

A simplified methodology for mapping groundwater vulnerability and contamination risk, and its first application in a tropical karst area, Vietnam

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Abstract A simplified methodology for mapping groundwater vulnerability and contamination risk is proposed, and the first application of the methodology, in a mountainous tropical karst area, is presented. The test site is the Tam Duong area, one of the poorest and remotest regions in northern Vietnam. The methodology requires a minimum of input data, which makes it particularly useful for developing countries. Vulnerability is assessed on the basis of two factors, which take into account the duality of recharge processes in karst aquifer systems: the overlying layers (O) and the concentration of flow (C). The risk map is obtained by putting together the vulnerability map and a simplified hazard assessment. The resulting maps provide a basis for groundwater protection zoning and land-use planning. Tracer tests and microbiological data confirmed the vulnerability and risk assessment in the test site.

Résumé Une méthodologie simplifiée de cartographie de la vulnérabilité des eaux souterraines et du risque de contamination est proposée. Une première application est présentée, dans une zone karstique montagneuse sous climat tropical. Le site expérimental choisi est le secteur de Tam Duong, une des régions les plus pauvres et les plus isolées du Nord Vietnam. Cette approche ne nécessite qu'une quantité minimale de données d'entrée, ce qui en fait un outil utile pour les pays en voie de développement.

Received: 3 December 2005 / Accepted: 25 May 2006
Published online: 1 August 2006

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L'appréciation de la vulnérabilité est basée sur deux facteurs prenant en compte la dualité des processus de recharge des systèmes karstiques: les couches supérieures ("overlying layers", facteur O), et la concentration des flux d'infiltration ("concentration of flow", facteur C). Le recoupement de la carte de vulnérabilité avec l'estimation simplifiée des aléas permet d'établir la carte des risques. Les cartes résultantes fournissent une base pour le zonage de la protection des eaux souterraines et l'aménagement de l'espace. Traçages et données microbiologiques ont confirmé les évaluations de la vulnérabilité et des risques effectuées sur le site expérimental.

Resumen Se propone una metodología simplificada para realizar la cartografía de la vulnerabilidad de agua subterránea y el riesgo a la contaminación y se presenta la primera aplicación de la metodología en un área kárstica tropical montañosa. El sitio evaluado es el área Tam Duong, una de las regiones más pobres y remotas del norte de Vietnam. La metodología requiere un mínimo de datos de entrada lo que la hace particularmente útil para países en desarrollo. La vulnerabilidad se evalúa en base a dos factores los cuales toman en cuenta la dualidad de los procesos de recarga en sistemas de acuíferos kársticos: las capas sobreyacentes (O) y la concentración de flujo (C). El mapa de riesgo se obtiene mediante la integración del mapa de vulnerabilidad y una evaluación simplificada de la amenaza. Los mapas producidos de esta manera aportan bases para la zonificación de la protección de aguas subterráneas y la planificación del uso de la tierra. Pruebas con trazadores y datos microbiológicos confirman la vulnerabilidad y la evaluación de riesgos en el sitio experimental.

Keywords Groundwater vulnerability · Contamination risk · Tropical karst aquifer · Developing country · Socio-economic aspects

Introduction

Groundwater is the main drinking water resource in many parts of the world. Contamination resulting from industry, urbanisation and agriculture poses a threat to water quality. Wise management strategies are thus required to find a balance between groundwater protection on one hand and

economic activities on the other hand (Foster and Chilton 2003). The task of balancing groundwater protection and economic activities is particularly challenging for karst groundwater, which is estimated as supplying water to one quarter of the world's population (Ford and Williams 1989). Karst aquifers are particularly vulnerable, as contaminants can easily enter the subsurface through thin soils and via swallow holes. Karst groundwater thus requires special protection (Drew and Hötzl 1999). A sound knowledge of the hydrogeological system is a prerequisite for any protection strategy. However, karst systems are more complicated than sand and gravel aquifers, because of their high degree of heterogeneity and the resulting duality of recharge (autogenic vs. allogenic), infiltration (diffuse vs. point) and porosity (conduits vs. fissured matrix; Bakalowicz 2005).

Contaminants usually enter the aquifer together with infiltrating water. Therefore, recharge and infiltration processes are particularly relevant for groundwater vulnerability. Autogenic recharge originates from the karst area itself and consists of diffuse infiltration into the soil or directly into exposed carbonate rocks, and subsequent percolation through the unsaturated zone. Allogenic recharge originates on non-karst formations that adjoin or overly the karst aquifer. It often enters the aquifer via swallow holes or other points or zones of infiltration. Inside the aquifer, contaminants can be rapidly transported over large distances in the conduit network together with the turbulent groundwater flow, while some storage might occur in the fissured matrix blocks (Loop and White 2001; White 2002). As a consequence of this duality, contaminants can either be transported and flushed out of the systems very rapidly or may be stored for prolonged periods and released with a long delay (e.g. Goldscheider 2005a).

Vulnerability and risk maps are valuable tools for land-use planning and groundwater protection zoning (Foster 1987). A large number of methods of vulnerability mapping have been proposed. Comparative studies have demonstrated that the application of different methods often leads to contradictory results, and that many of the common methods do not adequately consider the specific nature of karst (e.g. Gogu and Dassargues 2000; Gogu et al. 2003; Vias et al. 2005). Therefore, the EU COST Action 620 was established in order to develop an approach to “vulnerability and risk mapping for the protection of carbonate (karst) aquifers” (Daly et al. 2002; Zwahlen 2004). The methodology has successfully been applied in several karst areas in Europe (e.g. Andreo et al. 2006). However, it was developed by European scientists having in mind the hydrogeological and socio-economic conditions in their countries. Consequently, it is relatively complex and requires detailed data that are not available in many other parts of the world and particularly not in developing countries.

Groundwater from karst aquifers is crucial for the day-to-day water supply in many regions in northern Vietnam (Tuyet 1998). Protection zones are often absent, and many karst springs show contamination problems that mainly result from agricultural activities and untreated domestic

wastewaters. The implementation of protection schemes could help to improve the situation. Such schemes should be as simple as possible and require a minimum of data.

This report presents the basic principles of vulnerability and risk mapping, mainly considering the conceptual framework proposed by COST 620. On this basis, a simplified methodology for mapping groundwater vulnerability (“duality method”) and contamination risk is proposed. It can be applied to all types of aquifers while providing specific tools for karst systems. The new methods were first applied in the Tam Duong karst area in northern Vietnam, which is one of the remotest and poorest regions in the country. The last section of the report discusses how the resulting maps could be used as tools for sustainable groundwater and land-use management.

Basic concepts

The concept of assessing groundwater vulnerability and contamination risk is based on an origin-pathway-target model. Origin is the term used to describe the location of a potential contaminant release. The pathway comprises the passage of contaminants from the origin to the target, i.e. the water that shall be protected. Resource protection aims to protect the whole aquifer; source protection aims to protect a spring or well. For resource protection, the groundwater surface is defined as the target, and the pathway consists of the unsaturated zone. For source protection, the pathway additionally includes the flow in the aquifer towards the spring or well (Goldscheider 2004). From a quantitative point of view, three aspects are important for vulnerability assessment: the travel time of a contaminant from the origin to the target, the attenuation along its pathway, and the duration of a contamination at the target (Brouyère 2004). This approach makes it possible to validate vulnerability assessments by means of artificial tracer tests, and chemical and microbiological groundwater quality data (Goldscheider et al. 2001; Holman et al. 2005; Perrin et al. 2004).

Margat (1968) introduced the term “vulnerability of groundwater to contamination”, which can be used as an alternative to the term “natural protection against contamination”—the lower the natural protection, the higher the vulnerability. It is possible to distinguish between intrinsic and specific vulnerability (Daly et al. 2002; Vrba and Zaporozec 1994). The intrinsic vulnerability takes into account the hydrogeological characteristics of an area, but is independent of the nature of the contaminants. The specific vulnerability additionally considers the interaction between a specific contaminant type and the hydrogeological system. Both types of vulnerability maps can be prepared both for resource and source protection.

The pan-European approach to intrinsic karst groundwater vulnerability mapping considers four factors. The overlying layers (O) may provide some degree of protection to the groundwater. In karst areas, however, allogenic recharge may bypass these layers. Therefore, the concentration of flow (C) also has to be considered. The

precipitation regime (P) is important when comparing groundwater vulnerability in different climatic regions but less relevant for vulnerability mapping at a more local scale. The K factor describes the hydraulic properties of the karst aquifer. Resource vulnerability maps are created by a combination of the first three factors; source vulnerability maps additionally consider the K factor (Goldscheider and Popescu 2004). Specific vulnerability maps can be created for different types of contaminants, e.g. pesticides or pathogenic microorganisms (Sinreich et al. 2004).

Groundwater protection zones are areas in which land use is restricted in order to maintain good water quality (Adams and Foster 1992). Some countries use vulnerability maps as a basis for protection zoning. The importance of the groundwater is often considered as an additional criterion (NRC 1997). In Ireland, for example, resource protection zones are delineated on the basis of the vulnerability map and the importance of the aquifer, while source protection zones are delineated on the basis of the vulnerability map and the travel time in the aquifer (DoELG/EPA/GSI 1999).

A hazard can be defined as a potential source of groundwater contamination resulting from human activities (De Ketelaere et al. 2004). Three aspects are important when evaluating hazards: the quality (toxicity) of the contaminants, the quantity (mass, load), and the likelihood of contaminant release (chronically or accidental). A detailed rating, weighting and ranking system can be used for the evaluation of groundwater hazards.

The risk of groundwater contamination takes into account different aspects: the presence and harmfulness of hazards, the groundwater vulnerability, and, in some cases, the importance or value of the groundwater. COST Action 620 proposed different types of risk assessment, including risk intensity, risk sensitivity, and total risk assessment (Hötzl et al. 2004). These risk maps can be prepared for the groundwater resource or for a particular source, either for specific contaminants or on the basis of the intrinsic vulnerability map.

Proposed simplified methodology

Overview

The proposed simplified methodology is mostly based on the conceptual framework proposed by COST 620 (Zwahlen 2004), which was described in the previous section. However, the number of elements was reduced to form a methodology that includes only one type of vulnerability map, one type of hazard map, and one type of risk map. The number of factors was also reduced as much as possible, and the assessment schemes were simplified. Vulnerability mapping is based on the assessment of two factors only (Fig. 1), and the risk map is obtained by combining the vulnerability map and a very simple hazard assessment. The complete assessment scheme is presented in Fig. 2. The methodology can be applied in areas with limited available data and economic resources. It is applicable to different types of hydro-

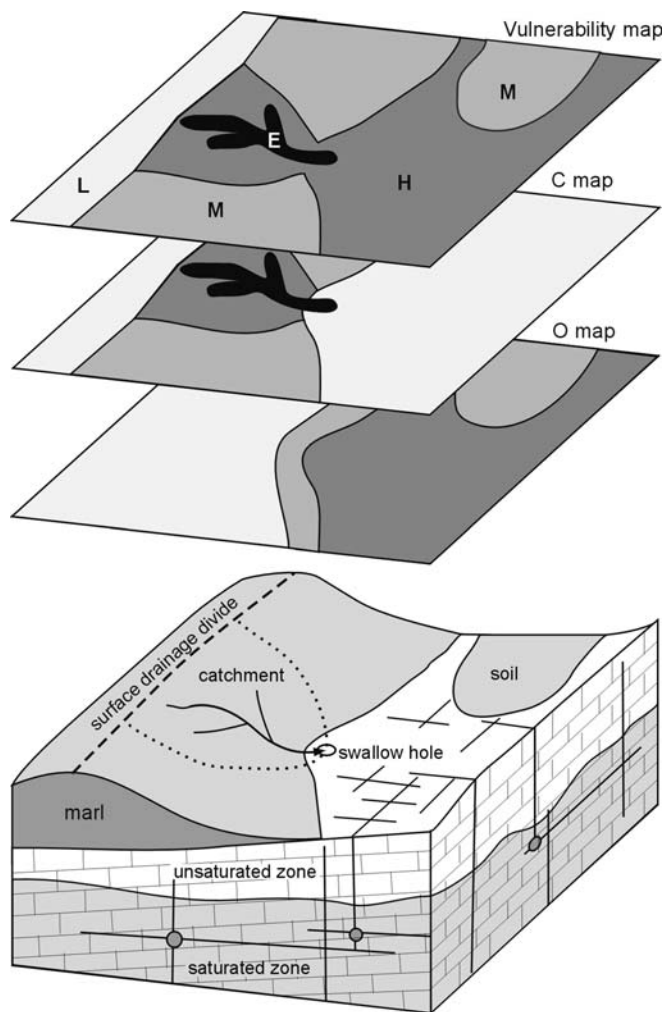


Fig. 1 Illustration of the proposed “Duality method” of karst groundwater vulnerability mapping, which takes into consideration the duality of recharge processes in karst aquifers. The O factor describes the protectiveness of the overlying layers, the C factor considers the concentration of flow towards swallow holes and other zones of infiltration, and the vulnerability map is created by overlaying the O and C maps. L light; M medium; H high; E extreme

geological environments, and it particularly considers the specific nature of karst, i.e. the duality of recharge and infiltration processes. The use of a GIS facilitates the application and makes it possible to update the hazard and risk maps on a regular basis.

Groundwater vulnerability mapping - the duality method

The first element of the proposed methodology is an intrinsic groundwater resource vulnerability map. The land surface is defined as the origin, and the pathway includes the passage from the origin to the groundwater table, which is taken as the target. Only two factors are considered: overlying layers (O) and flow concentration (C).

These factors take into account the duality of recharge processes in karst aquifer systems. The O factor describes the

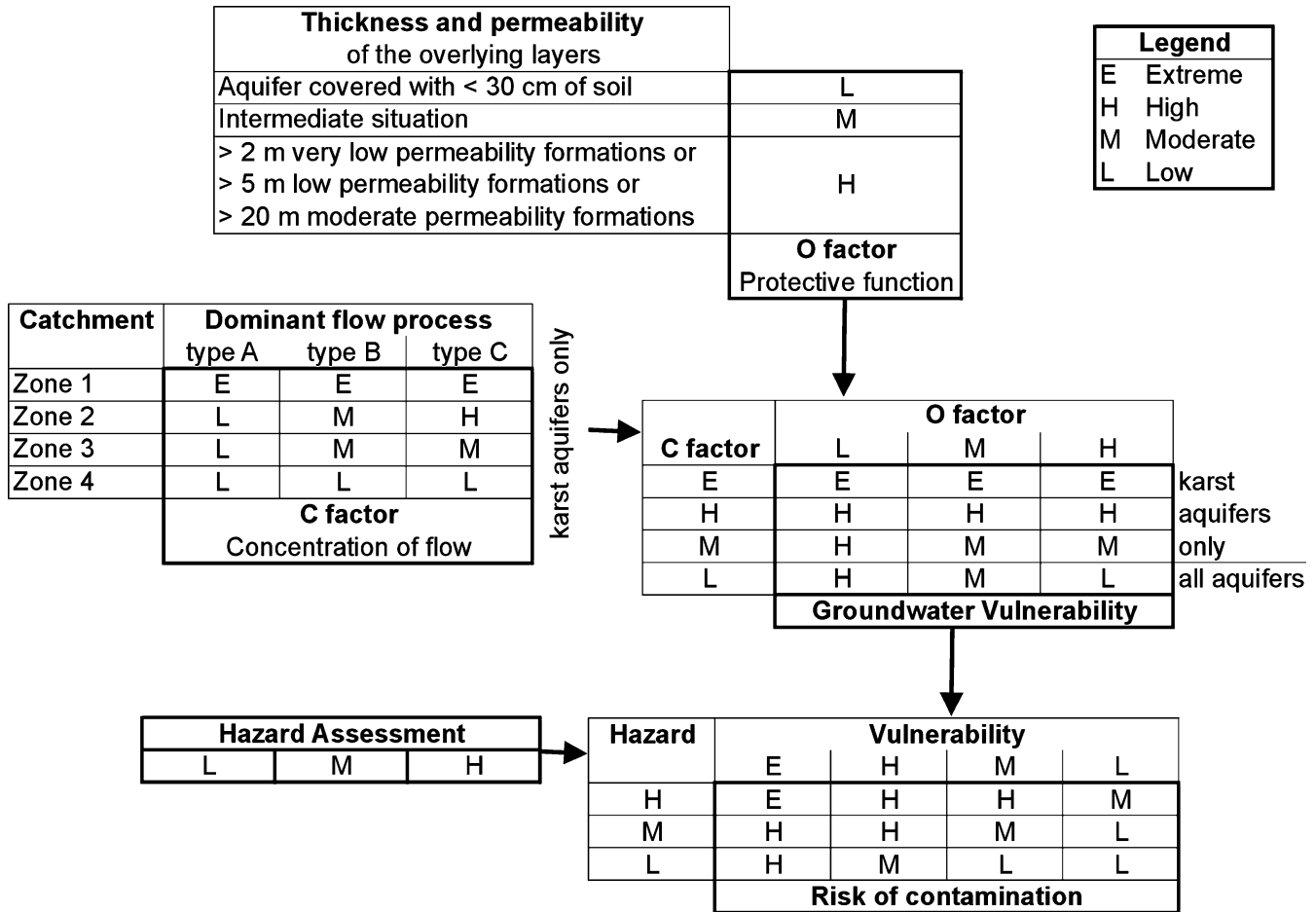


Fig. 2 Proposed methodology for mapping groundwater vulnerability and risk of contamination

protectiveness of the layers overlying the aquifer. The presence and properties of these layers determine the vulnerability resulting from autogenic recharge, i.e. infiltration and subsequent percolation of water and possible contaminants through the unsaturated zone. Autogenic recharge also occurs in unconsolidated sediments and fractured rocks. Therefore, the O factor applies to all types of aquifers. The C factor is specific to karst. It describes the vulnerability resulting from allogenic recharge processes. Surface flow originating on non-karst formations that sinks into the karst aquifer via swallow holes or at the slope foot can rapidly transport contaminants into the groundwater (Fig. 1).

The assessment scheme for the O factor is simple (Fig. 2). A low protective function is assigned to situations where the aquifer is covered by less than 30 cm of soil. Thick layers of low to moderate permeability provide high natural protection, e.g. >5 m of loam. A moderate protection is assigned to intermediate situations, e.g. 1 m of soil overlying the aquifer.

The assessment scheme for the C factor consists of two steps (modified after Goldscheider et al. 2000 and Goldscheider 2005b). The first step is to determine the dominant flow process:

- Type A: Direct infiltration and percolation takes place on high permeability formations

- Type B: Intermediate situations
- Type C: Frequent surface runoff takes place on low permeability formations

Type A indicates the predominance of autogenic recharge, while Type C means that allogenic recharge might occur if the given area actually drains towards a point or zone of infiltration. Therefore, the second step is to subdivide the land surface into four types of zones:

- Zone 1: Swallow holes, sinking streams up to 1 km upstream from the swallow holes, and 20 m buffer zones on both sides of the sinking streams
- Zone 2: The rest of the catchment areas of sinking streams
- Zone 3: Areas outside the catchments of sinking streams but within the karst area
- Zone 4: Areas that drain laterally out of the karst hydrogeological system

The C map is obtained by combining the “dominant flow process map” and the “surface catchment map”. For unconsolidated and fractured aquifers, the O map can directly be translated into a vulnerability map. For karst aquifers, the vulnerability map is obtained by overlying the O and C maps. In areas that generate runoff toward

swallow holes, the C factor overrides the O factor, i.e. such areas are always classified as highly to extremely vulnerable. Four classes of vulnerability are distinguished, symbolised by colours ranging from dark red for extreme vulnerability, to light blue for low vulnerability. The vulnerability map can be used as a basis for groundwater resource protection zoning. Stringent land-use restrictions are recommended in highly vulnerable zones.

Unlike other methods of karst groundwater vulnerability mapping, e.g. EPIK (Doerfliger and Zwahlen 1998), the proposed method does not explicitly include the mapping of karren, dolines and other karst landforms. Tracing-irrigation experiments and other field observations have revealed that the exokarst is not a reliable indicator for vulnerability (Goldscheider et al. 2001; Perrin et al. 2004). Contaminants might rapidly travel through shallow soils and the unsaturated zone even when no karst landforms are visible, while dolines and karren might be clogged with sediments and thus provide some degree of protection. Therefore, only dolines that actually act as swallow holes are considered for the proposed method and classified as zones of extreme vulnerability. The rest of the karst area that is covered with less than 30 cm of soil is classified as highly vulnerable, independent of the surface karst landforms.

Hazard and risk mapping

Hazards can be classified on the basis of three aspects: quality, quantity, and likelihood of a potential contaminant release. As these aspects are difficult to quantify, the proposed methodology simply classifies hazards into high, moderate and low. Urbanisation, industry, waste disposal sites, main roads, petrol stations, intensive agriculture and untreated domestic wastewater releases are classified as “high”; small roads, villages with wastewater treatment systems, and low-intensity agriculture are “moderate”; natural vegetation, forest and very low-intensity agriculture, e.g. organic fruit-tree-growing, are “low”.

The risk map is created by overlying the vulnerability map with the hazard map (Fig. 2). However, for future applications, the assessment scheme could be extended by considering the importance of the groundwater resource, i.e. its ecological or socio-economic value, as an additional element. The risk map highlights the necessity to act by changing land-use practices and removing existing pollution hazards in zones of high risk.

Application in the test site

Description of the test site

The Tam Duong karst area in NW Vietnam (Fig. 3) was selected as a test site for the first application of the proposed methodology on the basis of four criteria. First, it is a typical tropical karst landscape and quite representative of many other mountainous karst areas in Southeast Asia; second, the local population largely depends on drinking water from two karst springs, which are also used

for agriculture and a tea factory; third, it is an area with rapidly growing population and thus increasing freshwater demand and land-use pressure. Last but not least, the authors also investigated the hydrogeology and groundwater quality in the same test site so that the vulnerability and risk mapping can be included in a wider framework (Nguyet and Goldscheider 2006). The area is among the remotest and poorest regions in the country. At present (2004), approximately 10,000 inhabitants live in the rapidly expanding town of Tam Duong, which is situated in a wide valley at an altitude of 800 m. The surrounding steep conical hills reach altitudes of up to 1,400 m. The climate is tropical humid with an annual precipitation of 2,600 mm and an average air temperature of 20°C. The natural vegetation is tropical mountainous forests, which still exist in the mountains. Agricultural land use predominates in the main and side valleys, and includes rice paddies, tea, vegetable and fruit plantings, low-intensity cattle pasture and fishponds.

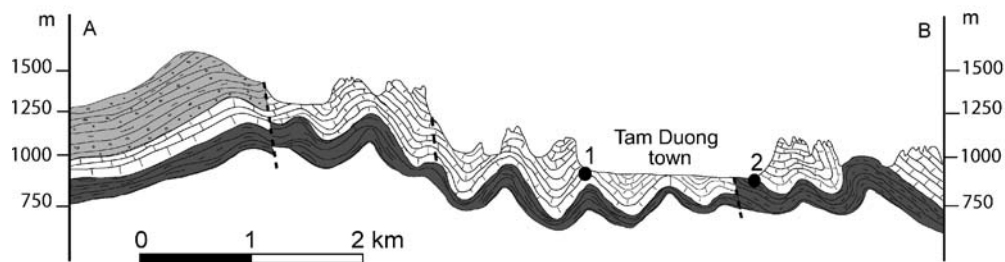
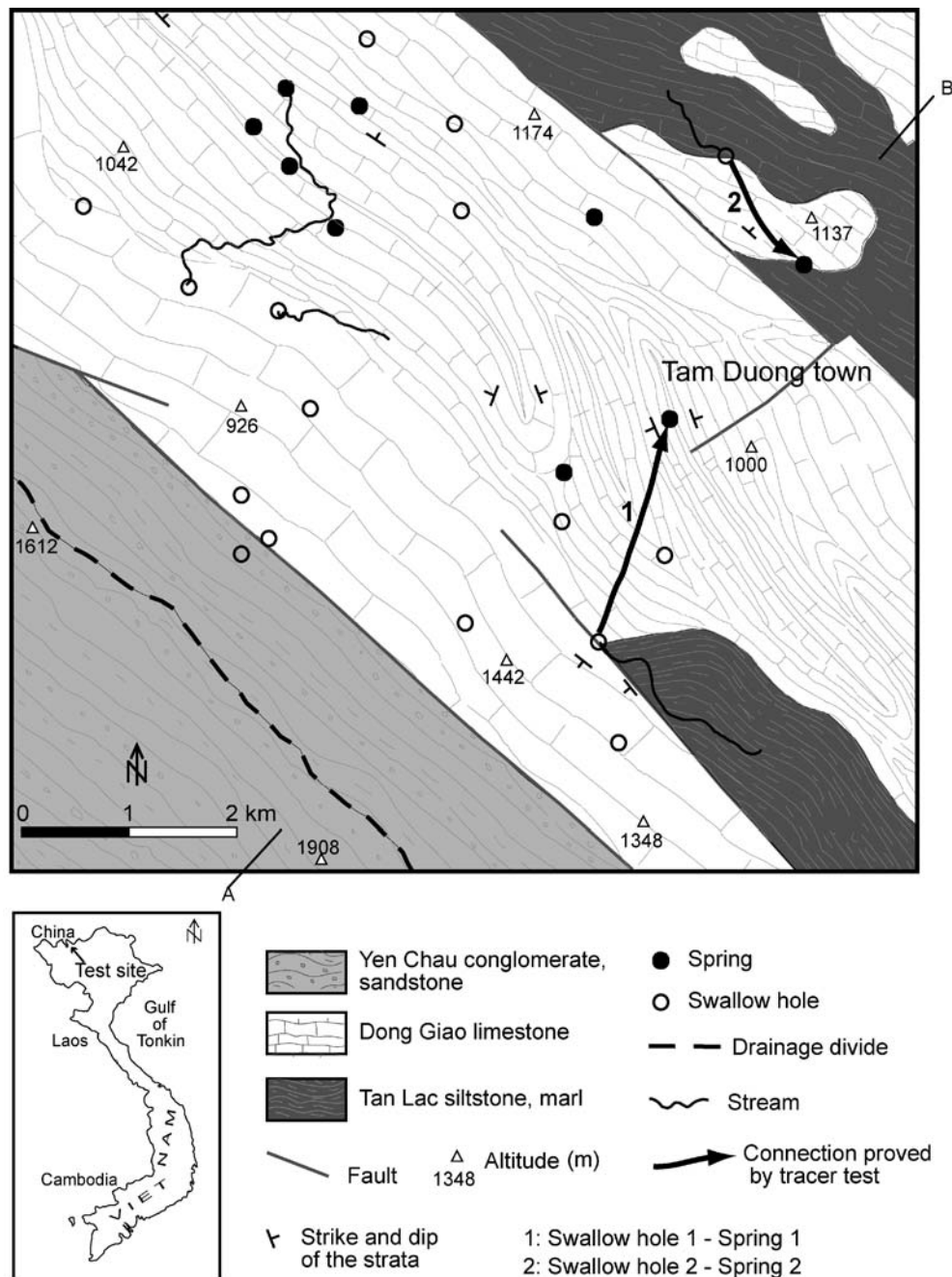
Geologically, the test site is formed of Mesozoic sedimentary rocks: the Early Triassic Tan Lac formation is 300–600 m thick and consists of siltstone and marl; the overlying Middle Triassic Dong Giao limestone formation is 300–800 m thick; the Cretaceous Yen Chau formation includes conglomerates and sandstones at the SW margin of the test site. The region is structured by NW–SE trending folds, which are essentially formed of Dong Giao limestone. The underlying marls are exposed along two anticlines. Two main fault directions can be observed in the area: NW–SE and NE–SW (My 1978; Thu and Ban 1996).

The Dong Giao limestone is karstified, and the test site represents a typical tropical tower karst landscape (Tuyet 1998). There are numerous caves and dolines. In most parts of the area, shallow soils and vegetation cover the karst rocks. Well-developed epikarst can be observed near roads and in a quarry. Thick loamy soils and residual deposits are locally present in the main valley. Hydrogeologically, the area is characterised by a thick karst aquifer (Dong Giao limestone) on top of a thick aquiclude (Tan Lac marl). Surface streams that flow over marl often sink into the karst aquifer via swallow holes, which are located at faults and/or near the geological contact between the marl and limestone formations. Most springs in the area discharge from the karst aquifer. Tracer tests proved rapid and straightforward connection between two swallow holes and the two above-mentioned karst springs, which are simply named spring 1 and spring 2 (Fig. 3; Nguyet and Goldscheider 2006). Each of the two spring catchments consequently includes an autogenic recharge area, i.e. limestone outcrops with predominantly diffuse infiltration via the overlying soil, and an allogenic recharge area, i.e. marl outcrops that generate surface flow towards swallow holes.

Groundwater vulnerability mapping

A geological and a topographic map (scale: 1:50,000), as well as direct field observations served as a basis for the

Fig. 3 Location, hydrogeological map and cross-section of the test site



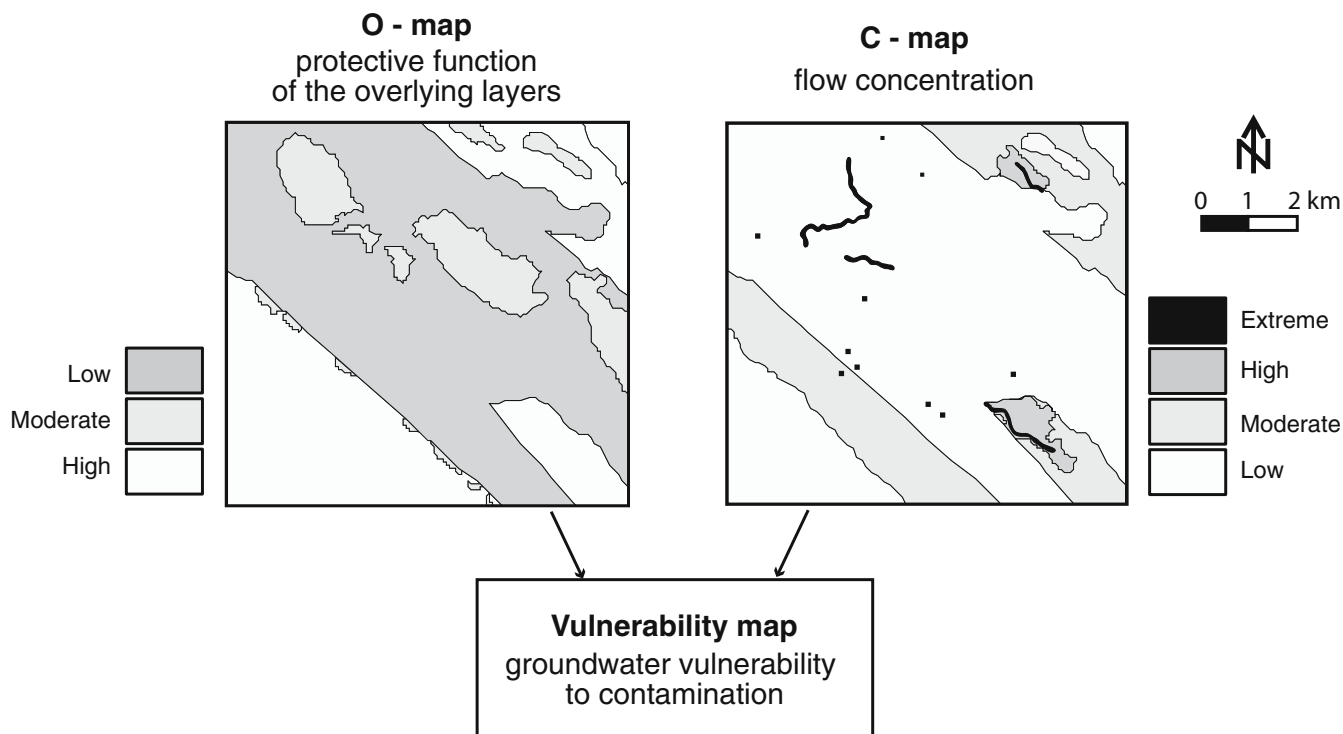


Fig. 4 O and C map of the test site. The resulting vulnerability map is shown in Fig. 5

vulnerability, hazard and risk mapping. The maps were prepared using the GIS ArcView 3.2. The O map for the Tam Duong area reflects the lithology and the soil pattern (Fig. 4). Large parts of the test site consist of karst limestone covered with shallow soils, which provide a low degree of protection, i.e. a low O factor. A moderate protectiveness was assigned to the thick loamy deposits that are locally present in the main valley. The O factor is high in areas of marl, conglomerate and sandstone.

Due to the demonstrated importance of point recharge, the C factor is crucial for vulnerability mapping in the Tam Duong test site. The first step toward delineating the C map was to identify the dominant flow processes based on the geological map and direct field observations. Limestone areas predominantly drain by infiltration and percolation (type A). Surface runoff occurs frequently on marl (type C), while the conglomerates and sandstones represent an intermediate situation (type B). The second step consisted of preparing the surface catchment map. The swallow holes, sinking stream and buffer zones were classified as zone 1. Their catchment areas, which essentially comprise marl, were classified as zone 2. The remaining karst area is categorised as zone 3. The steep conglomerate and sandstone slopes that dip towards the karst area also belong to this zone. The area SW of the topographic watershed, where these clastic sediments overly the karst aquifer, was classified as zone 4.

The vulnerability map reflects both the overlying layers and the concentration of flow, i.e. the vulnerability resulting from both autogenic and allogenic recharge

respectively. The swallow holes and the sinking streams with buffer zones were classified as zones of extreme groundwater vulnerability. A high vulnerability was attributed both to karst areas covered by shallow soils, and to sinking stream catchments underlain by marl. The areas in the main valley with thick loamy soils over the karst aquifer were classified as zones of moderate vulnerability, as were the conglomerate slopes that drain towards the adjacent karst aquifer system. The SW corner of the test site is a zone of low groundwater vulnerability, as the karst aquifer is covered by hundreds of metres of conglomerate and sandstone, which drain laterally out of the karst hydrogeological system towards a large river.

Hazard assessment, risk mapping, and validation

The hazards in the Tam Duong area are concentrated in the main valley in and around the town. The urbanisation itself, a hospital, a tea factory, some gasoline stations and the locally intense agriculture represent the most important hazards. Low-intensity agriculture and the roads were classified as moderate hazards. Some hazards resulting from untreated domestic wastewater, rice paddies and other agricultural activities are also present in the small side valleys, often near the sinking streams. Large parts of the mountainous areas, however, are overgrown by natural or quasi-natural vegetation, or used for very low-intensity agriculture.

The risk map was determined by overlying the hazard map and the groundwater vulnerability map. The risk map

helps to identify zones where action is required to reduce the risk of groundwater contamination. In the test site area, extreme risk is present in small zones, where important hazards are directly located at a swallow hole or near a sinking stream. The main valley and the side valleys are a mosaic of zones of high and moderate risk, which reflects the patterns of the vulnerability map and the hazard map. No significant risk is present in most parts of the mountainous areas, particularly in the SW corner of the area, where thick conglomerates and sandstones cover the karst aquifer.

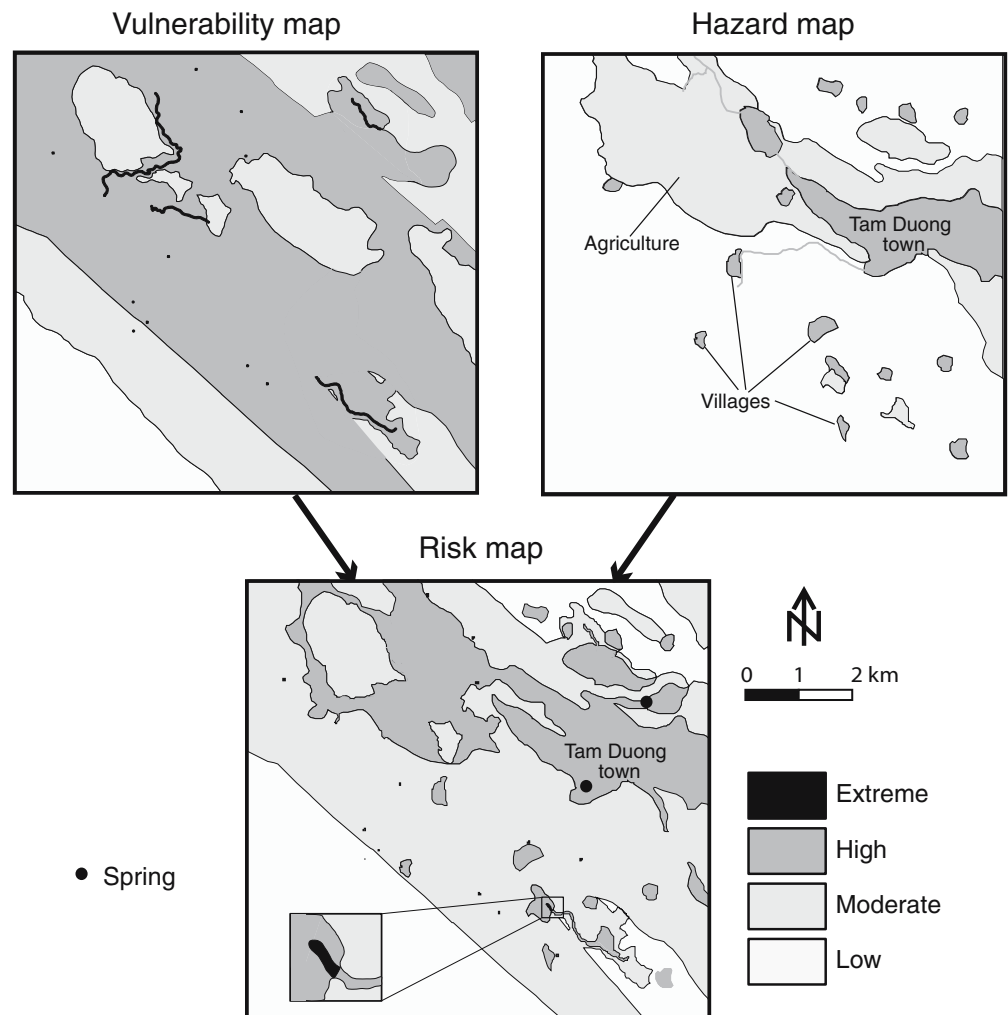
The tracer tests and microbiological investigations in the area can be used to validate the vulnerability and risk assessment. The tracers that were injected into the swallow holes reappeared at the springs 41.5 hours (spring 1) and 2.5 hours (spring 2) after the injections, which corresponds to maximum linear flow velocities of 72 m/h and 700 m/h, respectively. The recovery rates of both tracers exceeded 70% (Nguyet and Goldscheider 2006). These findings support the extreme vulnerability that was assigned to the swallow holes and sinking streams. For a more complete validation of the vulnerability assessment, however, it would be necessary to carry out several tracing-irrigation

experiments, also on sites that have been classified as areas of moderate to high vulnerability (Goldscheider et al. 2001). Both springs show highly variably microbial contamination. Spring 1 generally shows higher contents of thermotolerant coliform bacteria (up to 19,200 TTC/100 ml) than spring 2 (up to 3900 TTC/100 ml). According to the standards for drinking water defined by the WHO (2004), thermotolerant coliforms must be absent in a 100-ml sample. The poor microbial water quality of both springs can be attributed to the zones of elevated risk in their catchments, particularly in the areas of allogenic and point recharge, i.e. the catchment areas of the connected sinking streams. The very high contamination at spring 1 corresponds to the zone of extreme risk near swallow hole 1 and thus supports the risk assessment (Fig. 5, detail).

Discussion and conclusions

The proposed methodology was applied in a poor and remote area with limited data availability. The geological, topographic and hydrological characteristics of the test site

Fig. 5 Vulnerability, hazard and risk maps for the Tam Duong test site. Both the tracer test results and the high contents of bacteria in spring 1 confirm the vulnerability and risk assessment near swallow hole 1 (*detail*)



are relatively complicated. Nevertheless, the methodology was successfully applied in the area as it uses basic data which are available for most areas or can be readily assessed in the field. For vulnerability mapping, the basic data include geology, topography, and the location of swallow holes and sinking streams. Hazards are grouped into three classes, and the risk map is obtained by overlying the two maps. The use of a GIS facilitated the creation of the maps. The vulnerability, hazard and risk maps of the test site are plausible and were confirmed by tracer tests and microbiological data. The method will therefore be applied to other Vietnamese karst test sites and appears to be well adapted to be used in other developing countries, particularly in tropical karst regions. Although the duality method includes a karst specific element (the C factor), its applicability is not restricted to karst aquifers.

The vulnerability, hazard and risk maps provide a valuable basis for land-use planning and sustainable groundwater management in the Tam Duong area. The vulnerability map can be used to find a balance between human activities and economic interests on one hand and groundwater protection on the other hand. Groundwater protection should be prioritised in the most vulnerable zone. Stringent land-use restrictions are recommended in these zones. Fewer restrictions are required in the less vulnerable zones. However, contaminant release should clearly be reduced as much as possible on the entire land surface. In some cases, additional criteria should be considered for the delineation of groundwater protection zones and the definition of adequate land-use responses such as the importance of the groundwater resource. The risk map shows the risk of groundwater being contaminated by existing human activities, and hence the necessity to act. In the zones of elevated risk, the present land-use practices should be changed and hazards should be removed in order to improve the water quality, e.g. the untreated domestic wastewater release near swallow hole 1, which is likely to be a major cause of high microbial contamination at karst spring 1 (Figs. 3 and 5).

The vulnerability, hazard and risk maps neither replace detailed hydrogeological site assessments for specific issues, nor do they replace water-quality monitoring on a regular basis. As the land-use practices rapidly change in the Tam Duong test site as well as in many other areas, the hazard and risk maps should be frequently updated. The maps only deal with groundwater quality. They do not provide any information on groundwater quantity aspects such as the problem of overexploitation. Furthermore, they do not provide any information on the vulnerability of other natural resources to human activity.

Acknowledgements The Swiss Federal Commission for Foreign Students and the Belgian Technical Cooperation partially funded this study. We thank the RIGMR researchers for information and logistic support, and D. M. Cung and the people from Tam Duong for their help in the field. We are grateful to Prof. F. De Smedt and Dr. O. Batelaan (Free University of Brussels) and Prof. F. Zwahlen (CHYN) for their kind support, and D. Daly, M. Lee (GSI) and Prof. D. Drew (Trinity College Dublin) for valuable suggestions and corrections.

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