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Vulnerability assessment in karstic areas: validation by field experiments

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Abstract Several methods have been developed for vulnerability mapping in karstic areas. These methods need additional validation by field experiments. Several tests have been carried out in the Swiss Jura with natural and artificial tracers. The protective role of some intrinsic properties of the system, such as glacial deposits covering karst, epikarst storage and system dilution effect, have been clearly demonstrated. Use of three tracers in parallel showed the reactivity of the epikarst: all tracers arrived at the same time, but their relative concentration stayed clearly different. A classification of contamination scenarios into four classes is proposed. It is shown that the relevance of some intrinsic properties depends on the considered scenario class. The hydrodynamic state of the aquifer influences greatly flow velocities and can strongly modify contaminant concentrations at the output of the system. The spatial repartition (point vs diffuse) and the quantity of contaminant entering the system will also influence the output response. Hence, results from tracing experiments cannot be used straightforward for obtaining a representative value of flow velocity, dispersion or recovery rate.

Keywords Contamination scenario · Karst aquifer · Switzerland · Tracing test · Vulnerability

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Introduction and objectives of the study

Assessment of groundwater vulnerability in karst aquifers has to be carried out with especially adapted methods. These methods should account for the strong heterogeneity of karst systems: point or diffuse recharge, rapid flow through high permeability conduits or slow flow in low permeability volume (Doerfliger and others 1999).

Resource vulnerability assessment implies the characterisation of the pathway between the surface and the limit of the saturated zone. It has to be differentiated from source vulnerability assessment, which is the characterisation of the pathway between the surface of a catchment area and a well or a spring. Resource vulnerability maps are mainly generated for general groundwater management and land-use planning, whereas source vulnerability maps are more detailed and mainly used as a tool to delineate protection zones. Vulnerability, as discussed in this paper, deals with the latter approach.

Vulnerability will be considered at three different levels: intrinsic vulnerability, specific vulnerability and contamination scenario. Definitions of these terms are as follows (Daly and others 2002):

Intrinsic vulnerability takes account of the inherent geological, hydrological and hydrogeological characteristics of an area; however, it is independent of the nature of contaminants.

Specific vulnerability is used to define the vulnerability of groundwater to a particular contaminant or group of contaminants. It considers the properties of the contaminant in the different subsystems of the karstic aquifers.

A contamination scenario is defined by the temporal evolution and the spatial distribution of the input function of a given contaminant.

In Switzerland, the EPIK (epikarst, protective cover, infiltration and karstic network) method has been developed for intrinsic vulnerability mapping of a karst system catchment area (Doerfliger and others 1999). For each subsystem of the investigated catchment (EPIK), areas of contrasted vulnerability are mapped (e.g. soil thickness will be the criteria for protective cover mapping based on the principle that the thicker the soil, the lower the vulnerability). These four maps are then combined into a vulnerability map giving ‘protection index values’. In EPIK, these values depend mainly on the epikarst and infiltration subsystems, but less on protective cover and

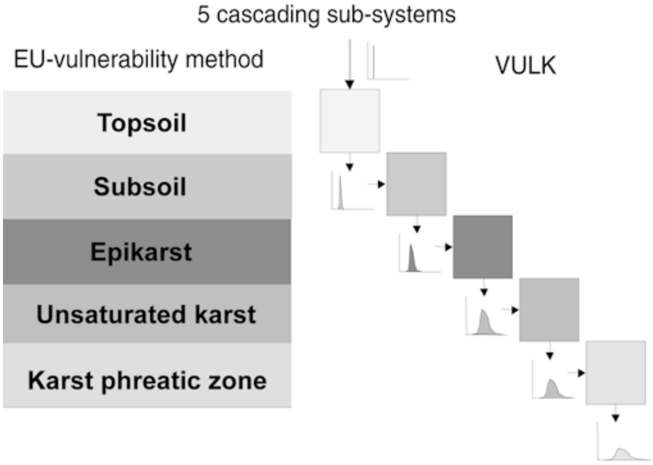

Fig. 1
Principle of the VULK model according to Jeannin and others (2001)

karstic network subsystems. This vulnerability map can be easily converted into protection zones for a drinking water supply. The main drawback of this method is the weighting of the parameters, which is completely qualitative, with no physical basis.

Recent developments within the framework of the European programme COST-620 led to the definition of intrinsic vulnerability using a physically based approach (Brouyère and others 2001). The idea is to consider the aquifer impulse response to a contaminant pulse. Vulnerability can be defined by three questions: (1) when does the pollution start? (2) to which maximum level? and (3) for how long? A 1-D dual porosity analytical dispersive–advective transport model called VULK has been developed to compute the transfer function of the system (Jeannin and others 2001). Five layers are considered: topsoil, subsoil, epikarst, unsaturated karst and karst phreatic zone (Fig. 1). For each, flow velocity, distance (or thickness), dispersivity and dilution should be entered into the model. Thickness is determined by geological mapping and geophysics, whereas dilution is simply the ratio of the output to input discharges. Velocity and dispersivity can be estimated by tracing tests.

For example, Smart and Friederich (1986) and Bottrell and Atkinson (1992) carried out tracing experiments in the unsaturated zone of karstic systems and were able to estimate tracer transit times. Goldscheider and others (2001) made a multitracing experiment aiming at testing EPIK mapping at the catchment scale. The present study uses, in the same manner, artificial and natural tracers for checking some theoretical hypotheses of vulnerability methods. These field experiments should help to improve existing models.

Field experiments

The three test sites are in the Jurassic limestone of the Swiss Jura mountains (Fig. 2). Lionne test site belongs to the folded part of the chain. The Lionne karstic spring drains a catchment of 20 km^2 situated between 1,000 and 1,400 m elevation (annual recharge is about 1,000 mm). The area is mainly covered by forests and pastures. The principal contaminant is faecal bacteria due to the presence of cattle. The Brandt site is also in the folded Jura at an elevation of 1,160 m (comparable annual recharge) in an area of pasture and forests. It consists of a cave of 260 m length draining a stream fed by several tributaries. The studied tributary is equipped for continuous recording of discharge. It is in the upstream part of the cave, 15 m under the surface (Blant and Puech 2001). The Milandre site is in the tabular Jura at an elevation of 450 m (annual recharge is about 600 mm). The Saivu karstic spring drains the Milandre catchment (13 km^2), which has different land uses: forests, meadows, pasture, cultures and urbanised areas (Perrin and others 2003).

Discharge data were obtained by continuous recording of water levels by a pressure gauge. The conversion of water levels into discharge is given by an extrapolation from several punctual discharge measurements. Fluorescent tracers were analysed at the lab with a spectrofluorimeter

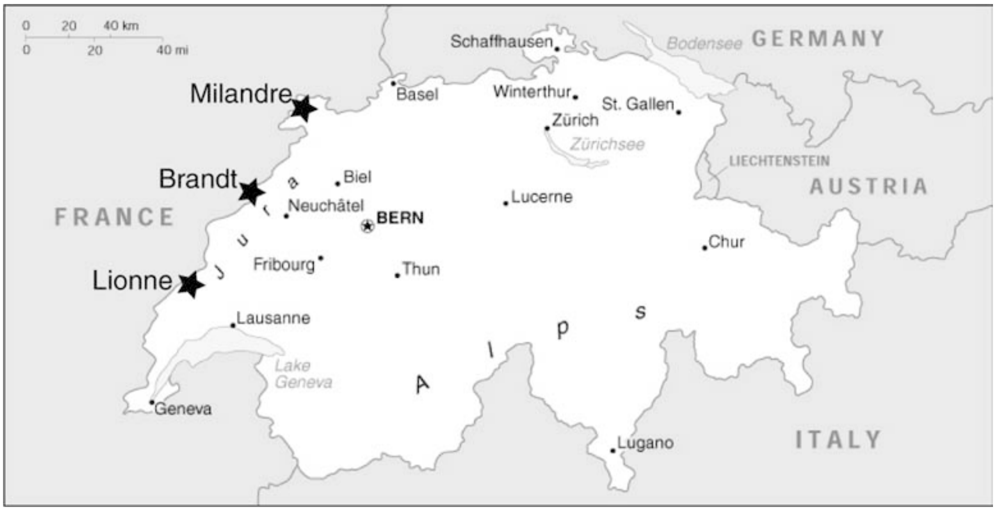

Fig. 2
Map of Switzerland with the location of the field test sites

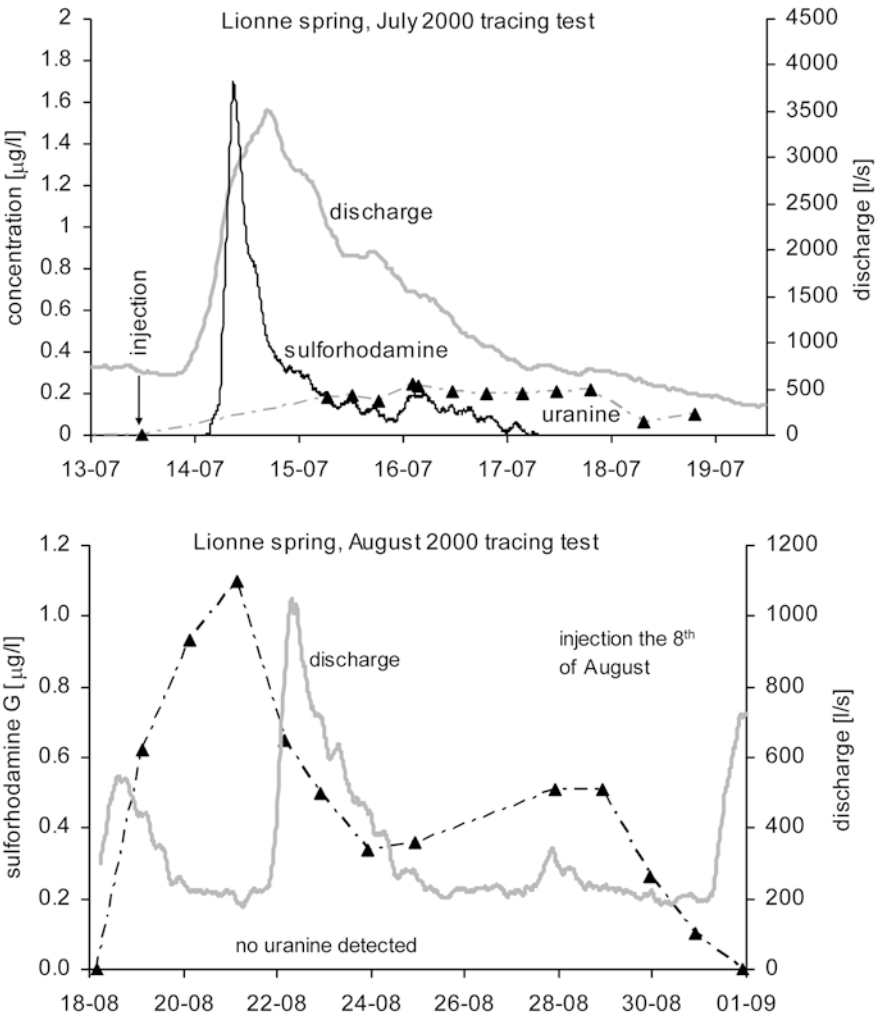

Fig. 3
Breakthrough curves of the tracing experiments carried out on the Lionne spring catchment area

(LS-50 B by Perkin–Elmer). Detection limits are 0.05 µg/L for uranine, 0.1 µg/L for sulforhodamine G and 0.1 µg/L for rhodamine B01. Continuous data were measured at 4-min intervals with a field fluorimeter and recorded data were calibrated with samples analysed in the lab (Schnegg and Doerfliger 1997). Lithium was analysed by Ionic chromatography (Dionex DX 20) with a detection limit of 10 µg/L. Iodide was analysed by a specific electrode with a detection limit at 5 µg/L.

Lionne catchment: intrinsic vulnerability and effect of the contamination scenario

The vulnerability of the Lionne spring catchment area has been mapped by the EPIK method. Two successive tracing experiments were then carried out in the medium part of the catchment to test the vulnerability map. The tested area is partly in a high vulnerability zone (mainly karrenfield with thin soils) and partly in a lower vulnerability zone (karst covered by thick glacial deposits). The objectives were:

- To check the protection effect of the protective cover.
- To assess and compare different contamination scenarios by generating point infiltration and at the same time diffuse infiltration.

Experiment of the 13.07.2000

Two tracers were injected on the karrenfield area: 400 g of sulforhodamine G diluted and flushed with 680 L of water was injected directly into a fissure, simulating a point contamination. Then 315 g of uranine diluted in 700 L of water was sprinkled over a 35-m^2 surface area to generate a diffuse pollution. Infiltration was rapid and thus possible photo-degradation was limited. Breakthrough curves at the spring are given in Fig. 3. Maximum velocity (calculated with the time of first arrival) are comparable with 49 m/h for sulforhodamine and 41 m/h for uranine. Mean velocity (calculated with the time of maximum concentration) is, respectively, 47 and 20 m/h and recovery rate of the tracer 40 and 16%. Diffuse pollution leads to lower maximum concentration and lower recovery rate; however, first arrival is not different than point pollution and the pollution lasts for a longer time.

Experiment of the 08.08.2000

Sulforhodamine G was injected at the same location as the previous month, and uranine was injected a few metres apart on top of glacial deposits of 5-m thickness. Flush was obtained with 1,000 L of water for sulforhodamine and 1,900 L for uranine. The low permeability of glacial deposits led to surface runoff on a few metres. Again, rapid infiltration limited the effect of photo-degradation. The breakthrough curve is illustrated in Fig. 3. Uranine was never detected: the concentrations were under the detection limit or the transit time was more than 1 month (velocity less than 45 m/day). First arrival of sulforhodamine gives a maximum velocity at 6 m/h and maximum concentration gives a mean velocity of 5 m/h. Estimated recovery rate was 50%. Low water gave flow velocities ten times less important than the previous month. The protective role of glacial deposits is clearly illustrated with no detection of uranine.

Brandt site: specific vulnerability testing

This site is suitable for studying hydraulics and transport in the epikarst. Percolation water inside the Brandt cave corresponds to the drainage of the epikarst. It is equipped for continuous measurement of discharge. For the experiment, an autosampler and a field fluorimeter was installed. The catchment area, with a surface estimated at 100 m^2, is 15 m above in a pasture. Soil (average thickness of 1 m) was removed in a square of 10 m corresponding to a large part of the catchment. This precaution allows the focus of the experiment on the epikarst subsystem. A sprinkling system was installed inside the square to generate artificial rainfall. Sprinkled water was previously traced with three chemicals (iodide, lithium, rhodamine) homogeneously dissolved in pools of 4-m^3 volume. Tracers were chosen for their chemical properties: iodide is an anion, lithium a cation and rhodamine an organic compound. A total of six pools were emptied in 18.5 h of duration, corresponding to a recharge intensity of 12 mm/h. Such a heavy rainfall was chosen with the aim to completely renew the hanging reserve of the epikarst. The chemistry of the sprinkled water was also analysed to compare it with the recovered groundwater.

The hydraulic response to sprinkling occurred with a 20-min delay. Water percolation discharge increased from 0.4 to 5 L/min in 1.3 h. The discharge then stayed constant except for short periods corresponding to the pools' changes at the surface.

The expected result was a progressive concentration increase in the percolation water up to the sprinkled concentration. Figure 4 gives the observed data: an increase occurs, but none of the tracers reach the input concentration. This result illustrates the important storage of traced water in the epikarst and the existence of a large spectrum of flow velocity in this zone. Moreover, the specific behaviour of the tracers is different: the most mobile is iodide with a strong increase in concentration at about 15 min after the start of sprinkling at the surface. At the end of the experiment, the concentration gets close to the injected water.

Rhodamine is intermediate with a first arrival 15 min after the start of the experiment and concentration stabilising at 60 μg/L after. However, this value stays lower than the injected water at 100 μg/L. The difference is partly due to adsorption, as illustrated by the continuous release of tracer after the sprinkling stopped. The variability of the injected concentration is probably due to a poor homogenisation of rhodamine in the pools.

Lithium is the less mobile: its first arrival occurred at 20 min after the sprinkling began and the maximum concentration reached half the concentration of the injected water. Concentration decreases rapidly after the end of sprinkling.

Milandre site: contamination scenarios

The catchment of this karst system is drained by an underground river fed by several tributaries (Jeannin 1996; Perrin and others 2003). Many chemical and stable isotope data have been collected from groundwater at different locations within the karst system. These natural tracers can be used to test contamination scenarios.

Example 1: nitrates

The catchment area of the Milandre karst system has different land uses, i.e. forests, pasture, cultivated land and urbanised areas. Thus, nitrate inputs are spatially highly heterogeneous with elevated inputs in cultivated areas and natural background in forests. Output responses show high concentrations for tributaries fed by a cultivated catchment (e.g. CA), low concentrations for tributaries fed by a forested catchment (e.g. SO) and average concentration at the spring (Fig. 5). No clear temporal evolution is visible, indicating that the inputs can be considered as constant. Slight short-term variations on the output signal might be caused by changes in hydraulic conditions (e.g. dilution during a flood event). Mitigation of a contamination by dilution from less contaminated tributaries is called a 'system dilution effect'.

Example 2: stable isotopes

On an annual basis, the oxygen 18/16 isotopic ratio can be considered to be a homogeneous input, both spatially and temporally: the input function is simply the annual mean isotopic ratio found in rainfall (Fig. 6). When entering the system, this function is degraded by evaporation and then should be reproduced at the spring. It corresponds to the annual mean ratio represented by the dashed line on Fig. 6.

Weekly samples taken at the spring deviate significantly from the annual mean. Such deviations have two main causes. First, the input signal is not constant, but shows a strong seasonal cycle with high values in summer and low values in winter. Second, the input signal during a rainfall event is far from constant. Hence, an important recharge event will modify the output signal. These perturbations are called 'flood dilution effects'.

Discussion

Experiments on the Lionne catchment area

Tracing experiments on the Lionne catchment show the efficiency of low permeability glacial deposits in the retardation of a contaminant. This protective cover is mapped under the attribute P by the EPIK method. The

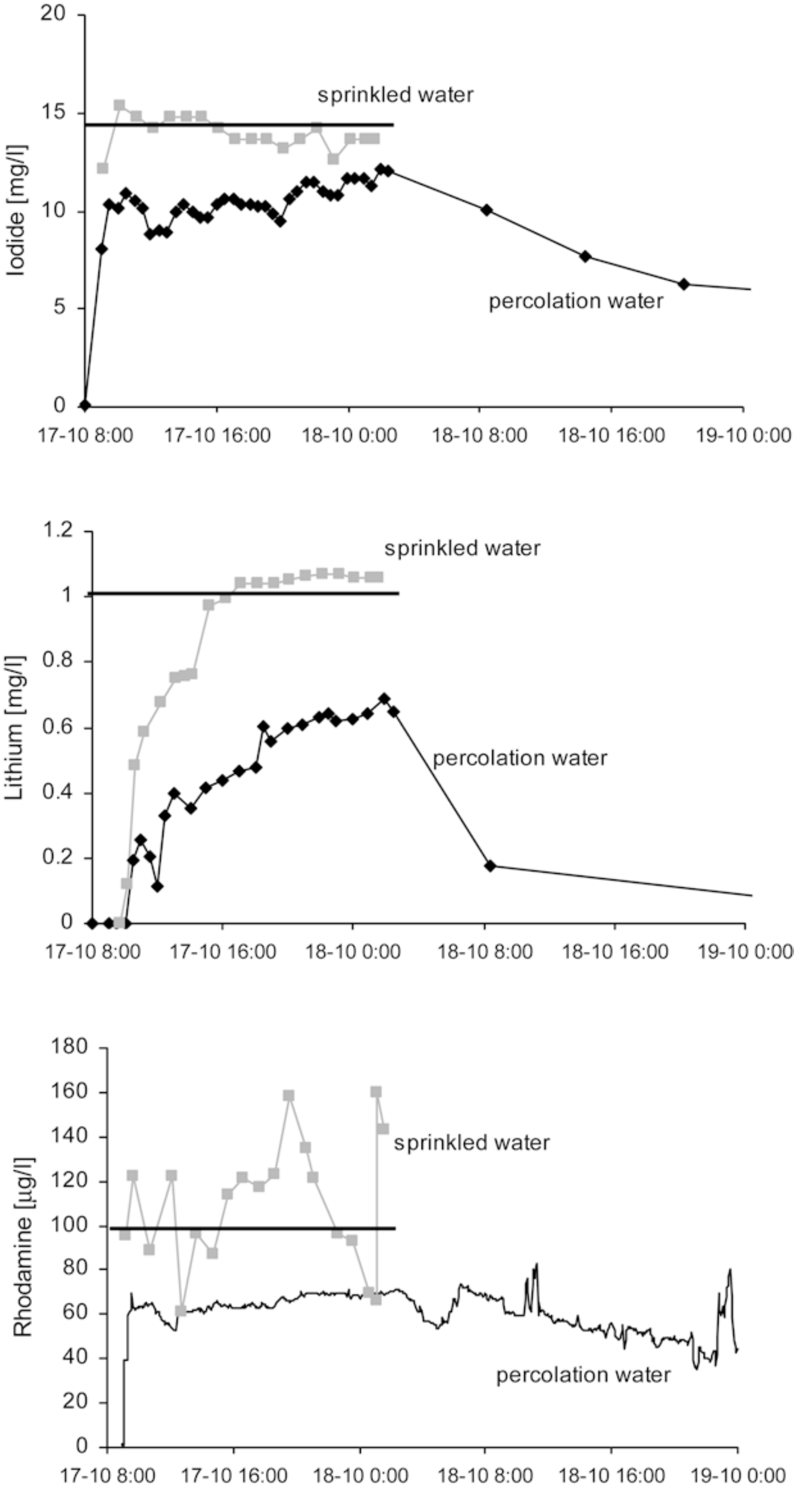

Fig. 4
Concentration evolution of the three tracers used for the Brandt sprinkling experiment, October 2001. *Points* are values obtained by lab analyses. Continuous measurement for rhodamine B01 was recorded with a field fluorimeter. *Thick lines* indicate the mean concentration of the sprinkled tracers

thickness is considered as the discriminating factor in the EPIK method. This assumption seems valid as the tested protective cover has a thickness of 5 m determined by geophysics (RMT method).

The type of infiltration (diffuse or concentrated) plays an important role on the shape of the contaminant breakthrough curve. First arrivals at the spring are similar, but the maximum concentration is much higher in the case of a point injection. However, diffuse contamination shows a longer duration. The result of this experiment shows the necessity to differentiate point and diffuse pollution.

Strong dilution effects associated with flood events can be seen on Fig. 3. This effect is not taken into account by the EPIK method, but can favour contamination attenuation. Its importance is dependant on the ratio between contaminant input flux and discharge at the spring (i.e. proportional to the size of the catchment area, intrinsic to the system) and to the hydraulic conditions during the

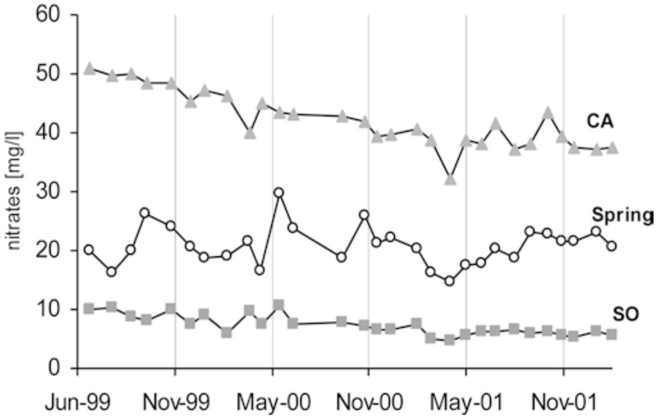

Fig. 5
Monthly nitrates measurements at two tributaries (CA, SO) and the spring of Milandre karst system

contamination (which can be considered in the pollution scenario phase). This intrinsic property is integrated in the VULK approach as the model needs a dilution factor for each subsystem.

Experiment at Brandt test site

The experiment at Brandt site illustrates the strong reactivity of the epikarst subsystem: first arrival of the three tracers is similar, but the recovery is clearly different because iodide is more mobile and lithium is less mobile. Soil was removed before injection to avoid retardation and soil storage, and to test the epikarst only. It appears that retardation is also efficient in the epikarst. This could be due to the presence of organic matter and clays in the fissured media. Retardation can also be caused by the structure of the epikarst: thin fissures and capillary tubes allow a high storage capacity. It is clear that the epikarst structure can play a protective role by retarding the flow velocity.

The use of a tracer such as tritium would help to discriminate between transport delay caused by structural properties or by chemical adsorption.

Data from Milandre test site

The intrinsic properties of the system (system dilution, dispersion, transit time) are relevant only for some contamination scenarios. Nitrate concentrations will undergo system dilution as inputs are not spatially homogeneous at the Milandre test site. However, neither transit time nor dispersion will influence the output concentrations as inputs are temporally constant. Long-term stable isotopes inputs can only be modified by evaporation (reactive effect specific to the tracer). The input is spatially homogeneous and no system-dilution effect will be possible. Modifications of the output signal are mainly caused by changes in the hydraulic state of the system.

By and large, the different contamination scenarios can be schematised by four end members characterised by the shape and the distribution of the input function (Fig. 7). In a previous study, Teutsch and Sauter (1998) also proposed a classification in four "problem classes", but they limited their scenario at the spatial dimension.

The output functions are first considered under steady-state conditions: the possible effect of degradation (specific vulnerability) is a decrease in output concentrations. Second, modifications of the output functions under transient conditions are given. General remarks are given in Table 1.

Contamination scenarios have to be described at three levels:

1. The shape and spatial distribution of the input function will directly determine the output function under steady-state conditions.
2. The hydrodynamic state of the aquifer for a given pollution will greatly influence the contaminant output. Velocity can increase more than one order of magnitude between base flow and flood conditions (results from the Lionne catchment and other unpublished data) and thus reduce Δt into $\Delta t'$. Karst spring discharges have typical variations of one to two orders of magnitude (e.g. Lionne spring discharge varies from 100 to 10,000 L/s). Such changes in fluxes will lead to flood dilution. Such an effect is illustrated by Fig. 3: sulforhodamine is diluted by the flood event occurring

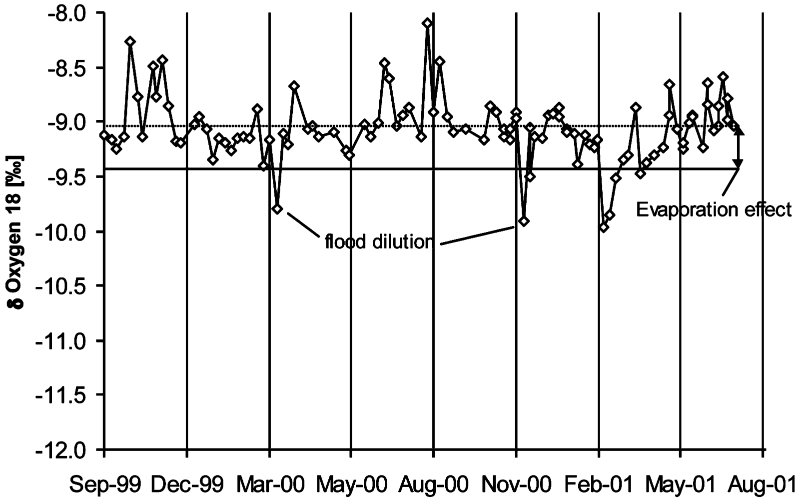

Fig. 6
Evolution of oxygen stable isotopes ratio in the Milandre karst system spring water. The *thick line* indicates the annual mean ratio in rainfall and the *dashed line* corresponds to the mean ratio at the spring

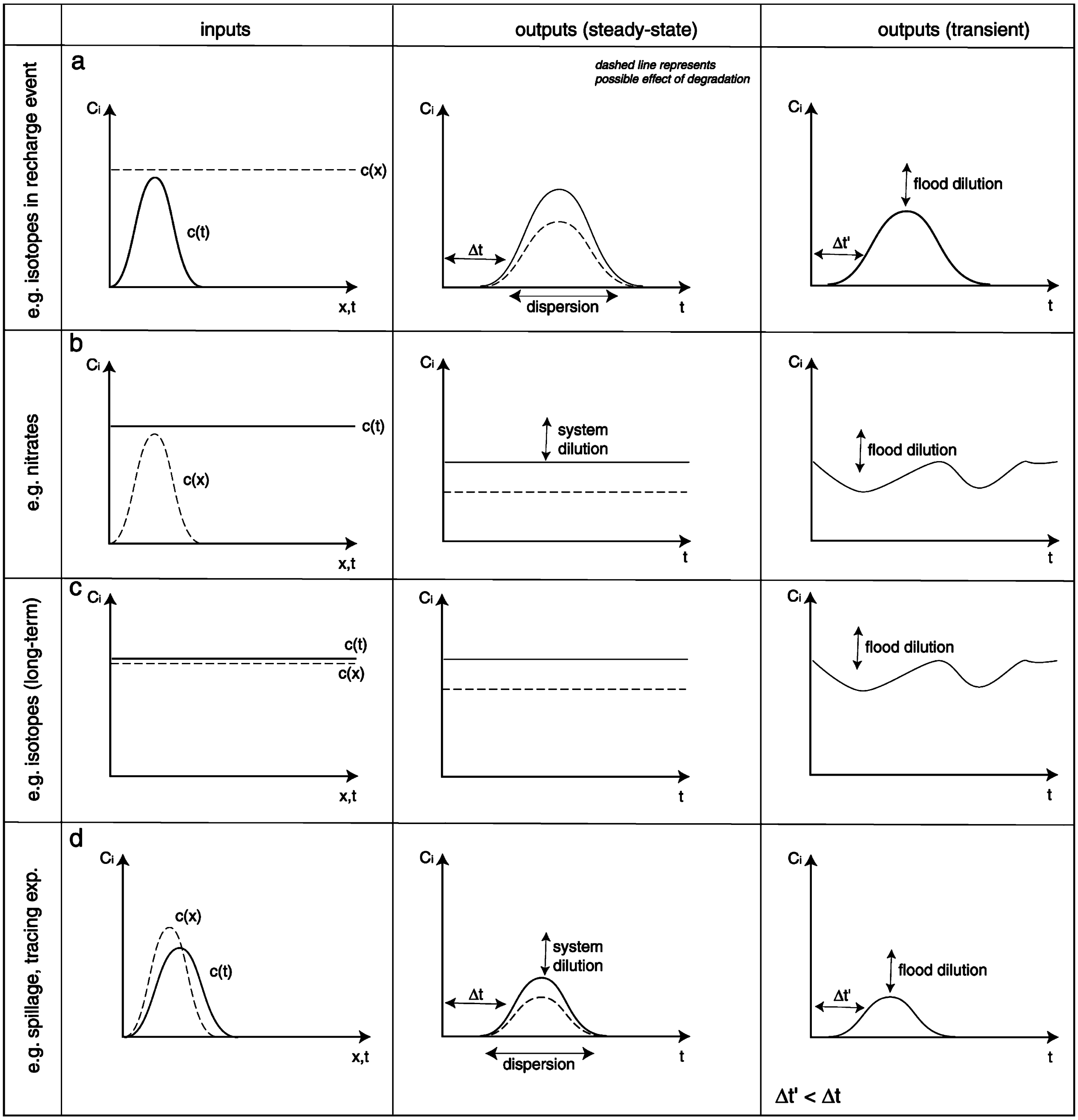

Fig. 7
Schematic representation of the four end-member contamination scenarios. Inputs are characterised by their spatial repartition (space is represented by *x*) and their duration (time represented by *t*). *Ci* corresponds to concentration of a given contaminant *i*. Outputs are theoretical breakthrough curves

during breakthrough. Concentration changes can also be caused by a differential contribution of the sub-catchments through the flood duration. As an example, one can imagine a catchment covered by forests in the downstream part and by cultivated land in the upstream part. If nitrates are considered, there can be a decrease in concentration in the first part of the flood followed by an increase in the second part.

3. Last, but not least, the quantity of the spread pollutant will be of major importance on the outputs. Figure 7 illustrates only cases where the quantity will significantly influence the system. However, scenarios with limited amounts of pollutant will lead to output at background levels. Such a case is illustrated by the tracing experiment on glacial deposit at the Lionne site. No response was obtained, even if the input function is described by case d. A second example is given by the short time-scale stable-isotope data at the Milandre site. A strong signal in the rain is transmitted to the spring only if the recharge is greater than 20 mm. Such a threshold value is an indicator of the storage capacity of the soil and epikarst subsystems. A signal at the spring will occur only if the tracer (or pollutant) exceeds this threshold value.

To summarise, the response to these contamination scenarios are dependant on:

Table 1
Comments to the four contamination scenarios schematised in Fig. 7

	Input	Steady-state output	Transient output
Case a	Short-term pollution spread over the entire catchment. Stable isotopes changes during a rainfall event can be a representative tracer	Transit time and dispersion are relevant but no system dilution is possible	Flood can decrease concentration by dilution. Transit time is reduced
Case b	Long-term pollution spread over part of the catchment. That is the nitrates example at Milandre site	Transit time and dispersion are not relevant. System dilution can mitigate pollution	Concentration changes are mainly caused by differential temporal contributions of the sub-catchments
Case c	Long-term pollution spread over the entire catchment. That is the stable isotopes example at Milandre site	Transit time, dispersion and system dilution are not relevant	Flood dilution possible if variations in the input occur on a short time scale
Case d	Short-term pollution spread on a limited area. It corresponds to the tracing experiments at Lionne site	Transit time, dispersion and system dilution will influence the output	Flood dilution will occur. Transit time is reduced

1. The structure of the aquifer (intrinsic vulnerability): system dilution, dispersion, flow velocity field given a certain retardation (Δt) and threshold of the soil–epikarst storage capacity.
2. The shape and spatial distribution of the input function, the volume of pollutant, the hydrodynamic state of the aquifer (contamination scenario).
3. The degradation of a given pollutant (specific vulnerability).

Major issues for vulnerability assessments

Intrinsic vulnerability

- Role of glacial deposits. Moraine covering karstic rocks plays a clear protective role as indicated by the Lionne tracing experiments.
- Role of epikarst. Epikarst can have an important storage capacity and limit flow velocity.
- Role of the karstic network. Dilution related to the size of the catchment can drastically decrease the output concentrations.

Specific vulnerability

- Role of the epikarst. Presence of clay materials and organic matter can significantly limit the mobility of certain contaminants.

Pollution scenarios

- Role of the contamination scenario. Input function shapes and flux of the contaminant will determine, to a large extent, the output function shape. Intrinsic vulnerability parameters (flow velocity, dispersion, system dilution) will be relevant only for some scenarios.
- Role of the hydrodynamic state of the aquifer. Changes in hydraulic conditions have an important effect on the concentrations at the output: a flood event can decrease transit time by one order of magnitude.

Conclusions

These field experiments show the adequacy of the subsystems conceptual model, which is used by the EPIK method: in summary, the possible protective role of the soil, the epikarst and the type of infiltration has been clearly illustrated. However, weighting factors of the subsystems would need to be adapted. Protective cover needs a higher weight than that proposed by the method and the possible protective role of the epikarst has to be integrated. The main difficulty lies in the absence of tools for epikarst mapping. More work has to be done on the infiltration of the subsystem: the spatial distribution of true diffuse infiltration, surface runoff or subcutaneous flow is still not clear.

An important point, which is not considered by EPIK, is the system dilution that is directly dependent on the catchment size. However, recent developments have integrated this parameter (e.g. VULK model).

It has to be kept in mind that classical tracing tests (point injection of a few cubic metres of traced water) carried out for the delineation of the catchment areas cannot be used to obtain straightforward information on the vulnerability of the system (e.g. flow velocity). In most cases, such experiments bypass the ‘soil–epikarst filter’ and can only give information on flow velocity and dispersion in the karstic network. The only way to obtain the flow parameters of soil and epikarst is by small-scale experiments using realistic recharge intensities.

It is clear that the contamination scenario will influence, to a large extent, the breakthrough curve at the output. To optimise the protection of karst groundwater quality, it is necessary to adapt the vulnerability mapping to the most probable contamination scenario.

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