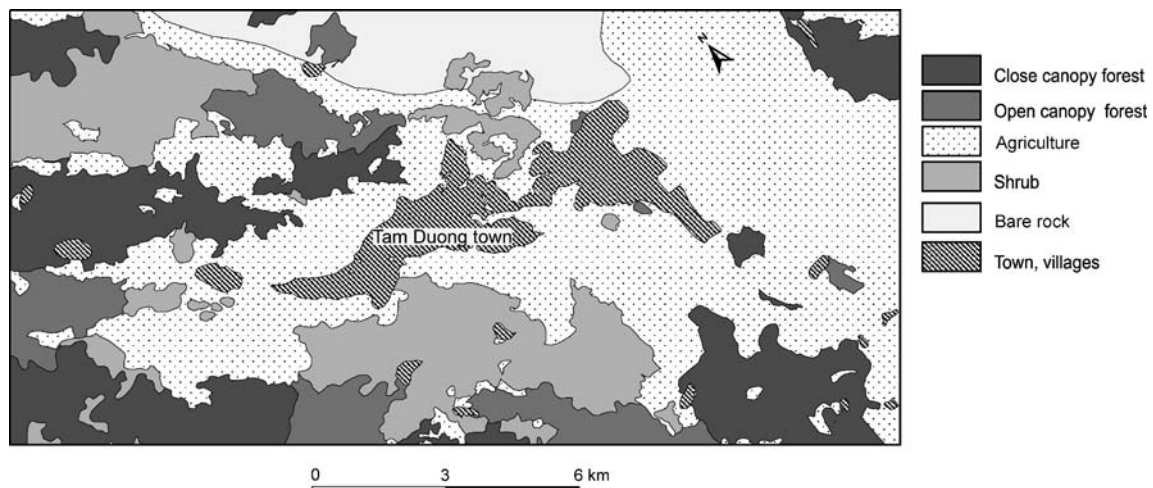

Fig. 3 Vegetation and land-use activities in the Tam Duong area. The map area is identical to Fig. 2

stratigraphic contact between the marl and the overlying limestone. Due to their difficult accessibility, no flow measurements were carried out at the swallow holes. The estimated discharge of the sinking streams during the observation period was 70–120 L/s at swallow hole 1, and 30–60 L/s at swallow hole 2.

Land use activities and contamination hazards

The land use and vegetation in the Tam Duong area can be classified into forest, agriculture, shrub, bare rock, town and villages (Fig. 3). Close and open canopy forest is preserved in the mountains and occupies approximately 26% of the area. Agricultural land uses predominate in the main valley of Tam Duong and in the higher valleys, occupying 43% of the area. Rice paddies and tea plantings are the most important regional agricultural products. There are also vegetable and fruit plantings, as well as cattle pasture and numerous fishponds that are often directly located at the springs. Settlements occupy 7% of the area. The town and some villages are situated in the central valley; other villages are located in the higher valleys.

The contamination hazards are concentrated in the agricultural and settlement areas. Possible contaminants include microbial pathogens, pesticides, and a wide range of organic and inorganic pollutants, such as gasoline. Pathogen contamination may originate from untreated domestic wastewaters, various agricultural activities and waste dumping. A hospital, a tea factory and two gasoline stations in the town are also possible sources of contamination.

Multi-tracer test

Objectives and overview

Tracer tests make it possible to obtain information on the underground flow pattern and the spring catchment areas, which is crucial for the development of groundwater source protection strategies. A multi-tracer test was carried out in the test site in order to:

– Confirm or refute the assumed connection between swallow hole 1 and spring 1, and between swallow hole 2 and spring 2 (Fig. 2)
– Quantify the proportion of water from the swallow holes that resurges at the springs
– Check if there is connection between the swallow holes and other springs in the area
– Determine the linear groundwater flow velocities and characterise contaminant transport in the karst conduit network

The two swallow holes were selected as injection points, while the karst springs were sampled to observe a possible tracer arrival. The common methodology of groundwater tracing had to be adapted to the conditions of a poor and remote tropical karst area.

Adaptation of the method and experimental design

Some fluorescent dyes are among the best groundwater tracers. Due to their extremely low detection limits (e.g. uranine: 0.005 µg/L), only small injection quantities are required (Käss 1998). This makes it possible to use fluorescent dyes even in remote and mountainous areas with limited transport facilities. For the tracer tests in the Tam Duong area, separate containers containing 500 g of uranine and 500 g of rhodamine B were prepared. The containers with the dry powder were carried to the injection points and dissolved on site in buckets full of water. On the 9 September 2004, uranine was injected into swallow hole 1 and rhodamine B into swallow hole 2.

There are three different monitoring strategies for fluorescent dyes: continuous measurement using a field fluorimeter, discrete water sampling, which can be done with an automatic sampler or manually, and integrative sampling with charcoal bags. The installation of field fluorimeters and automatic samplers was not considered in the test site, as these expensive instruments were not available in the region. Käss (1998) recommends 50-ml brown glass bottles for manual water sampling; the samples must be stored in the dark as most dyes decay when exposed to daylight. However, a large number of water filled glass bottles are heavy and expensive to transport. 'Lightproof' 13 ml plastic test tubes were thus used for sampling. A total of 96 water samples were taken during the tracer test, which means only about 1.3 kg of weight. Charcoal bags are also lightweight and stable when dry.

At the two main springs, water samples were taken at short time-intervals, ranging from 30 min to several hours. Charcoal bags were installed at ten other springs. Local people and the local army division did the sampling, perfectly following the instructions. The samples were transported to the CHYN laboratory and analysed with a spectrofluorimeter (PERKIN ELMER LS 50 B).

Results

The uranine that was injected into swallow hole 1 arrived only at spring 1, and the rhodamine B that was injected into swallow hole 2 reappeared only at spring 2 (Fig. 2). No trace of the two dyes was detected at any other sampling point in the area.

Uranine first arrived 41.5 h after injection and reached a maximum of 21.3 µg/L after 53.5 h (Fig. 4a; please note: all given time values are hours after injection). The distance between the swallow hole and the spring is 3,000 m, and so the maximum linear flow velocity is 72 m/h while the dominant flow velocity is 56 m/h. After roughly 200 h, the tracer breakthrough was completed, i.e. the concentration dropped below detection limit.

Rhodamine B first arrived at spring 2 between 2.0 and 2.5 h after the injection (Fig. 4b). As the sampling interval was 30 min, the time of first arrival cannot be determined more precisely. The highest concentration, 1,242 µg/L, was measured in a water sample taken after 3.0 h; the maximum must thus have occurred between 2.5 and 3.0 h.
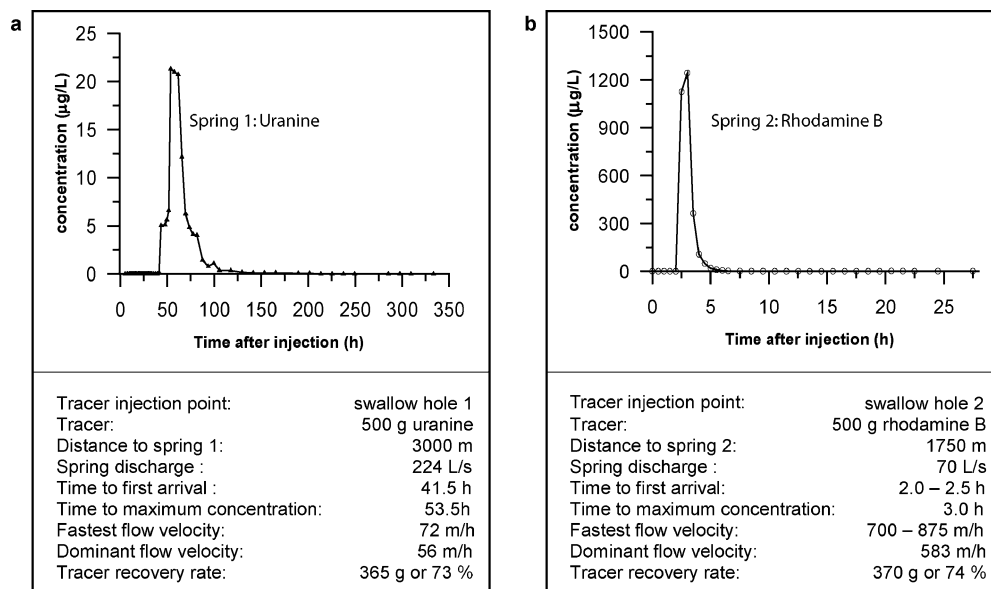
Fig. 4 Results of the multi-tracer test in the Tam Duong area: **a** spring 1 with uranine, **b** spring 2 with rhodamine B

The distance between the swallow hole and the spring is 1,750 m. The maximum linear flow velocity thus ranges between 700 and 875 m/h, while the dominant linear velocity ranges between 583 and 700 m/h. After 10.5 h, the concentration dropped below the detection limit.

The precise calculation of the tracer recovery requires continuous discharge data. As such data are not available, single flow measurements or estimations had to be used (see above). The approximate tracer recovery was then calculated by multiplying the discharge value with the area below the corresponding tracer breakthrough curve. At spring 1, a discharge of 224 L/s was measured on 10 September 2004. The calculated uranine recovery at spring 1 is 365 g or 73%. The estimated discharge at spring 2 during the tracer breakthrough was about 70 L/s, and the calculated tracer recovery for rhodamine B is 370 g or 74%.

For questions of groundwater protection, it is also interesting to estimate the percentage of spring discharge (P_Q) that can be attributed to the sinking stream flow. Assuming conservative tracer behaviour, this can be done using the following formula:

$$P_Q = R \cdot \frac{Q_{swh}}{Q_{sp}} \qquad (1)$$

where R is the tracer recovery rate (%), Q_{swh} is the discharge at the swallow hole where the tracer has been injected (L/s), and Q_{sp} is the discharge at the spring (L/s). During the tracer test, the estimated flow rates were 90 L/s at swallow hole 1 and 40 L/s at swallow hole 2. This means that 29% of the discharge of spring 1 can be attributed to swallow hole 1, while approximately 42% of the discharge of spring 2 originates from swallow hole 2. Although these calculations are based on estimated discharge values, it is possible to state that a significant proportion of the spring water originates from the corresponding sinking stream.

Hydrochemistry

Objectives and overview
The WHO (2004) guidelines for drinking-water quality defines limits for a variety of water constituents, including dissolved inorganic compounds like nitrate (50 mg/L). The research programme in the Tam Duong area thus included hydrochemical analyses that aimed at characterising spring water quality and its spatial and temporal variability. Another objective was to obtain information on geochemical aquifer properties, groundwater residence times and mixing processes between different water types, in other words, to use the chemical compounds as natural tracers (Scanlon 1990; Vaute et al. 1997).

Adaptation of the method, sampling strategy and analyses
Standard hydrochemical investigations for dissolved inorganic compounds usually comprise measurements in the field, water sampling and laboratory analyses. Field measurements in the test site included pH, temperature (T) and specific electrical conductivity (EC). Turbidity was measured visually using a simple turbidity tube. The monitoring of spring discharge and water level has been described above in the section on surface waters, springs and swallow holes.

Inorganic cations are usually analysed in filtered and acidified 100 ml water samples; filtered samples of 500 ml are often used for anions. Bicarbonate (HCO_3^-) is the dominant anion in many karst waters (Dreybrodt 2000). Inorganic carbon species, i.e. HCO_3^-, CO_3^{2-} and CO_2, are
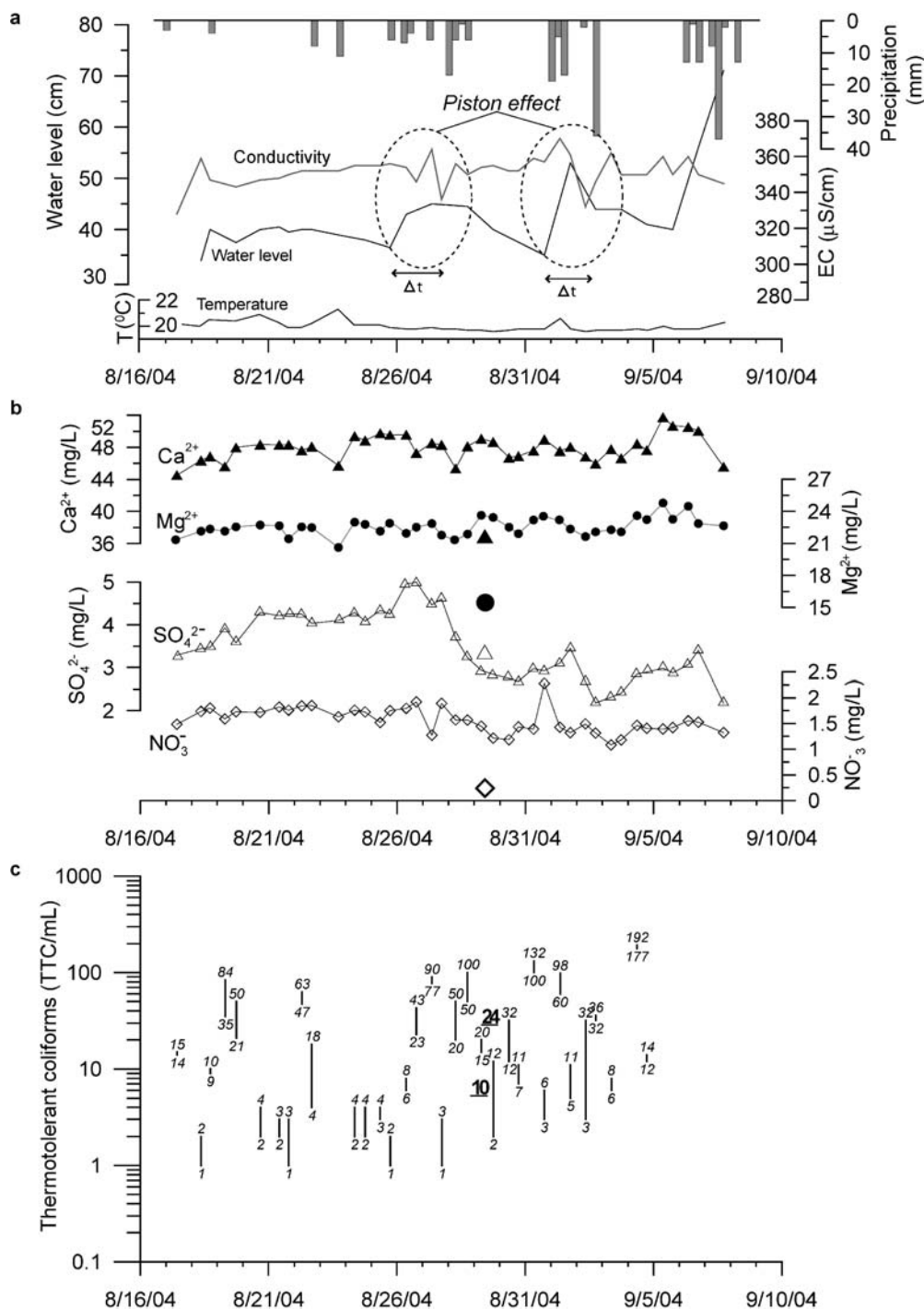
Fig. 5 **a** Precipitation in the Tam Duong area and observed variations of water level, electrical conductdivity (EC), temperature, **b** selected hydrochemical parameters, and **c** thermotolerant coliforms (TTC) at spring 1. The large symbols (*circle, triangles, diamond*) in **b** and the *bold underlined numbers* in **c** represent the hydrochemical and microbial parameters measured in a water sample taken at swallow hole 1 on 29 August 2004

generally analysed by means of titration with HCl and NaOH respectively. This can be done directly in the field or in large (e.g. 500 ml) untreated water samples that must be stored cool and analysed as soon as possible (Dean 1995; Drever 1997).

At the test site, it was not practicable to collect a large number of heavy water samples, store them cool and

transport them to a laboratory. Therefore, 13 ml plastic test tubes were used for sampling. The samples for the cations were filtered and acidified; the samples for the anions were only filtered. In the CHYN laboratory, the samples were analysed for Ca^{2+}, Mg^{2+}, Na^+, K^+, NH_4^+, SO_4^{2-}, Cl^-, NO_3^-, NO_2^- and F^- using ion chromatograph (DIONEX DX-120). Inorganic carbonate species were not measured, as
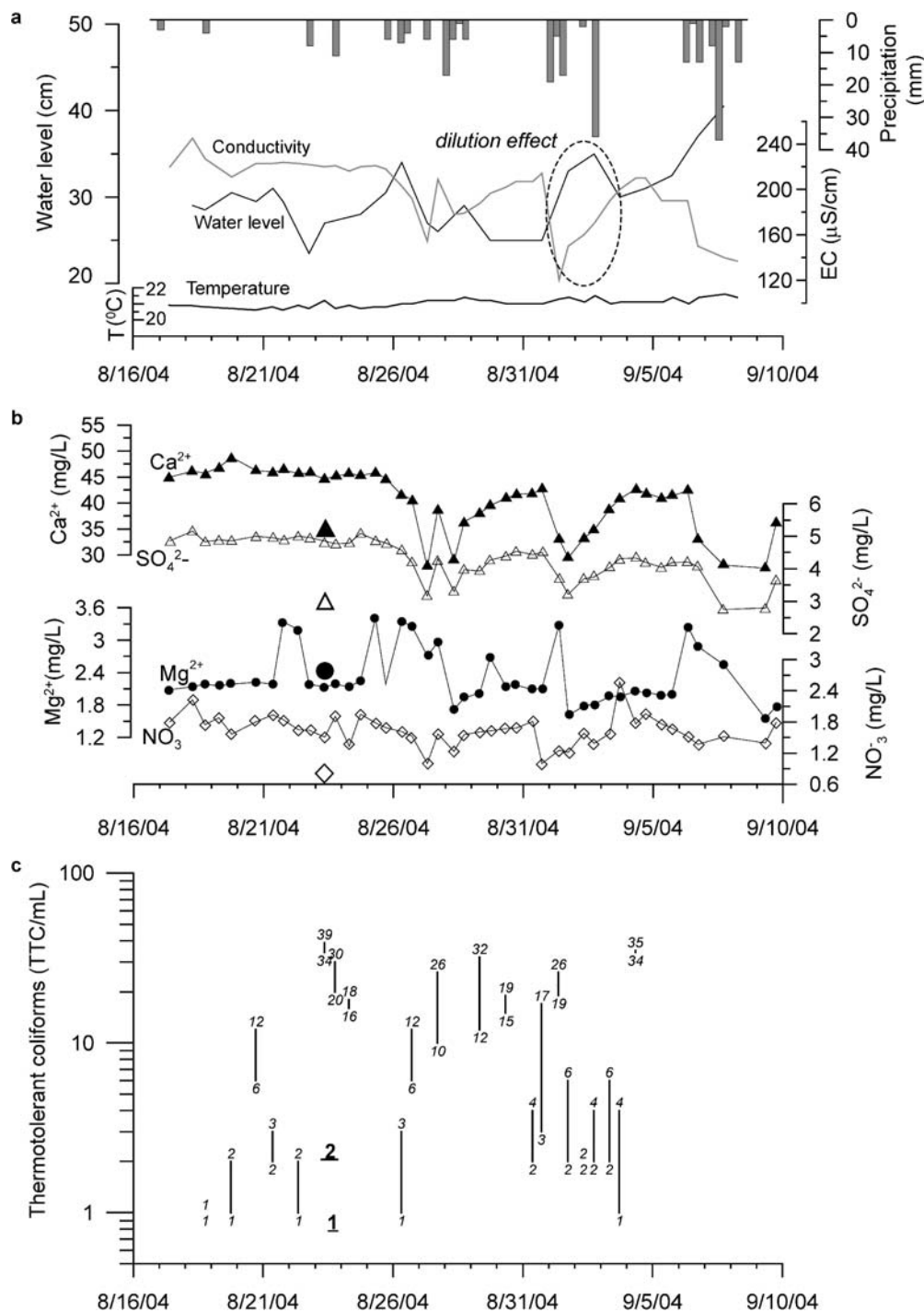
Fig. 6 **a** Variations of water level, electrical conductivity (EC), temperature, **b** hydrochemical and **c** microbiological parameters at spring 2. The large symbols (*circle, triangles, diamond*) in **b** and *bold underlined numbers* in **c** represent a sample taken at swallow hole 2 on 23 August 2004

this would have required additional field equipment or larger sample volumes. HCO_3^- was thus calculated on the basis of the ion balance, CO_3^{2-} is not relevant at pH<8.2, and CO_2 does not contribute to the ion balance.

Karst spring chemographs often show strong and rapid reactions on hydrologic events and contaminant release (Panno et al. 2001; Ryan and Meiman 1996). In most cases, it is thus insufficient to analyse only a single water

sample. On the other hand, it is not practicable to sample in short time-intervals at all springs. The temporal-spatial sampling strategy thus needs to be adapted to the local conditions, the goals of the study, and the budget.

As described above, the study in the Tam Duong area focused on the two most important springs. During the observation period (17 August 2004–9 September 2004), two samples per day were taken at these springs. Field

data (temperature, EC, pH, water level) were collected at each sampling event; turbidity was measured occasionally. Several rainfall events occurred during the observation period, and so it was possible to record the variability of the different parameters. Only one sample was taken at 15 other sites in the area, including the two main swallow holes, in order to get an overview of the spatial distribution of the hydrochemical characteristics.

Results

The hydrographs and chemographs of spring 1 (Fig. 5) and spring 2 (Fig. 6) show many similarities but also significant differences. At both springs, Ca^{2+} is the dominant cation and HCO_3^- (calculated from the ion balance; not shown) is the dominant anion. Other important cations in the order of decreasing concentration are Mg^{2+}, Na^+ and K^+, while SO_4^{2-}, NO_3^- and Cl^- are the most relevant anions. Nitrate concentrations at both springs range between 1.0 and 2.6 mg/L, far below the WHO standard of 50 mg/L. Ammonium and nitrite are below the detection limits (0.01 mg/L) in almost all samples. Fluoride concentrations of up to 0.8 mg/L were measured. This is below the WHO standard of 1.5 mg/L but higher than typical values for groundwater from limestone aquifers (Drever 1997; Saxena and Ahmed 2003). The elevated fluoride concentrations can be explained by the presence of hydrothermal fluorite mineralisation in the area, often visible as violet crystals in the limestone.

The main difference between the two springs is the Mg^{2+} content. At spring 1, Mg^{2+} concentrations range between 21.3 and 24.8 mg/L, while only 1.6 to 3.4 mg/L were found in spring 2. Magnesium was also analysed in samples from the two swallow holes. In swallow hole 1, 15.4 mg/L Mg^{2+} was measured, while only 2.4 mg/L was found in swallow hole 2. The different concentrations at the springs can thus partly be attributed to the geochemical characteristics of the sinking stream catchments.

The two springs show a high temporal variability of all hydrologic, physical and chemical parameters. However, spring 2 shows a higher variability than spring 1, this means it reacts more rapidly and strongly on hydrologic events.

After heavy rainfall events, the discharge (measured as water level) at spring 1 increases, and EC increases almost simultaneously. This observation indicates the arrival of higher mineralised water from deeper zones of the aquifer due to increasing hydraulic pressure in the aquifer. About 40 h after this first increase of spring discharge, EC decreases significantly, which indicates the arrival of freshly infiltrated water from swallow hole 1. This type of behaviour is known as a piston effect (Ford and Williams 1989). The time lag between the precipitation event and the arrival of fresh water at the spring roughly corresponds to the tracer travel time from the swallow hole to the spring 1 (see above). Spring 2 reacts differently. Discharge increases almost immediately after

a precipitation event while EC decreases. This dilution effect indicates the rapid arrival of rainwater at the spring.

Hydrochemical data from the other sampling sites are similar to those found at the two main springs. Slightly elevated nitrate concentrations were found at two springs that are close to rice paddies, 11.4 and 13.1 mg/L, which is still below the limits defined by the WHO (2004).

Microbiology

Objectives and overview

Waterborne microbial infections pose a major threat to human health, mainly in developing countries (WHO 2004). However, most microorganisms in groundwater are harmless, and some play important roles in natural attenuation processes (Chapell 2001; Goldscheider et al. 2006; Smets et al. 2002). Pathogenic microorganisms most often originate from faecal contamination at or near the land surface. The presence of faecal bacteria in the water thus indicates the possible presence of microbial pathogens including bacteria, protozoans and viruses (Auckenthaler and Huggenberger 2003). Karst aquifers are particularly vulnerable to microbial contamination. In rural karst areas, this type of contamination is often the only water quality problem, while chemical contaminants are not evident (Boyer and Pasquarell 1999; Mahler et al. 2000; Pasquarell and Boyer 1995).

One of the main goals of the study in the Tam Duong area was to characterise the microbial spring water quality and to better understand the occurrence, transport and variability of microorganisms in tropical karst aquifer systems. Therefore, microbiological water analyses played a crucial role within the framework of this study. In karst spring waters, microbiological parameters are often extremely variable. In some cases, it was possible to establish correlation between microbiological parameters on one hand and hydrologic, physical and hydrochemical parameters on the other hand, for example precipitation, discharge, turbidity, DOC or nitrate (Auckenthaler et al. 2002; Pronk et al. 2006). Therefore, the study in the Tam Duong area also aimed at identifying parameters that could be used as indicators for the presence of microbial pathogens.

Adaptation and application of the method

Microbiological analyses usually require sterile water sampling, cooling of the samples, and rapid transport to a microbiological laboratory (Hurst et al. 2002). In a poor, tropical and remote area like Tam Duong, such procedure is nearly impossible. Therefore, the portable water testing kit OXFAM-DELAGUA (2004) was used. This equipment is designed to test for the critical parameters specified in the WHO guidelines (2004).

The testing kit can be used to analyse for different types of indicator bacteria by varying the cultivation conditions, i.e. the growth medium, incubation temper-

ature and time. In the Tam Duong area, the samples were analysed for thermotolerant coliforms (TTC), as these are considered to be of high sanitary significance (WHO 2004). According to the WHO standards, thermotolerant coliforms must be absent in a 100-ml water sample.

The first step of the analysis is to pass a defined water volume through a sterile filter, which is then placed on a paper pad soaked in liquid growth medium. After 16–18 h of incubation at 44°C, the colonies are counted. The result is given in TTC/ml. Sampling volumes between 1 and 100 ml can be chosen dependent on the bacteria content. In order to minimise counting errors, each water sample was analysed at least in two different volumes. The sampling strategy for the microbiological investigations was the same as described for the hydrochemical sampling: Two samples per day were taken at the two main springs; only one sample was taken at the two swallow holes and the other springs in the area.

Results

The results of the microbiological investigations at the two main springs are presented in Figs. 5 and 6, together with the hydrological and hydrochemical data. As mentioned above, each sample was analysed in two different sampling volumes; the results from both analyses are presented in order to illustrate the reproducibility of the method. All samples taken at springs 1 and 2 contained thermotolerant coliforms and thus exceed the WHO standards.

The contents of thermotolerant coliform bacteria at the two springs show sudden and strong temporal variations. At spring 1, between 1 and 192 TTC/ml were counted; 1–39 TTC/ml were detected in samples from spring 2. It was not possible to establish a correlation between the bacteria contents and any hydrologic, physical or hydrochemical parameters. It is thus impossible to predict the bacteria content based on monitoring these parameters. The bacteria content in a sample from swallow hole 1 was similar to the content measured at spring 1 on the same day, and the bacteria content in a sample from swallow hole 2 was similar to the content measured at spring 2 (bold underlined data in Figs. 5 and 6). This observation is consistent with the tracer test results that proved direct connection between the swallow holes and the springs. It is also consistent with the hydrochemical data that show a high degree of similarity between the swallow holes and the springs.

Discussion and conclusions

Applicability of the methodology

Carrying out hydrogeological research in a remote and poor tropical karst area required several methodological adaptations. Besides basic hydrological and geological observations, the techniques applied in the test site included a multi-tracer test, hydrochemical investigations and microbiological analyses. The main adaptations that were done for the tracer tests consisted of the use of very small and 'lightproof' test tubes for water sampling, the installation of charcoal bags at sampling sites of secondary importance, and the participation of local people to the sampling campaign. Hydrochemical investigations included the use of simple field instruments, and water sampling in small plastic test tubes. All inorganic anions and cations can be analysed in such small volumes, except for bicarbonate. The concentration of this anion was thus calculated on the basis of the ion balance. As a consequence, it was not possible to use the ion balance to control the precision of the chemical analyses. A portable water testing kit was used for the microbiological monitoring. This kit allows total thermotolerant coliforms (TTC) to be analysed. These bacteria are considered as indicators for the presence of pathogenic microorganisms of faecal origin (WHO 2004). However, some coliforms (*Enterobacter*, *Klebsiella*, *Citrobacter*) are of non-faecal origin and may occur in 'non-contaminated' water (Payment et al. 2003).

The combination of tracer tests, hydrochemical and microbiological techniques made it possible to better understand the karst aquifer system, and to characterise the dynamics and interaction of hydrologic, hydrochemical and microbiological parameters. The study also provided a basis for the development of future groundwater protection schemes. The proposed methodology is also applicable in other poor, remote and tropical areas.

Hydrogeological characteristics of the karst aquifer system

The tracer tests proved direct, rapid and simple connection between swallow hole 1 and spring 1 (karst flow system 1), and between swallow hole 2 and spring 2 (flow system 2). The high tracer recovery rates, at least about 70%, suggest that most of the water sinking into the swallow holes reappears at the springs. The other way round, an important proportion of the spring water originates from the swallow holes, at least about one third, although this quantity is partly based on estimated discharge values. Hydrochemical data confirm the impact of the swallow holes on the springs. Allogenic point recharge thus predominates in the Tam Duong area, while autogenic diffuse recharge through the soil and epikarst seems to be less important. Such straightforward connections between a large swallow hole and a spring are rather an exceptional case. In many other karst systems, there are more complex connections between several swallow holes and springs, and autogenic recharge is often more important (Bakalowicz 2005; Ford and Williams 1989).

Linear groundwater flow velocities in karst aquifers determined by tracer tests often range between 10 and 300 m/h and rarely exceed 700 m/h (Ford and Williams 1989, Käss 1998). To the best of the authors' knowledge, the highest velocity documented in the literature is 1,450 m/h (Aley 1975). The maximum flow velocity of 700 to 875 m/h that was observed in flow system 2 is thus extremely high. The velocities in flow system 1 are within
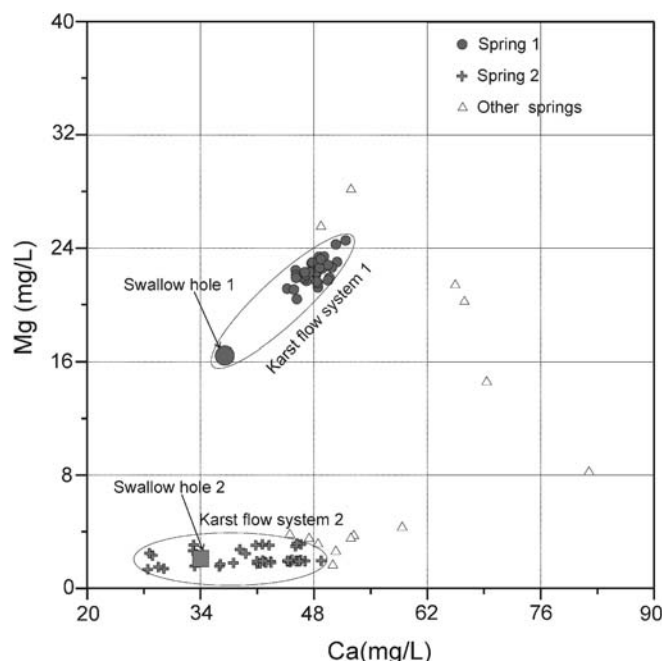
Fig. 7 Graphical presentation of the Mg^{2+} and Ca^{2+} concentrations measured in all water samples from the Tam Duong area. The samples from spring 1 form a group that is clearly separated from spring 2. There is a close hydrochemical relation between the springs and the swallow holes to which they are connected

the typical range for karst aquifers. The high velocities and tracer recovery rates suggest that underground flow mainly occurs in conduits. Speleological and geomorphological observations further confirm the existence of a linear karst conduit with a cave stream connecting swallow hole and spring 2.

Both paleo-tectonic and neo-tectonic fault directions control the underground flow pattern in the Tam Duong area. The straight karst conduit that connects swallow hole 2 to spring 2 runs parallel to the NW–SE faults (paleo-tectonics). Flow system 1 mainly follows SW–NE striking faults (neo-tectonics) and crosses several folds. Due to the high thickness of the karstified carbonate sequence, the degree of stratigraphic flow control is limited. Therefore, the influence of fold structures on the flow paths is also limited. In karst systems with a high degree of stratigraphic flow control, e.g. a thin karst aquifer between thick aquicludes, folds often have an important influence on the underground flow paths (Goldscheider 2005a).

Dynamics and interaction of the hydrochemical and microbiological parameters

Both hydrochemical and microbiological parameters at the two main springs show a high degree of variability, which is typical for karst springs (Ford and Williams 1989).

The hydro- and chemographs of the two springs react differently on rainfall events. Spring 2 shows a pure dilution effect, i.e. freshly infiltrated rainwater arrives rapidly at the spring and dilutes the water in the aquifer. The piston effect can be observed at spring 1. During high-flow events, increasing hydraulic pressure in the aquifer mobilises higher mineralised groundwater. The

freshly infiltrated rainwater arrives with roughly 40-h delay, which corresponds to the transit time between swallow hole 1 and spring 1 proved by the tracer test.

Hydrochemically, water from swallow hole 1 and spring 1 can clearly be differentiated from water from swallow hole 2 and spring 2. Water from the former contains significantly more magnesium, which indicates the presence of dolomites in the catchment area of swallow hole and spring 1. In the Mg^{2+}/Ca^{2+} plot, water samples flow system 1 form a cluster, which is clearly separated from the cluster representing flow system 2 (Fig. 7). The plot also shows that the Mg^{2+} and Ca^{2+} concentrations are increasing during the underground passage from the swallow holes to the springs, which can be explained by additional mineral dissolution and mixing processes within the aquifer.

The contents of thermotolerant coliforms at spring 1 varied between 1 and 192 TTC/ml, while 1–39 TTC/ml were measured at spring 2. The bacteria levels often showed sudden and strong variations, e.g. 1–2 TTC/ml in one sample and 34–39 TTC in the following sample that was taken only 12 h later. The bacteria levels do not correlate with any other parameters and thus appear to be largely unpredictable. On the basis of the existing data, it is thus not possible to use hydrological, physical or chemical data as indicators for microbial groundwater quality, as it can be done in other karst systems (Pronk et al. 2006).

Consequences for groundwater protection

In all water samples from the two main springs, the concentrations of nitrate, fluoride and all other inorganic

ions are clearly below the limits defined by the WHO (2004). The hydrochemical water quality thus seems to be excellent. The samples were not analysed for organic contaminants, like pesticides, which might be present in an agricultural area (Currens 2002; Young 1983). In contrast, all water samples contain thermotolerant coliforms, which should not be present in drinking water according to the WHO standards. The microbiological spring water quality is thus insufficient and measures should be taken to improve the quality. These measures should include the delineation of groundwater source protection zones and the implementation of an appropriate drinking water treatment, i.e. filtration and sterilisation.

Microbiological contamination of the spring water probably results from agricultural activities and untreated domestic wastewaters. The hydrogeological study clearly demonstrated that surface waters sinking into the two swallow holes rapidly arrive at the two springs. Most of the sinking stream water reappears at the springs, and an important percentage of the spring water in turn originates from the swallow holes. Protection zones and adaptations in land use practices around the two swallow holes and sinking streams, and within their hydrologic catchments, could thus help to reduce microbiological contamination of the two main springs.

Groundwater vulnerability, hazard and risk maps are important elements of groundwater protection schemes (Goldscheider 2005b; Veselic 2003). The European COST Action 620 proposed an approach to vulnerability, hazard and risk mapping for the protection of carbonate (karst) aquifers (Zwahlen 2004). This approach was developed by European scientists having in mind the hydrogeological and economic conditions in their countries. The authors of this paper also work on the adaptation of the European approach to the conditions of poor and remote areas, where little data are available (Nguyet et al. 2004b; Nguyet and Goldscheider in press). The simplified methodology will consist of a method of vulnerability mapping that takes into account the overlying layers (O) and the concentration of flow (C) that occur in the catchment areas of sinking streams. As illustrated above, the C factor is particularly relevant for the Tam Duong test site. The land use map (Fig. 3) is the starting point for a simplified hazard assessment. A risk map can be obtained by overlying the vulnerability map and the hazard assessment. The vulnerability map can be used as a basis to delineate groundwater protection zones, while the risk map illustrates the necessity to act in areas of high risk.

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