Geologia Croatica | 63/2 | 137–142 | 5 Figs. | Zagreb 2010

New insights into the transport of sediments and microorganisms in karst groundwater by continuous monitoring of particle-size distribution

Nico Goldscheider[1], Michiel Pronk[2] and Jakob Zopfi[3]

[1] Technische Universität München (TUM), Department for Civil, Geo- and Environmental Engineering, Hydrogeology and Geothermics Group, Arcisstr. 21, 80333 Munich, Germany; (goldscheider@tum.de)

[2] Centre of Hydrogeology, University of Neuchâtel, 2009 Neuchâtel, Switzerland; (michiel.pronk@unine.ch)

[3] Institute of Geology and Paleontology, University of Lausanne, 1015 Lausanne, Switzerland; (jakob.zopfi@unil.ch)

doi: 104154/gc.2010.10

Geologia Croatica

ABSTRACT

Mobile particles play crucial roles for contaminant transport in karst aquifers, but few studies have investigated the relationships between sediment dynamics and contaminants. This is partly due to the difficulty in monitoring suspended particles: Turbidity is easy to measure but does not deliver detailed information on the size and type of particles; mineralogical laboratory analyses are laborious and not suitable for continuous monitoring. A portable particle counter was used for the study presented here. The instrument delivers time-series of particle-size distribution (PSD), i.e. the number and diameter of suspended particles, grouped into different size-classes ranging from 0.9 to 139 µm. The test site is a karst system near the city of Yverdon-les-Bains, Switzerland. A swallow hole draining agricultural land is connected to two karst springs, 4.8 and 6.3 km away, which are occasionally contaminated by faecal bacteria at highly variable levels. Turbidity alone turned out not to be a reliable indicator for microbial contamination. To obtain more insight into bacteria and particle transport towards the springs, a comprehensive research program was carried out, including tracer tests and monitoring of PSD, turbidity, total organic carbon (TOC), faecal bacteria (*E. coli*) and various hydrologic and physicochemical parameters. Results show that there are two types of turbidity: A primary turbidity signal occurs shortly after rainfall during the rising limb of the hydrograph; a secondary signal typically occurs during spring flow recession. The first signal is explained by remobilization of conduit sediments due to a hydraulic pressure pulse (autochthonous or pulse-through turbidity). The second peak indicates the arrival of water from the swallow hole, often together with TOC and faecal bacteria (allochthonous or flow-through turbidity). PSD analyses revealed that autochthonous turbidity is composed of a broad mixture of fine and large particles, while allochthonous turbidity predominantly consists of very fine particles. This is explained by sedimentation of larger particles between the swallow hole and the springs. During allochthonous turbidity periods, very good correlation between the finest particles (0.9–1.5 µm) and *E. coli* was found ($R^2 = 0.93$). The relative increase of fine particles can consequently be used as an "early-warning parameter" for microbial contamination of karst spring water. Further applicability and limitations of this approach are also discussed.

Keywords: Particle-size distribution, turbidity, faecal bacteria contamination, karst groundwater monitoring, total organic carbon

1. INTRODUCTION

Sediments in karst conduits and suspended mineral particles in groundwater are crucial for the transport and attenuation of contaminants in karst aquifers, such as toxic metals, DNAPLs and pathogenic microorganisms. However, relatively few studies have investigated sediment dynamics and sediment-contaminant interactions in karst groundwater flow systems (MAHLER & LYNCH, 1999, MAHLER et al., 2000, VESPER & WHITE, 2003, VESPER & WHITE, 2004).

A major challenge lies in the monitoring of suspended particles in groundwater and spring water. Two conventional techniques are commonly used – turbidity measurements and mineralogical laboratory analyses of water samples. Both approaches have advantages but also major drawbacks: Turbidity is an optical parameter qualitatively indicating the amount of colloids and particles in the water; it can easily be measured continuously, but turbidity measurements do not deliver any detailed and quantitative information concerning the size, number and type of suspended particles (MASSEI et al., 2006, SCHNEGG, 2002). Mineralogical and geochemical analyses in the laboratory can deliver this type of information but are laborious and consequently not suitable for continuous monitoring (HERMAN et al., 2007).

Therefore, a modern portable particle counter was used for the study presented here. The instrument delivers quasi-continuous time-series of particle-size distribution (PSD), i.e. the number and size of suspended particles in water. The test site is a karst aquifer system in western Switzerland, consisting of a swallow hole draining agricultural land, connected to two karst springs, one of which is used as a drinking water source for the city of Yverdon-les-Bains. Occasional faecal bacteria contamination at highly variable levels poses a problem for the water supplier. Turbidity alone turned out not to be a reliable indicator for water quality – contamination sometimes occurred when turbidity was low, while high values did not always correspond to poor water quality. Therefore, the main objectives of this study were:

- to better understand the origin, transport and dynamics of suspended sediment particles and faecal bacteria in karst groundwater flow systems;
- to test the applicability and limitations of particle counters and continuous PSD monitoring for karst hydrogeological studies; and
- to identify reliable "early-warning parameters" indicating the possible presence of faecal and pathogenic microorganisms in karst spring water.

Major results of this study, which also included detailed microbiological investigations using methods from molecular microbiology and unsaturated zone investigations, have been published in several papers by the authors (PRONK et al., 2006, 2007, 2009a, b). This communication focuses on the application and usefulness of PSD measurements for the monitoring of microbial water quality for the springs of Yverdon-les-Bains.

2. TEST SITE AND METHODS

2.1. Test site

The studied karst aquifer system is located near the city of Yverdon-les-Bains, Switzerland, between two major geological and landscape units: the folded Jura Mountains and the Molasse Basin, forming the Swiss Plateau (Fig. 1). The SE slope of the Jura Mountains, where Upper Jurassic (Malm) and Cretaceous limestones outcrop, is the principal autogenic recharge area of the aquifer system. Further to the SE, due to a complex arrangement of folds and faults, limestone is exposed in two "hydrogeologic windows" within the low-permeability sediments of the Swiss Plateau. At the western window, a stream sinks into the Feurtille swallow hole at an altitude of 600 m. The stream drains agricultural land and frequently contains high levels of turbidity, TOC and faecal bacteria. About 4 km to the east, at the second window (Mont de Chamblon), two springs are located at approximately 450 m: The Moulinet spring, which consists of eight orifices showing identical physicochemical characteristics, and the Cossaux spring, which is captured by eight inclined drillings and contributes to the water supply of the city.

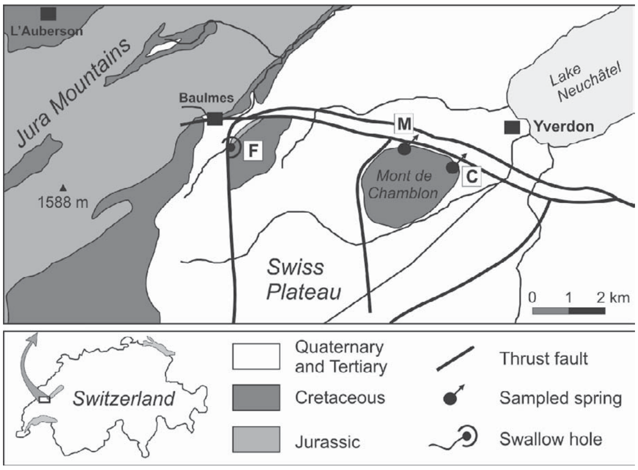

Figure 1: Geologic map of the karst system near Yverdon-les-Bains. The Feurtille swallow hole (F) is connected to two karst springs: Moulinet (M) and Cossaux (C). Reprinted with permission from PRONK et al. (2007). Copyright 2007 American Chemical Society.

Five tracer tests have been carried out during different hydrological conditions, ranging from low-flow to high-flow, in order to characterize the connection between the swallow hole and the springs. Transit times (first tracer detection) varied between 24 hours during very high-flow conditions and 12 days during extreme low-flow conditions. This also means that suspended particles and associated contaminants infiltrating into the swallow hole are expected to arrive at the springs after about 1 to 12 days, depending on the hydrological conditions. This discovery makes it easier to interpret the variability of natural parameters monitored at the springs, as described below.

2.2. Monitoring of physicochemical and microbiological parameters

Discharge, water temperature (T), electrical conductivity (EC), total organic carbon (TOC) and turbidity were monitored continuously at the swallow hole and the two springs using weirs and pressure probes (DL/N 64, STS, Sirnach, Switzerland), EC-T probes (Cond 340i, WTW, Weilheim, Germany), data loggers (DT50, dataTaker, Rowville, Australia) and field fluorometers (GGUN-FL30, Neuchâtel, Switzerland). Daily precipitation data (MeteoSwiss) from three stations were considered.

During selected hydrological events, water samples were collected hourly using automatic samplers (6712C Sampler, Teledyne ISCO, Lincoln, USA) with sterilized bottles, transported to the laboratory in cooling boxes, and processed within 6 h to 30 h for chemical and microbiological analyses. Samples were analyzed for major inorganic ion chemistry using ion chromatography (IC DX-120, Dionex, Sunnyvale, USA) and for faecal indicator bacteria, mainly *E. coli*, using standard cultivation techniques.

2.3. Monitoring of Particle-Size Distribution

Particle-size distribution (PSD) was monitored at the springs during selected high-flow events using a portable particle counter (Abakus mobil fluid, Klotz, Unterhaugstett, Germany) that counts suspended particles in the range of 0.9 to 139 µm and groups them into up to 32 definable size classes. The instrument takes discrete measurements in sufficiently short (minutes), definable time intervals, to be used for quasi-continuous monitoring. The measurement principle is as follows: The water sample, usually 10 ml, passes through a fine tube (0.3 mm) illuminated by a laser beam perpendicular to its axis. A light detector measures the intensity decline caused by the individual particles, i.e. the “shadow” of each particle (Fig. 2). This makes it possible to count the particles and measure their equivalent spherical diameters.

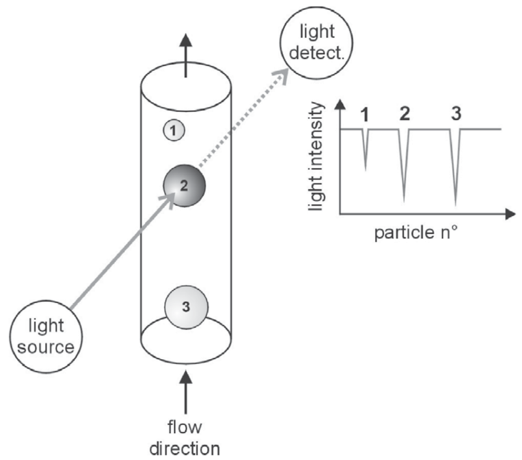

Figure 2: Schematic illustration of the particle counter. The water sample passes through a tube illuminated by a laser beam. Every particle (1, 2, 3) creates a “shadow” observed at a light detector, which makes it possible to determine the number and size of the particles.

3. RESULTS AND DISCUSSION

3.1. Spring response to an individual rainfall event

Two types of turbidity were observed at the springs during and after storm rainfall (Fig. 3). A primary turbidity signal (T1) occurred during the rising limb of the spring hydrograph, explained by the remobilization of sediments from karst conduits due to a hydraulic pressure pulse; it is thus referred to as autochthonous or pulse-through turbidity. A secondary turbidity signal (T2) occurred 1 to 12 days later and is explained by the arrival of turbid storm-derived water

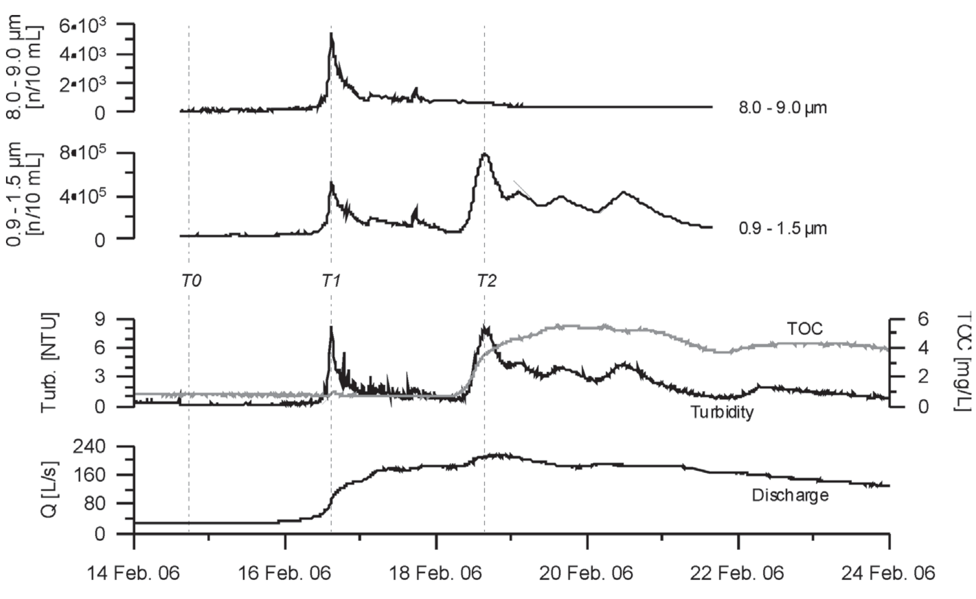

Figure 3: Variability of discharge, turbidity, TOC and two different particle-size classes at the Moulinet spring. The primary turbidity signal (T1) consists of a mixture of fine and large particles; the secondary signal (T2) is mainly composed of fine particles (0.9–1.5 µm) and high TOC levels.

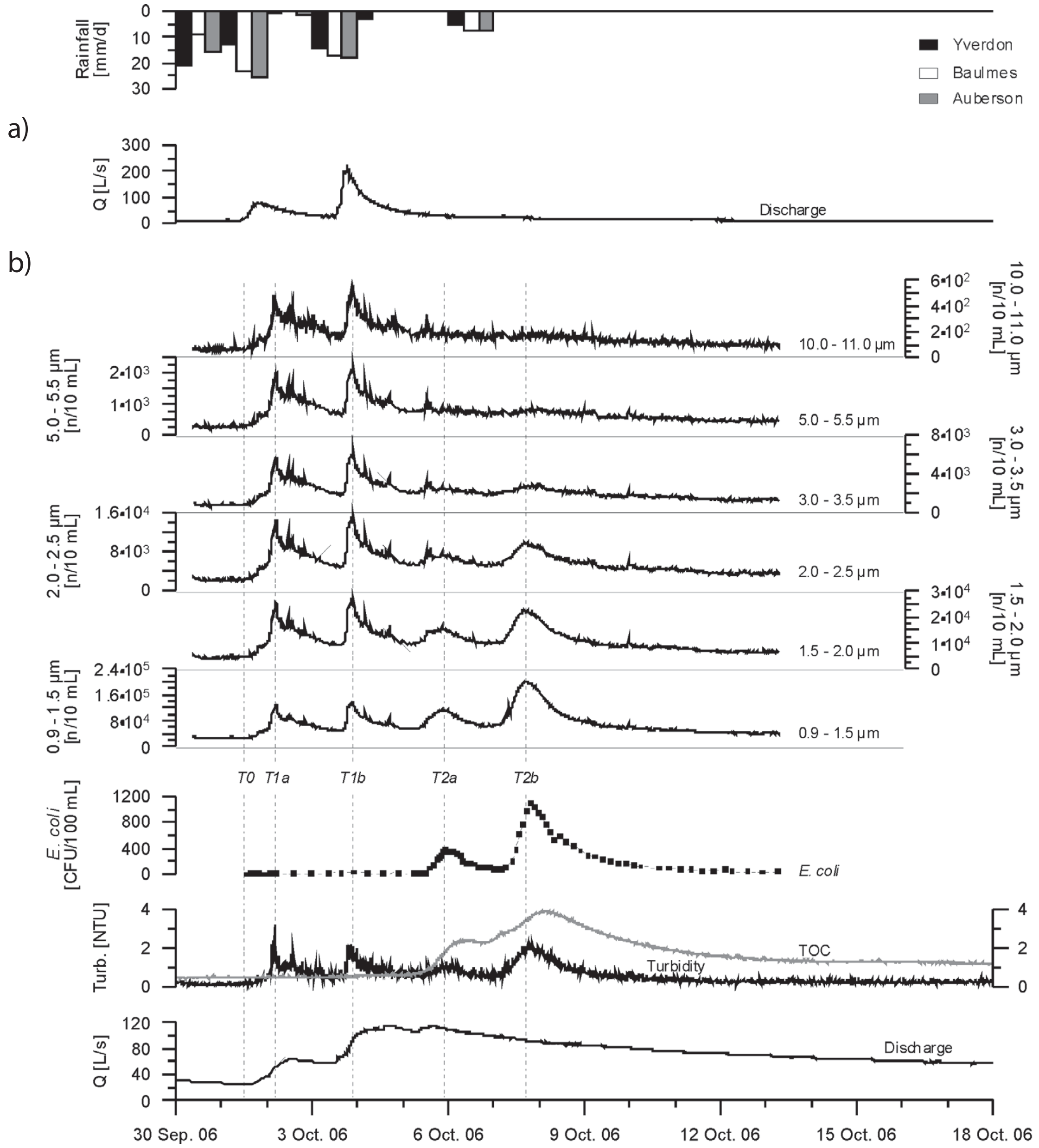

Figure 4: Variability of PSD, *E. coli* and various hydrological and physicochemical parameters at the Moulinet spring following a double rainfall event. (a) Feurtille swallow hole and (b) Moulinet spring. Adapted with permission from PRONK et al. (2007). Copyright 2007 American Chemical Society.

that entered the swallow hole; it is thus referred to as allochthonous or flow-through turbidity. This range of transit times and its dependency on the hydrological conditions coincide well to the transit times obtained by tracer tests. During the first turbidity signal, TOC remains constant and low at pre-storm levels, while the second turbidity signal coincides with a significant increase of TOC. As TOC typically originates from the soil, land surface and sinking streams, this observation supports the allochthonous origin of the second turbidity signal.

PSD monitoring allowed further differentiation of the two turbidity signals. While the primary turbidity signal (T1) consists of a broad mixture of fine and larger particles, the secondary turbidity (T2) signal is predominantly composed of very fine particles (colloids) with an equivalent spherical diameter of 0.9–1.5 µm. The explanation can be found in the classical Hjulström diagram, which describes the relations between flow velocity and erosion, transport and deposition of sediment particles of different size. Increased flow velocities during the rising limb of the spring hydrograph mobilize a mixture of clay and silt particles, but only the very fine particles are transported from the swallow hole to the spring, while larger particles are removed by sedimentation.

3.2. Spring response to a double rainfall event

Fig. 4 presents monitoring results from the Moulinet spring following two successive intense precipitation events. Two primary, autochthonous turbidity signals (T1a, T1b) were observed shortly after the two rainfalls, when spring discharge was rapidly increasing. These signals consist of a mixture of fine and larger particles and are characterised by stable and very low levels of *E. coli* and TOC. Two second-

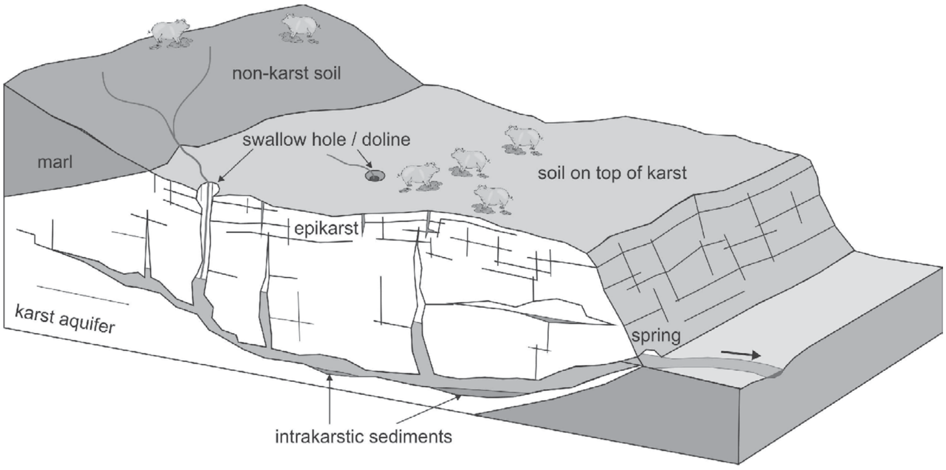

Figure 5: Block diagram of a karst aquifer illustrating different origins of sediment particles and faecal bacteria in spring water. Particles either originate from remobilization of intrakarstic sediments (autochthonous) or from the soil and sinking streams, often including high levels of bacteria and organic carbon (allochthonous) (modified after GOLDSCHEIDER & DREW, 2007).

ary, allochthonous turbidity signals (T2a, T2b) occurred several days later and are mainly composed of very fine particles (0.9–1.5 µm). TOC increases in two steps and *E. coli* display two distinct peaks, highly correlated to the evolution of fine particles ($R^2 = 0.93$). These findings clearly indicate the arrival of storm-derived water from the swallow hole, containing high levels of TOC and faecal bacteria. Most large particles have been removed by sedimentation between the swallow hole and the springs, attenuation processes.

4. CONCLUSIONS AND OUTLOOK

Turbidity in karst groundwater has two principal origins: Autochthonous turbidity results from the mobilization or remobilization of sediments in karst conduits, while allochthonous turbidity originates from the soil zone, land surface or sinking surface streams (Fig. 5). Monitoring of particle-size distribution (PSD) makes it possible to characterise and differentiate the two turbidity types. Autochthonous turbidity consists of a broad mixture of different particle-size classes. In the allochthonous turbidity, most large particles have been removed by sedimentation in the system, so that this turbidity is predominantly composed of fine particles.

TOC and faecal bacteria also originate from the land surface or sinking streams, i.e. they are also allochthonous (Fig. 5). Therefore, the differentiation of autochthonous and allochthonous turbidity has practical implications for spring water quality monitoring. Two alternative "early-warning systems" for the possible presence of faecal bacteria and pathogenic microorganisms can be proposed:

- The simultaneous increase of turbidity and TOC;
- The selective increase of fine particles (0.9–1.5 µm) without significant variation of larger particles.

Monitoring of various high-flow events at the Yverdon-les-Bains test site, at another karst aquifer system in the Jura Mountains, and at an unsaturated zone experimental site (PRONK et al., 2009b), demonstrated that these early-warning systems are reliable in the case of microbial contamination resulting from agricultural activities at the land surface. Such contamination enters the aquifer during rainfall and recharge periods, while direct and permanent wastewater injections into sinking streams, or into groundwater, are likely to cause permanent spring water contamination without distinct TOC or PSD variations. Besides the practical use for water-quality monitoring, PSD measurements can also aid the acquisition of better insights into other relevant processes in karst systems, such as soil erosion and the removal of residual clay and silt during karstification and speleogenesis.

ACKNOWLEDGMENT

We thank the water supply company of Yverdon-les-Bains for technical and logistic support, and the Swiss National Science Foundation (grant no. 200020-113609/1) for funding.

REFERENCES

GOLDSCHEIDER, N. & DREW, D. (2007): Methods in karst hydrogeology IAH: International Contributions to Hydrogeology, 26.– Taylor & Francis, London, 264 p.

HERMAN, E.K., TANCREDI, J.H., TORAN, L. & WHITE, W.B. (2007): Mineralogy of suspended sediment in three karst springs.– Hydrogeology Journal, 15/2, 255–266.

MAHLER, B.J. & LYNCH, F.L. (1999): Muddy waters: temporal variation in sediment discharging from a karst spring.– Journal of Hydrology, 214/1–4, 165–178.

MAHLER, B.J., PERSONNE, J.C., LODS G.F. & DROGUE C. (2000): Transport of free and particulate-associated bacteria in karst.– Journal of Hydrology, 238/3–4, 179–193.

MASSEI, N., DUPONT, J.P., MAHLER, B.J., LAIGNEL, B., FOURNIER, M., VALDES, D. & OGIER, S. (2006): Investigating transport properties and turbidity dynamics of a karst aquifer using correlation, spectral, and wavelet analyses.– Journal of Hydrology 329/1–2, 244–257.

PRONK, M., GOLDSCHEIDER, N. & ZOPFI, J. (2006): Dynamics and interaction of organic carbon, turbidity and bacteria in a karst aquifer system.– Hydrogeology Journal, 14/4, 473–484.

PRONK, M., GOLDSCHEIDER, N. & ZOPFI, J. (2007): Particle-size distribution as indicator for fecal bacteria contamination of drinking water from karst springs.– Environmental Science & Technology 41/24, 8400–8405.

PRONK, M., GOLDSCHEIDER, N. & ZOPFI, J. (2009a): Microbial communities in karst groundwater and their potential use for biomonitoring.– Hydrogeology Journal, 17/1, 37–48.

PRONK, M., GOLDSCHEIDER, N., ZOPFI, J. & ZWAHLEN, F. (2009b): Percolation and particle transport in the unsaturated zone of a karst aquifer.– Ground Water, 47/3, 361–369.

SCHNEGG, P.A. (2002): An inexpensive field fluorometer for hydrogeological tracer tests with three tracers and turbidity measurement; XXXII IAH and ALHSUD Congress Groundwater & Human Development. Balkema, Mar del Plata, Argentina, 1484–1488.

VESPER, D.J. & WHITE, W.B. (2003): Metal transport to karst springs during storm flow: an example from Fort Campbell, KY/TN, USA.– Journal of Hydrology, 276/1–4, 20–36.

VESPER, D.J. & WHITE, W.B. (2004): Spring and conduit sediments as storage reservoirs for heavy metals in karst aquifers.– Environmental Geology, 45/4, 481–493.

Manuscript received November 24, 2009
Revised manuscript accepted March 19, 2010
Available online May 31, 2010