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Process-based monitoring and modeling of Karst springs – Linking intrinsic to specific vulnerability

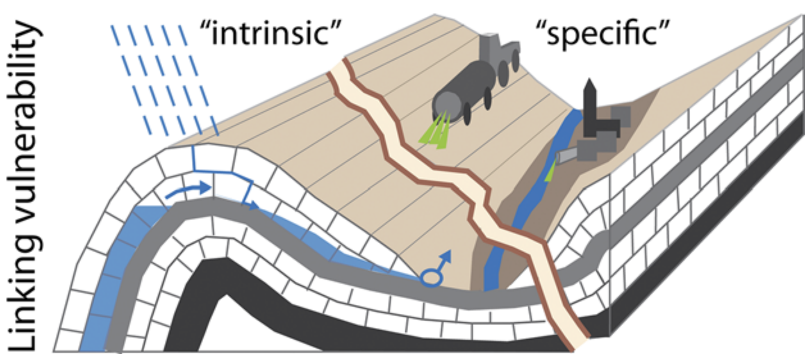
Jannis Epting [a,*], Rebecca M. Page [b], Adrian Auckenthaler [c], Peter Huggenberger [a]

[a] Department of Environmental Sciences, Applied and Environmental Geology, University of Basel, Switzerland
[b] Endress + Hauser (Schweiz) AG, Reinach, Switzerland
[c] Department of Environmental Protection and Energy, Canton Basel-Landschaft, Liestal, Switzerland

HIGHLIGHTS

- Approaching the complexity of subsurface catchments of the Folded Jura
- Temporal variation of groundwater recharge most relevant for intrinsic vulnerability
- Revealing the importance of surface water infiltration for vulnerability assessment
- Release events from storm sewers can severely impact Karst groundwater quality.

GRAPHICAL ABSTRACT



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ABSTRACT

The presented work illustrates to what extent field investigations as well as monitoring and modeling approaches are necessary to understand the high discharge dynamics and vulnerability of Karst springs. In complex settings the application of 3D geological models is essential for evaluating the vulnerability of Karst systems. They allow deriving information on catchment characteristics, as the geometry of aquifers and aquitards as well as their displacements along faults.

A series of Karst springs in northwestern Switzerland were compared and Karst system dynamics with respect to qualitative and quantitative issues were evaluated. The main objective of the studies was to combine information of catchment characteristics and data from novel monitoring systems (physicochemical and microbiological parameters) to assess the intrinsic vulnerability of Karst springs to microbiological contamination with simulated spring discharges derived from numerical modeling (linear storage models). The numerically derived relation of fast and slow groundwater flow components enabled us to relate different sources of groundwater recharge and to characterize the dynamics of the Karst springs.

Our study illustrates that comparably simple model-setups were able to reproduce the overall dynamic intrinsic vulnerability of several Karst systems and that one of the most important processes involved was the temporal variation of groundwater recharge (precipitation, evapotranspiration and snow melt). Furthermore, we make a first attempt on how to link intrinsic to specific vulnerability of Karst springs, which involves activities within the catchment area as human impacts from agriculture and settlements. Likewise, by a more detailed representation of system dynamics the influence of surface water, which is impacted by release events from storm sewers, infiltrating into the Karst system, could be considered.

* Corresponding author.
E-mail addresses: jannis.epting@unibas.ch (J. Epting), rebecca.page@ch.endress.com (R.M. Page), adrian.auckenthaler@bl.ch (A. Auckenthaler), peter.huggenberger@unibas.ch (P. Huggenberger).

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Overall, we demonstrate that our approach can be the basis for a more flexible and differentiated management and monitoring of raw-water quality of Karst springs.

1. Introduction

The heterogeneous structure of Karst aquifers consists of a diffuse flow system in the rock matrix and a conduit flow system in solutionally enlarged Karst voids (Atkinson, 1977; Estrela and Sahuquillo, 1997; Kiraly, 1998). Episodic rainfall events can lead to rapid recharge, which has a strong impact on discharge and contaminant transport to Karst springs, particularly if the conduit system is well developed (Butscher et al., 2011b; Goldscheider et al., 2010). Therefore, Karst groundwater is very susceptible to pathogen contamination because of point recharge to the Karst conduits and little filtration within the system (Auckenthaler et al., 2002; Drew, 1996; Ryan and Meiman, 1996). During dry weather periods, however, when the diffuse (matrix) flow system is dominant, only low levels of pathogen contamination occur. Furthermore, for many Karst aquifers interactions between ground and surface waters have to be considered (McCormack et al., 2016).

Fecal bacteria mainly originate from agricultural activities and are flushed into the aquifer during high flow periods (Mahler et al., 2000; Pronk et al., 2009b). They generally perish in the diffuse flow system within a few days (Bogosian et al., 1996; OECD, 2003). In contrast, in the conduit flow system, attenuation processes are generally not very effective because of the fast input and short travel times. As aquifers must be considered as ecosystems harboring indigenous biocenoses (e.g. Danielopol et al., 2003), the microbiological status of groundwater should not only examine the presence of pathogenic, i.e. fecal microorganisms, but should also address the issue of other occurring microorganisms. This factor is important as suspended bacteria in groundwater, as determined using total cell counts from flow cytometry measurements, generally only present a portion of the entire aquifer's microbial community (Alfreider et al., 1997). However, to date, knowledge about the baseline conditions of ecological criteria even for basic microbiological parameters is still limited.

Taking the characteristics of Karst environments into account, various methods have been developed for Karst groundwater vulnerability assessment, with vulnerability mapping as the most important of these (National Research Council 1993). "Vulnerability" means, in this context, the sensitivity of a groundwater system to natural or human impact (Albinet and Margat, 1970; Vrba and Zaporozec, 1994).

Some of the methods for vulnerability mapping are specifically designed for Karst environments (Doerfliger et al., 1999; Goldscheider, 2005; Vias et al., 2006). However, mapping approaches to vulnerability assessment may not always be sufficient for spring water protection as spring vulnerability represents an overall response of the hydrogeological system with respect to recharge, flow and transport characteristics. The various flow systems in Karst terrains, especially rapid recharge into and fast flow in the conduit system, make the delineation of groundwater protection zones very difficult. Even if all the "hot-spots" for rapid recharge were known and included in protection zones, an uncertain input of microorganisms into the groundwater would still occur (Auckenthaler and Huggenberger, 2003). In addition, the likelihood of contamination strongly depends on the recharge conditions, which are highly time dependent.

At the national scale of Switzerland and for the Swiss Jura mountains, systematic mapping approaches to assessing and describing vulnerability as KARSYS have been introduced (Jeannin et al., 2013). KARSYS seeks to construct a representation of the Karst groundwater system and to identify (a) where the main sinks and springs are; (b) approximate volumes and geographical dimension of recharge/discharge areas by means of 3D geological models; and (c) approximate discharge rates. However, spring dynamics are only discussed in a qualitative way. Furthermore, the classification of vulnerability is limited to a general hydrogeological characterization of spring dynamics, karstification and recharge. A further mapping approach, the aquifer base gradient approach, was introduced by Butscher and Huggenberger (2007). This approach is based on an analysis of the aquiclude topography and allows deriving subsurface catchments and compartments of different geological units.

A practical alternative to mapping approaches or modeling an actual bacterial breakthrough at a spring is to model the intrinsic vulnerability of the spring instead (Butscher and Huggenberger, 2009b). Originally, Butscher and Huggenberger (2008) introduced a method to assess hydrodynamics using a numerical groundwater modeling approach based on linear storage models that can be used to simulate Karst water flow. Specifically, the temporal variation in the vulnerability to microbial contamination, depending on rainfall events and overall recharge conditions, was assessed and quantified using first the Vulnerability Index (VI; (Butscher and Huggenberger, 2008)), which was subsequently further developed to the Dynamic Vulnerability Index (DVI; (Butscher et al., 2011a)), whereas these indices serve as indicators of intrinsic vulnerability of the spring water to short-lived (or microbial) contamination and its variation over time.

Contemporary management of Swiss Karst water supplies include spring-oriented and planning-oriented protection measures related to Karst groundwater resources. Despite these different protection concepts, practical experience has shown that the quality of spring water is often below the acceptable standard in spite of protection zones delineated based on vulnerability mapping. What are the reasons and why are the current protection measures not sufficient?

Generally, it has to be differentiated between (A) intrinsic and (B) specific vulnerability (Vrba and Zaporozec, 1994). Intrinsic vulnerability takes the hydrological and hydrogeological characteristics of an area into account, independent of the nature of the contaminants and of the amount and temporal variation of the contaminant release. Specific vulnerability considers the human activities, including impacts from agriculture and settlements, in the catchment but also the properties of a contaminant.

Whereas spring-oriented protection measures are related to risk-oriented management of spring discharge, planning-oriented protection measures are related to the activities within the catchment. The intrinsic vulnerability can directly be related to precipitation and high-discharge events and be described e.g. by VI or DVI, which also account for the variability of vulnerability. However, one reason for these indexes cannot be a measure for absolute pathogen concentrations in spring water is that pathogen concentrations depend not only on the intrinsic but also on the specific vulnerability of the system. Concerning microbiologically related contaminations it is difficult to distinguish between intrinsic (indigenous biocenoses) and specific (e.g. fecal bacteria) quantities. Therefore, new approaches have to link intrinsic to specific vulnerability and the impacts of the various activities within the catchment area.

Whereas, Butscher and Huggenberger (2008) already presented how to include further processes within Karst systems for numerical groundwater modeling approaches, the influence of surface water infiltration, linking to one element of specific vulnerability, was not covered yet. In scope of our studies we included the impact of a losing creek, which typically are located within the synclines of the Folded Jura. These surface waters often only sporadically contain water and due to pollution risks are highly significant for Karst water quality.