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Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region

Volume 4

Guideline for Groundwater Vulnerability Mapping and Risk Assessment for the Susceptibility of Groundwater Resources to Contamination

Damascus

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Guideline for Groundwater Vulnerability Mapping and Risk Assessment for the Susceptibility of Groundwater Resources to Contamination

Authors:	Dr. Armin Margane (BGR)
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Foreword

The increasing awareness of water issues in the Arab Region and the prospect of an emerging water crisis during the first decade of the 21st century has led to growing concern about the sustainable use of water resources.

Since the Arab Region extends over arid and semi-arid zones, groundwater constitutes the main source of water supply. Protection of this resource is indispensably necessary to ensure sustainable development.

ACSAD and BGR focus exactly on this issue by implementing their joint project **"Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region".**

This report constitutes one of the important outputs of the project. The report aims at the prevention of groundwater pollution and presents suitable methods for the protection of groundwater resources in the Arab Region.

ACSAD is indebted to BGR and its staff for their fruitful cooperation in our joint project.

By making this publication available to a wider audience, we hope to provide not only technical solutions but also promote awareness for these aspects in the Arab Region.

Dr. Adel Safar
Director General
ACSAD

Table of Contents

List of Annexes

List of Figures

List of Tables

Foreword

This report is part of a series of Technical Reports published by the Technical Cooperation Project “Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region”, which is being implemented by the Federal Institute of Geosciences and Natural Resources (BGR), Germany, and the Arab Centre for the Studies of Arid Zones and Dry Lands (ACSAD). This project started in August 1997 and ends with its second phase in December 2003.

ACSAD was established in 1971 as an autonomous, intergovernmental organization, working within the framework of the Arab League.

Many Arab countries are facing major environmental challenges. Water scarcity and pollution in conjunction with the loss, degradation and contamination of land resources have become core problems affecting public health and the socio-economic development. Water and soil resources represent exhaustible and vulnerable resources. Thus, a sustainable development of the Arab region requires the implementation of guidelines concerning the protection and sustainable use of groundwater resources and soils. The formulation and dissemination of such guidelines is the main goal of the project.

The mapping of groundwater vulnerability is widely used in developed countries as a basic tool for the protection of groundwater resources. Such maps are not only used by groundwater specialists but also in the framework of land use planning. The intention of the guideline presented in this report is to facilitate the preparation of groundwater vulnerability maps in the Arab region.

Groundwater vulnerability maps in conjunction with maps showing existing potential hazards to groundwater resources help to identify possible risks. The identification and assessment of risks for the susceptibility of water supply utilities to contamination is needed in order to undertake countermeasures against pollution risks. Therefore, the risk assessment also plays an important role for the protection of groundwater resources.

To provide an effective protection of the groundwater resources, it is also important to convince the land use planning authorities to take the issue of groundwater protection into consideration when deciding about locations and conditions for the establishment of facilities and activities which are possibly hazardous to groundwater, such as waste disposal sites, sewage treatment plants and sewer mains, industrial and commercial estates, storage facilities for oil products and toxic hazardous substances, etc. By locating such sites in areas where a contamination of the groundwater resources cannot occur, a deterioration of the groundwater resources can be actively avoided.

The preparation of groundwater vulnerability maps helps to create awareness among land use planners for the issue of groundwater protection.

Summary

A selection of the presently most applied methods for groundwater vulnerability mapping is presented and evaluated in this report:

- The DRASTIC method, used mainly in the USA,
- The GLA-Method and its recent modification, the PI-Method, used by the German States and Federal Government authorities,
- The EPIK-Method used by the Swiss authorities and the
- COP-Method which may become the method to be used by all European authorities for vulnerability mapping in karst areas.

The choice of the most appropriate method for groundwater vulnerability mapping to be used in a certain area depends on the data availability, spatial data distribution, the scale of mapping, the purpose of the map and the hydrogeological setting. The above mentioned methods are mainly designated for the support of land use planning and general groundwater protection measures, such as e.g. the establishment of groundwater protection zones. In most such cases the mapping scale is between 1:50,000 and 1:100,000. However, the scale mainly depends on the availability of data and their spatial distribution. The better the data availability, the more detailed the map could be, i.e. the larger the mapping scale.

In areas where data availability is low but the general hydrogeological setup is known, DRASTIC would be a suitable method of choice. If not all required parameters are known, it may be considered using an even more simple method, such as GOD (FOSTER & HIRATA, 1988).

The most suitable method, however, is the GLA-Method and its modification, the PI-Method because the used rating system is more based on scientific considerations and less subjective than in DRASTIC. The GLA-Method has some shortcomings in karst environments. These were taken into account by the PI-Method, so that this method may principally be applied in all hydrogeological settings.

In pure karst environments, however, the application of EPIK is more recommended because it was specifically designed for this purpose and takes the influence of karst features much better into account than the PI-Method.

No sufficient practical experience has been made with the COP-Method, so that until now it can not be recommended as a standard method for the mapping of groundwater vulnerability in karst areas, even though it may well become the standard tool for this purpose throughout Europe.

In areas with different lithological units, i.e. where karst and non-karst aquifers may occur, it is recommended to use either the GLA-Method or the PI-Method.

1. Introduction

Groundwater vulnerability maps have become a standard tool for protecting groundwater resources from pollution. They are especially valuable in the decision making process related to land use planning. Land use planners have mostly little experience and expertise at hand to decide which land uses and activities are to be allowed in certain areas without causing a negative impact on the quality of groundwater resources.

Groundwater vulnerability maps are widely used since about 30 years. There are a number of methods used worldwide (VRBA & SAPOROZEC 1994, MARGANE et al. 1997). However, there is until now no generally accepted standard mapping method. This is mainly due to the fact that the hydrogeological conditions and the availability of data are highly different from one area to another. There are methods which require the knowledge of the spatial distribution of up to ten parameters and thus a very detailed data availability. On the other hand there are also methods which require the input of only two or three parameters. Such methods may preferringly be applied in areas where data availability is low. Many of these methods are, however, rather simple and fail to yield appropriate results.

In all methods the vulnerability of an aquifer is classified according to the traveltime of a drop of water from the land surface to the aquifer (percolation time). This flow is very different in porous rocks compared to hard rocks where flow preferentially follows fractures and cavities. In this respect karst aquifers play an important role since infiltration may be highly concentrated in certain areas and travel time from the land surface to the aquifer may be extremely short.

The Federal Institute for Geosciences and Natural Resources (BGR) is a member of the European COST 620 working group on “Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers” which is trying to come up with a standard method for groundwater vulnerability mapping in karst areas. BGR has prepared a number of groundwater vulnerability maps in developing countries over the past decade. Among the first groundwater vulnerability maps in the Arab region were those established in Jordan within the framework of the Technical Cooperation project 'Advisory Services to the Water Authority of Jordan – Groundwater Resources of Northern Jordan' (1992-2001) between the Water Authority of Jordan (WAJ) and the BGR for the area around Irbid (MARGANE et al. 1997, MARGANE et al. 1999a) and the South Amman area (HIJAZI et al., 1999). They were supplemented by maps of hazards to groundwater in order to identify where groundwater resources might be at risk and draw the necessary conclusions concerning groundwater monitoring for these hazards and land use planning decisions. The mapping scale was 1:50,000 and the output scale 1:100,000. This scale was chosen in order to provide land use planners with appropriate planning tools for larger areas. As a standard method, the method proposed by HOELTING et al. (1995; also called GLA-Method) was used, which is largely applied in Germany.

The Technical Cooperation Project "Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region" prepared similar maps, based on the same method for the Beka'a Valley in Lebanon (HOBLER & RAJAB, in prep.) and the Ghouta area in Syria (east of Damascus; HOBLER & RAJAB, 2002).

In Switzerland groundwater vulnerability maps are used as a standard tool for groundwater protection zone delineation in karst areas (BUWAL, 2000). The Swiss Government decided to use the EPIK method (SAEFL, 2000) for this purpose. Other European countries intend to follow a similar concept in the near future. Within the framework of the new Jordanian-German Technical Cooperation project 'Groundwater Resources Management' (2002-2005) the project team will delineate groundwater protection zones for at least two wells or springs based on groundwater vulnerability maps for karst aquifers (MARGANE & SUNNA, 2002).

2. Definition of Groundwater Vulnerability

The term „vulnerability of groundwater to contamination" was first used by MARGAT (1968). The term "groundwater vulnerability" is used in the opposite sense to the term natural protection against contamination".

Although many efforts have been made to reach a common understanding of the term ground-water vulnerability, different authors still use it in differing senses. FOSTER & HIRATA (1988) defined **'Aquifer Pollution Vulnerability'** as the *'intrinsic characteristics which determine the sensitivity of various parts of an aquifer to being adversely affected by an imposed contaminant load'*. They describe **'Ground Water Pollution Risk'** as *'the interaction between the natural vulnerability of an aquifer, and the pollution loading that is, or will be, applied on the subsurface environment as a result of human activity'*. The US EPA (1993) distinguishes between 'Aquifer Sensitivity' and 'Ground Water Vulnerability'. Although these definitions are more closely related to agricultural activities, they should hold true for all other activities as well. US EPA defines **'Aquifer Sensitivity'** as the *'relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest. Aquifer sensitivity is a function of the intrinsic characteristics of the geologic materials of interest, any overlying saturated materials, and the overlying unsaturated zone. Sensitivity is not dependent on agronomic practices or pesticide characteristics'*. According to US EPA **'Ground Water Vulnerability'** is *'the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest under a given set of agronomic management practices, pesticide characteristics and hydrogeologic sensitivity conditions'.*

The "Committee on Techniques for Assessing Ground Water Vulnerability" of the NATIONAL RESEARCH COUNCIL (1993) and VRBA & ZAPOROZEC (1994) define groundwater vulnerability as "*the tendency or likelihood for contaminants to reach (a specified position in) the groundwater system after introduction at some location above the uppermost aquifer".* In addition, distinctions are made between "**Intrinsic**

Vulnerability" and "**Specific Vulnerability**". For the determination of the "Intrinsic Vulnerability" the characteristics and specific behaviour of contaminants are not taken into consideration, whereas the term "Specific Vulnerability" refers to a specific contaminant, class of contaminants or a certain prevailing human activity. VOWINKEL et al. (1996) defined vulnerability as sensitivity plus intensity, where 'intensity' is a measure of the source of contamination. In this sense, groundwater vulnerability is a function not only of the properties of the groundwater flow system (intrinsic susceptibility) but also of the proximity of contaminant sources, characteristics of the contaminant, and other factors that could potentially increase loads of specified contaminants to the aquifer and/or their eventual delivery to a groundwater resource.

The COST 620 workgroup on "Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers" defines intrinsic vulnerability as "the term used to define the vulnerability of groundwater to contaminants generated by human activities. It takes account of the inherent geological, hydrological and hydrogeological characteristics of an area but is independent of the nature of human activities." COST 620 regards the (present) land surface as the standard point of reference for a possible release of contaminants (source). It is distinguished between two different targets for protection as shown in *Figure 1*: the resource (aquifer) and the source (well or spring used for water supply).

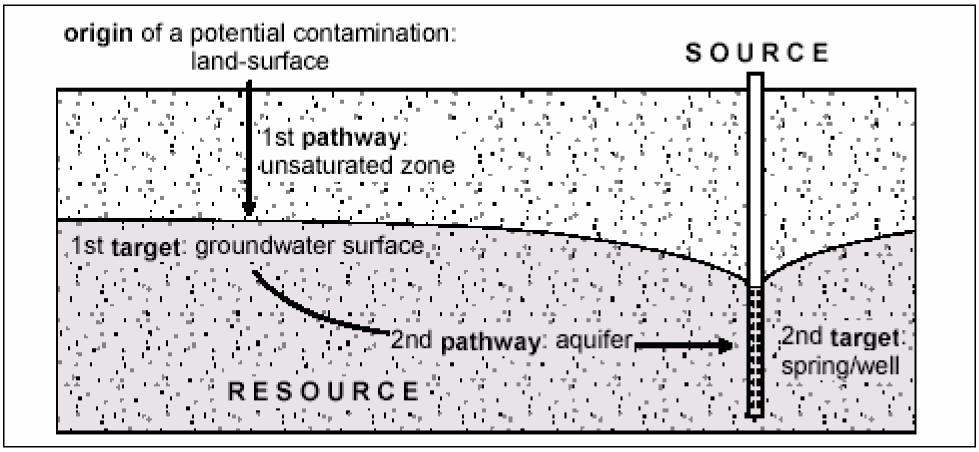

Figure 1: Source-Pathway-Target Model of Groundwater Vulnerability (GOLDSCHEIDER 2002)

The intrinsic vulnerability of groundwater is a relative, non-measurable property which is not verifiable since it depends on the attenuation and retardation properties of the sediments and rocks overlying the aquifer as well as on the properties of contaminants. Nonetheless, some efforts have been undertaken in recent years to establish a methodology which yields better defensible results and is less arbitrary with respect to the delineation of vulnerability classes (COST 620, in prep.).

Generally, maps of intrinsic vulnerability are closely tied to policy or management objectives whereas specific vulnerability maps are often tied to scientific objectives and typically require additional interpretation on the part of decision makers.

3. Parameters determining Groundwater Vulnerability

FOSTER & HIRATA (1988), MORRIS & FOSTER (2000) and VRBA & ZAPOROZEC (1994) list possible processes and mechanisms leading to an attenuation of the contaminant load in different media, through which water and contaminants pass on their way to the water table (soil, unsaturated and saturated zone).

The following factors determine the protective effectiveness or filtering effect of the rock and soil cover :

- mineralogical rock composition,
- rock compactness,
- degree of jointing and fracturing,
- porosity,
- content of organic matter,
- carbonate content,
- clay content,
- metal oxides content,
- pH,
- redox potential,
- cation exchange capacity (CEC),
- thickness of rock and soil cover
- percolation rate and velocity.

Specific chemical characteristics have to be taken into account when considering the behaviour of pollutants below the ground and the time they take to migrate through the soil, in both the unsaturated and the saturated zone. Such characteristics include:

- natural parameters influencing the solubility and chemical reactivity (temperature, pressure, etc.),
- dispersion/diffusion,
- chemical complexation, sorption and precipitation
- degradation (chemical/biological/radiological transformation, hydrolysis, etc.).

The behaviour of each chemical substance differs considerably in the underground. When assessing the specific vulnerability of a natural groundwater system, the specific behaviour of the expected individual chemical substances has to be evaluated. Contaminants can be transformed by geochemical, radiological, and microbiological processes as they are transported through various environments within the groundwater system. Some chemical transformations can change harmful contaminants into less harmful chemical species, while other processes can produce compounds that are more harmful to ecosystems or human health than the parent compound. The natural decay of some radionuclides can produce daughter products with different transport properties and health effects than the parent product. In some cases, transformation products are found in the environment more often than parent compounds. For example, groundwater remediation programs are increasingly focused on natural attenuation processes controlled by mixing, advection, and biodegradation as these processes serve to decrease concentrations and/or viability of contaminants. Similarly, some chemical transformations can change relatively immobile compounds into highly mobile compounds, and change parent compounds to transformation products. Knowledge of the path and timing of groundwater movement as well as the chemistry and biology relevant for the contaminant present is important in determining the fate and transport of a contaminant and its associated transformation products. This is important for contaminants that rapidly change to other chemicals in the environment particularly when transformation or daughter products are more persistent than the parent compound. In addition, the vulnerability of a groundwater supply facility to many contaminants is dependent on the solubility and subsequent mobility of the contaminant as influenced by the specific mineralogy and associated geochemical conditions within the aquifer and pumped well. The chemical properties of a contaminant are important in the unsaturated zone as well as the aquifer itself. For example, some (hydrophobic) compounds strongly attach to soils in the unsaturated zone (as well as the saturated zone) before reaching the water table, and these compounds are attached until released by geochemical or other changes such as when the binding capacity of the soil is exceeded.

For mapping of the intrinsic vulnerability, the behaviour of different pollutants is not taken into consideration. In this case the assessment of vulnerability is reduced to the parameters determining the general protective effectiveness of the soil and rock cover. Such a simplification allows for the assessment of groundwater vulnerability over large areas at a relatively low cost and in a comparatively short amount of time. This general assessment forms the basis of further investigations. Studies of the specific vulnerability could then be performed at a later stage, in sensitive areas, where groundwater pollution is expected to occur in the near future or already exists.

Soil cover often plays an important role in the attenuation process as it leads to retardation of contaminants of adsorbable pollutants. Furthermore, soils can promote elimination of contaminants by chemical complexation or precipitation and biochemical transformation or degradation (*Figure 2*). Depending on the type of consolidated or unconsolidated rocks these processes are often less effective in the unsaturated zone due to limited availability of oxygen, moisture and microbes, and the often lower cation exchange capacity.

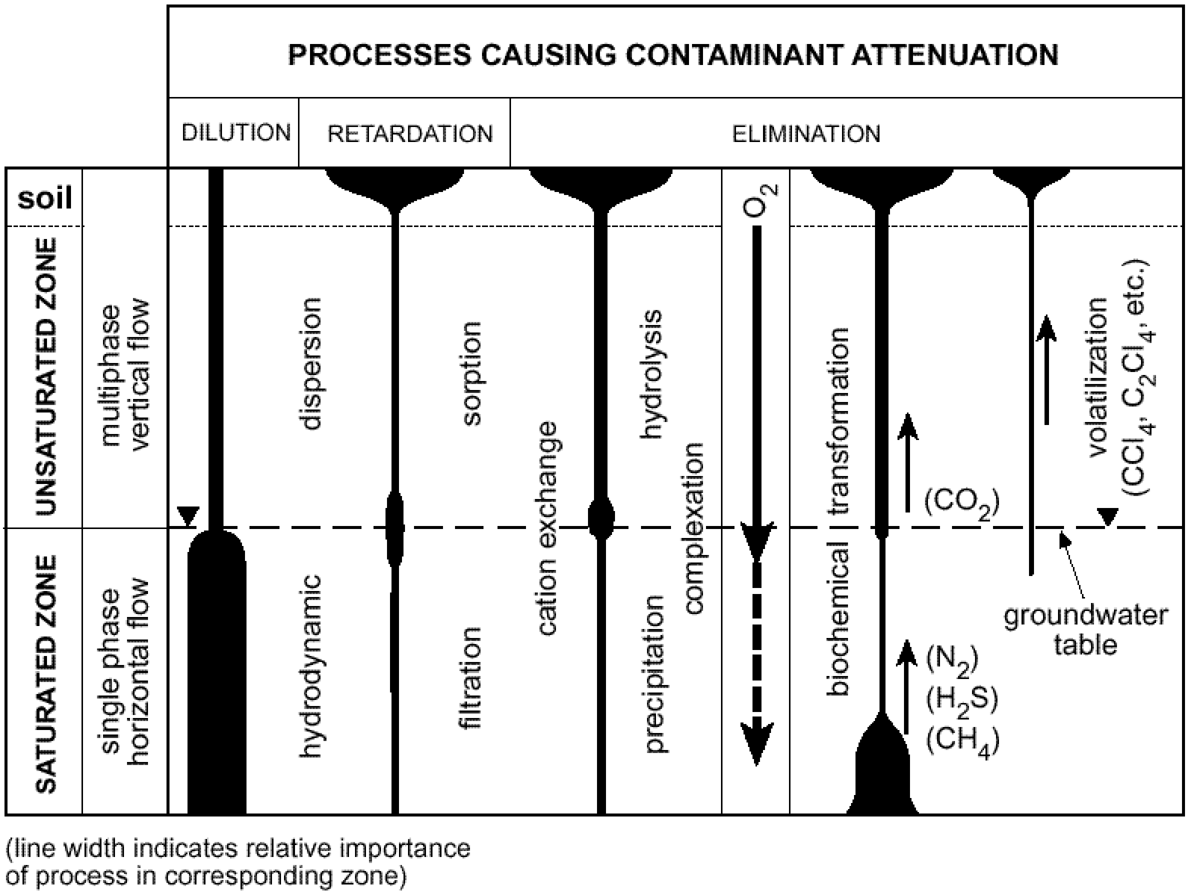

Figure 2: Processes leading to contaminant attenuation (MORRIS & FOSTER 2000)

Another factor that influences the vulnerability of groundwater resources is the way in which groundwater recharge actually takes place. This process is very much different under different hydrogeological conditions. The location where recharge enters the geological system and the rate and intensity of recharge are important controls on the quality of groundwater. Groundwater recharge mechanisms are different for hard rock and especially karst aquifers compared to unconsolidated sediments. In the former case, it mainly takes place via fractures and cavities so that the travel time of a drop of water from the land surface to the aquifer is often relatively short. In unconsolidated rocks, however, the spatial distribution of groundwater recharge rates is more homogeneous. This fact has nowadays been largely acknowledged by integrating this factor into groundwater vulnerability methods, such as the PI-Method, EPIK or the COP-Method.

4. Methods

VRBA & ZAPOROZEC (1994), COST 65 (1995), MARGANE et al. (1997), MAGIERA (2000), GOGU & DASSARGUES (2000b), FOCAZIO et al. (2002) and GOLDSCHEIDER (2002) give a good overview about mapping methods for groundwater vulnerability.

The following approaches can be distinguished :

➢ **Hydrogeological Complex and Setting Methods (HCS)**

This group of methods assesses groundwater vulnerability by setting up classes of two or more levels of vulnerability. The classes are based on criteria found to be representative of groundwater vulnerability under certain hydrogeological conditions. This type of mapping is mainly used for small to medium scale maps and uses basic information often being available from geological, hydrogeological and topographic maps. The groundwater vulnerability map of France (ALBINET & MARGAT 1970; scale 1:1 Mio) and the map of Germany (VIERHUFF et al. 1981; scale 1:1 Mio) are examples for this type of method.

➢ **Parametric System Methods** can be divided into :

- Matrix Systems,
- Rating Systems and
- Point Count System Models.

Matrix Systems assess groundwater vulnerability based on a selection of two or more parameters considered to be representative for a certain area. The selected parameters, like depth to aquifer, soil leaching, groundwater recharge, or others are then grouped into classes (VRBA & ZAPOROZEC, 1994).

Rating Systems use many parameters and attribute fixed ranges of ratings to them according to their variation in the area. The total rating is calculated by overlaying the ratings for the different parameters and then dividing the total rating into different levels of vulnerability. The following methods can be attributed to this method:

- GOD (FOSTER, 1987),
- The system developed by MARCOLONGO & PRETTO (1987) for mapping of the Po Valley in Italy,
- PRZM (Pesticide Root Zone Model), used e.g. by the Hawaii Department of Health (EPA 1993),
- SAFE, used by the Idaho Department of Health and Welfare,
- The system developed by the State Geological Surveys of Germany (GLA-Method; HOELTING, et al., 1995; see Chapter 4.1.2 and *App. 1*) and its modification (PI-Method).

Point Count System Models use the same approach as rating methods but attribute different weights in the form of a multiplier to reflect the importance of each parameter for the overall assessment of groundwater vulnerability. This method includes:

- DRASTIC, developed by the US EPA (ALLER et al., 1985; see Chapter 4.1.1) and
- SINTACS, developed by CIVITA (CIVITA & MAIO, 1997a; CIVITA & MAIO, 1997b; CIVITA et al. 1999: SINTACS Application in Morocco)

The most renowned of the above listed methods is DRASTIC (ALLER et al. 1985). However, many investigations indicate that in some cases, the DRASTIC approach does not adequately match with the hydrogeological conditions and shows some general shortcomings (NATIONAL RESEARCH COUNCIL, 1993).

➢ Index Methods and Analogical Relations

The index methods (IM) and analogical relations (AR) are based on mathematical standard descriptions of hydrological and hydrogeological processes (e.g. transport equations) that are analogously used to assess the groundwater vulnerability. MAGIERA (2000) describes 13 methods of that type. Most of them are used for the evaluation of the specific vulnerability of groundwater to pesticides on a large to medium scale. The IM/AR methods take into account the properties of the overlying layers and the properties of the contaminant.

➢ Mathematical Models

It can be distinguished between numerical methods and statistical methods.

Numerical Methods (flow and transport models for the unsaturated and saturated zone) are so far not being used for vulnerability mapping. MAGIERA (2000) describes nine examples for the application of mathematical models for specific vulnerability mapping on a large to medium scale. Those models take into account the properties of the contaminant (mostly nitrates and pesticides) and the properties of the overlying layers. For the preparation of maps reflecting the specific groundwater vulnerability such methods will certainly play a major role in the future because only combined groundwater flow and transport models will be able to deal with the large quantity of the various input data required for such maps.

A vast number of other numerical models have been established to simulate the transport of certain substances through the unsaturated zone, such as the pesticide-leaching model used by HOLTSCHLAG & LUUKONEN (1997).

Statistical Methods
The physical processes that control the vulnerability of groundwater to contamination are often too complex to be described by taking into account only a selected number

of parameters. Therefore, statistical approaches provide an alternative to parametric system models and have been successfully used for specific vulnerability mapping on a small to medium scale (MAGIERA 2000). Statistical methods can be verified and allow to take into account the reliability of the data.

The first step of a geostatistical vulnerability analysis is to map a selected number of influencing factors, such as depth to groundwater table, soil type, permeability and recharge. The second step is to map the spatial distribution of the concentration of a certain contaminant in the groundwater. The third step is to establish a correlation between the influencing factors and the contaminant concentration which can then be used to prepare a map of groundwater vulnerability to the selected contaminant.

However, the large number of parameters makes the application of statistical methods for vulnerability mapping problematic and often it is difficult to establish a meaningful correlation between the distributions of the influencing factors and the contaminant concentration.

What needs to be kept in mind is that all methods of intrinsic vulnerability mapping are highly subjective and difficult to validate.

The methods being applied most frequently on the international level are the **DRASTIC** method, developed by the US EPA (ALLER et al., 1985) and the method established by the State Geological Surveys of Germany (**GLA-Method**; HOELTING et al., 1995). This method has in recent years been further developed, taking into account infiltration typical for karst areas, and is now called **PI-Method** (GOLDSCHEIDER, 2002). The method which was solely developed for karst areas and is used by the Swiss authorities for the delineation of groundwater protection zones is called **EPIK** (BUWAL 2000).

The COST 620 working group has recently proposed to use the so-called **COP-Method** on the European level. This method integrates elements (O factor – overlying layers) of the German approach with other elements which are especially important in karst areas, such as the concentration of flow (C factor) and the quantity and intensity of precipitation (P Factor).

For reasons of comparison these four methods are described below.

4.1 The US EPA Approach (DRASTIC)

4.1.1 Introduction to the Drastic Method

The DRASTIC methodology was developed by the US Environmental Protection Agency (ALLER et al., 1985). DRASTIC is an acronym for :

D - **D**epth to water table
R - net **R**echarge
A - **A**quifer media
S - **S**oil media
T - **T**opography
I - **I**mpact of the vadose zone
C - hydraulic **C**onductivity of the aquifer

The overall 'Pollution Potential' or 'DRASTIC index' is established by applying the following formula :

$$\text{Pollution Potential} = D_R{*}D_W + R_R{*}R_W + A_R{*}A_W + S_R{*}S_W + T_R{*}_T + I_R{*}_I + {}_C{*}_C.$$

where : R - rating
W - weight.

The ratings are determined from tables and graphs presented in the DRASTIC manual. They are assigned values between 1 and 10. The weight has a fixed value which is listed in *Table 1* below. As seen in the table, two different systems are used: the normal DRASTIC and the agricultural DRASTIC. The latter is mainly used when assessing groundwater vulnerability in areas that are mainly affected by agricultural usage of herbicides and pesticides.

The summation process for these seven parameters, as shown in the 'Pollution Potential' formula, is relatively complex and requires the use of Arc/Info or a similar computer program.

Table 1 : Assigned Weights for DRASTIC Parameters

Parameter	DRASTIC	Agricultural DRASTIC
Depth to Water Table	5	5
Net Recharge	4	4
Aquifer Media	3	3
Soil Media	2	5
Topography	1	3
Impact of the Vadose Zone	5	4
Hydraulic Conductivity	3	2

4.1.2 Examples for DRASTIC Applications

The DRASTIC method has been used to produce maps in many parts of the United States (DURNFORD et al., 1990), in Israel (MELLOUL & COLLIN, 1998), Nicaragua (JOHANSSON et al., 1999), Portugal (LOBO-FERREIRA & OLIVEIRA, 1997), South Africa (LYNCH et al., 1997), and South Korea (KIM & HAMM, 1999). The index method has been used in the USA to develop maps at a variety of scales, including national (KELLOGG et al., 1997; LYNCH et al., 1994), statewide (HAMERLINCK & AMESON, 1998; SEELIG, 1994), and individual counties and townships (REGIONAL GROUNDWATER CENTER, 1995; SHUKLA et al., 2000).

As an example for a DRASTIC application in the ACSAD member countries the groundwater vulnerability map of the Nile Delta, prepared by the Egyptian Groundwater Research Institute is enclosed in this report (*Annex 11*). Other examples are the vulnerability maps of the Al Ain area in the eastern United Arab Emirates (AL-ZABET, 2002) and the one prepared by LYAKHLOUFI et al. (1999) for the Haouz area in Morocco.

4.1.3 Advantages and Disadvantages of the DRASTIC Method

The method is a popular approach to groundwater vulnerability assessments because it is relatively inexpensive, straightforward, and uses data that are commonly available or estimated, and produces an end product that is easily interpreted and incorporated into the decision-making process. The method has some general shortcoming, as pointed out by FOSTER (1998), such as that it under-estimates the vulnerability of fractured aquifers and that its weighting system is not scientifically based.

4.2 The German Concept of Vulnerability Mapping (GLA-Method and PI-Method)

This methodology was first proposed by HOELTING et al. (1995; GLA-Method; *Annex 1*) and is based on a point count system. It was further developed into the PI-Method by GOLDSCHEIDER (2002) in the framework of the European COST 620 program because it was recognized that both, the EPIK method and the GLA-Method had some shortcomings. In the following both methods are presented.

4.2.1 Introduction to the GLA-Method
(HOELTING et al., 1995)

The GLA-Method only takes the unsaturated zone into consideration. Attenuation processes in the saturated zone are not included in the vulnerability concept. The degree of vulnerability is specified according to the **protective effectiveness** of the soil cover and the unsaturated zone. The following parameters are considered for the assessment of the overall protective effectiveness :

Parameter 1: S - effective field capacity of the soil (rating for ΣeFC in mm down to 1 m depth)
Parameter 2: W - percolation rate
Parameter 3: R - rock type
Parameter 4: T - thickness of soil and rock cover above the aquifer
Parameter 5: Q - bonus points for perched aquifer systems
Parameter 6: HP - bonus points for hydraulic pressure conditions (artesian conditions)

The overall protective effectiveness (P_T) is calculated using the formula:

$$P_T = P_1 + P_2 + Q + HP$$

P_1 - protective effectiveness of the soil cover: $P_1 = S * W$
P_2 - protective effectiveness of the unsaturated zone (sediments or hard rocks): $P_2 = W * (R_1*T_1 + R_2*T_2 + \ldots + R_n*T_n)$.

To adopt this method for the use in Arab countries the factor for the percolation rate (W) was modified as follows (MARGANE et al., 1997):

In many dry areas groundwater recharge is below 100 mm/a. However, according to the German mapping approach, the highest value assigned for factor W, would be 1.75 for a groundwater recharge of less than 100 mm/a (HOELTING et al., 1995). Therefore, a modified scale for the factor W was introduced which reflects the low amounts of groundwater recharge in many areas (*Table 2*).

Table 2 : Modification of Factor W (Percolation Rate)

Groundwater Recharge [mm/a]	Factor W
> 400	0.75
> 300 – 400	1
> 200 – 300	1.25
> 100 – 200	1.5
> 50 – 100	*1.75*
> 25 – 50	*2*
≤ 25	*2.25*

The application of these higher factors for the percolation rate leads to a higher overall protective effectiveness of the soil and rock cover in areas of low groundwater recharge.

True groundwater recharge varies considerably from place to place. The amount of recharge depends on factors like topography (slope), soil cover, fracturing, etc. Indirect recharge plays an important role in the study area and might lead to higher recharge in certain areas, such as wadis or morphological depressions. These local differences have to be taken into consideration by assigning lower values for the percolation factor to such areas. It is also important to analyse the function of faults and fracture zones pertaining to their infiltration capacity.

The process of calculating the overall protective effectiveness is very complex and requires the use of Arc/Info or similar software. PETERS et al. (2000) used Arc/View in combination with the module “spatial analyst” and avenue script programming.

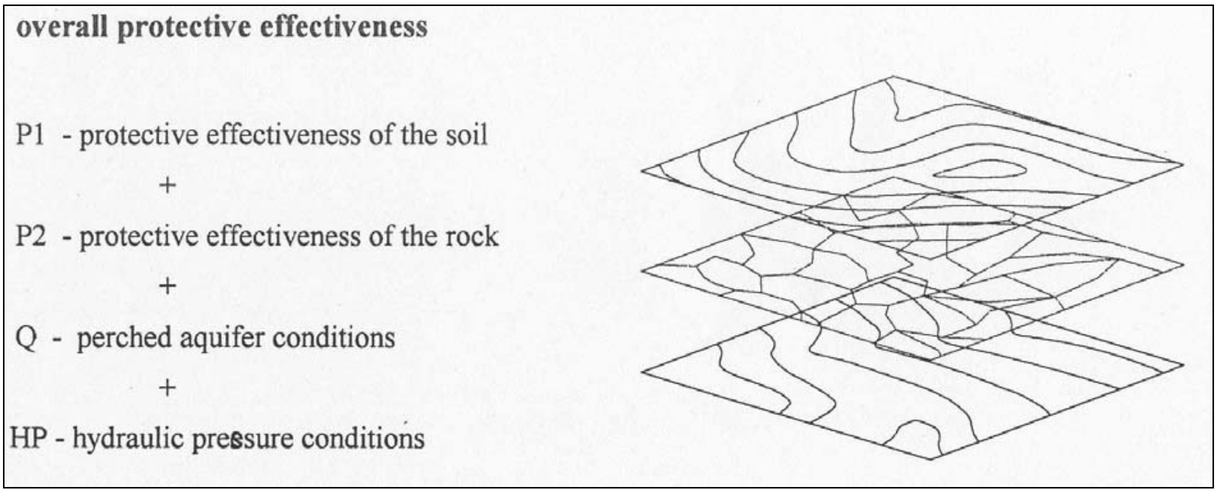

Figure 3: Overlay process for vulnerability mapping

Over the past few years, the German system has been tested in several countries throughout the world by BGR. In the Arab region it was applied in Jordan (Irbid area: MARGANE et al., 1997, and South Amman area: HIJAZI et al., 1999), Syria (Ghouta, east of Damascus; HOBLER & RAJAB, 2002) and Lebanon (Beka’a Valley; HOBLER & RAJAB, in prep.) and has proven to be useful and effective.

For further information about the GLA-Method please refer to *Annex 1*. Please note that the acronyms for the parameters are different from those used in the description of the PI-Method.

4.2.2 Introduction to the PI-Method
(GOLDSCHEIDER, 2002)

The GLA-Method does not take into account preferential infiltration paths which are typical for karst aquifers. The PI-Method is a modification of the GLA-Method that integrates the protective cover (P) and the infiltration factor (I). The I factor was influenced by the EPIK method but strongly modified. The PI-Method has been successfully tested in several sites all over Europe.

In the PI-Method both factors, the protective cover and the infiltration are separately mapped as individual maps and then combined to the groundwater vulnerability map (*Figure 4*).

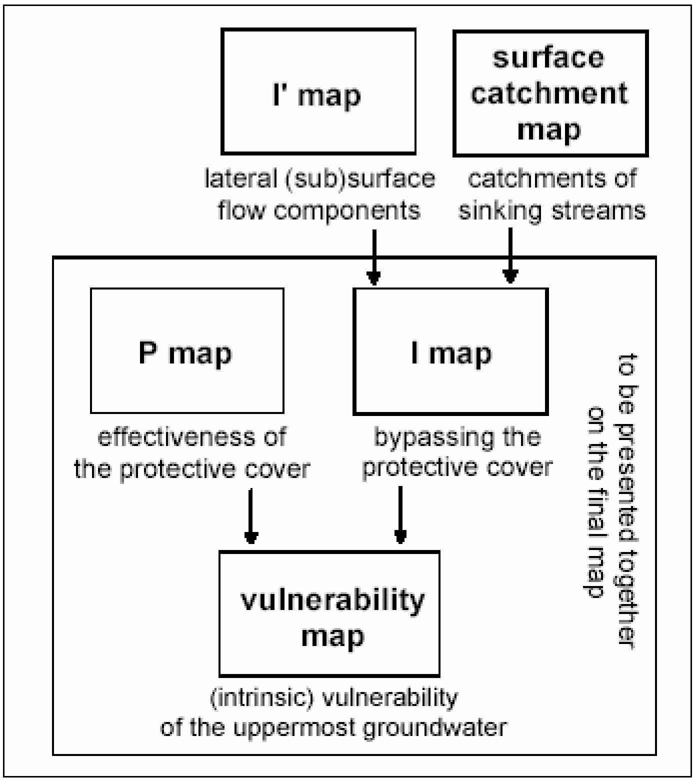

Figure 4: Simplified flow chart for the PI method.

The P Factor

The P factor indicates the effectiveness of the protective cover and is calculated using a modified version of the GLA method (HOELTING et al., 1995). The calculation and assessment scheme is shown in *Figure 5*. The score B for the bedrock is obtained by multiplying the factor L for the lithology and the factor F for the degree of fracturing and karstification. The F factor was modified in order to describe the development of the epikarst and its influence on groundwater vulnerability. The P map shows the spatial distribution of the P factor.

Topsoil - T

eFC [mm] up to 1 m depth	T
> 250	750
> 200-250	500
> 140-200	250
> 90-140	125
> 50-90	50
< 50	0

Recharge - R

Recharge [mm/y]	R
0-100	1.75
>100-200	1.50
>200-300	1.25
>300-400	1.00
>400	0.75

Subsoil - S

Type of subsoil (grain size distribution)	S	Type of subsoil (grain size distribution)	S
clay	500	very clayey sand, clayey sand, loamy silty sand	140
loamy clay, slightly silty clay	400	sandy silt, very loamy sand	120
slightly sandy clay	350	loamy sand, very silty sand	90
silty clay, clayey silty loam	320	slightly clayey sand, silty sand, sandy clayey gravel	75
clayey loam	300	slightly loamy sand, sandy silty gravel	60
very silty clay, sandy clay	270	slightly silty sand, slightly silty sand with gravel	50
very loamy silt	250	sand	25
slightly clayey loam, clayey silty loam	240	sand with gravel, sandy gravel	10
very clayey silt, silty loam	220	gravel, gravel with breccia	5
very sandy clay, sandy silty loam, slightly sandy loam, loamy silt, clayey silt	200	non-lithified volcanic material (pyroklastica)	200
sandy loam, slightly loamy silt	180	peat	400
slightly clayey silt, sandy loamy silt, silt, very sandy loam	160	sapropel	300

Lithology - L

Lithology	L
claystone, slate, marl, siltstone	20
sandstone, quarzite, volcanic rock plutonite, metamorphite	15
porous sandstone, porous volcanic rock (e.g. tuff)	10
conglomerate, breccia, limestone, dolomitic rock, gypsum rock	5

Fracturing - F

Fracturing	F
non-jointed	25.0
slightly jointed	4.0
moderately jointed, slightly karstified or karst features completely sealed	1.0
moderately karstic or karst features mostly sealed	0.5
strongly fractured or strongly karstified and not sealed	0.3
Epikarst strongly developed, not sealed	0.0
not known	1.0

Thickness of each stratum in [m] - M

Bedrock - B $B = L \cdot F$

Artesian pressure A 1500 points

Total protective function P_{TS}

$$P_{TS} = \left[T + \left(\sum_{i=1}^{m} S_i \cdot M_i + \sum_{j=1}^{n} B_j \cdot M_j \right) \right] \cdot R + A$$

score P_{TS}	effectiveness of protective cover	P-factor	example
0-10	very low	1	0-2 m gravel
>10-100	low	2	1-10 m sand with gravel
>100-1000	medium	3	2-20 m slightly silty sand
>1000-10000	high	4	2-20 m clay
>10000	very high	5	> 20 m clay

P-map

Figure 5: Determination of the P factor (modified after HOELTING et al., 1995)

The epikarst is defined as the uppermost zone of karstified rock outcrops, in which permeability due to fissuring and karstification is substantially higher and more uniformly distributed than in the rock below. Its thickness ranges between a few decimeters and tens of meters. The possible functions of epikarst are storage and concentration of flow. If the epikarst is developed in a way that leads to extreme concentration of flow, e.g., a bare karrenfield connected with hidden, karstic shafts, the structural factor is assigned a value of zero, expressing that the protective cover of the unsaturated zone below this epikarst is completely bypassed (*Figure 6*).

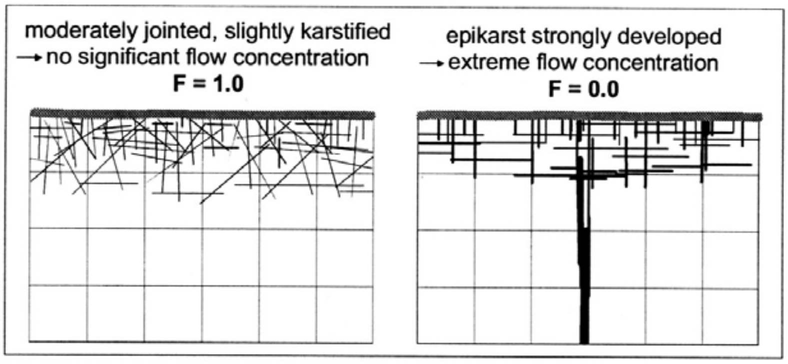

Figure 6: Epikarst and protective function
a) the unsaturated karstic bedrock may provide a protective function if the epikarst is slightly developed so that water storage is the dominant process.
b) concentration of flow in a highly developed epikarst decreases the protective function.

The I Factor

The overlying layers can protect the groundwater only if the precipitation infiltrates directly into the ground without significant concentration of flow. However, the disappearance of a surface stream into a swallow hole is common in karst areas. In this case, the protective cover is completely bypassed at the swallow hole and bypassed in part by the surface runoff in the catchment area of the sinking stream. Therefore, the I factor was introduced. It expresses the degree to which the protective cover is bypassed as a result of lateral, surface and subsurface concentration of flow, especially within the catchment of a sinking stream. If the infiltration occurs directly on a flat surface without significant lateral flow, the I factor is 1, indicating that the protective cover is not bypassed and 100 % effective. On the other hand, the protective cover is completely bypassed by a swallow hole through which surface water directly enters the karst aquifer. In this case, the I factor is 0. The catchment area of a sinking stream is assigned a value between 0 and 1, according to the extent of lateral (sub)surface flow. It has to be emphasized that the I factor cannot be precisely defined in terms of hydrology. It is a semi-quantitative tool to express the vulnerability of groundwater resulting from bypassing of the protective cover by surface and lateral subsurface flow. The I map shows the spatial distribution of the I factor.

The I map is obtained using the following components:

- The I’ factor expresses the estimated direct infiltration relative to surface and lateral subsurface flow. The controlling factors are soil properties, slope and vegetation. The spatial distribution of the I’ factor is shown on the I’ map.

- The 'surface catchment map' shows the surface catchment areas of sinking streams disappearing into a swallow hole and buffer zones of 10 m and 100 m on both sides of the sinking streams.

The assessment scheme for the I factor is presented in *Figure 7*.

1st Step: Determination of the dominant flow process

Saturated hydraulic conductivity [m/s]	Depth to low permeability layer < 30 cm	30-100 cm	> 100 cm
$> 10^{-4}$	Type D	Type C	Type A
$> 10^{-5}$-10^{-4}		Type B	
$> 10^{-6}$-10^{-5}	Type E		
$< 10^{-6}$	Type F		

2nd Step: Determination of the I'-factor

Forest				
dominant flow process		Slope < 3.5 %	3.5 - 27 %	> 27 %
infiltration	Type A	**1.0**	**1.0**	**1.0**
subsurface flow	Type B	1.0	0.8	0.6
	Type C	**1.0**	**0.6**	**0.6**
surface flow	Type D	0.8	0.6	0.4
	Type E	1.0	0.6	0.4
	Type F	**0.8**	**0.4**	**0.2**

Field/Meadow/Pature				
dominant flow process		Slope < 3.5 %	3.5 - 27 %	> 27 %
infiltration	Type A	**1.0**	**1.0**	**0.8**
subsurface flow	Type B	1.0	0.6	0.4
	Type C	**1.0**	**0.4**	**0.2**
surface flow	Type D	0.6	0.4	0.2
	Type E	0.8	0.4	0.2
	Type F	**0.6**	**0.2**	**0.0**

3d Step: Determination of the I-factor

	Surface Catchment Map	I' factor 0.0	0.2	0.4	0.6	0.8	1.0
a	swallow hole, sinking stream and 10 m buffer	0.0	0.0	0.0	0.0	0.0	0.0
b	100 m buffer on both sides of sinking stream	0.0	0.2	0.4	0.6	0.8	1.0
c	catchment of sinking stream	0.2	0.4	0.6	0.8	1.0	1.0
d	area discharging inside karst area	0.4	0.6	0.8	1.0	1.0	1.0
e	area discharging out of the karst area	1.0	1.0	1.0	1.0	1.0	1.0

↓ **I-map**

Figure 7: Determination of the I factor.
If it is impossible to distinguish six different flow processes (1st step), it is sufficient to distinguish between infiltration (white), subsurface (light grey) and surface flow (dark grey). In this case, the bold numbers can be used to determine the I' factor (2nd step).

Compilation of the Groundwater Vulnerability Map

The vulnerability map shows the intrinsic vulnerability and, in the opposite sense, the natural protection of the groundwater in the uppermost aquifer. The map shows the spatial distribution of the protection factor π, which is obtained by multiplying the P and I factors:

$$\pi = P \cdot I$$

The π factor ranges between 0.0 and 5.0, with high values representing a high degree of natural protection and low vulnerability. Small maps of the protective cover and the infiltration conditions are also printed as insets on the vulnerability map. The areas on each of the three maps are assigned to one of five classes, symbolized by five colors: from red for high risk to blue for low risk. One legend can thus be used for the three maps (*Figure 8*).

	vulnerability map vulnerability of groundwater		**P-map** protective function of overlying layers		**I-map** degree of bypassing	
	description	π-factor	description	P-factor	description	I-factor
red	extreme	0-1	very low	1	very high	0.0-0.2
orange	high	>1-2	low	2	high	0.4
yellow	moderate	>2-3	moderate	3	moderate	0.6
green	low	>3-4	high	4	low	0.8
blue	very low	>4-5	very high	5	very low	1.0

Figure 8: Legend for the vulnerability map, the P and the I map.

For more detailed information about the PI-Method refer to GOLDSCHEIDER (2002) or GOLDSCHEIDER et al. (2000). Please note that the acronyms for the parameters are different from those used in the description of the GLA-Method.

4.2.3 Examples for Applications of the GLA and PI-Methods

The GLA-Method was applied in the framework of several Technical Cooperation Projects with BGR assistance. Examples for maps established in ACSAD member countries are:

- The map of the Irbid area, northern Jordan (MARGANE et al., 1997, MARGANE et al., 1999a),
- The map of the area south of Amman, central Jordan (HIJAZI et al., 1999),
- The map of the Ghouta area, east of Damascus, central Syria (HOBLER & RAJAB, 2002),

- The map of the Beka'a Valley, Central Lebanon (HOBLER & RAJAB, in prep.).

The maps of the Irbid area and of the Ghouta area are shown as examples in *Annexes 9-1 and 10-1*.

The PI-Method was applied in:

- Engen, Swabian Alb, Germany (GOLDSCHEIDER, 2002),
- Hochifen-Gottesacker, Alps, Germany/Austria (GOLDSCHEIDER, 2002),
- Winterstaude, Alps, Austria (GOLDSCHEIDER, 2002),
- Albiztur unit, Basque county, Spain (MUGUERZA, 2001),
- Veldensteiner Mulde, Franconian Alb, Germany (SCHMIDT, 2001),
- Hydrogeological unit of Mt. Cornacchia and Mt. della Meta, Latium, Italy (COVIELLO, 2001),
- Muehltalquellen, Thuringia, Germany (SAUTER et al., 2001),
- Sierra de Libar, Andalusia, Spain (BRECHENMACHER, 2002).

4.2.4 Advantages and Disadvantages of the GLA and PI-Methods

The concept of the GLA-Method is logical and applicable. It can be used for resource protection and land use planning for all types of aquifers. Furthermore, the GLA-Method can be used for source protection together with the DVGW guidelines W101 (DVGW, 1995). According to these guidelines, the main criterion for the delineation of source protection zones is the travel time in the aquifer. However, the guidelines allow a reduction in the size of the zones if the overlying layers are sufficiently protective and the GLA-Method can be used for that evaluation.

Even though the GLA-Method is in principle applicable for all types of aquifers, it does not sufficiently take into account the special properties of karst. The basic assumption of the GLA-Method is that infiltration occurs diffusely and all the infiltrating water slowly percolates vertically through the unsaturated zone towards the groundwater table. In non-karstic areas with permeable soils and gentle topography, this assumption is generally fulfilled. However, especially in karst areas and in mountainous landscapes, lateral concentration of flow occurs frequently at or near the surface and these flow components often sink into the karst aquifer via swallow holes. This process can bypass the protective cover partially or completely. In this case, the GLA-Method is not applicable. This is where the PI-Method, which takes into account the lateral concentration of flow via the I factor, becomes more valuable. With the integration of the infiltration factor the PI-Method is suitable for all kinds of geological conditions.

4.3 The EPIK Method

4.3.1 Introduction to the EPIK Method

This method was elaborated in the framework of the COST activities of the European Commission by the University of Neuchâtel, Center of Hydrogeology, for groundwater vulnerability mapping in karst areas. It was later developed by the Swiss Agency for the Environment, Forests and Landscape into a standard tool for groundwater protection zone delineation in karst areas (SAEFL, 2000).

EPIK takes the following parameters into account:

- Development of the **E**pikarst,
- effectiveness of the **P**rotective cover,
- conditions of **I**nfiltration and
- development of the **K**arst network.

A standard classification matrix for each of these parameters is used (*Table 3*) together with standard values (*Table 4*). For each parameter a standard weighing coefficient is used (*Table 5*). The classification for each parameter and area is obtained by systematic mapping for these parameters. Guidance on how to classify the different features in the field is laid down in chapter 3.1 of the EPIK practice guide (SAEFL, 2000; compare *Annex 3*).

Table 3: Standard classification matrix for the EPIK parameters

parameter **E**pikarst			
Karstic morphology observed (pertaining to epikarst	E_1	caves, swallow holes, dolines, karren fields, ruin-like relief, cuestas	
	E_2	Intermediate zones situated along doline alignments, uvalas, dry valleys, canyons, poljes	
	E_3	Rest of the catchment area	
parameter **P**rotective cover			
		A. Soil resting directly on limestone formations or on detrital formations with very high hydraulic conductivity[1]	B. Soil resting on > 20 cm of low hydraulic conductivity geological formations[2]
Protective cover absent	P_1	0 – 20 cm of soil	
	P_2	20 – 100 cm of soil	20 – 100 cm of soil and low hydraulic conductivity formations
	P_3	> 100 cm of soil	> 100 cm of soil and low hydraulic conductivity formations
Protective cover important	P_4		> 8 m of very low hydraulic conductivity formations or > 6 m of very low hydraulic conductivity formations with > 1 m of soil (point measurements

[1] E.g.: scree, lateral glacial moraine
[2] E.g.: silt, clay

			necessary)
parameter **I**nfiltration			
Concentrated infiltration	I_1	Perennial or temporary swallow hole – banks and bed of temporary or permanent stream supplying swallow hole, infiltrating surficial flow – areas of the water catchment containing artificial drainage	
	I_2	Areas of a water catchment area which are not artificially drained and where the slope is greater than 10% for ploughed (cultivated) areas and greater than 25% for meadows and pastures	
	I_3	Areas of a water catchment area which are not artificially drained and where the slope is less than 10% for ploughed (cultivated) areas and less than 25% for meadows and pastures Outside the surface water catchment area: bases of slopes and steep slopes (greater than 10% for ploughed (cultivated) areas and greater than 25% for meadows and pastures) where runoff water infiltrates	
Diffuse infiltration	I_4	Rest of the catchment area	
parameter **K**arst network			
Well developed karstic network	K_1	Well developed karstic network with decimeter to meter sized conduits with little fill and well interconnected	
Poorly developed karstic network	K_2	Poorly developed karstic network with poorly interconnected or infilled drains or conduits, or conduits of less than decimeter size	
Mixed or fissured aquifer	K_3	Porous media discharge zone with a possible protective influence – fissured non-karstic aquifer	

Table 4: Standard values for the EPIK parameters

E_1	E_2	E3	P_1	P_2	P_3	P_4	I_1	I_2	I_3	I_4	K_1	K_2	K_3
1	3	4	1	2	3	4	1	2	3	4	1	2	3

Table 5: Standard weighing coefficients for the EPIK parameters

Parameter	**E**pikarst	**P**rotective cover	**I**nfiltration	**K**arst network
Weighing coefficient	α	β	γ	δ
Relative weight	3	1	3	2

The overall protection index F is calculated based on the following equation:

$$F = \alpha E + \beta P + \gamma I + \delta K$$

F can obtain values between 9 and 34. The following matrix of protection indices provides the basis for the classification of the groundwater vulnerability into three classes:

- high (corresponding to Swiss protection zone S1),
- medium (corresponding to Swiss protection zone S2) and

- low (corresponding to Swiss protection zone S3)

Table 6: Protection index

$K_1=1$	$I_1=1$			$I_2=2$			$I_3=3$			$I_4=4$		
	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$
$P_1=1$	9	15	18	12	18	21	15	21	24	18	24	27
$P_2=2$	10	16	19	13	19	22	16	22	25	19	25	28
$P_3=3$		17	20	14	20	23	17	23	26	20	26	29
$P_4=4$		18	21	15	21	24	18	24	27	21	27	30
$K_2=2$	$I_1=1$			$I_2=2$			$I_3=3$			$I_4=4$		
	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$
$P_1=1$	11	17	20	14	20	23	17	23	26	20	26	29
$P_2=2$	12	18	21	15	21	24	18	24	27	21	27	30
$P_3=3$		19	22	16	22	25	19	25	28	22	28	31
$P_4=4$		20	23	17	23	26	20	26	29	23	29	32
$K_3=3$	$I_1=1$			$I_2=2$			$I_3=3$			$I_4=4$		
	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$
$P_1=1$	13	19	22	16	22	25	19	25	28	22	28	31
$P_2=2$	14	20	23	17	23	26	20	26	29	23	29	32
$P_3=3$		21	24	18	24	27	21	27	30	24	30	33
$P_4=4$		22	25	19	25	28	22	28	31	25	31	34

Non-existent situation in the field

Protection index value corresponding to high groundwater vulnerability, respectively Swiss groundwater protection zone S1

Protection index value corresponding to medium groundwater vulnerability, respectively Swiss groundwater protection zone S2

Protection index value corresponding to low groundwater vulnerability, respectively Swiss groundwater protection zone S3

Conditions applicable to the rest of the catchment area

4.3.2 Examples for Applications of the EPIK Method

The EPIK method has been applied in Switzerland (St. Imier spring: SAEFL, 2000; Blatti springs/Lenk catchment: SAEFL, 2000), Belgium (GOGU & DASSARGUES, 2000a) and Lebanon (delineation of groundwater protection zone for a spring that provides water for bottled water; pers. comm. Dr. A. Pochon, Centre Hydrogéologique de l’Université de Neuchâtel). The Jordanian-German Technical Cooperation Project “Groundwater Resources Management” between BGR and the Ministry of Water and Irrigation (MWI) plans to establish groundwater protection zones for the Qunayyah spring (Zerqa Governorate) and the Wadi al Arab well field (Irbid Governorate) in Jordan.

4.3.3 Advantages and Disadvantages of the EPIK Method

The method requires a detailed evaluation of karst features, which is often difficult, costly and time consuming as they involve field studies, geophysics, isotope studies, hydrologic studies, an analysis of the hydraulic character, etc. The detection of typical karst features like swallow hole and sinks often requires the interpretation of aerial photograph or high resolution satellite images.

GOLDSCHEIDER (2002) made the following critical remarks concerning the EPIK-Method:

- Some important factors are missing: The recharge and the thickness of the unsaturated zone (depth to water table) are not taken into account although most authors consider these factors to be of major importance (e.g. ALLER et. al., 1987; FOSTER, 1987; HOELTING et al., 1995; MAGIERA 2000).
- The E factor is evaluated in an unreliable way: The epikarst is mapped on the basis of geomorphologic karst features (karrenfields, dolines, dry valleys). However, surface karst features are only one expression of epikarst, but most of it cannot be seen at the surface. Epikarst can be highly developed without visible karst features.
- The weighting system is contradictory: DOERFLIGER (1996) points out that the protective cover is very important for the natural protection and, vice versa, for the vulnerability of an aquifer, but the lowest weighting factor is assigned to the parameter P.
- The zero is missing: The minimum value of each attribute is 1 even if its effect on protection is zero. Together with the different weighting factors, this may lead to inconsistent results. For example: Both a swallow hole and a 5 m thick low permeability cover contribute 3 points to the protection index, although the cover provides some protection while the swallow hole is a point of extreme vulnerability.
- The EPIK formula is not always applicable: The protection index F is calculated by summing up the weighted values of the four factors. However, not all the factors always contribute to the protection of the system. For example: A thick low permeability formation (P = 4) is not protective if it produces surface runoff towards a swallow hole (I=2). Thus, it is inconsistent to sum up the values of P and I.
- EPIK is not defined for all hydrogeological settings: In some cases, it is impossible to define and quantify all the parameters. For example: E, P and K can not be defined for a non-karstic area that discharges into a bordering karst system by surface flow.
- The transformation of the vulnerability classes into source protection zones is disputable: The EPIK vulnerability classes are directly translated into source protection zones without using any additional criteria such as travel time in the aquifer or distance to the source. However, for source protection zoning, the spring or well must be taken as the target. Thus, it is indispensable to take into account the pathway to the spring or well.

4.4 COP-Method (European Approach for Karst Aquifers)

4.4.1 Introduction to the COP-Method

This method was introduced by the Group of Hydrogeology in the University of Malaga/Spain (GHUMA) in the framework of the COST 620 program as a standard method for groundwater vulnerability mapping in karst aquifers (VIAS et al., 2002). It uses the parameters

- C – concentration of flow,
- O – Overlying layers and
- P – Precipitation.

As outlined by DALY et al. (2002) the COP-Method may become the European approach for groundwater vulnerability mapping in karst areas, provided its application proves to be successful in the coming few years.

The COP-Index is obtained by (*Figure 9*):

$$\text{COP-Index} = (\text{C score}) * (\text{O score}) * (\text{P score})$$

<u>Step 1: Calculation of O Factor</u>

The O factor takes into account the protective function of the unsaturated zone and the properties of the layers soil (O_S – soil subfactor) and unsaturated zone (O_L – lithology subfactor). Both are separately calculated and then added to obtain the O factor:

$$O = O_S + O_L$$

The parameters texture (mainly dependent on grain size) and thickness are used to evaluate the subfactor O_S, as shown in *Figure 9*. The calculation of the subfactor O_L is based on the parameters lithology and fracturation (ly), thickness of each individual layer (m) and hydraulic (confined) condition (cn). Similar to the GLA-Method and the PI-Method the “layer index” is calculated by successively adding the products of the lithology and fracturation values of each individual layer with its thickness:

$$\text{Layer index} = \Sigma\, (ly * m)$$

The corresponding value of the layer index (process IV of *Figure 9*) is then multiplied by the value of the hydraulic (confined) conditions to obtain subfactor O_L.

The spatial distribution of the total rating for the O factor is displayed on the O map.

Step 2: Calculation of C Factor

The C factor represents the degree of concentration of the flow of water towards karstic conduits that are directly connected with the saturated zone and thus indicate how the protection capacity is reduced. It is differentiated between two distinct geological settings: the catchment area of a swallow hole (scenario 1) and the rest of the area (scenario 2). In the first case, all water is considered to ultimately flow towards the swallow hole, whereas in the second case the amount of infiltration depends on the characteristics of the land surface.

For scenario 1 the factor C is calculated based on the parameters distance to the swallow hole (d_h), distance to the sinking stream (d_s) and the combined effects of slope and vegetation (sv):

$$C = d_h * d_s * sv$$

In the area where the aquifer is not recharged through a swallow hole (scenario 2), the C factor is calculated based on the parameters surface features (sf) and slope (s) and the combined effects of slope and vegetation (sv):

$$C = sf * sv$$

The surface features represent geomorphological karst features and the presence or absence of a protective layer that influences the character of the runoff/infiltration process.

The spatial distribution of the total rating for the C factor is displayed on the C map.

Step 3: Calculation of the P Factor

This factor represents the total quantity, frequency, duration of precipitation as well as the intensity of extreme events, which are considered to be the chief influencing factors for the quantity and rate of infiltration. The P factor is obtained by a summation of the subfactors quantity of precipitation (P_Q) and intensity of precipitation (P_I):

$$P = P_Q + P_I$$

For the evaluation of P_Q the mean precipitation of wet years with precipitation exceeding 15% of the average is used. An increasing precipitation is believed to decrease protection, arguing that the transport process in this case is more important than the dilution process. This is thought to occur up to a precipitation of 1200 mm/a, the value above which the potential contaminant becomes increasingly diluted.

The calculation of the subfactor P_I is based on the assumption that a higher rainfall intensity results in an increased recharge and thus a reduced protection of the groundwater resource. The “mean annual intensity” or P_I is calculated from:

$$\text{mean annual intensity} = \frac{\text{mean annual precipitation (mm)}}{\text{mean number of rainy days}}$$

It is believed that intense rainfall yields more runoff to those conduits that favor concentrated infiltration and that, if rainfall intensity is low, more diffuse and slow infiltration takes place because evaporation is higher in this case.

DALY et al. (2002) point out that the COP-Method could also be used for source protection (protection of wells/springs). In this case the factor K is added, describing the function of the karst network (similar to the K factor of EPIK).

Step 4: Calculation of the K Factor

For assessing the karstic source (well or spring) intrinsic vulnerability, a factor taking into account the karst network of the mostly saturated aquifer is needed. The “vertical” pathway (from the soil to the groundwater) must be combined with the mostly horizontal pathway through the saturated karstic bedrock to the source being considered (compare *Figure 1*; GSI, 1999; GOLDSCHEIDER, 2002).

A classification system previously developed (COST 620, internal report 2000) for karst aquifers has been adopted. It is based on a general description of the bedrock, giving a range of possibilities from porous carbonate rock aquifers to highly karstified networks (*Table 7*).

By characterizing the different types of flow (migration mechanisms) and the matrix-storage capacity (physical attenuation), a more detailed classification of the aquifer can be derived, if required. This K factor is very similar to the K factor of the EPIK method (SAEFL, 2000).

The description “slow active conduit network” reflects conduit systems which are not extensive and not very efficient in draining the aquifer. “Fast active conduit system” implies an extensively developed karst network which is efficient in draining the aquifer. The matrix characteristics of the bedrock have been included, as the interaction between the conduits and the matrix may be sufficient to change the behavior of the aquifer and hence the attenuation potential.

The means of assessing the karst network factor are the following: (1) geology, geomorphology; (2) cave and karst maps; (3) groundwater-tracing results; (4) pumping tests results; (5) hydrochemistry, geochemistry; (6) remote sensing and geophysical prospecting; (7) borehole data and geophysical-logging results; (8) bedrock sampling and laboratory experiments; and (9) calibrated modeling results.

Table 7: Classification system for the karst aquifers
(adapted from COST 620, internal report 2000). The increasing degree of karstification and concentration of flow within the aquifer is from left to right.

Fractured and intergranular system			Solutionally-enlarged fissures			Conduit systems					
Inter-granular flow	Fractures		High matrix storage	Low matrix storage	No significant matrix storage	Slow active conduit network			Fast active conduit network		
	High matrix storage	Low matrix storage				High matrix storage	Low matrix storage	No significant matrix storage	High matrix storage	Low matrix storage	No significant matrix storage

It has to be clearly stated, however, that this method is not sufficiently tested yet and hence cannot be recommended, except for scientific purposes .

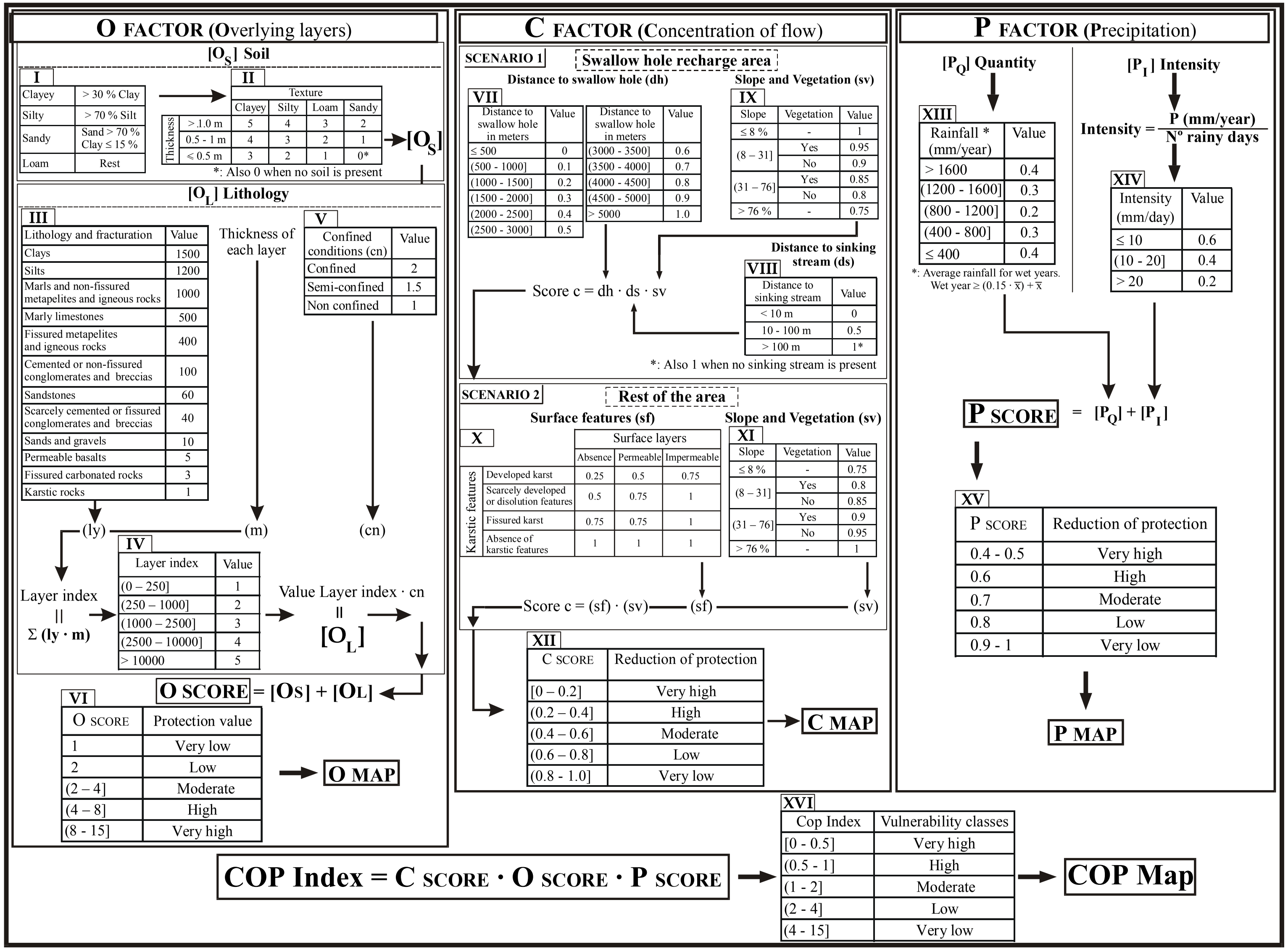

Figure 9: Flow Chart of the COP-Method (VIAS et al. 2002)

4.4.2 Examples for the Application of the COP-Method

The COP-Method was applied within the framework of the COST 620 program in the Sierra de Líbar and around Torremolinos, both in the Malaga province of southern Spain (VIAS et al., 2002). Both areas represent karst aquifers which receive high amounts of rainfall. The Sierra de Líbar area is highly karstified, whereas the Torremolinos area is dominated by fissured limestone. A more detailed description of the method will be included in the final report of the COST 620 program to be finalized in the first half of 2003 (pers. comm. Dr. M. von Hoyer, BGR).

4.4.3 Advantages and Disadvantages of the COP-Method

The COP-Method is similar to the PI-Method with the exception that the COP-Method integrates the factor precipitation. The parameters needed for the COP-Method are relatively easy to acquire and the method is straightforward. However, due to the large number of calculation processes, the map compilation is time consuming and requires the use of a GIS system by which these procedures can be performed.

So far there is too little experience with applications of this method to be able to judge about the suitability and applicability of the method.

4.5 Comparison of Methods and Recommendation for their Application

The choice of the most appropriate method for groundwater vulnerability mapping to be used in a certain area depends on the data availability, spatial data distribution, the scale of mapping, the purpose of the map and the hydrogeological setting. The above mentioned methods are mainly designated for the support of land use planning and general groundwater protection measures, such as e.g. the establishment of groundwater protection zones. In most such cases the mapping scale is between 1:50,000 and 1:100,000. However, the scale mainly depends on the availability of data and their spatial distribution. The better the data availability, the more detailed the map could be, i.e. the larger the mapping scale.

In areas where data availability is low but the general hydrogeological setup is known, DRASTIC would be a suitable method of choice, since it is rather simple. If not all required parameters are known, it may be considered using an even more simple method, such as GOD (FOSTER & HIRATA, 1988).

The most suitable method, however, is the GLA-Method or its modification, the PI-Method because the used rating system is more based on scientific considerations and less subjective than in DRASTIC. The GLA-Method has some shortcomings in karst environments. These were taken into account by the PI-Method, so that this method may principally be applied in all hydrogeological settings.

In pure karst environments, however, the application of EPIK is more recommended because it was specifically designed for this purpose and takes the influence of karst features much better into account than the PI-Method.

No sufficient practical experience has been made with the COP-Method, so that until now it cannot be recommended as a standard method for the mapping of groundwater vulnerability in karst areas, even though it may well become the standard tool for this purpose throughout Europe.

In areas with different lithological units, i.e. where karst and non-karst aquifers may occur, it is recommended to use either the GLA-Method or the PI-Method.

Concerning the planning of the preparation of groundwater vulnerability maps the involved costs need to be taken into consideration. The costs increase with the complexity of the applied method. For instance the application of the EPIK method requires a detailed knowledge about the occurrence of karst features. In many cases these may only be obtained by highly sophisticated technologies, such as remote sensing and tracer tests.

The Swiss authorities are, in cooperation with the Centre d'Hydrogéologie de l'Université de Neuchâtel, in the process of developing a practice guide for the preparation of groundwater vulnerability maps in non-karstic rocks, called DISCO.

5. Criteria for the Preparation of Groundwater Vulnerability Maps

The purpose of groundwater vulnerability mapping could be manifold. Mostly such maps are being used to protect the groundwater resources in a very general way. Such maps are generally useful in the land use planning process. Here, the vulnerability maps help the decision makers to decide which sites or activities to locate in which areas. They also help the water resources management authorities to more carefully plan the development and protection of groundwater resources. In all such instances intrinsic groundwater vulnerability maps should be used.

There may, however, also be the need to protect the groundwater resources against specific pollutants, such as pesticides or nitrate. In this case, methods for the mapping of specific vulnerability are needed. In many cases, combined groundwater flow and transport models could be used for this purpose. So far these are, however, not fully able to integrate all possible processes which might occur in the unsaturated and the saturated zone.

In the future, groundwater vulnerability maps will certainly play a major role in protecting water supply sources (wells or springs). An application which was developed with this intent is EPIK. This method was specifically developed by the Swiss authorities as a standard tool for groundwater protection zone delineation. The groundwater vulnerability mapping method used by the Geological Survey of Ireland (DELG, EPA & GSI, 1999) goes into the same direction.

This chapter describes which methodological approach should be used for which purpose, which parameters are needed and how they can be obtained, what are the most suitable input and output scales, and which the process of map compilation is.

5.1 Groundwater Vulnerability Maps for Land Use Planning Purposes (Scales 1:50,000 or 1: 100,000)

In a larger area, where vulnerability mapping is to be conducted for land use planning, there are commonly a larger number of different geological units. For this reason a method must be used by which all different lithological units can be mapped. For this reason it is recommended to use either the GLA-Method, the PI-Method or DRASTIC (if only few data are available).

For the GLA-Method the following parameters are needed :

Table 8: Parameters required and Source of Information for the Preparation of a Groundwater Vulnerability Map following the GLA-Method

Parameter	Description	Source
Factor S: effective field capacity of the soil (ΣeFC in mm down to 1 m depth)	The effective field capacity is equivalent to the so-called water holding capacity of a soil. It is determined by the texture, structure, mineral content and content in organic matter.	Soil maps, soil surveys
Factor W: percolation rate	Corresponds to the groundwater recharge rate	Estimation based on direct methods or indirect methods (LERNER et al. 1990)
Factor R: rock type (hard rocks or unconsolidated rocks)	The type of rock needs to be determined and classified according to Annex 1 for all lithological units overlying the uppermost main aquifer for which vulnerability is to be determined	Borehole data, geological maps, field surveys
Factor T: thickness	The thickness needs to be determined for all lithological units overlying the uppermost main aquifer for which vulnerability is to be determined	Borehole data, geological maps, field surveys
Factor Q: bonus points for perched aquifers	In case perched aquifers are present bonus points need to be added	Borehole data, geological maps, field surveys
Factor HP: bonus points for hydraulic	In case the hydraulic system, for which the vulnerability is to be	Borehole data, hydrogeological data, field surveys

Parameter	Description	Source
pressure conditions	determined, is under artesian conditions or the hydraulic gradient is directed upwards (often in valleys, depressions), bonus points have to be added.	

From the authors experience the parameter which is most difficult to acquire is the effective field capacity of the soil. If there are soil maps which do not directly allow for the assessment of this parameter, it should be evaluated whether it is possible to assess this parameter from the soil type or other soil parameters. Otherwise, it may be considered to integrate this sequence into parameter P_2 (protective effectiveness of the unsaturated zone). In general the difference is negligible.

In order to give an example for the problems arising when compiling such a map, the following paragraph was included in this report:

Recommendations for the assessment of the needed parameters with special emphasis of the local conditions in Jordan

For assessment of the effective field capacity of the soil (ΣeFC) the maps of the Land Use Project (HUNTING TECHNICAL SURVEYS & SOIL SURVEY AND LAND RESEARCH CENTER, 1994) provide an excellent base. Soil maps at the following scales are available:

- level 1, reconnaissance level, soil maps of the entire country; scale of 1:200,000
- level 2, soil maps of the intensively cultivated parts of the country; scale of 1:50,000
- level 3, detailed mapping for certain small areas of special interest; scale of 1:10,000.

The explanatory notes to these maps contain the names of the soil types, their USDA code together with their equivalent Jordanian soil code, their description, average composition, average thickness, average elevation, average slope, average rainfall and average effective field capacities. From these values the effective field capacity of the soil (ΣeFC) can be calculated easily (compare Table 3 of MARGANE et al., 1997). According to HOELTING et al. (1995), the total effective field capacity of the soil is calculated by multiplying the effective field capacity [mm/m] by the average thickness of the soil down to a depth of 1 m (the average rooting depth). The value of the effective field capacity of the soil then is converted to factor S, based on *Table 1-1* of *Annex 1* of this report. The maps of the scale 1:50,000 were used for the vulnerability mapping in the Irbid area.

For assessment of the parameter percolation rate the classification proposed by HOELTING et al. (1995) had to be modified. In large parts of the study area groundwater recharge is below 100 mm/a. Because of these low values, a modified scale for Parameter 2, the percolation rate W, had to be introduced in order to adapt the methodology to the situation in Jordan (compare *Table 1-1* of this report). It is recommended to prepare a map that displays the spatial distribution of the percolation rate.

For the parameter rock cover (R), the lithological composition and especially the degree of fracturing and karstification should be known as precisely as possible. The geological maps 1:50,000 (issued by the NRA) often do not yield sufficient information on the location and effect of fractures. If possible fracture zones should be mapped by aerial photograph and satellite image interpretation. It is recommended to prepare a map that displays the value of factor R for each geological unit above the main saturated aquifer.

The accuracy of the assessment for the parameter thickness of the rock cover above the aquifer (T), depends on the accuracy of the structural and piezometric maps. In many parts of the country the accuracy of these maps for the relevant aquifers are not very precise because only very few reference points are available. It is recommended to prepare a map that displays the unsaturated thickness for all relevant geological units.

Information on the appearance of perched aquifers (parameter Q) is usually not available. Such localized aquifers may play a role in alluvial aquifers. Since the mapping of this parameter would be too costly and time consuming and the parameter is not really relevant in Jordan, it is recommended to neglect it, if not local circumstances warrant its evaluation.

The parameter hydraulic pressure (HP) is relevant mainly in areas with an upward hydraulic gradient, as is the case generally at the foot of the escarpment to the Jordan Valley and the Araba Valley. Since there are until now no multi-level piezometers in Jordan, a meaningful evaluation of this parameter is somewhat difficult. Where required (and possible), it is recommended to prepare a map that displays the zones of appearance of upward hydraulic gradients.

5.2 Groundwater Vulnerability Maps for Karst Areas

For the mapping of groundwater vulnerability and the delineation of groundwater protection zones in a karstic environment (limestone, dolomite, dolomite limestone), the EPIK method (*Annex 3*) should be used as standard method. (In areas with mixed lithological composition, i.e. where other lithological units comprised of sandstone, alluvial deposits, basalt, etc. occur, the GLA-Method or the PI-Method should be applied, because only in this case the calculated vulnerability values will be comparable.) The EPIK method uses the following parameters :

Table 9: Parameters required and Source of Information for the Preparation of a Groundwater Vulnerability Map following the EPIK Method

Parameter	Description	Source
Development of the **E**pikarst	Epikarst is defined as a highly fissured zone corresponding to the decompressed and weathered formations near the ground surface). This upper karst zone is not continuous. It can be decimeters to meters thick and can contain perched aquifers which can rapidly concentrate infiltrating water towards the karstic network. The availability of features like swallow holes, depressions, dolines, karren fields, ruin-like structures, intensely fractured outcrops, dry valleys helps to classify this parameter	Field work (including hand auger drillings, excavations, trenches) interpretation of aerial photographs and detailed topographic maps (scales between 1: 5,000 and 1: 25,000)
Effectiveness of the **P**rotective cover	The soil cover generally determines the possibility and character of attenuation and infiltration processes. Important parameters in this respect are: thickness, texture/structure, organic matter content, clay content, types of clay minerals, cation exchange capacity, water content and hydraulic conductivity. Since the determination of all these parameters is time consuming and costly only the thickness of the protective cover is used	Field measurements of soil thickness and lithology (hand auger drillings, excavations, trenches), interpretation of aerial photographs and detailed topographic maps (scales between 1: 5,000 and 1: 25,000)
Conditions of **I**nfiltration	It is distinguished between concentrated, intermediate and diffuse infiltration conditions. They can be identified by the surface water runoff characteristics (slope, runoff coefficient) and the presence or absence of preferential infiltration zones. The availability of the following features helps to classify this parameter: swallow holes, buried karst, exposed karst.	Field work, hydrological measurements and interpretations (such as spring discharge measurements over long enough time periods), interpretation of aerial photographs and detailed topographic maps (scales between 1: 5,000 and 1: 25,000)
Development of the **K**arst network	The size (diameter) and connectivity of conduits in a karst network determines the flow velocity in a karst system. Part of the karst network may have been created earlier but not be in use anymore.	The presence or absence of a karst network can be determined by direct identification of the components of the network, such as caves, potholes, active cave systems or by indirect methods, such as flow hydrograph analysis, tracer test and water quality variability.

Extensive experience has been collected during the mapping of groundwater vulnerability in Jordan. Until now, the GLA-Method was used for this purpose. However, it is now intended to prepare groundwater vulnerability maps for the delineation of groundwater protection zones in karst area using the EPIK method, like it is being done in karst regions in Switzerland. From the preparatory phase of this project a number of conclusions can be drawn that should generally be considered before applying this method in other areas (see also MARGANE & SUNNA, 2002).

Recommendations for the assessment of the needed parameters with special emphasis of the local conditions in Jordan

The classification of the parameters E, P, I and K is based on a detailed mapping in the field and by aerial and/or satellite images of high resolution/output scale. The mapping scale for the preparation of a groundwater vulnerability map for the delineation of groundwater protection zones will usually have to be 1:10,000 or maximum 1:25,000. The purchase and processing of high resolution satellite images can, however, be quite expensive. Also, since the catchment areas of some groundwater protection zones can reach several km in length (zone III of the protection zone for the Tabaqat Fahel (Pella) spring established by the WAJ-BGR project 'Groundwater Resources of Northern Jordan' (MARGANE et al., 1999b) measures 11 km), the total costs of vulnerability mapping can become quite high and the process could be very time consuming. A balance has to be stricken between what is scientifically required and what is absolutely necessary. When establishing a mapping program it has therefore to be weighed between what means are available (budget, existing data, required data) and what has to be achieved.

5.3 Criteria for the Selection of Mapping Areas

Generally, groundwater vulnerability maps at a scale of 1:100,000 or 1:50,000 should be prepared for all densely populated urban areas in order to assist land use planning. Here, environmental problems are most serious and have a direct impact on the population. These problems chiefly result from unthorough planning. Only by integrating aspects of groundwater protection into the land use planning process and by providing the decision makers in the land use planning agencies with suitable planning tools, a better land use planning can be achieved that takes the needs of groundwater protection into consideration. All groundwater vulnerability maps should in general be supported by a map of hazards to groundwater, which displays all relevant potential pollution sources in the area. For the preparation of a map of hazards to groundwater an inventory of all potential pollution hazards needs to be inventoried (*Annex 5*). This requires extensive field work. Finally a data base of groundwater hazards should be established (*Annex 6*), based upon which the map could be prepared. *Annexes 7 and 8* may help assessing which hazardous substances could occur in which process or land use activity, so that a monitoring program for the relevant substances could be established.

Since the preparation of groundwater vulnerability maps is a costly and time consuming task, it is recommended first to establish a ranking list for the regions to be mapped that ranks the priority of map preparation. It is recommended to start with areas where a rapid expansion of activities hazardous to groundwater, such as industry, commercial activities or agriculture, is expected.

Groundwater vulnerability maps at a scale of 1:100,000 or 1:50,000 should also be prepared for the main recharge areas of groundwater resources of prime importance.

Only by these means it can be avoided that important groundwater resources become polluted by facilities and activities which are potentially hazardous to groundwater.

A third target area for groundwater vulnerability mapping is the mapping of groundwater protection zones. The project 'Groundwater Resources Management' has proposed the use of groundwater vulnerability maps for the delineation of groundwater protection zones in karst areas (MARGANE & SUNNA, 2002), similar to the Swiss regulations for groundwater protection. In this case mapping needs to be more detailed, if possible at a scale of 1:10,000 or at least 1:25,000. Often such topographic maps are not available or rather outdated. In this case, it is recommended to use geocoded aerial photographs or high resolution satellite images, such as IKONOS (1 m resolution) or SPOT (5 m resolution). For this process too, a ranking list should be established, as mentioned above.

6. Risk Assessment

Risk can be defined as the likelihood or expected frequency of a specified adverse consequence. Risk is not intended as an absolute measure but as a means of relative measure or comparison. The Royal Society of London defined an environmental hazard as "*an event, or continuing process, which if realized, will lead to circumstances having the potential to degrade, directly or indirectly, the quality of the environment*". Consequently, a hazard presents a risk when it is likely to affect something of value (for instance groundwater resources).

There are three key stages in risk analysis (modified after COST 620's homepage): risk estimation, risk evaluation and risk management. The **risk estimation** requires the identification of possible hazards and an assessment of the likelihood of events that could cause certain risks associated with these hazards. The **risk evaluation** looks at what would happen, if an event took place. The **risk management** deals with the questions which kind of risks are acceptable or not and includes the assessment and selection of options as well as the implementation of measures to prevent or minimize the probability of an event and its consequences, should it occur. Risk estimation and risk evaluation are commonly summarized under the term **risk assessment**.

Transferred to the issue of groundwater protection, the risk estimation implies the identification of hazards to groundwater and the analysis how likely it is that they may pollute the groundwater resources. To do so the individual hazards to groundwater have to be assessed. The preparation of maps of hazards to groundwater is a standard tool which is frequently used in this respect (VRBA & ZAPOROZEC, 1994).

Risk evaluation requires the availability of a tool to determine the pathway to the target. One of the tools for this assessment is the groundwater vulnerability map. It evaluates how long it might take until an impact on the target (groundwater resources or well/spring) might occur.

The risk management demands a response to the risk in the form of engineering/changing the characteristics of the source, pathway, the protection target, or a combination of these. For instance: control of land use practices and in particular directing developments towards lower risk areas, suitable building codes that take account of the vulnerability and value of the groundwater, lining of landfill sites, installation of monitoring networks, specific operational practices, etc.

Consequently, assessing the risk of contamination to groundwater is a highly complex task. It encompasses geological and hydrogeological factors and factors that relate to the potentially polluting activity. The geological and hydrogeological factors are the vulnerability to contamination and the relative importance or value of the groundwater resource. The factors that relate to the potentially polluting activity are the contaminant loading and the preventive measures.

The US EPA follows in its Superfund program a similar approach (*Figure 10*).

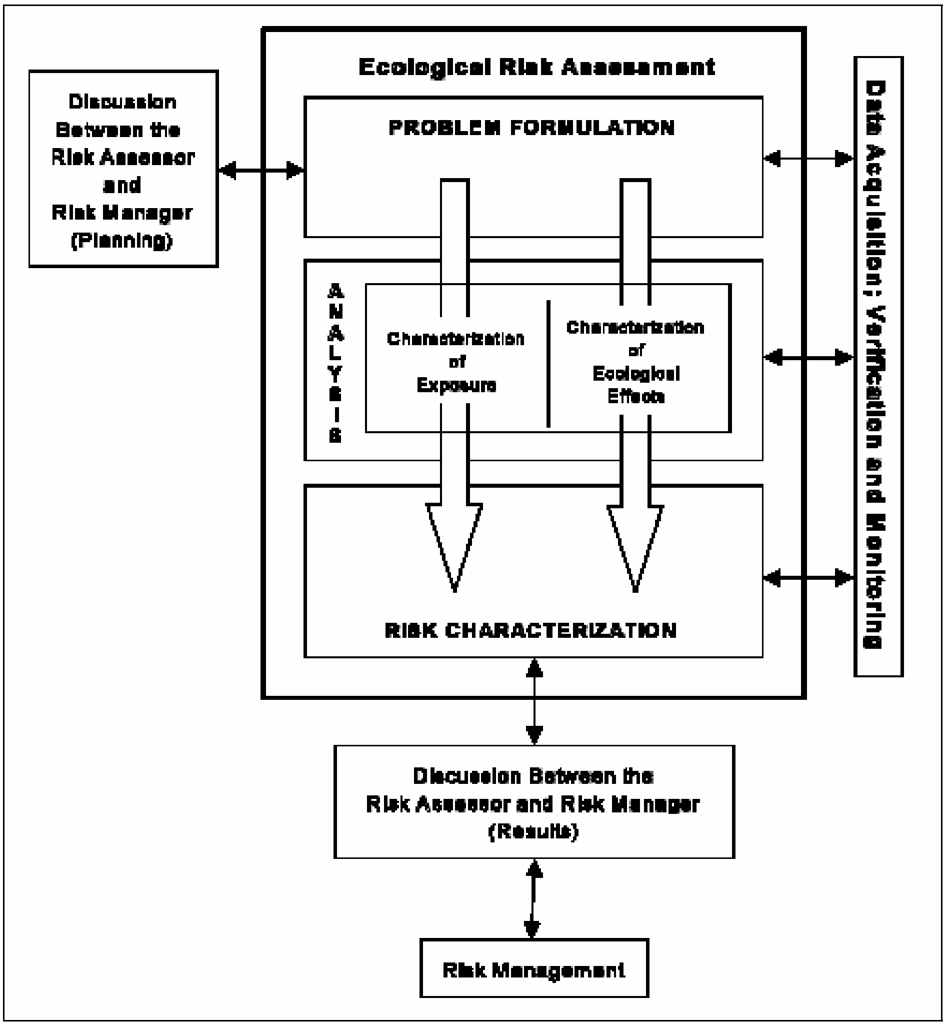

Figure 10: Risk Assessment Framework adopted by US EPA (EPA, 1997)

Risk assessment is a stepwise process by which scientific and environmental information from many sources are integrated, in order to estimate the possible harmful effects of contamination. It is a tool based on scientific principles with the objective to provide information for environmental management. The main goals are to identify problems, establish priorities and create a basis for regulatory actions, in order to minimize the risk.

The focus of risk management has shifted over the past decades from land reclamation to pollution prevention, after it was recognized how costly clean-up operations can become. Nowadays, most developed countries invest increasing efforts and amounts of money into the pollution prevention at an early stage by imposing strict regulations on land use activities in areas with important (ground)water resources. This goal can, however, only be reached when the legal basis supports the enforcement of such regulations and the aspects of (ground)water protection are integrated into the land use planning processes. Thus, the existence of a strong legal basis is the most important precondition for groundwater protection measures. The proposed measures for groundwater protection can, however, only become effective if the involved authorities strictly enforce them.

A standard procedure (guideline) with a clear and concise concept needs to be followed during risk assessment. This concept will, however, largely depend on the local conditions, especially the legal basis. Several countries/states have developed their own (computer assisted) assessment system, like e.g. the US Hazards Assessment System (HRS) developed by the US EPA, in order to establish objective rankings for priority actions. Nonetheless, a number of uncertainties remain when assessing risks. These uncertainties must be made clear to the policy makers.

For a risk assessment to be legally defensible, it has to be (after CAIRNEY, 1995):

- *Consistent*: The same outcome should always be obtained, when risk is assessed by different assessors. This means it has to be provided that the same weightings and significances are applied to a certain set of information.
- *Formal*: A formal procedure must be followed and its results documented. Individual choices and biases must be reduced to a minimum.
- *Flexible*: Due to new information or increased knowledge formerly evaluated “facts” may prove to have been wrong in the past (e.g. concerning the toxicity of certain substances or their behavior in the environment or the geological structure). The risk assessment procedure should be designed in such a way that in such a case not the entire risk assessment would need to be repeated but only certain components of it.
- *Comprehensive*: All feasible risks should be evaluated. Often only the direct impact is being analyzed. However, there are often different possible pathways and impacts.
- *Able to identify information deficiencies*: The often complex (hydro)geological setting or the (often insufficiently recoverable) history of a site make it impossible to establish certain parameters with absolute certainty. Then these inherent deficiencies have to be pointed out to the decision makers. It has to be made clear how a better knowledge could be obtained and at which costs.

For preliminary risk assessment a worst-case analysis should then be conducted.

Concerning groundwater protection, a number of different steps are required in the risk assessment process.

1. Identification of hazards (inventory of type of hazard and identification of possible associated substances).
2. Determination of the likelihood of a release of these substances. Has a release already occurred ?
3. Determination of the possible points of release of the substances (delineation of pollution source; point or diffuse source).
4. Evaluation of the toxicity of the used substances to human health (do these substances have an impact on the ecosystem or on human beings and are thus relevant for further investigations ?).
5. Determination of the possible pathways of pollution.
6. If a contamination has occurred already, what are the goals for the remediation of groundwater resources.
7. Determination of the "value" of the protection target (groundwater resource or well/spring). Is protection/remediation feasible ?
8. Evaluation of the costs for protection/remediation.
9. Decision to protect/ remediate a resource/source or not (definition of goal).

Identification of hazards to groundwater

This is a time consuming task because the locations of all possibly polluting sites and activities have to be determined (field survey using GPS; see *Annex 5*: inventory form sheet) and it has to be evaluated what kind of substances are used in the process (see *Annexes 7 and 8*), where waste and sewage water is disposed of, and whether spills are likely to occur or have already occurred. The result should be displayed on a map of hazards to groundwater. Good examples are shown in *Figures 9-2 and 10-2*, which used the legend proposed by VRBA & ZAPOROZEC, 1994). Only based on the comparison of the map of hazards to groundwater and the groundwater vulnerability map the necessary conclusions pertaining to a risk assessment could be drawn. Both maps are therefore essential for a thorough risk assessment. However, further hydrogeological information is required, such as the geological structure of the considered aquifer system, the piezometry (piezometric maps of all aquifers), and the groundwater recharge/discharge conditions.

The potential pollution sources which have to be considered in this process are :

- Features associated with sewage water, such as: sewerage network, treatment plants for urban or industrial/commercial wastewater, cesspools, septic tanks, areas where spray irrigation of treated/untreated sewage water is applied,

- Features related to waste disposal: storage facilities for waste, treatment facilities for waste, municipal/inert/industrial waste disposal sites, incinerators for waste,
- Hospitals (waste, sewage water),
- Cemeteries,
- Slaughterhouses,
- Industrial sites (waste, sewage water, handling/processing/storage of hazardous substances ?),
- Commercial sites (waste, sewage water, handling/processing/storage of hazardous substances ?),
- Oil/fuel storage sites,
- Refineries,
- Storage facilities for hazardous substances,
- Processing facilities for hazardous substances,
- Wells for injection of sewage water or hazardous substances,
- Pipelines,
- Power plants, transformer stations,
- Highways, main roads, railway lines,
- Airports,
- Military establishments,
- Mines, quarries,
- Animal husbandries,
- Livestock waste storage facilities,

The list in *Annex 4* gives a good overview about the potentially polluting facilities and activities that have to be inventoried within the framework of the delineation of groundwater protection zones. This list was proposed to be included in the new guideline for the establishment of groundwater protection zones in Jordan (MARGANE & SUNNA, 2002).

Commonly the risk assessment is conducted in several steps. After each of these steps is has to be decided whether there could be a possible risk or not. The following five steps are distinguished in the risk assessment scheme for contaminated land of the state of Lower Saxony, Germany (modified after NLWA & NLfB, 1989 (*Figure 11*); BDG, 1988; MINISTERIUM FUER UMWELT BADEN-WUERTTEMBERG, 1988; similar concepts are applied in most other states of Germany):

1. Identification (Initial Historic Evaluation),
2. Initial Risk Assessment (Detailed Historic Evaluation, Initial Site Characterization),
3. Preliminary Investigation (Preliminary Risk Assessment),
4. Detailed Investigation (Final Risk Assessment),
5. Cleanup Investigation.

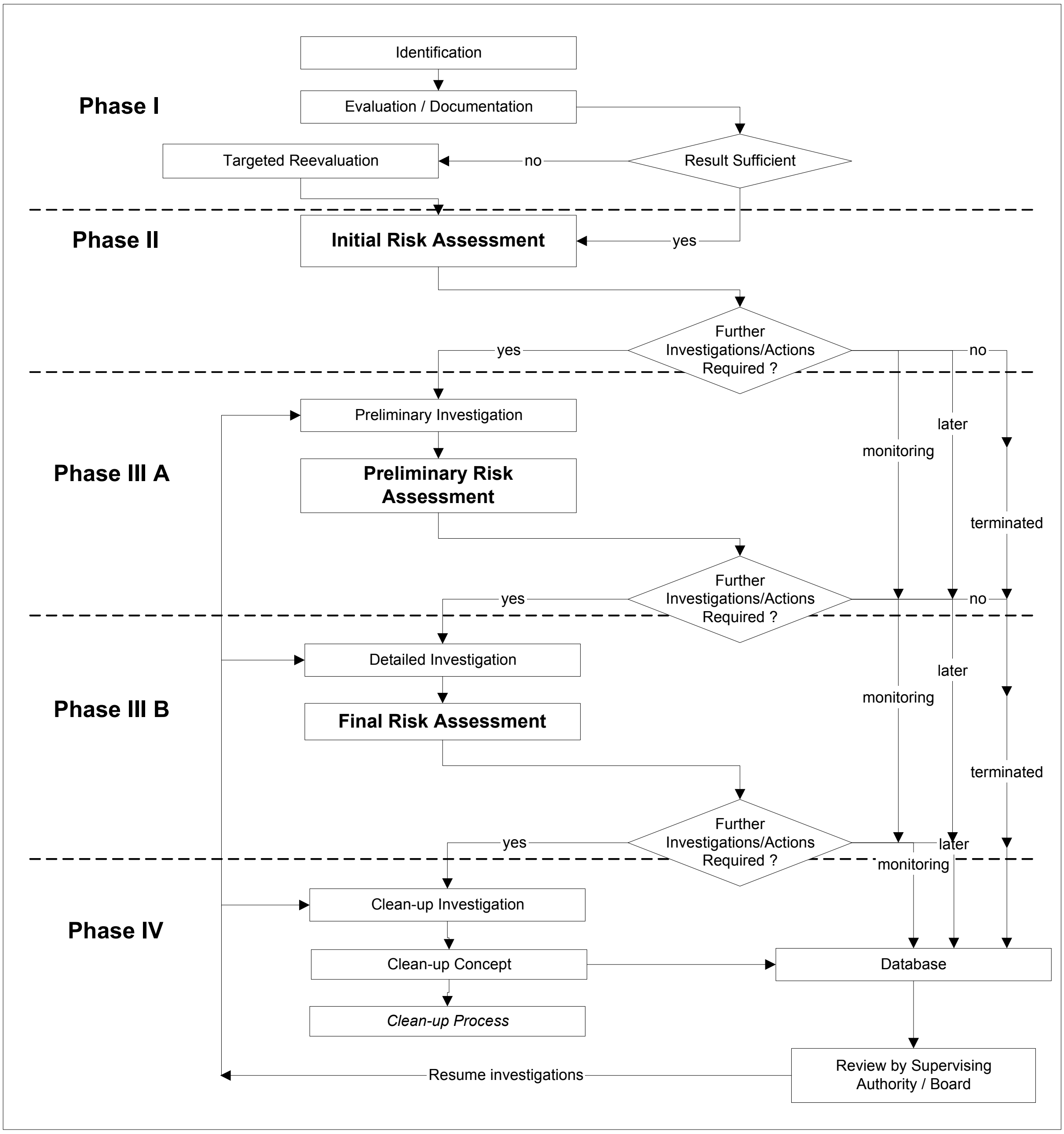

Figure 11: Flow Chart of the Risk Assessment Process applied in the German State of Lower Saxony in the Framework of Contaminated Land Investigations (modified after NLWA & NLfB, 1989)

The risk assessment process which is being followed in the US Superfund program distinguishes 8 steps (EPA, 1997; *Figure 12*) and follows a somewhat similar concept. Steps 1 and 2 of the US EPA approach correspond approximately to steps 1 and 2 of the German system. Whereas the German system distinguishes 3 different levels of field investigations (steps 3 – 5), the US EPA systems has only one (steps 3 – 7). In the German system, the risk management is not included in the (risk assessment) program, whereas the risk management is part of the Superfund program.

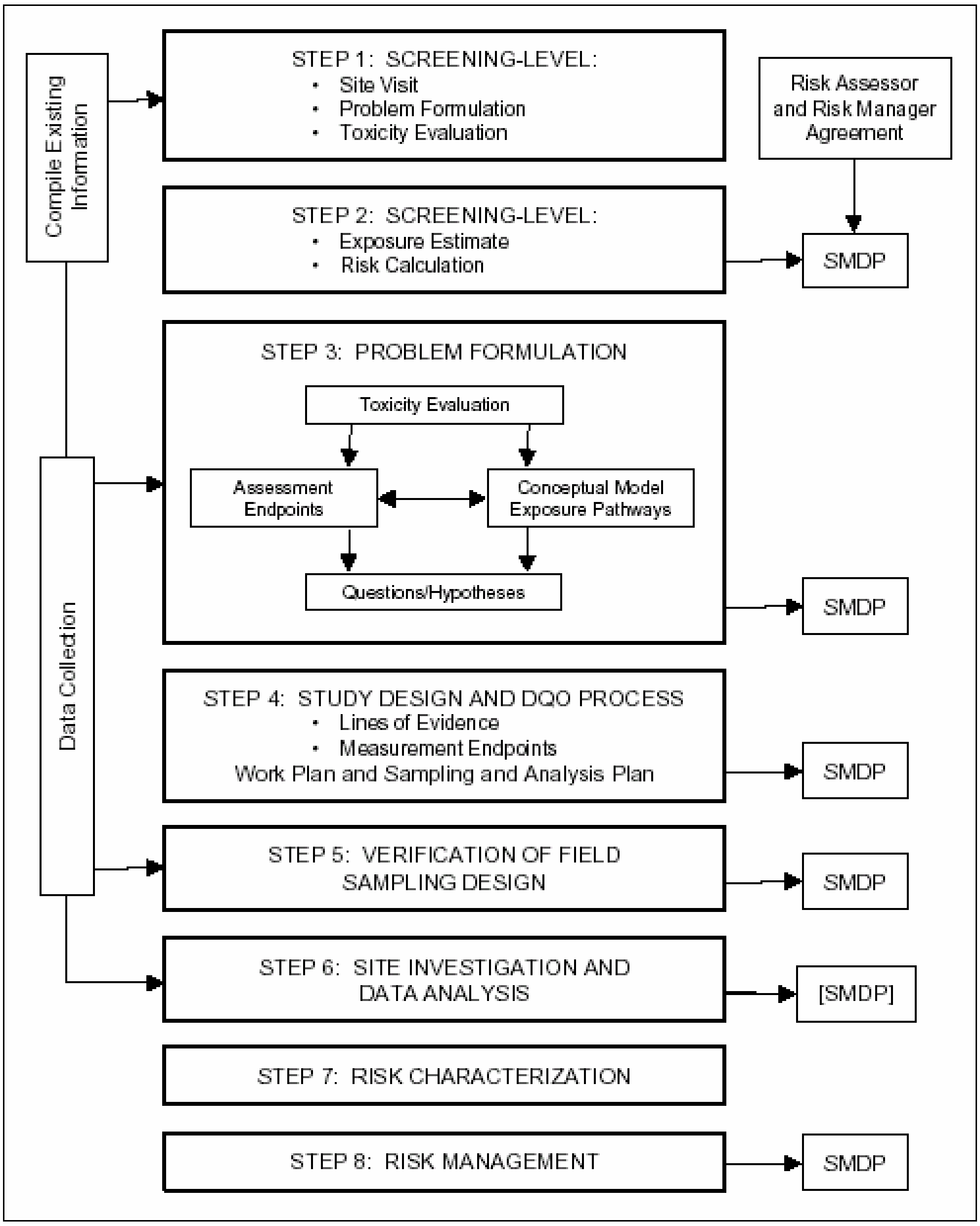

Figure 12: Ecological Risk Assessment Process for the US Superfund Program (SMDP – Scientific/Management Decision Point, DQO – Data Quality Objective)

Steps and Scientific/Management Decision Points (SMDPs):

1.	Screening-Level Problem Formulation and Ecological Effects Evaluation	
2.	Screening-Level Preliminary Exposure Estimate and Risk Calculation	SMDP (a)
3.	Baseline Risk Assessment Problem Formulation	SMDP (b)
4.	Study Design and Data Quality Objectives	SMDP (c)
5.	Field Verification of Sampling Design	SMDP (d)
6.	Site Investigation and Analysis of Exposure and Effects	[SMDP]
7.	Risk Characterization	
8.	Risk Management	SMDP (e)

Corresponding Decision Points in the Superfund Process:

(a) Decision about whether a full ecological risk assessment is necessary.

(b) Agreement among the risk assessors, risk manager, and other involved parties on the conceptual model,including assessment endpoints, exposure pathways, and questions or risk hypotheses.

(c) Agreement among the risk assessors and risk manager on the measurement endpoints, study design, and data interpretation and analysis.

(d) Signing approval of the work plan and sampling and analysis plan for the ecological risk assessment.

(e) Signing the Record of Decision.

[SMDP] only if change to the sampling and analysis plan is necessary.

Figure 13: Steps and Corresponding Decision Points in the US Superfund Program

CARACAS, the *Concerted Action on Risk Assessment for Contaminated Sites in the European Union,* was established in 1996 as part of the EC Environment and Climate RTD Program to tackle the problem of contaminated land. It analyzed the policies and practices in 16 European countries (FERGUSON, 1999) and gives a good overview about the different approaches used in Europe.

The assessment of hazards to groundwater, as suggested in this guideline, will mostly not go beyond phases 1 or 2 of the processes in *Figures 11 and 12*.

A careful planning of the work to be conducted during all these steps is paramount, because huge costs may be involved, depending on the size of the site, the contaminants involved and the scale of pollution.

For the preliminary risk assessment the following information has to be made available:

Site Description

- Ownership of land plot (cadastre),
- Present land use (aerial photographs, field surveys),
- Land use history (time series analysis of aerial photographs, questioning),
- Distance and relative location to nearest surface water feature,
- Distance and relative location to flood-pone areas (mapping of flood-prone area),
- Distance and relative location to water supply utilities,
- Distance and relative location to groundwater protection zones,
- Distance and relative location to nature/landscape preservation areas,
- Distance and relative location to cultivated areas,
- Distance and relative location to built-up area,
- Assessment of existing and planned groundwater abstraction facilities and abstracted amounts,
- Other existing or planned land uses which could be affected.

Substances

- Type and amount of substances (questionnaire),
- Which substances were handled/processed/deposited where (historic records, questioning) ?
- When/over which time period were the substances handled/processed/ deposited (historic records, questioning) ?

Infiltration Conditions

- Present situation (is an infiltration of the hazardous substances possible or not),
- Which technical facilities are in place to reduce infiltration of the hazardous substances ?
- Groundwater recharge rate (field survey, official meteorological records),
- Is a drainage system in place and where is the drained water treated/disposed of ?
- Are technical barriers hindering infiltration ?

Pathway

- Are geological barriers hindering infiltration (geological map, boreholes) ?
- Description of geological/hydrogeological situation (records of groundwater wells, pumping tests, groundwater studies, geophysical investigations, etc.),
- Groundwater contamination observed or not (monitoring wells) ?
- Description of hydrological conditions (hydrological/meteorological data),
- Determination of possible pathways: surface water – groundwater and groundwater – surface water interactions,
- Description of soils (soil maps),
- Soil contamination observed or not ?

(Remark: Chemical data (air, soil, groundwater) have to be acquired following certain quality procedures (VITALE, 1997))

Exposure Assessment

- Which doses of a certain substance a target (human being) could be exposed to by the hazard ?
- Which are the human health risks associated with a certain substance (US NCEA homepage (see below; ELLIOTT, 1994)?

The risk assessment, based on these data, should answer the following questions:

- Which is the emission path ?
- Which resources are endangered (soil, surface water, groundwater, air) ?
- Which substances cause a risk ?
- Which concentrations of critical substances are to be expected where and when (prognosis of contaminant spreading) ?
- Which impact on the environment is to be expected ?
- Have human beings already been affected ?
- Which are the possible risks for human health (human toxicity) or the environment (ecotoxicity) ?
- Is the number and location of observation wells sufficient (present situation/groundwater quality must be documented) ?
- Which further measures have to be implemented to counter/monitor a contamination risk (which target is to be protected by which means) ?

For further reading the guideline established by EPA (1997) is recommended as well as the EPA homepages of the Superfund Risk Assessment (http://www.epa.gov/superfund/programs/risk/index.htm) and of the National Center for Environmental Assessment (http://cfpub1.epa.gv/ncea/cfm/nceahome.cfm), which both contain a vast amount of information pertaining to risk assessment.

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Annex 1: German Concept of Groundwater Vulnerability Mapping

Concept for the determination of the effectiveness of the rock and superficial cover above the topmost aquifer as a protective barrier against groundwater pollution [translated by BGR from HOELTING et al., 1995]

1. Introduction

When assessing the vulnerability of the groundwater to contamination, the protective effect of the cover of rocks and superficial deposits above the topmost aquifer in of decisive importance. This in true when considering the impact of agriculture (fertilizers, pesticides) and when assessing potential waste disposal sites, abandoned hazardous sites etc. Determination of the protective effectiveness of the rock or superficial cover above an aquifer is carried out to assess the risks to groundwater by pollutants migrating through the soil and rock cover into the groundwater, und to represent the degree of risk on a map.

The protective effectiveness or filtering effect of the rock and soil cover depends an many different factors, mainly the compactness, mineralogical composition, porosity, content of organic matter, pH, and cation exchange capacity, the thickness of rock and soil cover, as well as the percolation rate and percolation velocity. Moreover, it should be borne in mind that the numerous substances that may pollute groundwater show differing migration, sorption and degradation behavior underground, about which little is known.

In principle, it would be necessary to develop special assessment methods for all of these pollutants or at least for the main pollutant groups, depending on their behavior in the ground, and then compile the corresponding hazard maps.

In order to provide a practical method for the qualitative determination of the protective effectiveness of the rock und soil cover above an aquifer in spite of these problems, assessment scheme was developed. Although it involves considerable simplification, it provides valuable information related to many of the pending problems. Starting from assessments at point sites on the basis of existing data and without any costly determination of further parameters, the method allows the protective effectiveness of the rock and soil cover above an aquifer to be assessed over large areas. Thus, in many individual cases, time-consuming, detailed investigations and/or mapping can be avoided.

Maps showing the protective effectiveness of the rock and soil cover above an aquifer represent a valuable tool for the remediation of contaminated catchment areas for potable groundwater. This is due to the fact that they show areas where changing the land-use or removing sources of contamination can lead to a comparatively rapid diminution of pollutant input and thus and thus an improvement of groundwater quality. Additionally, such naps provide useful information for assessing the effects of water pollutants originating from point sources.

2. Basic aspects

During the passage of percolating water through the rock and soil cover above the topmost aquifer, pollutants in the water may be subject to mechanical, physicochemical, and microbial processes leading to their degradation. The effectiveness of these processes is mainly determined by the residence time of the percolating water in the rock and soil cover. The longer the residence time, the longer the degradation and sorption processes can be effective and thus reduce the input of pollutants into the groundwater. In the most favorable case, contamination does not even reach the groundwater, even in the long term.

The cover dealt with in this paper comprises the rock and superficial deposits above the uppermost, interconnected, generally laterally extensive aquifer system that can be used far groundwater development.

The residence time of the percolating water in the rock and soil cover is mainly determined by three factors:

- the thickness of the rock and soil cover,
- the permeability of the rock and soil cover, which depends on the pedological constitution and/or lithology,
- the percolation rate.

When assessing protective effectiveness, the soils and the lower part of the cover below the soil are considered separately. These two zones are linked by the amount of water, which passes the lower boundary of the rooting zone.

For soils, the effective field capacity (eFC) is taken as a measure of the capacity of a soil to store plant-available water. The residence time of the percolating water in the soil, and thus also the evapotranspiration and groundwater recharge, are considerably affected by this parameter. The effective field capacity of a soil depends mainly on grain size, degree of compaction and humus content and is generally determined for the profile down to the effective rooting depth (AG BODENKUNDE, 1982) [The handbook on pedological mapping generally used in Germany, third edition 1982].

The residence time of percolating water below the soil, i.e. in the rock and superficial deposits covering the aquifer, depends not only on the percolation rate but also on the geohydraulic rock properties. Due to their fundamentally different geohydraulic properties, unconsolidated sediment and solid rock are assessed on the basis of different criteria.

In unconsolidated deposits below the soil it is mainly the fine-grained sediments or sediment components that reduce the permeability and thus reduce the percolation velocity. The cation exchange capacity, upon which sorption depends, increases from sand via silt to clay. A decrease in the percentage of clay and/or silt, however, causes a decrease in the residence time and cation exchange capacity and is equivalent to a decrease in the protective effectiveness.

Determination of the permeability of unconsolidated rock on the basis of a lithological description, or figures for the percolation velocity or residence time, especially in the case of coarse-grained material, is rather reliable. For the purpose of keeping the assessment scheme consistent, a method of determination analogous to that used for soil, i.e. via the effective field capacity, would be desirable. Since, however, if this method were used, complex model calculations would be necessary, problems would occur in the case of non-log-normal grain-size distributions, and the cation exchange capacity would have to be taken into consideration, a simpler way is chosen here. This does not involve any significant loss of essential information. Due to its ease of estimation, the cation exchange capacity can function as an approximate measure of the residence time and, at the same time, appropriately, measure of the protective effectiveness of unconsolidated deposits below the soil. Coarse elastic sediments, which have no cation exchange capacity worth mentioning, and unconsolidated rocks for which the close relationship between cation exchange capacity and residence time mentioned above is hardly valid (e. g. peat, sapropel), are accommodated in the system in a way which takes account of the shorter residence time of percolating water in these sediments (see *Table 1-3*).

A different assessment scheme is used for solid rocks, since water moves mainly along joints and/or karst cavities; for this reason, the percolation velocity is generally high, and, due to the comparatively small contact area, the cation exchange capacity is likely to be correspondingly low. Thus it must be concluded that the properties of solid rocks are altogether less favorable with regard to protecting an underlying aquifer from contamination, even when the permeability is low. Decisive for the assessment of the protective effectiveness of these rocks are primarily the rock properties that determine its permeability.

Due to the relatively low protective effectiveness of solid rocks, primary importance must be assigned to the protection provided by a possible weathering zone and Quaternary cover. Therefore, strongly and deeply weathered zones must be assessed using criteria normally applied to unconsolidated rock.

The percolation rate, i.e. the amount of water infiltrating the ground per unit time, affects the movement and thus the residence time of the percolating water, both in the soil and in the lower parts of the rock cover above the aquifer. A high percolation rate means more rapid downward movement of water (possibly contaminated) and thus a lower protective effectiveness.

Moreover, it must be considered that, in the curse of the sorption and exchange processes in the lower parts of the rock cover above the aquifer, the potential of the cover to retain and/or degrade pollutants is gradually reduced. This is due to the fact that here, in contrast to the soil zone, which contains the normal assemblage of organisms, the absorption capacity is not regenerated. Therefore, in the case of a persistently large input of pollutants, it must be expected that in the long run the protective effectiveness of the lower part of the reek cover will be reduced, possibly to zero.

As the long-term maintenance of this "purifying potential" is of fundamental importance for groundwater protection, large quantities of percolating water and/or a high groundwater recharge rate must be regarded as having a negative effect on the protective effectiveness of the cover above an aquifer. It is true that a high percolation rate tends to dilute any pollutants in the water; however, the total amount of pollutants leached from the ground is higher than when the groundwater recharge rate is low. This means that the reactive and/or absorptive components in the substrate are more rapidly "used up".

The protective effectiveness of the soil and rock cover above groundwater aquifers is assessed on the basis of the assumption that the sole source of the percolating water is rainfall. In the case of high input of pollutants from a point source, e.g. a spillage of a toxic chemical, this is not strictly true, and in this case specific studies on the pollutants themselves and the amounts involved are necessary.

Perched aquifer systems may delay or even prevent downward transport of pollutants. Moreover, artesian conditions make it almost impossible for contaminated water to percolate downwards into the aquifer. Local hydrogeological conditions, such as these, which provide additional protection for the main aquifer, will be considered in the final assessment by assigning extra points in the grading.

The protective effectiveness of the soil and rock cover above an aquifer, is assessed on the basis of a point system, a large number of points denoting a high protective effectiveness. The assignment of points to the different parameters and the protection-effectiveness classes are partly based on the system compiled by the Working Group "Criteria for the assessment of the soil and rock cover above an aquifer within the framework of the soil in formation system". The assessment of the different parameters is explained below.

3. Assessment of the parameters

3.1 Soil

Parameter 1: ***Effective field capacity*** (eFC) (number of points = **S**)

The effective field capacity [mm/dm] is determined for each individual soil horizon by field and laboratory measurements or is derived using standard tables in the Pedological Mapping Handbook (AG BODENKUNDE 1982). The eFC is then multiplied by the thickness of the horizon in decimeters [dm]. To simplify the calculation, the rooting depth is assumed to be constant at 10 dm. The total effective field capacity of a soil (ΣeFC) is obtained by addition of the effective-field-capacity values calculated for each horizon down to 1 m depth (or to the water table if < 1 m below ground surface). For shallow soils, the effective field capacity of the substrate below the actual soil zone is assessed down to a depth of 1 m and included in the calculation.

The total effective field capacity is subdivided into 6 classes as in the Pedological Mapping Handbook. Each of these classes is given a number of points, a large number corresponding to a comparatively long residence time of the percolating water (*Table 1-1*).

Table 1-1: Assessment of soils on the basis of effective field capacity for the GLA-Method (ΣeFC) (number of points = S)

ΣeFC [mm]	**S**
down to 1.0 m depth	
> 250	750
> 200 - 250	500
> 140 - 200	250
> 90 - 140	125
> 50 - 90	50
< 50	10

In the calculations on the basis of the effective field capacity referred to here, comparatively unfavorable assessment is made of argillaceous soils. However, this feature of the classification is justified because the soils often show regular desiccation cracks, which tend to accelerate the downward migration of pollutants.

Within this scheme, the protective effectiveness of the soil in general is assessed rather unfavorably in order to take into consideration the effect of macro-pores, which give rise to considerable small-scale variations.

Parameter 2: ***Percolation rate*** (factor **W**)

As far as possible, the available data on the annual groundwater recharge from rainfall is used to determine the percolation factor W (*Table 1-2*). If this data is not available, a comparable figure is determined by taking the difference between the annual rainfall (N) and the potential evapotranspiration ($ETP_{pot.}$). Due to the lack of initial data, the effect of the slope cannot normally be taken into consideration, which means that the calculation is done on the basis of an almost horizontal ground surface.

Table 1-2: Percolation rates and the corresponding factor (W) used in the GLA-Method (based on the actual groundwater recharge (GWR) or an alternative figure given by N - ETPpot.)

GWR [mm/a]*	N - $ETP_{pot.}$ (mm/a]*	factor W
< 100		*1.75*
> 100 - 200	*< 100*	*1.5*
> 200 - 300	> 100 - 200	*1.25*
> 300 - 400	*> 200 - 300*	*1.0*
> 400	*> 300 - 400*	*0.75*
	> 400	*0.5*
*If the data is available, the actual groundwater recharge rate should be used		

3.2 Rock cover above the uppermost aquifer, below the soil

The protective effectiveness of the rock cover above the uppermost aquifer and below the soil, i.e. from a standard depth of 1 m below ground surface down to the water table (in the case of a confined aquifer down to the top of the aquifer), is calculated for each bed individually. The points for all the beds in the section are then added up. The protective effectiveness of the rock cover below the soil depends on various parameters, which are assessed as follows:

Parameter 3: ***Rock type*** (number of points = **R**)

Due to their fundamentally different geohydraulic rock properties, unconsolidated and consolidated rocks are assessed separately.

In the case of unconsolidated rocks, the residence time is derived via the cation exchange capacity (CEC), since both these factors depend directly on the proportion of fine-grained material present. The cation exchange capacity is more easily quantifiable because it can be obtained from standard lithological tables. To incorporate coarse material, which has a negligible cation exchange capacity, in the system, its residence time, which is invariably low, has been estimated.

The proportions of clay and silt contained in different soil types are given in weight percent in Table 11 and Figure 3 in AG BODENKUNDE (1982). On the basis of literature data, the cation exchange capacity of clay is taken as 60 $cmol_c$ /kg and that of silt as 10 $cmol_c$ /kg. Using these figures, a mean cation exchange capacity was calculated for different types of unconsolidated rock (100 g) and converted into mol_c /m^3, assuming an average dry density of 1.5 g/cm^3. The number of points (R_u) was then estimated on the basis of the cation exchange capacity for each of the different types of unconsolidated rock. These are listed in *Table 1-3*.

Table 1-3: Assessment of unconsolidated rocks for the GLA-Method (number of points = R_u).

Type of a unconsolidated rock	**R_u = no. of points per meter bed thickness**
clay	500
loamy clay, slightly silty clay	400
slightly sandy clay	350
silty clay, clayey silty loam	320
clayey loam	300
very silty clay, sandy clay	270
very loamy silt	250
slightly clayey loam, clayey, silty loam	240
very clayey silt, silty loam	220
very sandy clay, sandy silty loam, slightly sandy loam, loamy silt, clayey silt	200
sandy loam, slightly loamy silt	180
slightly loamy silt, sandy loamy silt, silt, slightly sandy loam	160
very clayey sand, clayey sand, loamy silty sand	140
sandy silt, very loamy sand	120
loamy sand, very silty sand	90
slightly clayey sand, silty sand, sandy clayey gravel	75
slightly loamy sand, sandy silty gravel	60
slightly silty send, slightly silty sand with gravel	50
sand	25
sand with gravel, sandy gravel	10
gravel, gravel and breccia	5
unconsolidated volcanic material	200
peat	400
sapropel	300

If the rock contains visible amounts of organic matter, the number of points is increased by 75 per meter thickness (not applicable to peat and sapropel).

If the content of organic matter is visibly elevated, 75 points are added per meter thickness. In the cases of peat, consolidated volcanic material and sapropel, as with the coarser material mentioned above, there is limited correlation between cation exchange capacity and residence time; thus a large number of points are given to reflect the comparatively high percolation velocity.

Owing to the presence of deep desiccation cracks, clay- and silt-rich superficial deposits up to 3 m thick resting on permeable bedrock containing no groundwater are treated as moderately jointed claystone (*Table 1-4*).

Solid rocks, in spite of their mostly very low intrinsic permeability, often show high permeability due to jointing and/or karstification, and thus comparatively short residence times for percolating water. Therefore, the umber of points (R_s) is determined as the product of a figure (O) for the rock type that reflects the low intrinsic permeability of the rock, and a factor (F) reflecting the presence of joints, karst cavities, etc. (*Table 1-4*).

The numbers of points given in *Table 1-4* apply to consolidated rocks which are only slightly weathered. Thoroughly weathered rocks should be assessed as if they were unconsolidated rocks (*Table 1-3*).

Parameter 4: ***Thickness of the soil and rock cover above the aquifer*** (factor **T**)

The distance covered by percolating water (assuming vertical percolation), i.e. the thickness of the soil and rock above the topmost aquifer, affects the residence time and thus the time that percolating water is exposed to mechanical, physico-chemical, and microbial processes. In assessing the protective effectiveness, the thickness of each bed in meters is used as a factor in the calculation.

Table 1-4: Assessment of consolidated rocks for the GLA-Method
(number of points (**R_s**) = product of points for rock type (**0**) and factor for joints, karst cavities, etc. (**F**), i.e. $R_s = O \times F$).

Rock type	O
claystone, slate, marlstone, siltstone	20
sandstone, quartzite, volcanic rock, plutonic rock, metamorphic rock	15
porous sandstone, porous volcanic rock (e. g. tuff)	10
conglomerate, breccia, limestone, tuffaceous limestone, dolomitic rock, gypsum rock	5

Structure	F
non-jointed	25.0
slightly jointed	4.0
moderately jointed, slightly karstic	1.0
moderately karstic	0.5
strongly jointed, fractured or strongly karstic	0.3
not known	1.0

Local conditions that may provide additional protection to the main aquifer are taken account of using standard point bonuses as follows:

Parameter 5: ***Perched aquifer systems*** (number of bonus points **Q**)

A perched aquifer may prevent the migration of pollutants to greater depths and/or may prevent or delay contamination of the main aquifer system. This protection is most effective where natural springs occur.

A bonus (**Q**) of **500 points** is added for each **perched aquifer with springs**.

Parameter 6: ***Hydraulic pressure conditions*** (number of bonus points **HP**)

The hydraulic pressure conditions depend, among other things, on the lithology of the soil and rock cover above the aquifer, which has already been taken account of by the points awarded for each rock type. However, permanent **artesian conditions** are particularly effective as a natural protection against percolation of contaminated water into the aquifer. Therefore, a bonus (**HP**) of **1500 points** is given in this case.

6. Determination of the overall protective effectiveness

To determine the overall protective effectiveness (P_t) of the soil and rock cover above the topmost aquifer, the following procedure is used: initially, the protective efficiencies of the soil ($\mathbf{P_1}$) and the rock cover ($\mathbf{P_s}$) are calculated separately.

Soil cover (P_1)
The number of points (S) given for the effective field capacity (eFC) of the soil from *Table 1-1* is multiplied by factor W, which represents the percolation rate (see *Table 1-2*).

$$\mathbf{P_1 = S \times W}$$

Rock cover (P_2)

Each individual bed in the rock cover below the soil (below one meter depth) and above the aquifer is assessed separately: in the case of unconsolidated rock (no. of points = $\mathbf{R_u}$) using *Table 1-3* and in the case of solid rock (no. of points = $\mathbf{R_s}$) using Table 5; the number of points is then multiplied by the stratigraphic thickness in meters (factor **T**). The sum of all the points for the individual rock units, i.e. the entire section from 1 m below the surface to the water table (to the top of the aquifer in the case of a confined aquifer) gives a figure representing the protective effectiveness of the rock cover below the soil. This figure, as in the case of the soil cover, is multiplied by factor **W** (from *Table 1-2*), which represents the percolation rate.

If applicable, bonus(es) is (are) then added for each perched aquifer with springs (bonus **Q**) and/or artesian conditions (bonus **HP**).

The number of points (**P_2**) representing the protective effectiveness of the rock cover below the soil is calculated as follows

$$P_2 = W * (R_1T_1 + R_2T_2 + ... + R_nT_n) + Q + HP$$

The protective effectiveness coefficient (**P_t**) for the entire soil and rock cover above the aquifer is the sum of **P_1** and **P_2**.

$$P_t = P_1 + P_2$$

In *Table 1-5*, five classes of protective effectiveness are shown, based on the above coefficient, and for which the ranges of the residence times of percolating water in the soil and rock cover above the aquifer are given.

Table 1-5: Classes of overall protective effectiveness for the GLA-Method.

Overall protective effectiveness	**total no. of points P_t**	**approximate residence time of percolating water in the soil and rock cover above the aquifer**
very high	> 4000	> 25 year
high	> 2000-4000	10-25 years
moderate	> 1000-2000	3-10 years
low	500-1000	several months to about 3 years
very low	500	a few days to about 1 year, in karstic rock often less

5. Examples

In examples 1 to 4 the following assumptions are made:

- soil containing 2 X of organic matter and having a effective average density (referred to as Ld 3 in AG BODENKUNDE 1982)
- N – $ETP_{pot.}$ = 250 mm/a
- no perched mater table present
- topmost aquifer unconfined

Example 1:

Total thickness of soil and rock cover above aquifer = 6 m.

- O,8 m topsoil, sandy with gravel
- 2,0 m slightly silty sand with gravel
- 3,0 m sandy gravel
- 4,0 m sand
- 6.0 m sandy gravel

		points * W
S	= 10	= 10 x 1,0 = P_1
R_{u1}*T	= 50 * 1,0	
R_{u2}*T	= 10 * 1,0	
R_{u3}*T	= 25 x 1,0Jt	
R_{u4}*T	= 10 x 2,0	
		105 * 1,0 = P_2

$P_t = P_1 + P_2$ = 115 points

Protective effectiveness very low.

Example 2:

Total thickness of soil and rock cover above aquifer = 16 m.

- 1,1 m topsoil, silty loam
- 5,0 m silty clay
- 15,0 m slightly silty clay
- 16,0 m slightly silty sand with gravel

		points x W	
S	= 500	= 500 x 1,0	= P_1
R_{u1}*T	= 320 x 4,0		= 1280
R_{u2}*T	= 400 x 10,0		= 4000
R_{u3}*T	= 50 x 1,0		= 50
		5330 * 1,0	= P_2

$P_t = P_1 + P_2$ = 5830 points

Protective effectiveness very high.

Example 3:

Total thickness of soil and rack cover above aquifer 50 m.

- 1,2 m topsoil, silty loam
- 2,2 m loamy silty sand
- 50.0 m strongly karstic limestone

	points * W		
S	= 500 = 500 * 1,0		= P_1
R_u*T	= 140 x 1,2		= 168
R_s*T	= (5 x 0,2)	x 47,8	= 72
`		240 x 1,0	= P_2

$P_t = P_1 + P_2$ = 740 points

Protective effectiveness low.

Example 4:

Total thickness of soil and rock cover above aquifer m 70 m.

- 1,2 m topsoil, silty loam
- 40,0 m sandy silty gravel
- 60,0 m conglomerate
- 70,0 m sandy gravel

	points x W		
S	= 500 = 500 x 1,0		= P_1
R_{u1}*T	= 60 x 39,0		= 2340
R_s*T	= (5 x 1,0)	x 20,0	= 100
R_{u2}*T	= 10 x 10,0		= 100
		2540 * 1,0	= P_2

$P_t = P_1 + P_2$ = 3040 points

Protective effectiveness high.

Example 5:

Assumptions as in examples 1 to 4, but N – $ETP_{pot.}$ = 350 mm/a, total thickness of soil and rock cover above aquifer = 80 m.

- 0,8 m	topsoil, sandy with gravel
- 2,4 m	sandstone, strongly weathered (equal to sand with gravel)
- 5,5 m	claystone, strongly weathered (equal to silty clay)
- 11,0 m	claystone, slightly jointed
- 80,0 m	sandstone, moderately jointed, with intercalations of moderately jointed claystones and siltstones totaling 18,0 m thickness

		points x W	
S	= 10	= 10 x 0,75	= P_1
R_{s1}*T	=	10 x 1,4	= 14
R_{s2}*T	=	400 x 3,1	= 1240
R_{s3}*T	=	(20 x 4,0) x 5,5	= 440
R_{s4}*T	=	(15 x 1,0) x 51	= 765
	+	(20 x 1,0) x 18	= 360

2819 x 0,75 = P_2
2114 = P_2

$P_t = P_1 + P_2 = 2122$ points

Protective effectiveness high.

Example 6:

Assumptions as in examples 1 to 4, but perched aquifer with springs present; total thickness of soil and rock cover above aquifer = 10 m.

- 1,1 m	topsoil, sandy
- 2,5 m	slightly silty sand
- 3,5 m	sandy gravel, 3,0 to 3,5 m water bearing
_ 4,5 m	clay
- 10,0 m	slightly silty sand

		points x W		
S	= 10	10 x 1,0		= P_1
R_{u1}*T	=	50 x 1,5	=	75
R_{u2}*T	=	10 x 1,0	=	10
R_{u3}*T	=	500 x 1,0	=	500
R_{u4}*T	=	50 x 5,5	=	275

860 x 1,0
bonus HP + 500
= 1360 = P_2

$P_t = P_1 + P_2 = 1370$ points
Protective effectiveness moderate.

Example 7:

Assumptions as in examples 1 to 4, but N – ETP $_{pot.}$ < 100 mm/a and confined aquifer, total thickness of soil and rock above aquifer = 5,0 m.

- 0,8 m topsoil, sandy with gravel
- 4,0 m sandy clayey gravel
- 5,0 m very silty clay

		points x W	
S	= 10	= 10 x 1,5	= P_1
R_{u1}*T	= 75 x 3,0		= 225
R_{u2}*T	= 270 x 1,0		= 270
		495 x 1,5	= 723
	bonus HP		+ 1500
			2243 = P_2

$P_t = P_1 + P_2$ = 2258 points

Protective effectiveness high.

6. Plausibility test

To test whether the points assigned to the various rock types and the suggested calculation methods lead to plausible results, comparisons are made of the protective effectiveness of lithologically different rock types.

a) The protective effectiveness of 1.0 m clay corresponds to that of

1,6 m silty clay
1,9 m very silty clay; sandy clay
2,3 m very clayey silt; silty loam
2,5 m very sandy clay
3,2 m slightly clayey silt; silt; very sandy loam
3,6 m clayey sand; loamy silty sand
5,6 m very silty sand
7 m slightly clayey sand; sandy clayey gravel
8 m sandy silty gravel
10 m slightly silty sand
20 m sand
50 m sand with gravel; sandy gravel
100 m gravel, gravel with breccia

b) comparison of the protective effectiveness of different rock types, each rock type is assumed to be 10 m thick. The soil cover is neglected.

Unconsolidated rock	Points	Protective effectiveness
gravel	50	very low
sand with gravel	100	
sand	250	
slightly silty sand with gravel	500	low
silty sandy gravel	600	
slightly clayey sand	750	
very silty sand	900	
sandy silt	1200	moderate
silt	1600	
very sandy clay, clayey silt	2000	high
very clayey silt	2200	
very silty clay, sandy clay	2700	
silty clay	3200	
slightly sandy clay	3500	
loamy clay, slightly silty clay	4000	very high
clay	5000	

Solid rock	Points	Protective effectiveness
limestone, strongly karstic	15	very low
sandstone, porous, strongly jointed	30	
sandstone, strongly jointed	45	
claystone, strongly jointed	60	
sandstone, porous, moderately jointed	100	
sandstone, moderately jointed	750	
claystone, moderately jointed	200	
limestone, slightly jointed	200	
sandstone, slightly jointed	600	low
claystone, slightly jointed	800	

c) As in b) but thickness of each rock type is assumed to be 25 m

Unconsolidated rock	Points	Protective effectiveness
gravel	125	very low
sand with gravel	250	
sand	625	low
slightly silty sand with gravel	1250	moderate
silty sandy gravel	1500	
slightly clayey sand	1875	
very silty sand	2250	high
silt	4000	very high
very sandy clay, clayey silt	5000	
very clayey silt	5500	
clay	>10000	

Solid rock	Points	Protective effectiveness
limestone, strongly karstic	38	very low
sandstone, porous, strongly jointed	75	
sandstone, strongly jointed	113	
claystone, strongly jointed	150	
sandstone, moderately jointed	375	
claystone, moderately jointed	500	
limestone, slightly jointed	500	
sandstone, porous, slightly jointed	1000	low
sandstone, slightly jointed	1500	
claystone, slightly jointed	2000	moderate

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Annex 2: Description of the Evaluation Process for Preparing a Groundwater Vulnerability Map

Map of the Surat Thani Area (Example from Southern Thailand; MARGANE, 2001)

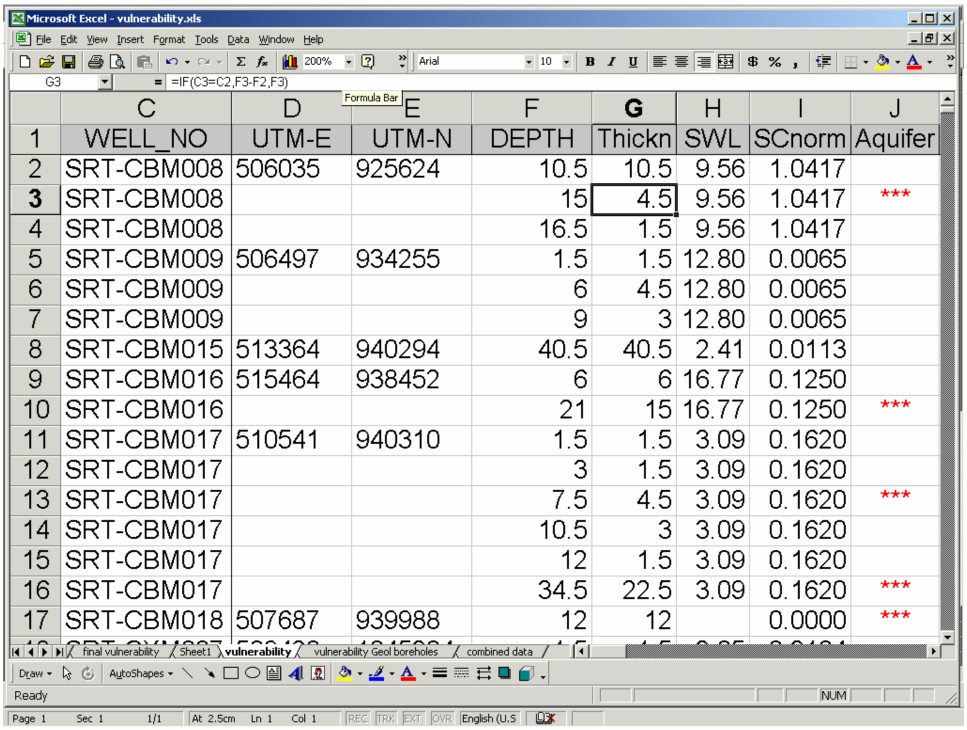
(Remark: In this case the effective field capacity of the soil was not available, so that parameter P_1 was integrated into P_2. The distribution of the groundwater recharge rate is homogeneous, so that the preparation could be done by calculating the P_2 values for each known point (borehole) and then delineating the vulnerability classes. This method is much easier than the application of the original GLA-Method or PI-Method because it does no require the use of Arc/Info or a similar GIS system.).

All relevant data were stored in the hydrogeological database HYDRA. From there they were exported to EXCEL spreadsheets. The data from the geological boreholes were extracted from the program GeODin, were all boreholes were entered for graphical presentation and the preparation of cross sections. The following data fields were needed:

- Well no.,
- E-coordinate,
- N-coordinate,
- lithological description (with: depth, detailed information about the main and auxiliary components of each layer),
- depth of screens,
- yield and drawdown at pumptest (or specific well capacity).

Based on this information the thickness of each layer was calculated. For every layer the vulnerability rating was calculated by using a lookup table for assigning standard vulnerability values to the lithology (defined as key codes in GeODin and HYDRA) and multiplying them with the actual thickness of the layer.

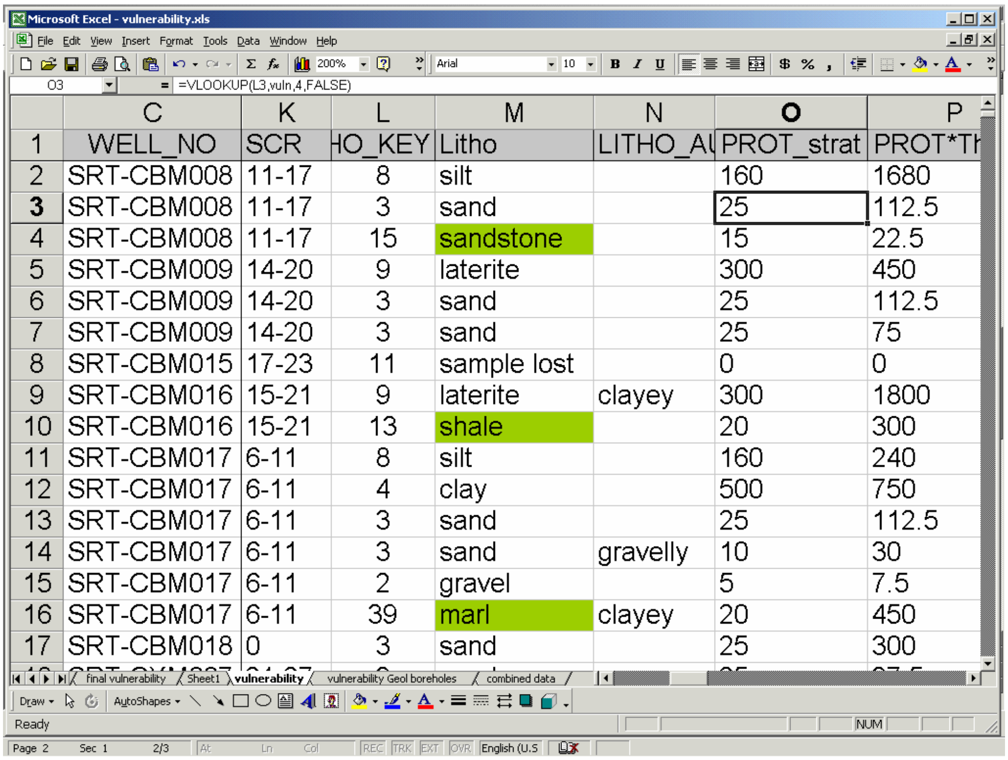
Based on the information about lithology, screen depth and specific well capacity, it was then manually sorted out which layer(s) constitute(s) the main aquifer. In the case of a confined aquifer the protective effectiveness is the rating of the overlying layer of low permeable rocks or sediments above the aquifer. In the case of an unconfined aquifer the protective effectiveness is the rating of the overlying layers down to the depth of groundwater (water level). The values were calculated accordingly.



G3 = =IF(C3=C2,F3-F2,F3)

	C	D	E	F	G	H	I	J
1	WELL_NO	UTM-E	UTM-N	DEPTH	Thickn	SWL	SCnorm	Aquifer
2	SRT-CBM008	506035	925624	10.5	10.5	9.56	1.0417	
3	SRT-CBM008			15	4.5	9.56	1.0417	***
4	SRT-CBM008			16.5	1.5	9.56	1.0417	
5	SRT-CBM009	506497	934255	1.5	1.5	12.80	0.0065	
6	SRT-CBM009			6	4.5	12.80	0.0065	
7	SRT-CBM009			9	3	12.80	0.0065	
8	SRT-CBM015	513364	940294	40.5	40.5	2.41	0.0113	
9	SRT-CBM016	515464	938452	6	6	16.77	0.1250	
10	SRT-CBM016			21	15	16.77	0.1250	***
11	SRT-CBM017	510541	940310	1.5	1.5	3.09	0.1620	
12	SRT-CBM017			3	1.5	3.09	0.1620	
13	SRT-CBM017			7.5	4.5	3.09	0.1620	***
14	SRT-CBM017			10.5	3	3.09	0.1620	
15	SRT-CBM017			12	1.5	3.09	0.1620	
16	SRT-CBM017			34.5	22.5	3.09	0.1620	***
17	SRT-CBM018	507687	939988	12	12		0.0000	***

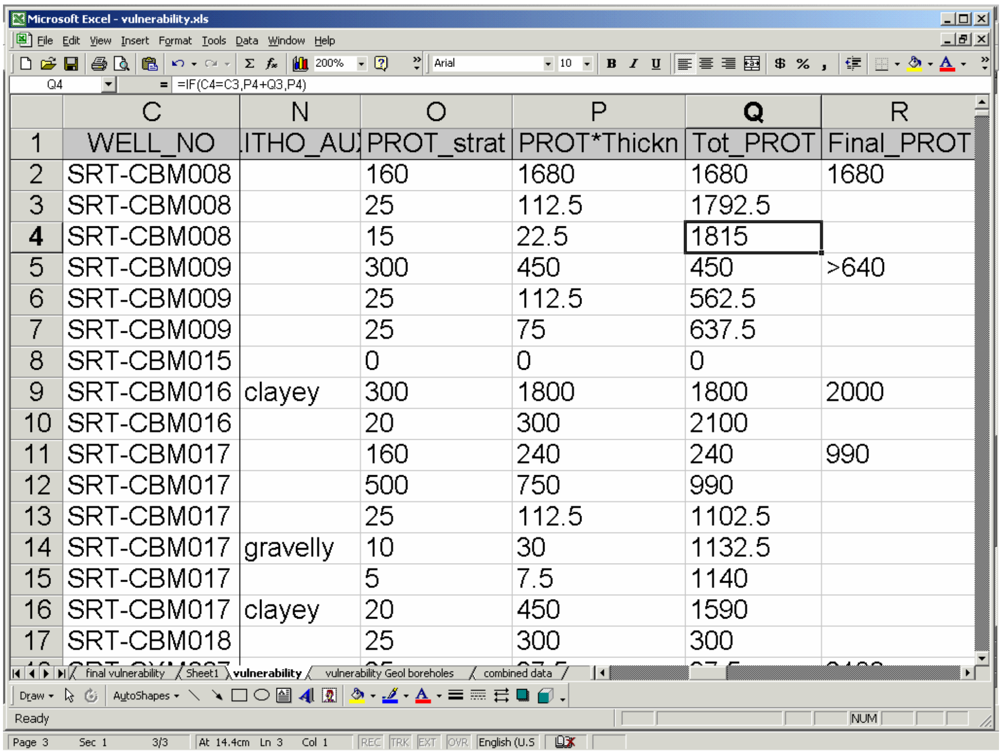
Figure 2-1: Calculation of thickness of layer and marking the main aquifer



O3 = =VLOOKUP(L3,vuln,4,FALSE)

	C	K	L	M	N	O	P
1	WELL_NO	SCR	HO_KEY	Litho	LITHO_A	PROT_strat	PROT*Th
2	SRT-CBM008	11-17	8	silt		160	1680
3	SRT-CBM008	11-17	3	sand		25	112.5
4	SRT-CBM008	11-17	15	sandstone		15	22.5
5	SRT-CBM009	14-20	9	laterite		300	450
6	SRT-CBM009	14-20	3	sand		25	112.5
7	SRT-CBM009	14-20	3	sand		25	75
8	SRT-CBM015	17-23	11	sample lost		0	0
9	SRT-CBM016	15-21	9	laterite	clayey	300	1800
10	SRT-CBM016	15-21	13	shale		20	300
11	SRT-CBM017	6-11	8	silt		160	240
12	SRT-CBM017	6-11	4	clay		500	750
13	SRT-CBM017	6-11	3	sand		25	112.5
14	SRT-CBM017	6-11	3	sand	gravelly	10	30
15	SRT-CBM017	6-11	2	gravel		5	7.5
16	SRT-CBM017	6-11	39	marl	clayey	20	450
17	SRT-CBM018	0	3	sand		25	300

Figure 2-2: Assigning the standard protective effectiveness rating for a layer and multiplying it with the thickness of the layer



	C	N	O	P	Q	R
1	WELL_NO	LITHO_AU	PROT_strat	PROT*Thickn	Tot_PROT	Final_PROT
2	SRT-CBM008		160	1680	1680	1680
3	SRT-CBM008		25	112.5	1792.5	
4	SRT-CBM008		15	22.5	1815	
5	SRT-CBM009		300	450	450	>640
6	SRT-CBM009		25	112.5	562.5	
7	SRT-CBM009		25	75	637.5	
8	SRT-CBM015		0	0	0	
9	SRT-CBM016	clayey	300	1800	1800	2000
10	SRT-CBM016		20	300	2100	
11	SRT-CBM017		160	240	240	990
12	SRT-CBM017		500	750	990	
13	SRT-CBM017		25	112.5	1102.5	
14	SRT-CBM017	gravelly	10	30	1132.5	
15	SRT-CBM017		5	7.5	1140	
16	SRT-CBM017	clayey	20	450	1590	
17	SRT-CBM018		25	300	300	

Figure 2-3: Assigning the final protective effectiveness rating for a well

The values were marked with “>” if required and the displayed in the program SURFER. For areas which are sufficiently covered with data, the kriging method could be applied and the lines then afterwards be adjusted according to the geology. This method was used e.g. for drawing the groundwater vulnerability map of the Chiang Mai – Lamphun basin. However, in the Surat Thani Greater City area this was not the case. In this case the symbols for the 4 different classes were (low, moderate, high and very high, with different symbols for groundwater wells and geological boreholes) were plotted out together with the labels (the labels with the information “>” have to be stored in a separate column because SURFER does not recognize values with “>”), the geological boundaries and the hydrographical net. In the case of the Surat Thani Greater City area the geological boreholes indicate only that the protective effectiveness must be higher than this value. On the plot the classes were delineated by hand using all the above-mentioned information.

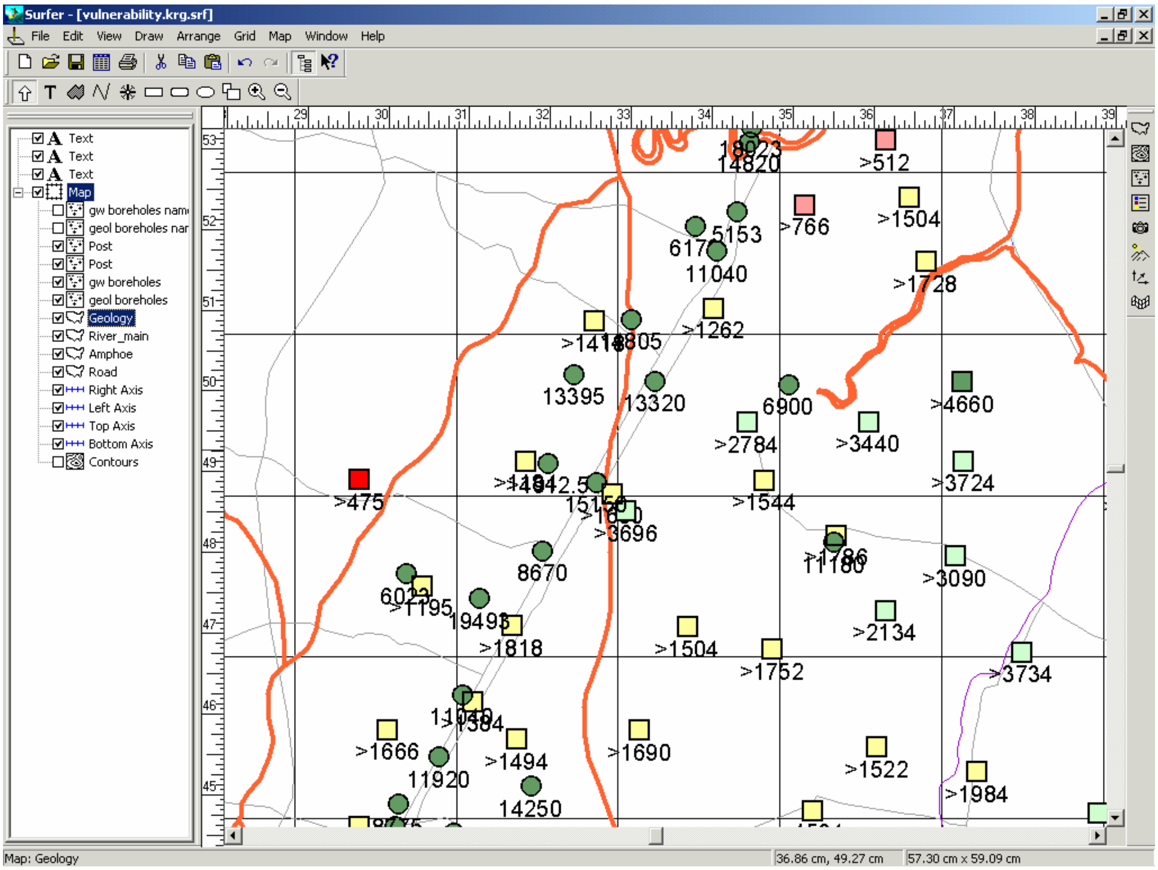


Figure 2-4: Delineation of vulnerability classes using borehole information, topography and geology

Annex 3: Groundwater Vulnerability Mapping in Karst Areas – The EPIK Method

(from SAEFL, 2000)

Environment in practice

Practical Guide

Groundwater Vulnerability Mapping in Karstic Regions (EPIK)

1998

Swiss Agency for the Environment, Forests and Landscape (SAEFL)

Practical Guide

Groundwater Vulnerability Mapping in Karstic Regions (EPIK)

1998

Application to Groundwater Protection Zones

Published by the Swiss Agency for the Environment, Forests and Landscape (SAEFL)

Authors

Nathalie Doerfliger
François Zwahlen
University of Neuchâtel, Centre of Hydrogeology,
Rue Emile-Argand, 11
CH-2007 Neuchâtel

Expert Group

Jean-Pierre Tripet*, President
Swiss National Hydrological and Geological Survey

Pierre-Alain Gretillat*
University of Neuchâtel, Centre of Hydrogeology

Daniel Hartmann
SAEFL, Water Protection and Fisheries Division

Benjamin Meylan
SAEFL, Water Protection and Fisheries Division

Christian Schlüchter*
University of Berne, Geological Institute

Gianni della Valle*
OEHE/WEA, Geology Division, Berne

Andres Wildberger*
Dr von Moos AG, Zurich

Jürg Zobrist*
IFAEPE/EAWAG, Dübendorf

**Swiss Society of Hydrogeology Delegate*

TABLE OF CONTENTS

ABSTRACTS

Vulnerability mapping in karst areas (EPIK)

EPIK is a multiparameter method that was developed as an aid in mapping groundwater vulnerability in karst regions, with special respect to catchment areas of sources. Groundwater vulnerability maps based on this method are an indispensable tool for establishing groundwater protection zones.

EPIK is based on the specific groundwater dynamics in karst aquifers. Four parameters are taken into account: (1) Development of the **E**pikarst, (2) effectiveness of the **P**rotective cover, (3) conditions of **I**nfiltration and (4) development of the **K**arst network.

After having been given a quality-ranking index, each of the four parameters is mapped throughout the groundwater catchment area. A weighting coefficient is then attributed to each of the indexed parameters according to their degree of protection against contamination. By adding the protection values of each parameter a protection index F for each surface element of the catchment area is calculated. In this way a groundwater vulnerability map is produced, representing the spatial distribution of F. F may be determined manually or by means of a GIS. Furthermore, F values can be used to establish the groundwater protection zones S1, S2 and S3 in an objective manner.

The EPIK method was adjusted in several pilot studies in different types of karst in Switzerland where groundwater is polluted mainly by agricultural activities. The groundwater vulnerability maps allowed the establishment of new protection zones, which were subsequently verified by tracer tests and geophysical investigations.

Key words : *Groundwater, karst hydrology, vulnerability, mapping, source protection zones, Switzerland, EPIK.*

Cartographie de la vulnérabilité en régions karstiques (EPIK)

La méthode multicritère EPIK a été établie pour cartographier de manière générale la vulnérabilité des aquifères karstiques et plus spécifiquement celle des bassins d'alimentation des sources ou captages en milieu karstique. La carte de vulnérabilité obtenue constitue ainsi une base indispensable pour la délimitation des zones de protection.

Basée sur l'organisation spécifique des écoulements dans les aquifères karstiques, cette méthode prend en compte 4 critères: 1) développement de l'**E**pikarst, 2) importance de la couverture **P**rotectrice, 3) conditions d'**I**nfiltration et 4) développement du réseau **K**arstique.

On évalue chaque critère en le qualifiant par des indices, qui sont cartographiés sur l'ensemble du bassin d'alimentation des sources ou captages considérés. A chaque critère indexé, on attribue une valeur en fonction du rôle protecteur qu'il représente. L'addition des valeurs obtenues pour chacun des critères fournit la valeur du facteur de protection F pour chaque élément de surface du bassin d'alimentation étudié. De cette manière on obtient, sous forme d'une carte de vulnérabilité, une représentation de la répartition du facteur F pour l'ensemble du bassin. Cette opération peut se faire manuellement ou à l'aide d'un système d'information géographique. Grâce à une relation d'équivalence, on peut transformer de manière rigoureuse le document obtenu en carte des zones de protection S1, S2 et S3.

Cette méthode a été ajustée sur plusieurs sites en milieu karstique en Suisse (différents types de karst) où se posaient des problèmes de contamination des sources essentiellement dus à l'agriculture. Les cartes de vulnérabilité ont permis d'établir de nouvelles zones de protection, vérifiées à l'aide d'essais de traçage et d'investigations géophysiques.

Mots-clés : *Eaux souterraines, karst, vulnérabilité captages, cartographie, zones de protection, Suisse, EPIK.*

Kartierung der Vulnerabilität in Karstgebieten (Methode EPIK)

EPIK ist eine Multikriterien-Methode zur kartographischen Erfassung der Vulnerabilität in Einzugsgebieten von Karstquellen und Karst-Grundwasserfassungen. Vulnerabilitätskarten bilden die Grundlage für die Ausscheidung der Grundwasserschutzzonen in Karstgebieten.

Die EPIK-Methode trägt der spezifischen Grundwasserdynamik in Karstaquiferen Rechnung. Berücksichtigt werden vier Kriterien: (1) Entwicklung des **E**pikarsts, (2) Schutzwirkung der Deckschicht (**P**rotection), (3) **I**nfiltrationsverhältnisse und (4) Entwicklung des **K**arstnetzes.

Für jedes Flächenelement eines Untersuchungsgebietes werden für jedes der vier Kriterien E, P, I und K die zugehörigen Indizes ermittelt und separat auskartiert. Jedes Kriterium ist zudem, in Abhängigkeit seiner Schutzfunktion, mit einem Koeffizienten gewichtet. Die Summe der ermittelten Werte ergibt den Schutzfaktor F für jedes Flächenelement. Aus der räumlichen Verteilung von F resultiert eine Vulnerabilitätskarte, welche manuell oder mittels eines GIS erstellt werden kann. F-Werte können direkt und in nachvollziehbarer Weise zur Ausscheidung der Grundwasserschutzzonen S1, S2 und S3 verwendet werden.

Die EPIK-Methode wurde im Rahmen mehrerer Pilotstudien in verschiedenen Gebieten der Schweiz mit unterschiedlichen Karsttypen - im Zusammenhang mit periodischen Verschmutzungen des Trinkwassers durch die Landwirtschaft - geprüft. Dabei ermöglichten die Vulnerabilitätskarten die Ausscheidung neuer Schutzzonen, die in der Folge durch Markierversuche und geophysikalische Untersuchungen verifiziert wurden.

Stichworte : *Grundwasser, Karst, Vulnerabilität, kartographische Aufnahme, Grundwasserschutzzonen, Schweiz, EPIK.*

Cartografia della vulnerabilità in regioni carsiche (EPIK)

Il metodo a più criteri EPIK è stato concepito allo scopo di cartografare in generale la vulnerabilità degli acquiferi carsici e in particolare quella dei bacini di alimentazione delle sorgenti o captazioni in regioni carsiche. La carta della vulnerabilità ottenuta costituisce una base indispensabile alla delimitazione delle zone di protezione.

Tale metodo, basato sull'organizzazione specifica del deflusso negli acquiferi carsici, prende in considerazione quattro criteri: 1) lo sviluppo dell'**E**picarso, 2) l'importanza della copertura di **P**rotezione, 3) le condizioni d'**I**nfiltrazione, 4) lo sviluppo della rete carsica (**K**arst).

Ogni criterio viene valutato in base a una qualificazione per indici che sono cartografati sull'insieme del bacino di alimentazione delle sorgenti o captazioni considerate. A ogni criterio indicizzato viene attribuito un valore in funzione del ruolo di protezione che esso rappresenta. L'addizione dei valori ottenuti per ciascun criterio fornisce il valore del fattore di protezione F per ciascun elemento della superficie del bacino di alimentazione studiato. In questo modo si ottiene, sotto forma di una carta della vulnerabilità, una rappresentazione della ripartizione del fattore F per l'insieme del bacino. Tale operazione può essere svolta manualmente o con l'aiuto di un sistema d'informazione geografica. Grazie a una relazione di equivalenza è possibile trasformare in modo rigoroso il documento ottenuto in carte delle zone di protezione S1, S2, S3.

Detto metodo è stato adattato su diversi siti carsici in Svizzera (tipi differenti di carso) in cui vi erano problemi di inquinamento delle sorgenti dovuti essenzialmente all'agricoltura. Le carte di vulnerabilità hanno permesso di stabilire nuove zone di protezione che sono state valutate per mezzo di prove con traccianti e di analisi geofisiche.

Parole chiave : *acque sotterranee, carso, vulnerabilità delle captazioni, cartografia, zone di protezione, Svizzera, EPIK.*

PREFACE

With the objective of ensuring potable water quality, the water protection law states that groundwater protection zones must be determined for public groundwater catchment installations. For interstitial porosity aquifers, the delineation of the size of a protection zone is based on the distance travelled by water over a given period of time, before reaching the catchment installation. Determination of this distance and consequently the size of the protection zone are generally ascertained based on specific measurements taken during a hydrogeological investigation.

In karstic aquifers the distribution of groundwater flow velocities is very heterogeneous, such that the risk of groundwater supply pollution does not decrease in a regular manner with increasing distance from the catchment installation, as is generally the case for interstitial porosity aquifers. Moreover, karstic groundwater flow velocities vary greatly with atmospheric conditions. Consequently the time criteria used for interstitial porosity aquifer protection zone delineation is not applicable to karstic aquifers.

The current publication provides a hydrogeological basis for the determination of protection zones in karstic regions. The method is not based on the evaluation of flow velocities, rather on the evaluation of a certain number of hydrogeological parameters which characterise the degree of groundwater protection in different parts of a catchment area of a source. The protection zones are consequently defined on the basis of their sensitivity to groundwater pollution, in other words, based on groundwater vulnerability.

This method was developed by the Centre of Hydrogeology of the University of Neuchâtel on behalf of the Swiss Agency for the Environment, Forests and Landscape (SAEFL) and with the assistance of the Swiss National Hydrological and Geological Survey (SNHGS). A work group consisting of members of the Swiss Society of Hydrogeology was given responsibility for the projects oversight, in collaboration with the Water Protection and Fisheries Division of the SAEFL along with the SNHGS.

This publication is intended for authorities, consulting geologists and engineers as well as research specialists.

PRÉFACE

Dans le but d'assurer la qualité des eaux potables du pays, la loi sur la protection des eaux exige que des zones de protection des eaux souterraines soient délimitées autour des captages d'intérêt public. Pour les aquifères à porosité d'interstice, le dimensionnement de ces zones de protection est basé sur la distance parcourue par l'eau, pendant une durée déterminée, avant d'arriver au captage. La détermination de cette distance, et donc le dimensionnement des zones de protection, sont généralement effectués sur la base de mesures spécifiques réalisées dans le cadre d'une étude hydrogéologique.

Dans les aquifères karstiques, la répartition des vitesses de circulation des eaux souterraines est très hétérogène, de sorte que le risque de pollution de l'eau captée ne diminue pas régulièrement avec l'éloignement du captage, comme c'est généralement le cas pour les aquifères à porosité d'interstice. De plus, les vitesses de circulation des eaux souterraines karstiques sont très variables en fonction des conditions atmosphériques. Le critère temps utilisé pour la délimitation des zones de protection dans les aquifères à porosité d'interstice n'est donc pas applicable aux aquifères karstiques.

Avec la présente publication, on a voulu jeter les bases d'une délimitation hydrogéologiquement fondée des zones de protection dans les régions karstiques. La méthode proposée n'est pas basée sur la détermination des vitesses de circulation des eaux souterraines, mais sur l'évaluation d'un certain nombre de critères hydrogéologiques caractérisant le degré de protection des eaux souterraines dans les différentes parties du bassin d'alimentation d'un captage. Les zones de protection sont par conséquent délimitées sur la base de leur sensibilité à la pollution des eaux souterraines, autrement dit, de la vulnérabilité des eaux souterraines.

Cette méthode a été développée par le Centre d'hydrogéologie de l'Université de Neuchâtel dans le cadre d'un mandat de l'Office fédéral de l'environnement, des forêts et du paysage (OFEFP) et du Service hydrologique et géologique national (SHGN). Un groupe de travail composé de membres de la Société suisse d'hydrogéologie a été chargé d'accompagner le projet, en collaboration avec la division Protection des eaux et pêche de l'OFEFP et avec le SHGN.

Cette publication s'adresse aux autorités, aux géologues et ingénieurs conseils, ainsi qu'aux spécialistes de la recherche.

VORWORT

Zum Schutz der im öffentlichen Interesse liegenden Trinkwasserfassungen vor Verschmutzungen verlangt das Gewässerschutzgesetz die Ausscheidung von Grundwasserschutzzonen. Die Dimensionierung dieser Schutzzonen beruht in Lockergesteins-Grundwasserleitern auf einer bestimmten Fliesszeit, welche das Grundwasser braucht, um zur Fassung zu gelangen. Die Bestimmung dieser Fliesszeit - und damit auch die Bemessung der Grundwasserschutzzonen - erfolgt in der Regel aufgrund eindeutiger Resultate einer hydrogeologischen Untersuchung.

In Karst-Grundwasservorkommen sind die Fliessgeschwindigkeiten des Grundwassers sehr heterogen, sodass die Gefahr einer Verschmutzung des gefassten Wassers nicht generell mit zunehmender Entfernung des Gefahrenherdes abnimmt, wie dies bei Lokkergesteins-Grundwasser normalerweise der Fall ist. Zudem wird die Fliessgeschwindigkeit des Karst-Grundwassers von den meteorologischen Verhältnissen beeinflusst. Das Kriterium der Grundwasserfliesszeit ist demnach für die Ausscheidung von Grundwasserschutzzonen in Karst-Grundwassergebieten grundsätzlich ungeeignet.

Mit der vorliegenden Publikation - welche sich an Fachbehörden, beratende Geologen und Ingenieure sowie an Fachkreise in der Forschung wendet - wird dem Bedürfnis nachgekommen, die Ausscheidung von Grundwasserschutzzonen in Karstgebieten auf eine hydrogeologisch fundierte Basis zu stellen. Es wird eine Methode zur Ausscheidung von Grundwasserschutzzonen vorgestellt, die nicht auf der Bestimmung von Grundwasserfliessgeschwindigkeiten, sondern auf der Beurteilung verschiedener hydrogeologischer Kriterien beruht, die den Schutz des Grundwassers für die verschiedenen Teilgebiete des Einzugsgebiets einer Fassung kennzeichnen. Die Grundwasserschutzzonen werden also aufgrund der Vulnerabilität (Empfindlichkeit in Bezug auf eine Verschmutzung des Trinkwassers) ausgeschieden.

Diese Methode wurde im Auftrag des Bundesamtes für Umwelt, Wald und Landschaft (BUWAL) und der Landeshydrologie und -geologie (LHG) durch das "Centre d'hydrogéologie" an der Universität von Neuenburg entwickelt. Eine Arbeitsgruppe, bestehend aus Mitgliedern der Schweizerischen Gesellschaft für Hydrogeologie, in Zusammenarbeit mit der Abteilung Gewässerschutz und Fischerei des BUWAL und der LHG, begleitete das Projekt.

SUMMARY

Groundwater produced from karstic aquifers plays a vital role in providing potable water for large parts of Switzerland. In order to apply the federal water protection law 814.20, studies to improve groundwater protection in karstic areas have been carried out. It is acknowledged that, amongst other things, current groundwater protection zones in karstic areas frequently lack a hydrogeological basis, and for that reason, often have a limited effect. Under these conditions, it is not unusual for groundwater pollution to occur. In order to remedy this situation, the Swiss Agency for the Environment, Forests and Landscape (SAEFL), in collaboration with the Swiss National Hydrological and Geological Survey (SNHGS), has initiated investigations for a new approach to groundwater source protection area delineation that incorporates the most recent conceptual models of groundwater flow in karstic aquifers. This approach needs to provide protection zones that have a hydrogeological basis, which are based on scientifically credible parameters. These protection zones must satisfy the aims of a groundwater protection strategy concerning land use activities.

Given the above requirements, a new method called EPIK has been developed by the Centre of Hydrogeology of the University of Neuchâtel, Switzerland. It employs an evaluation of ground conditions and field mapping to assess the groundwater vulnerability of catchment areas. Groundwater vulnerability is defined here as an intrinsic property of aquifers which expresses their sensitivity to natural and human impacts. The method is based on objective geological, geomorphological and hydrogeological factors. Moreover, it is independent of current or future land use activities and of economic considerations.

EPIK is a multiparameter-based method. It is based on a groundwater vulnerability map of a spring or a borehole catchment area and takes the following four objective parameters into account: Epikarstic development ("E", the subsurface zone adjacent to the surface which is intensively karstified and has a very high permeability), protective cover properties ("P"), infiltration conditions ("I"), which can be focused or diffuse, and the development of a karstic network ("K"). These parameters are necessary and sufficient to define groundwater vulnerability.

After the zone of contribution of a spring or borehole supply has been delineated, the EPIK method is implemented in three stages:

(a) Semi-quantitative evaluation and field mapping of the four parameters mentioned.

(b) Calculation of a protection index by combining and weighting the values of the four parameters for each unit area in the catchment.

(c) Cartographic representation of the distribution of the protection index for the entire catchment; thanks to an equivalence relationship between this index and the groundwater protection zones, the resulting map allows the protection zones (S1, S2 and S3) to be defined accurately according to the Swiss water protection legislation.

The EPIK method was tested and adjusted at a number of sites in Switzerland (St. Imier, Bure, St. Gingolph, and Lenk) that have different geological settings and where groundwater contamination problems due to agriculture regularly occur.

Application of the method in two of these test sites, one in the Folded Jura Mountains and the other in the Helvetic Alps are presented in this report. The examples demonstrate the feasibility and the use of this novel approach. Karstic aquifer contamination does not occur by chance. Protection zones that are delineated with appropriate consideration

given to karstic hydrogeological characteristics combined with appropriate protective measures can reduce the risk of contamination considerably. The EPIK method, based on specific hydrogeological parameters must allow for better protection of drinking water produced from springs and wells in karstic environments. The SAEFL has incorporated the results of these studies in its new water protection ordinance of October 28, 1998 (814.201).

RÉSUMÉ ÉTENDU

Les eaux souterraines provenant des aquifères karstiques jouent, pour de larges régions de Suisse, un rôle décisif dans l'approvisionnement en eau potable. Afin de faciliter l'application de la loi fédérale sur la protection des eaux de 1991 (RS 814.20), des études destinées à améliorer la protection des eaux souterraines dans les régions karstiques ont été réalisées. On constate, entre autres, que les zones de protection établies en régions karstiques manquent, fréquemment, de fondement hydrogéologique et, pour cette raison, montrent souvent une efficacité limitée. Dans ces conditions, il n'est pas rare que des pollutions se produisent. Pour remédier à cette situation, l'Office fédéral de l'environnement, des forêts et du paysage (OFEFP), en collaboration avec le Service hydrologique et géologique national, a cherché une nouvelle approche de la délimitation des zones de protection dans les régions karstiques, qui tienne compte des connaissances les plus récentes relatives au modèle conceptuel de l'écoulement des eaux souterraines dans les aquifères karstiques, et qui conduise à des zones de protection fondées au point de vue hydrogéologique et établies selon des critères rigoureux. De telles zones de protection sont alors à même de satisfaire aux buts d'une stratégie de protection des eaux souterraines agissant sur l'utilisation du territoire.

Ainsi, une nouvelle méthode, appelée "EPIK", a été développée par le Centre d'hydrogéologie de l'Université de Neuchâtel. Elle est basée sur l'évaluation et le lever cartographique de la vulnérabilité du bassin d'alimentation des captages. La vulnérabilité est définie, ici, comme une propriété intrinsèque des aquifères, qui exprime la sensibilité de ces derniers aux impacts naturels et anthropogènes. La méthode se veut rigoureuse; elle est basée sur des critères géologiques, géomorphologiques et hydrogéologiques. De plus, elle est indépendante de l'occupation du sol actuelle ou future et des considérations économiques.

La méthode EPIK est une méthode multicritère à indices. Elle repose sur une carte de la vulnérabilité du bassin d'alimentation d'une source ou d'un puits de captage donné, qui prend en compte les quatre critères objectifs suivants: développement de l'épikarst ("E", un domaine du sous-sol voisin de la surface du terrain, intensément karstifié et de perméabilité très élevée), propriétés de la couverture protectrice ("P"), conditions d'infiltration ("I", infiltration diffuse ou ponctuelle) et développement du réseau karstique ("K"). Ces critères sont nécessaires et suffisants pour définir la vulnérabilité.

Après la délimitation du bassin d'alimentation de la source ou du captage étudié, la méthode se déroule en trois étapes:

a) évaluation semi-quantitative et lever cartographique de chacun des quatre critères mentionnés;

b) calcul de la valeur d'un "facteur de protection", par combinaison et pondération de la valeur des quatre critères, pour chaque surface unitaire du bassin d'alimentation;

c) représentation cartographique de la répartition du facteur de protection pour l'ensemble du bassin d'alimentation; grâce à une relation d'équivalence entre ce facteur et les zones de protection, la carte obtenue permet de délimiter de manière rigoureuse les zones définies par la législation suisse en matière de protection des eaux (S1, S2 et S3).

La méthode EPIK a fait l'objet de tests et d'ajustements sur plusieurs sites en Suisse (St-Imier, Bure, St-Gingolph et La Lenk), dans différents contextes géologiques, où des problèmes de contamination des sources dus à l'agriculture se posent régulièrement.

L'utilisation de la méthode dans le cas de deux de ces zones tests, dans le Jura plissé et dans les Alpes helvétiques, est présentée dans ce rapport. Les exemples d'application ont démontré la faisabilité et l'intérêt de cette nouvelle approche. La contamination des aquifères karstiques n'est pas une fatalité. Des zones de protection délimitées en adéquation avec le fonctionnement hydrogéologique du karst, combinées avec leurs mesures de protection respectives, peuvent à l'évidence réduire considérablement les risques de pollution. La méthode EPIK, basée sur des critères hydrogéologiques spécifiques, doit permettre une meilleure protection des sources et captages en milieu karstique. L'OFEFP a tenu compte du résultat de ces études dans la nouvelle ordonnance sur la protection des eaux du 28 octobre 1998 (RS 814.201).

1 INTRODUCTION

Karstic groundwater resources are important potable water supplies for several Swiss regions such as the Jura Mountains, the northern part of the Alps and some regions in the southeast of the country (in the Austro-alpine domain). Agricultural and forestal activities are common in these regions; industry and tourism also often play an important role in regional economic development. From a water quality perspective, Swiss karstic aquifers generally do not pose major problems; often simple water treatment processes (such as flocculation, sedimentation, filtration and/or disinfection) are sufficient for drinking water supply. However, water quality can be altered following high discharge periods by an increase in turbidity or organic matter content. Furthermore karstic groundwater is often sensitive to human impacts and consequently, can be generally considered vulnerable.

This ***vulnerability*** can be mainly explained as a result of the highly heterogeneous structure of karstic systems, which on the one hand have diffuse and focused recharge, and on the other have very high permeabilities in subsurface conduits and a low permeability in the blocks of unkarstified rock. This double duality manifests itself in characteristic hydrodynamic behaviour; high discharges due to concentrated infiltration in highly permeable zones occur rapidly. Filtration and natural purification processes do not have time to have an effect, as in primary porosity aquifers. Given their specific behaviour, karstic aquifers require particular protection measures.

Article 20 of the Swiss ***Federal Law on the Protection of Water*** (Water Protection Law) of January 24, 1991 (814.20) requires the determination of groundwater protection zones for all public groundwater catchments (springs and wells), as well as artificial recharge facilities of public interest. The most important restrictions in these zones are limitations on industrial development and a ban on extractive activities. Application of the law is the responsibility of the cantons, based on federal ordinances. The Water Protection Ordinance of October 28, 1998 (814.201) advocates three protection zones. These zones, called S1, S2 and S3 come with rules relating to land use.

Groundwater protection zones must guarantee the prevention objectives (see the boxed text).

Protection zones established in karstic regions frequently lack a hydrogeological basis. Notably, the necessary objective factors for delineation of Zones S2 and S3 are lacking. For this reason, protection zones in karstic areas often have limited efficiency. Since the publication of a practical guide for the determination of water protection areas and groundwater protection zones (OFPE – Office fédéral de la protection de l'environnement 1982), knowledge of the hydraulic behaviour of karst has evolved significantly.

Groundwater protection zones

S1 Zone. This zone must prevent damage to the groundwater catchment installations or artificial recharge facilities as well as prevent pollution in their immediate surroundings.

S2 Zone. This zone defines an area suitable to prevent biological contamination to reach drinking water catchments. It must also prevent drinking water supply from being polluted by excavations and subsurface works, or that the flow of water towards the source is disturbed by subsurface works.

S3 Zone. This zone must provide sufficient space and time for remediation when accidental pollution threatens a catchment installation.

Consequently, it was necessary to develop a new approach to improve the means of preventing contamination. Groundwater vulnerability mapping methods in karstic environments based on different scientific parameters concerning specific system behaviour must meet this objective. Methods need to be rigorous, i.e. based on geological, geomorphological and hydrogeological principles. In addition they need to be independent of current or future land use and economic considerations. In particular cases, notably delineation in non-karstic subcatchments and urbanised areas, the method must be applied with caution.

2 SOURCE VULNERABILITY IN KARSTIC ENVIRONMENTS

Karstic Processes

Particular geomorphological features and hydrological phenomena characterise karstic aquifers. Geomorphological features include sizeable springs, swallow holes, the absence of surface drainage networks and the presence of karstic drainage networks due to the dissolution of carbonate rocks. Hydrological features include spring hydrographs that have peaky discharge, fast recession and low base flow rates. Water quality reflects chemical variations as a function of groundwater discharge rates.

Based on these characteristics, a karstic aquifer can be defined as follows (Jeannin et al. 1993): *An **aquifer** consisting of a network of interconnected conduits (a karstic network) flowing to discharge zones and draining, or being supplied by water from low permeability fissured and fractured rock.*

> ***Vulnerability***
>
> Vulnerability is defined and used in the scientific literature in a number of ways. For the current study, the following definition was employed:
>
> Vulnerability is an intrinsic aquifer property which depends on an aquifers sensitivity to natural and human impacts (Gilbrich & Zaporozec 1994). It cannot be measured directly, but is determined by using geological and hydrogeological data and by the sensitivity of an aquifer to point and diffuse human contamination.
>
> Contamination sources such as landfills, underground oil storage tanks, oil spills due to road accidents and natural or artificial fertiliser spreading are accounted for in this definition.

Basin scale flow balance studies in the karst of the Swiss Jura Mountains have shown that between 50% and 75% of effective rainfall recharges groundwater by *rapid drainage **conduits***; the remaining 25% to 50% infiltrates directly into *lower permeability **blocks*** which provide spring baseflow during dry periods (Jeannin & Grasso 1995). Rapid infiltration does not flow through low permeability blocks but rather through ***focussed infiltration points*** such as swallow holes that connect directly to the karstic network as well as the ***epikarst***.

> ***Epikarst*** is defined as a very fissured zone corresponding to the decompressed and weathered formations in the vicinity of the ground surface (Dodge 1982). This upper karstified zone is not continuous. It can be decimetres to metres thick and can contain perched aquifers which can rapidly concentrate infiltrating water towards the karstic network (Mangin 1975).

Consequences of Karstic Processes for Groundwater Vulnerability

The schematic representation of a karstic aquifer shown in ***Figure 1*** corresponds to a coherent conceptual model of hydrodynamic behaviour and transport processes in karstic media. Karstic groundwater vulnerability is based on this model.

In terms of baseflow, water flowing through low permeability blocks provides the main contribution to spring discharge. This water spends a relatively long time in the aquifer and flows mainly through lower permeability zones. In periods of high water-level, more than half the infiltrating rainfall resulting from a precipitation event flows rapidly through the aquifer via the main conduits. Filtration processes have a limited influence at this time but dilution potential for contaminants is generally high. Groundwater vulnerability therefore depends on aquifer infiltration conditions, as well as on the spatial distribution of hydraulic conductivity and storage coefficients (the range of physical parameters) which play a primary role in flow and transport processes.

The spatial distribution of aquifer parameters and their influence on source vulnerability are linked to two main parameters in the field: the ***karstic network*** and the ***epikarst***. Karstic networks have complex geometries because of the numerous possible influences on the three dimensional formation of the aquifer. They may be more or less developed and subdivided as a result of their geological, hydrogeological, chemical, physical and biological history.

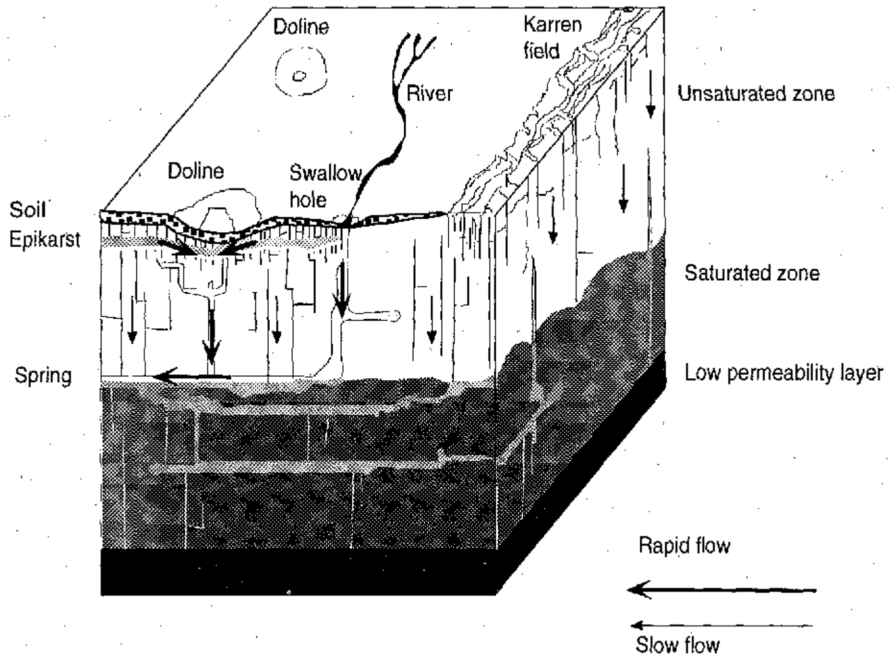


Figure 1. Schematic representation of the hydrological processes operating in a karstic aquifer.

Wells and springs in karstic media are, in principle, very vulnerable if there is a well developed karst network and epikarst which are directly linked to them (***Figure 2c***). Wells and springs are less vulnerable if the epikarst is not directly linked to the karstic network; in general the source is less vulnerable if the aquifer contains neither a karstic network nor epikarst (it may then be regarded as a fissured non-karstic aquifer). Consequently, it is obvious that protection zone delineation in karstic media cannot be completed based on a single criterion. In fact the implementation and use of a ***multiparameter-based method***, which accounts for karstic processes is essential.

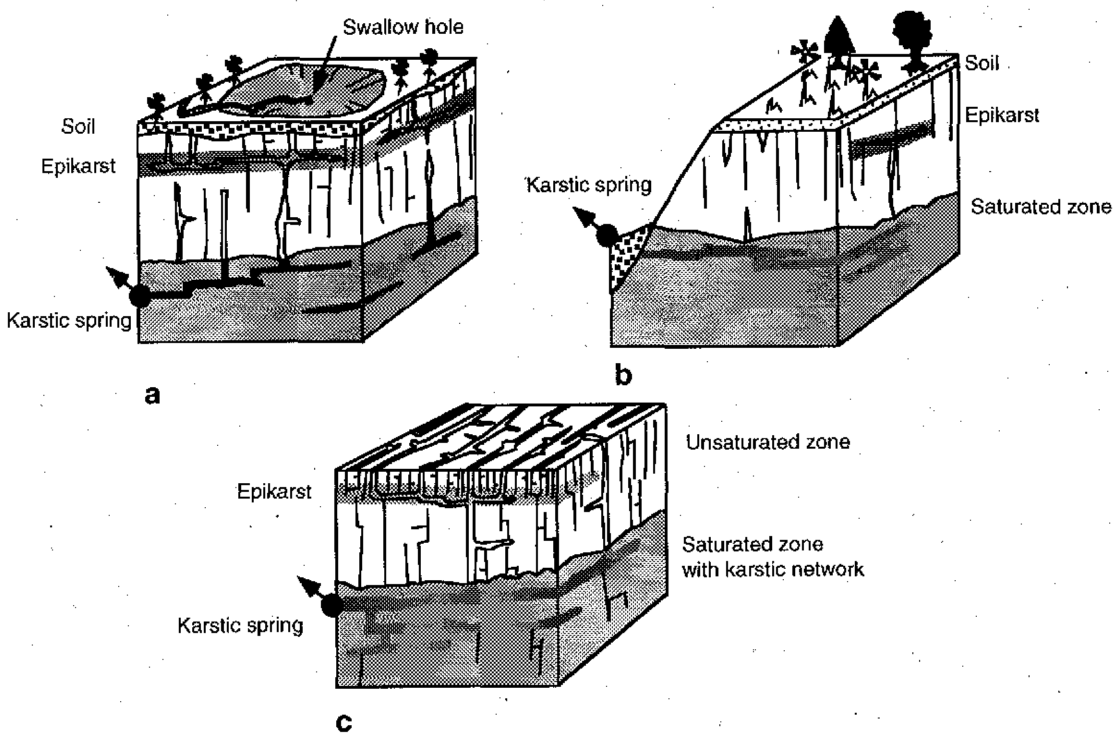


Figure 2a,b,c. Some examples of combinations of the main vulnerability factors in a karst aquifer.

The Role of Protective Cover and Infiltration Conditions

Aquifer ***cover*** is one of the natural ***protection*** parameters generally accounted for in vulnerability mapping. It is routinely considered to have an important attenuating influence (Zaporozec 1985) depending mainly on the following parameters: thickness, texture/structure, organic matter and clay mineral content, cation exchange capacity, water content and hydraulic conductivity.

Infiltration conditions determine the means by which aquifer recharge occurs. They can be concentrated, intermediate or diffuse. In the former two cases it is defined by the surface runoff properties (slope, runoff coefficient) and by the presence of preferential infiltration zones. Infiltration conditions can influence karst water source vulnerability in three ways:

(a) *Concentrated infiltration of precipitation in* ***swallow holes*** and their supplying streams. Concentrated surface water infiltration represents very high vulnerability locations for the entire water course catchment up to the point of infiltration (***Figure 2a***).

(b) *Infiltration through residual cover (**buried karst**).* The vulnerability of these areas depends essentially on the protective cover permeability and thickness and thus its filtration capacity (***Figure 2b***). It is noteworthy that permeability will vary as a function of water content.

(c) *Diffuse infiltration over the whole area (**exposed karst**).* Vulnerability will essentially depend on the travel time for water to reach the karstic network either via epikarst or through low permeability blocks (***Figure 2c***).

Epikarst Characteristics

Epikarst, also known as the "subcutaneous zone" is a high permeability zone found in the top metres of limestone directly below the soil cover. The zone is fractured due to the relaxation of tectonic constraints linked to its emplacement. It therefore favours alteration (Dodge 1982) and karstification processes. Epikarst generally has a thickness of between 0.5 and 2 metres (Bonacci 1987), but can be up to between 5 and 10 metres thick (***Figure 3*** and Doerfliger 1996a). The epikarst may contain a temporary perched aquifer at its base (Mangin 1975) where its hydraulic conductivity is significantly greater than the underlying strata. This allows stored water to percolate along fissures or to drain rapidly through vertical conduits (Ford & Williams 1989; Klimchouck 1995). Water flowing in the epikarst zone possesses a predominantly horizontal component (water flowing through fractures toward vertical conduits) and a less significant vertical component corresponding to slow seepage in fissures and flow in conduits (***Figure 4***).

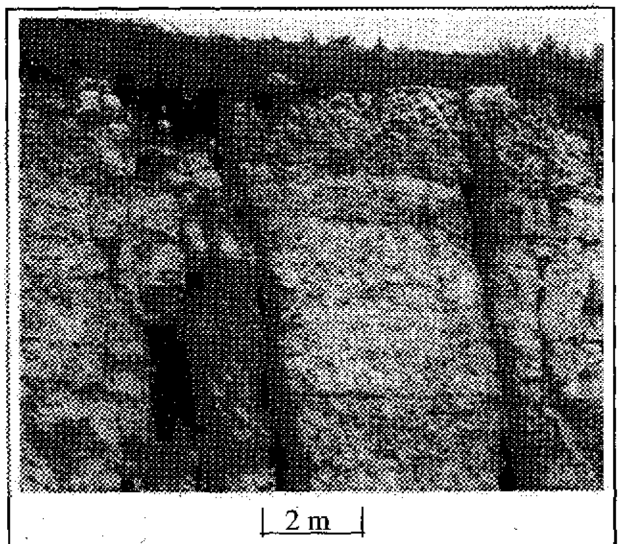


Figure 3. Epikarst (lower limit not visible) in the Portlandian limestone; Breuleux Quarry. (photo: Natalie Doerfliger)

Epikarst is found in both buried and exposed karst areas and is not necessarily laterally extensive. According to the doline formation hypotheses, e.g. the solution doline hypothesis (Williams 1983), epikarst can exist under soil cover without any morphological expression (***Figure 5***).

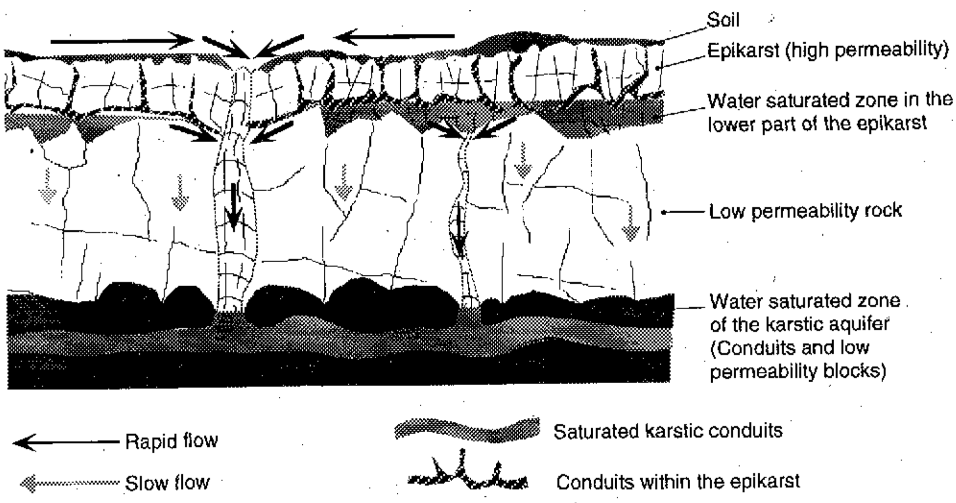


Figure 4. Schematic representation of epikarstic hydrological processes (Jeannin 1996, after Smart and Frederich 1986).

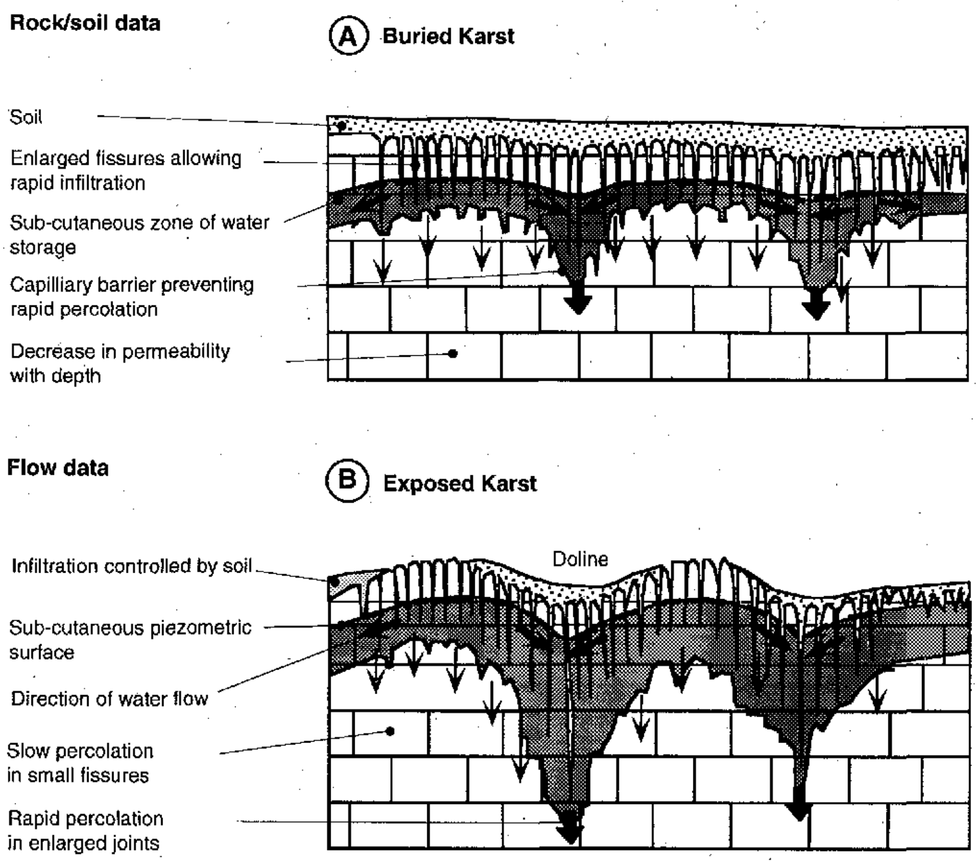


Figure 5. Subcutaneous storage, lateral flow toward high hydraulic conductivity zones and the resulting development of a solution doline (Williams 1983).

Principles and Approach

The new method proposed to evaluate vulnerability mapping in karstic environments is a multiparameter method called EPIK, which accounts for ***four parameters***: **E**pikarst, **P**rotective cover, **I**nfiltration conditions and the degree of **K**arstic network development (Doerfliger 1996a). These parameters correspond to specific aspects of the flow regime within a karstic aquifer, as already described. The method allows the sensitivity of a karstic aquifer to natural and human influences to be determined in a general and effective manner.

Once the extent of a groundwater catchment area has been determined, ***the method is implemented in three stages:***

(1) Semiquantitative evaluation and mapping of each of the four parameters *– epikarst, protective cover, infiltration conditions and karstic network development – for every unit area within the catchment, after discretisation into elemental areas* (ideally into a grid containing squares with 20 metre long sides). During this evaluation, each parameter is assigned a range of categories, ranging from one to four. This semiquantitative evaluation of E, P, I and K is carried out with the help of a number of direct and indirect investigation methods, and may be applied globally or locally. These methods include tracer tests, geophysics, geomorphological studies, flow hydrograph analysis, aerial photograph interpretation and drilling/excavation using a hand held soil corer or a mechanical excavator.

⇓

(2) Calculation of the F protection index *for every point in the catchment, by assigning a category value to each parameter, weighting the parameter according to its protective role and summing the values obtained.* The maps of the four parameters are subsequently superimposed to provide a cartographic representation of the F index for the entire catchment. Depending on the circumstances, this stage can normally be easily carried out using a geographic information system (GIS; the Windows PC version of the IDRISI GIS was applied during the development of the EPIK method).

⇓

(3) Delineation of protection zones: *Because of the equivalence relationship between the F index and the protection zones, the F protection index map can effectively be transformed into a map of S1, S2 and S3 protection zones.*

When the method was being developed, the values, the weighting factors and the equivalence relationship between steps two and three above were adjusted and verified at four different representative sites in various geological settings (the Folded Jura Mountains, the Tabular Jura Mountains, the Median Prealps and the Helvetic Alps).

3.1 Evaluation of the E, P, I and K Parameters

E Epikarst

Epikarst characterisation is based on the study of karstic landforms. The previous chapter concerning epikarstic processes illustrates the difficulty in characterising epikarstic zones in terms of their development and connection to karstic networks. This is particularly difficult given that there is no specific model available to identify covered epikarst in the field, even with currently available geophysical methods. The E parameter is subdivided into three categories that indicate decreasing vulnerability.

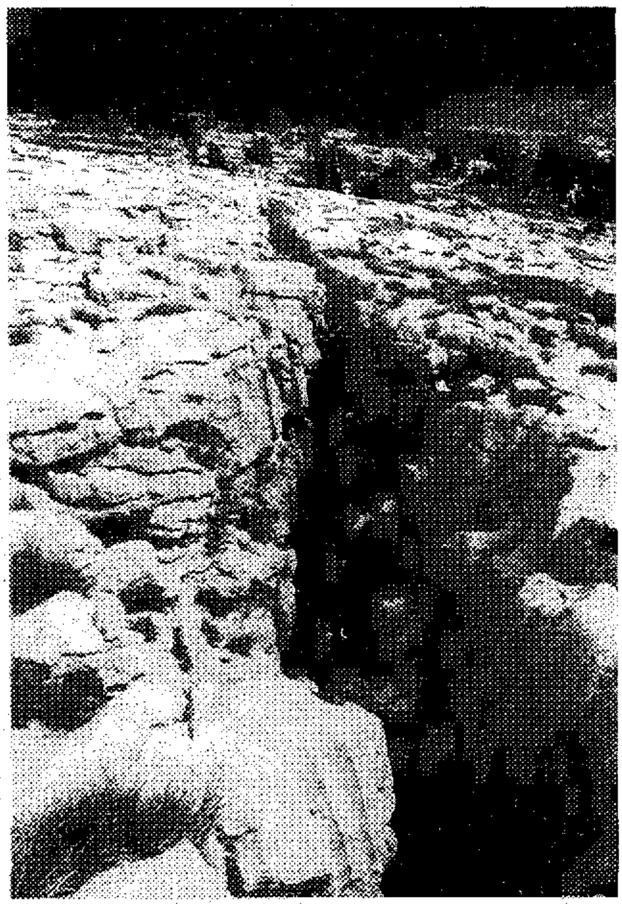


Figure 6. Fracture traversing karren fields (limestone pavement) of the Sieben Hengste Massif, Berne, Switzerland. (photo V. Puech)

- ***Category 1 (E_1)*** indicates the most vulnerable situation. It is associated with swallow holes and depressions with water intakes, and includes dolines, karren fields, ruine-like relief and intensely fractured outcrops (***Figure 6***). The outcrops may correspond, for example to cuts in the land along lines of communication (roads, railways) or to quarries.
- ***Category 2 (E_2)*** incorporates intermediate zones in the doline fields and dry valleys.
- ***Category 3 (E_3)*** incorporates the rest of the catchment lacking the morphological features already mentioned.

The classification (evaluation) of E into three categories, E_1 through E_3, is mainly determined by mapping geomorphological features. Most of the information required to make this determination may be derived from topographic maps at scales of 1:5,000, 1:10,000 and even 1:25,000. Aerial photographs can also be used and serve as a source of complementary information. Field verification at the time that the other parameters are being mapped is also recommended.

The term protective cover includes the soil (in a pedological sense) as well as other geological formations which may overlie a karstic aquifer, such as Quaternary deposits (moraine, silt, loess and scree) or pre-Quaternary non-karstic formations (clays, sandstones, marls) (Doerfliger 1996a).

Pedological parameters vary spatially and are not easily ascertained, apart from soils maps where available; moreover the terminology used by soil scientists is not based on parameters which define the protective function of the soil, such as texture, organic matter content or hydraulic conductivity.

For financial reasons, it is not possible to map these parameters individually within the scope of protection zone delineation. Consequently, at the time of intrinsic vulnerability evaluation, ***only protective cover thickness was considered*** (Doerfliger & Tâche 1995, Doerfliger 1996a).

Areas of a catchment containing protective cover can be identified and separated from the areas lacking cover using ***existing information*** (geological maps and regional monographs). Aerial photographs and satellite imagery can also provide data on the presence or absence of soil (depending on image resolution). They may be used to define cover thickness, assuming that there will be field control.

Soil thickness may be measured directly in the field with a ***soil corer (Figure 7).*** If the catchment doesn't cover a too large area, soil thickness can be determined using a regularly spaced sampling grid. If the catchment covers a large area (e.g. greater than 15 km^2), the grid spacing becomes larger and it is necessary to apply the principle of morphological equivalence: for a particular point, the measured thickness is assigned to all points in a square with sides of 100 m to 200 m, should the areas have identical morphology. Excavations such as drainage ditches can also provide important information concerning cover thickness.

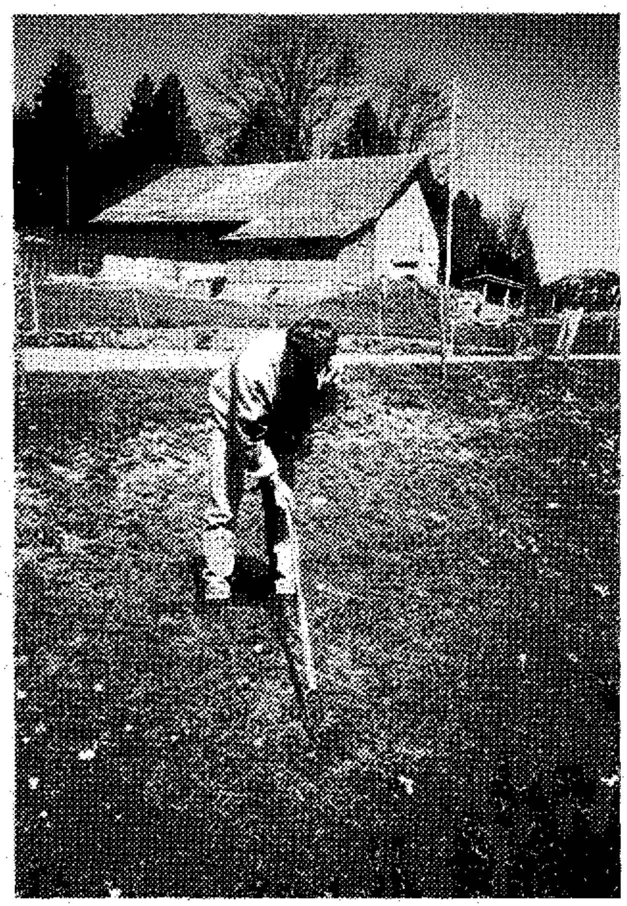


Figure 7. Measurement of soil thickness using a hand auger. (photo N. Doerfliger)

In order to classify P (***Figure 8***), two cases are considered, according to whether or not low hydraulic conductivity geological formations occur below the soil:

(A) ***Soil directly overlying calcareous formations*** or on top of coarse, very permeable detrital formations (e.g. scree or lateral moraine).

- ***Category 1 (P_1)*** represents a cover of 0-20 cm of soil.
- ***Category 2 (P_2)*** represents a cover of 20-100 cm of soil.
- ***Category 3 (P_3)*** represents a cover of more than 100 cm of soil.

(B) ***Soil overlying low permeability geological formations*** (with at least 20 cm of lacustrine silt, clay or marl)

- ***Category 1 (P_1)*** is omitted for low permeability formations that are less than 20cm thick since the units are considered to provide very little protection. In this case, one falls back on Case A.
- ***Category 2 (P_2)*** represents a combined soil/low permeability geological formation thickness from 20 to 100 cm. Soil is considered to have a better protective effect than an equivalent thickness of a low permeability geological formation.
- ***Category 3 (P_3)*** represents a combined soil/low permeability geological formation protective cover thickness of more than one metre. The soil may be absent; however, a thin layer of soil can provide important protection if underlying low permeability formation cover is comparatively thin.
- ***Category 4 (P_4)*** represents a cover of more than 8 metres of low permeability geological formations (very silty or very clayey), or a soil of more than one metre on six or more metres of low permeability geological formations. Formation thickness is determined from point data, for example from boreholes or holes drilled using a power auger.

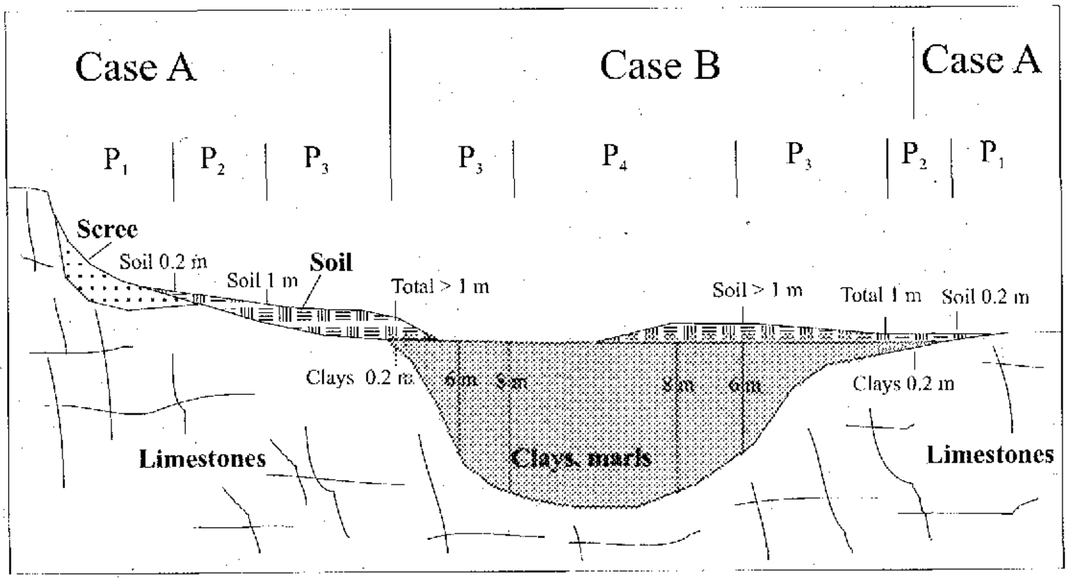


Figure 8. Illustration of the different protective cover categories.

Evaluation of infiltration conditions is based on the identification of zones of ***concentrated infiltration*** (swallow holes - ***Figure 9*** - or beds of temporary or perennial streams, artificially drained zones) and an assessment of ***diffuse infiltration*** areas. The later are characterised by their runoff coefficient which depends on the ***slope of the ground*** and ***land use***.

Based on a table of runoff coefficients as a function of slope and land use (forest, pasture and arable land) established for Switzerland (Sautier 1984), the limit between low and high runoff coefficients was set at 0.22 for pasture, and at 0.34 for arable fields (the coefficient of 0.34 is representative of cultivated fields with furrows in the slope direction). In order to assign categories (see below), these values were allowed to correspond to slopes of 25% and 10% respectively (Doerfliger 1996a). The I parameter is also differently assessed for the areas inside and outside the ***catchment of swallow holes and associated streams***; on the outside of these catchments, the ***bases of slopes*** act as surface water collectors.

The data necessary for characterising infiltration conditions are obtained by studying surface water catchments of swallow holes and their streams using topographic maps. The delineation of critical slopes and slope bases can be carried out manually using topographic maps. However, if an altitude numerical model (ANM) is available for the study area, it is easier to determine these zones using a GIS. This also represents a significant time saving.

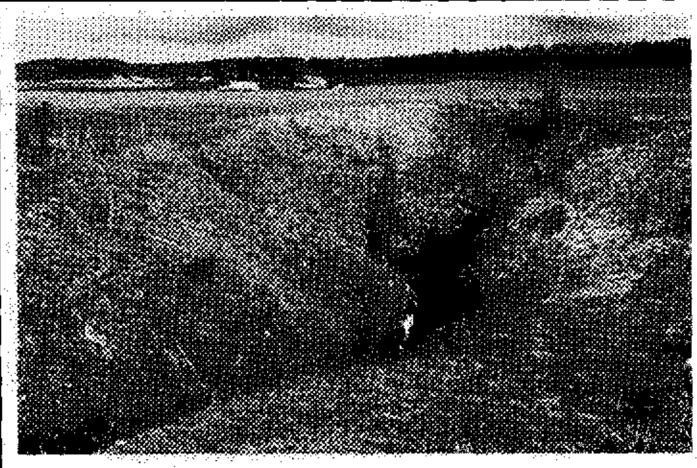


Figure 9. Disappearing stream in the Brevine Valley. (photo P.-Y. Jeannin)

Four categories are distinguished in the characterisation of I, ranging from the most vulnerable I_1 to the least vulnerable I_4. Two cases, A and B, are considered which correspond to the inside and outside of a stream catchment supplying a karstic swallow hole:

A) *Inside the catchment of a swallow hole and its water course (Figure 10)*

- ***Category 1 (I_1)*** represents perennial and temporary swallow holes as well as the banks and bed of perennial and temporary streams recharging a swallow hole, sinking streams and artificially drained parts of the catchment.
- ***Category 2 (I_2)*** represents parts of the swallow hole catchment or water course referred to in I_1 which are not artificially drained, and with a high runoff coefficient, that is, areas where the ground slope is greater than 10% for arable areas and greater than 25% for meadows and pastures.
- ***Category 3 (I_3)*** represents parts of the swallow hole catchment or water course referred to in I_1 not artificially drained and with a low runoff coefficient, i.e. those areas where the slope is less than 10% for arable zones and less than 25% for meadows and pastures.

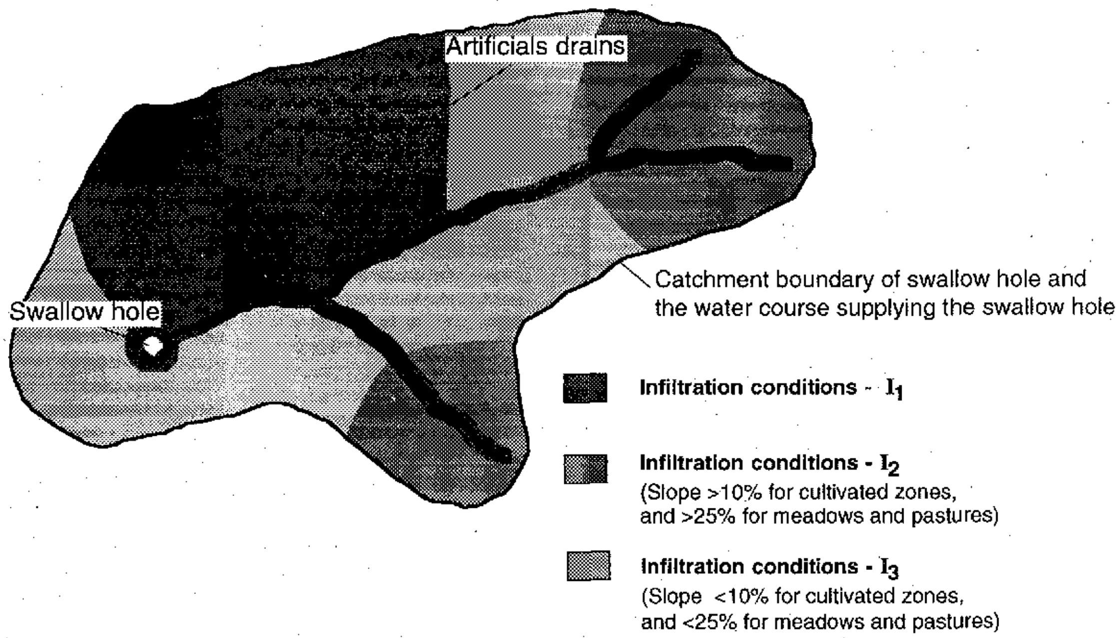


Figure 10 . Infiltration conditions ***inside the catchment (case A)*** *of a swallow hole and its supplying water course.*

B) Outside the swallow hole catchment and water course (Figure 11)

- ***Category 3 (I_3)*** represents areas at the bases of slopes which collect surface runoff, as well as slopes recharging these low points (slopes with an elevated runoff coefficient, that is greater than 10% for arable zones and greater than 25% for meadows and pasture).
- ***Category 4 (I_4)*** represents the rest of the catchment.

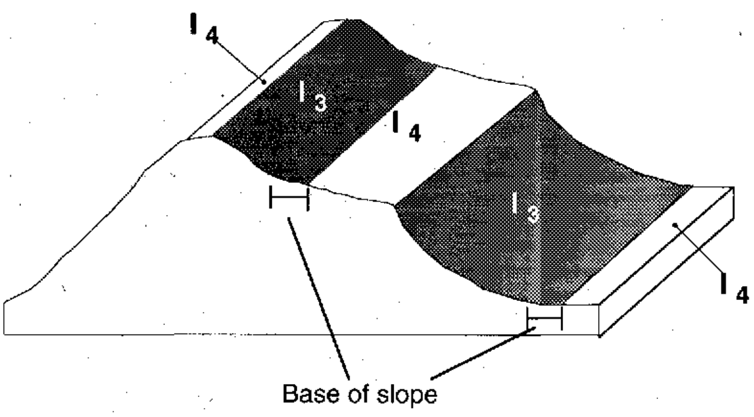


Figure 11. Infiltration conditions ***outside the catchment (case B)*** *of a swallow hole and its supplying water course (gentle slopes, steep slopes and the bases of slopes).*

Vulnerability is evaluated in terms of the presence or absence of a karstic network and the degree to which the network is developed. In order to determine the importance of the network relative to the volume of surrounding low permeability rock (fissured or massive) different indicators are considered.

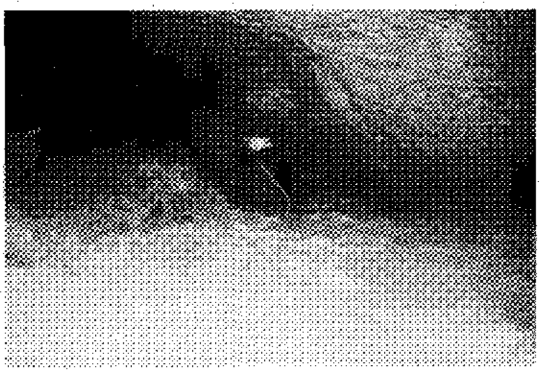


Figure 12. Active cave network, Môtiers Cave, NE. (photo P.-Y. Jeannin)

The first indicator is ***direct identification*** of the components of the network such as caves, potholes (swallow holes), active cave systems (***Figure 12***) in the catchment being considered.

If no karstic network indicators are apparent, one must resort to ***indirect methods***. These are based on flow hydrograph analysis, tracer tests interpretation and examination of water quality variability.

Flow hydrographs (Figure 13) allow the degree of karst aquifer development and aquifer structure to be interpreted. The reaction time of a source to rainfall events, as determined according to a hydrograph, is a significant indicator for characterising the degree of karst network development. If one observes a rapid recession, a significant flow rate (at least twice that of the base flow) followed by a rapid recession, one can suppose that a karstic network is present. By a rapid response, one means, for example, a response with a 6 to 12 hour time lapse (according to the size of the catchment basin) after a rainfall event with an intensity of greater than 15 mm. This rule cannot always be applied if evapotranspiration is important.

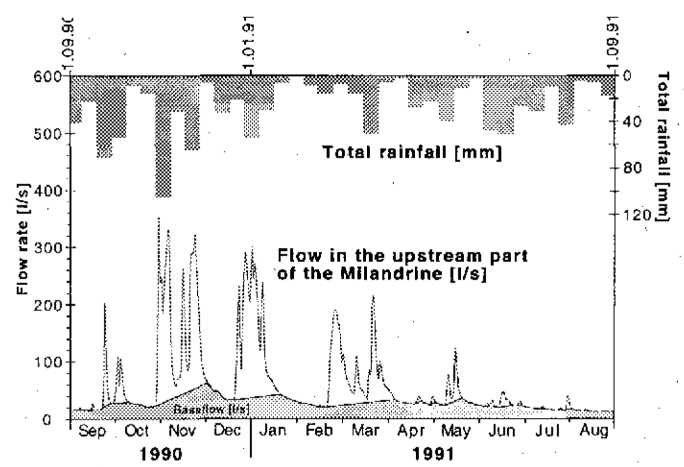


Figure 13. Flow hydrograph, Bure, Tabular Jura Mountains (Jeannin & Grasso 1995).

The average travel time, as calculated by ***tracer tests***, is an indicator which permits the presence or absence of a karstic network to be established. A velocity of more than 15 m/h during low flow periods in sinking streams and greater than 75 m/h in high flow periods allows the existence of a karstic network to be assumed.

Water quality variation at a spring is a good indicator of the presence or absence of a karstic network. If the water quality is bacteriologically stable after heavy precipitation, the karstic network is inferred to be either poorly developed or protected by a porous medium and the composite system may be regarded as a fissured rock system. Where this is not the case, a karstic network may be assumed.

A final indicator is provided by the ***number of springs*** present in a karstic system. A well-developed system will be characterised by the presence of a single discharge outlet, whereas a poorly developed system will very often possess many springs. This concept is based on the hypothesis that there is a karstic network hierarchy (Mangin 1975).

The K parameter is assigned to three categories, ranging from the most vulnerable to the least vulnerable. The categories are

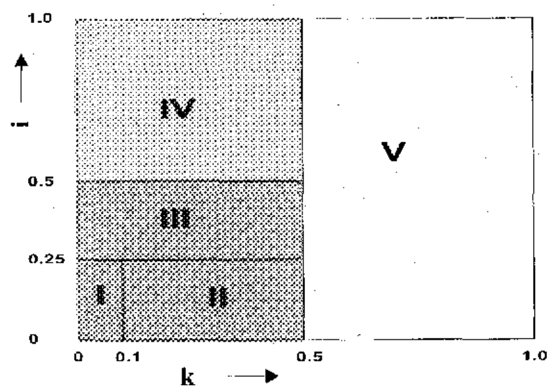
- ***Category 1 (K_1)*** for a moderate to well developed karstic network with decimetre to metre wide conduits which have little blockage and that are well interconnected.
- ***Category 2 (K_2)*** for poorly developed karstic networks with blocked or poorly developed drains or conduits with decimetre or smaller diameters.
- ***Category 3 (K_3)*** for systems where porous media play a role in filtration (the protective effect can be verified by on-going water quality monitoring) as well as for fissured non-karstified limestone aquifers.

The K parameter is generally applied globally for the entire catchment under study; however, it can be subdivided into areas based on to the degree of karstic development where these can be characterised in more detail.

Without speleological information, the distinction between K_1 and K_2 is not often obvious. If one has at least an annual flow hydrograph available, it is possible to apply Mangins (1975) system for classifying karstic aquifers. This method is based on the aquifers regulating capacity k and an infiltration parameter i. The k parameter is defined as the relationship between the dynamic volume (calculated by integrating between the start of flow recession and infinity) and the total volume flowing in the average hydrological cycle. The i parameter (see ***Figure 14*** for definition) expresses the importance of retardation of infiltrating water arriving at the outflow. Mangin distinguishes five classes. Classes I, II and III can be associated with the K_1 category, class IV with category K_2 and class V with category K_3. However, it must be noted that aquifer classification based on recession curves is not always unequivocal; while the k parameter varies little from one discharge to another, the i parameter depends strongly on the rainfall which generates the discharge (Grasso and Jeannin 1994). The distinction between K_1 and K_2 according to this method thus does not depend on the aquifer system alone.

Classes I, II and III correspond to K_1, class IV to K_2 and class V to K_3

Infiltration parameter i = value of the function $Y = (1-\eta t)/(1+\varepsilon t)$ for
t = 2 (2 days after the flood peak)
η = 1/duration of the recession between the peak and the start of the baseflow (characterises the velocity of infiltration)
ε = heterogeneity index (characterises the concavity of the recession curve)
(see Grasso & Jeannin 1994)



Regulating capacity k = Vd/Vt

Vd = maximum observed dynamic volume (baseflow integrated between the start of the flood recession and infinite time)
Vt = annual transit volume (total measured flow)

Figure 14. Classification of karstic aquifers (after Mangin 1975).

Summary of the Evaluation of the E, P, I and K Parameters

Table 1 summarises the categories of the four EPIK parameters. The evaluation of each parameter is outlined.

Table 1. Subdivision of the four EPIK parameters.

Karstic morphology observed (pertaining to epikarst)	E_1	Caves, swallow holes, dolines, karren fields, ruine-like relief, cuestas
	E_2	Intermediate zones situated along doline alignments, uvalas, dry valleys, canyons, poljes
Karstic morphology absent	E_3	The rest of the catchment

		A. Soil resting directly on limestone formations or on detrital formations with very high hydraulic conductivity*	B. Soil resting on > 20 cm of low hydraulic conductivity geological formations**
Protective cover absent	P_1	0 - 20 cm of soil	-
	P_2	20 - 100 cm of soil	20 - 100 cm of soil and low hydraulic conductivity formations
	P_3	> 1 m of soil	> 1 m of soil and low hydraulic conductivity formations
Protective cover important	P_4	-	> 8 m of very low hydraulic conductivity formations **or** > 6 m of very low hydraulic conductivity formations with > 1 m of soil (point measurements necessary)

Concentrated infiltration	I_1	Perennial or temporary swallow hole - banks and bed of temporary or permanent stream supplying swallow hole, infiltrating surficial flow – areas of the water course catchment containing artificial drainage
	I_2	Areas of a water course catchment which are not artificially drained and where the slope is greater than 10% for ploughed (cultivated) areas and greater than 25% for meadows and pastures
	I_3	Areas of a water course catchment which are not artificially drained and where the slope is less than 10% for ploughed (cultivated) areas and less than 25% for meadows and pastures. Outside the catchment of a surface watercourse: bases of slopes and steep slopes (greater than 10% for ploughed (cultivated) areas and greater than 25% for meadows and pastures) where runoff water infiltrates
Diffuse infiltration	I_4	The rest of the catchment

Well developed karstic network	K_1	Well developed karstic network with decimetre to metre sized conduits with little fill and well interconnected
Poorly developed karstic network	K_2	Poorly developed karstic network with poorly interconnected or infilled drains or conduits, or conduits of decimetre or smaller size
Mixed or fissured aquifer	K_3	Porous media discharge zone with a possible protective influence – fissured non-karstic aquifer

* Examples: Scree, lateral glacial moraine. ** Examples: silts, clays.

3.2 Calculation of the F Protection Index

The four parameters categorised previously allow a protection index value, F to be calculated for all parts of the catchment. The calculation is carried out as follows:

$$F = \alpha E_i + \beta P_j + \gamma I_k + \delta K_l \qquad (1)$$

Where F = Protection index

$\alpha, \beta, \gamma, \delta$ = Weighting coefficients of each parameter

E_i, P_j, I_k, K_l = Categories of each parameter

Assignment of Category Values

In order to define the category values in equation 1, different aspects have been taken into account, for example:

- A doline with a thick soil cover ($E_1 + P_3$) represents a more vulnerable situation than a slab of compact (massive) limestone overlain by a thin soil cover ($E_3 + P_1$).
- A stream flowing to a swallow hole (I_1) represents a very vulnerable situation, independent of the protective cover.
- A dry valley (E_2) represents a situation that is as vulnerable as the base of a slope that acts as a collector for surface runoff (I_3).

The category values used to calculate the protection index are shown in ***Table 2***.

Table 2. Category values E_i, P_j, I_k et K_l.

E_1	E_2	E_3	P_1	P_2	P_3	P_4	I_1	I_2	I_3	I_4	K_1	K_2	K_3
1	3	4	1	2	3	4	1	2	3	4	1	2	3

Note that the lowest value represents the most vulnerable situation.

Weighting Coefficients

The E (epikarst) and I (infiltration conditions) parameters are considered the most important; they make up the main contribution to the F protection index and have an elevated coefficient (α and γ =3). The P parameter (protective cover) has a lesser influence on the protection index and a lower weighting coefficient (β=1). The K parameter (karstic network development) has an intermediate weight (δ=2). ***Table 3*** shows the weighting coefficients for E, P, I and K parameters.

Table 3. Weighting coefficients attributed to the E, P, I and K parameters.

Parameter	E	P	I	K
Weighting coefficient	α	β	γ	δ
Relative weight	3	1	3	2

Protection Index

The different possible solutions to equation 1 provide values ranging between 9 and 34 for the F protection index. By knowing the protection index F for all parts of the catchment, it is possible to represent this index in map form. A high protection index represents high protection. ***Table 4*** shows the different F values and groups them into three classes as a function of their connection with protection zones S1 through S3 (see the following paragraph). Situations which cannot be encountered in the field are placed into an additional category. They correspond to a combination of $I_1 + E_1 + P_{3,4}$ (a swallow hole in a doline with a thick soil cover).

Table 4. Protection index values.

$K_1=1$	$I_1=1$			$I_2=2$			$I_3=3$			$I_4=4$		
	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$
$P_1=1$	9	15	18	12	18	21	15	21	24	18	24	27
$P_2=2$	10	16	19	13	19	22	16	22	25	19	25	28
$P_3=3$		17	20	14	20	23	17	23	26	20	26	29
$P_4=4$		18	21	15	21	24	18	24	27	21	27	30

$K_2=2$	$I_1=1$			$I_2=2$			$I_3=3$			$I_4=4$		
	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$
$P_1=1$	11	17	19	14	20	23	17	23	26	20	26	29
$P_2=2$	12	18	20	15	21	24	18	24	27	21	27	30
$P_3=3$		19	22	16	22	25	19	25	28	22	28	31
$P_4=4$		20	23	17	23	26	20	26	29	23	29	32

$K_3=3$	$I_1=1$			$I_2=2$			$I_3=3$			$I_4=4$		
	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$	$E_1=1$	$E_2=3$	$E_3=4$
$P_1=1$	13	19	22	16	22	25	19	25	28	22	28	31
$P_2=2$	14	20	23	17	23	26	20	26	29	23	29	32
$P_3=3$		21	24	18	24	27	21	27	30	24	30	33
$P_4=4$		22	25	19	25	28	22	28	31	25	31	34

- Non-existent situation in the field
- Protection index values corresponding to S1 protection zone
- Protection index values corresponding to S2 protection zone
- Protection index values corresponding to S3 protection zone
- Conditions that are applicable to the rest of the catchment

Groupings of P_4 and E_1 are rare or difficult to detect. Those of E_1 and I_4 (karren fields/cuesta outside the catchment of a swallow hole or small stream) are unusual. Nonetheless they represent 10% of the mapped area in the Lenk case study (Chapter 4.2). The most common groupings are those of E_3 or E_2 with I_4, I_3 or I_2. At the Lenk site (Chapter 4.2) combinations of E_3 with P_1 or P_3 and I_2 or I_4 represent 82% of the area mapped. In the case of the St. Imier study area (see Chapter 4.1) the groupings of E_2 or E_3 with I_3 or I_4 and P_2 or P_3 represent the vast majority of the area mapped.

3.3 Protection Zone Delineation

The equivalency between the F index and the protection zones was the subject of an intensive study at the time that the method was developed and at the test sites previously mentioned. The issues that have determined the equivalency between the F index and S protection zones are mainly as follows:

- Swallow holes and, where applicable, supplying streams (I_1) should be classified as ***S1***.
- Dolines, karren fields and cuestas (E_1) should generally be mapped as ***S1***, but where there is thick soil cover and if they are outside the catchment of a swallow hole, they should be mapped as ***S2***.
- Areas classified as E_2 and I_3 should be preferentially assigned to the ***S2*** protection zone.
- Dry valleys should, as a rule, be classified in zone ***S2***.
- Areas with a protection index value that is greater than 25 should be classified in the ***S3*** zone.
- Areas with a protection index value exceeding 25 and that have significant protective cover (P_4, verified by appropriate investigation methods) should be classified outside the S protection zones (in the "***rest of the catchment***" category) so long as they represent a significant area.

At the time that the method was being developed, the application and comparison of these parameters to different examples showed that the limits of the F protection index values were around 20 for the ***S1*** zone (F ranging from 9 to 19 for a well developed karstic network, K_1, and 11 to 21 for a poorly developed karstic network, K_2) and around 25 for the ***S2*** zone (F ranging from 20 to 24 for K_1 and 22 to 26 for K_2). The F values for ***S3*** ranged between 26 and 31 and those for the ***rest of the catchment*** between 26 and 34 (with the additional presence of P_4 and $I_{3,4}$ categories).

For a strict definition of the method, see the fixed relationship shown in ***Table 5***. The table also presents a classification of vulnerability terms (ranging from very high to low).

Table 5. Equivalence relationship between protection index, F and groundwater protection zone, S.

Vulnerability	Protection index F	Protection zone S
Very high	F from 9 to 19	S1
High	F from 20 to 25	S2
Moderate	F greater than 25	S3
Low	F greater than 25 with the presence of P_4+($I_{3,4}$) categories	Rest of the catchment area

3.4 Adjustment and Method Verification

The category values and weighting coefficients, as well as the limiting protection index values, which reflect the equivalence with the protection zones, were established in an experimental manner after a certain number of iterations and sensitivity tests. This was carried out in the case study areas within the scope of the methods development (Tâche et al. 1996). The study areas (***Figure 15***) are located in the Folded Jura Mountains (St. Imier), the Tabular Jura Mountains (Bure), the Median Prealps (St. Gingolph) and the Helvetic Alps (Lenk).

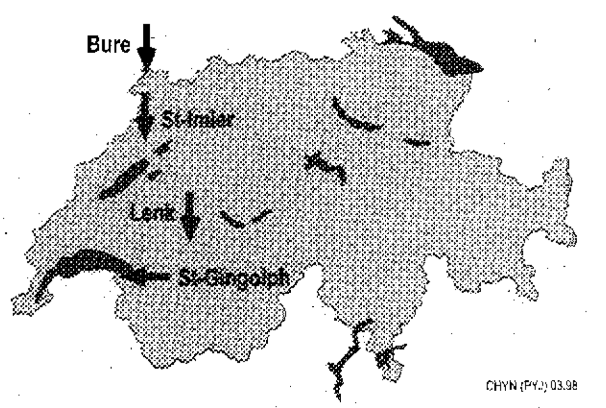


Figure 15. Location of EPIK method test sites.

The results have been checked at the different sites mentioned, partly by means of tracer tests and detailed geophysical investigations of low vulnerability areas to highly vulnerable areas. The objective of these checks was to verify that the chosen category values and the weighting values are adequately defined as well as the limiting values for the equivalency relationship between the degree of vulnerability and the protection zones. The results of these investigations have shown that the proposed values are coherent and accurate. ***This system is generally applicable to the conditions in the Jura Mountains, Prealps and Calcareous Alps in Switzerland.***

In practice, it does not seem necessary to proceed systematically for each site by verifying vulnerability using complementary methods such as geophysics and tracing tests. However, should the protection index value appear inappropriate to a particular geological or hydrogeological situation, the geologist/hydrogeologist may justify verification investigations using, for example, tracing tests during periods of high and low groundwater levels in a given area.

4 EXAMPLES OF APPLICATION : 2 CASE STUDIES

The results of vulnerability mapping using the EPIK method at two sites, one in the Folded Jura Mountains (St. Imier, BE) and the other in the Helvetic zone of the Alps (Lenk, BE) are presented in the following sections as case studies of the methods application.

These examples have shown the feasibility of such a method for delineating groundwater protection zones in karstic environments. They give an idea of the spatial distribution of different category values of the EPIK parameters, of groundwater vulnerability zones and of the resulting protection zones. The case studies equally illustrate the characterisation methods used as well as the problems that may be encountered. The investment in work time in the office and in the field is also discussed at the end of the section.

4.1 Example of the St. Imier Springs Catchment

Introduction

The sources of La Raissette, La Grande Dou, La Petite Dou and Le Torrent are located in the St. Imier valley (Bernese Jura Mountains), in an area owned by the Cormonet commune. La Grand Dou spring is not exploited as a water source. The other three sources are exploited for different water supply networks in the St. Imier commune.

The catchment of the four springs is located in the cantons of Berne and Neuchâtel and covers an area of approximately 120 km^2. Only the 70 km^2 within the canton of Berne were investigated in this study.

Geologically, the catchment is part of the Folded Jura Mountains (***Figure 16***). The aquifer, with a thickness of 200 to 400 metres, consists of fissured and karstified Malm limestones (from the Sequanian to the Portlandian). The Argovian marl (Lower Malm) formation forms the aquifer base. Structurally, the springs catchment consists of the northern limb of the Gurnigel - Chasseral anticline and the southern limb of the Montagne Du Droit - Mont Soleil - Mont Crosin anticline. These two anticlines generally trend northeast-southwest.

The La Raissette, La Grande Dou, La Petit Dou and Le Torrent sources are springs situated at an altitude of 720 to 750 metres above mean sea level (Jäckli AG & OEHE 1981). Subartesian water upwells at low points where the Malm limestones are outcropping.

Protection zones developed in the 1980s for the northern part of the catchment (Schindler 1988) were delineated using the practical guidelines in use at the time (OFPE 1982). The S3 zone established using this method covers almost all of the area. Only two areas of approximately 0.04 km^2 around the springs correspond to the S1 and S2 zones. Despite the establishment of these protection zones, agricultural pollution problems (from liquid manure spreading) have appeared on average four times a year, at the time of snow melt or shortly after intense summer storms.

In order to attempt to remedy this situation, the EPIK method was applied to this site. The method needed to effectively delineate realistically sized protection zones that were compatible with application regulations in force.

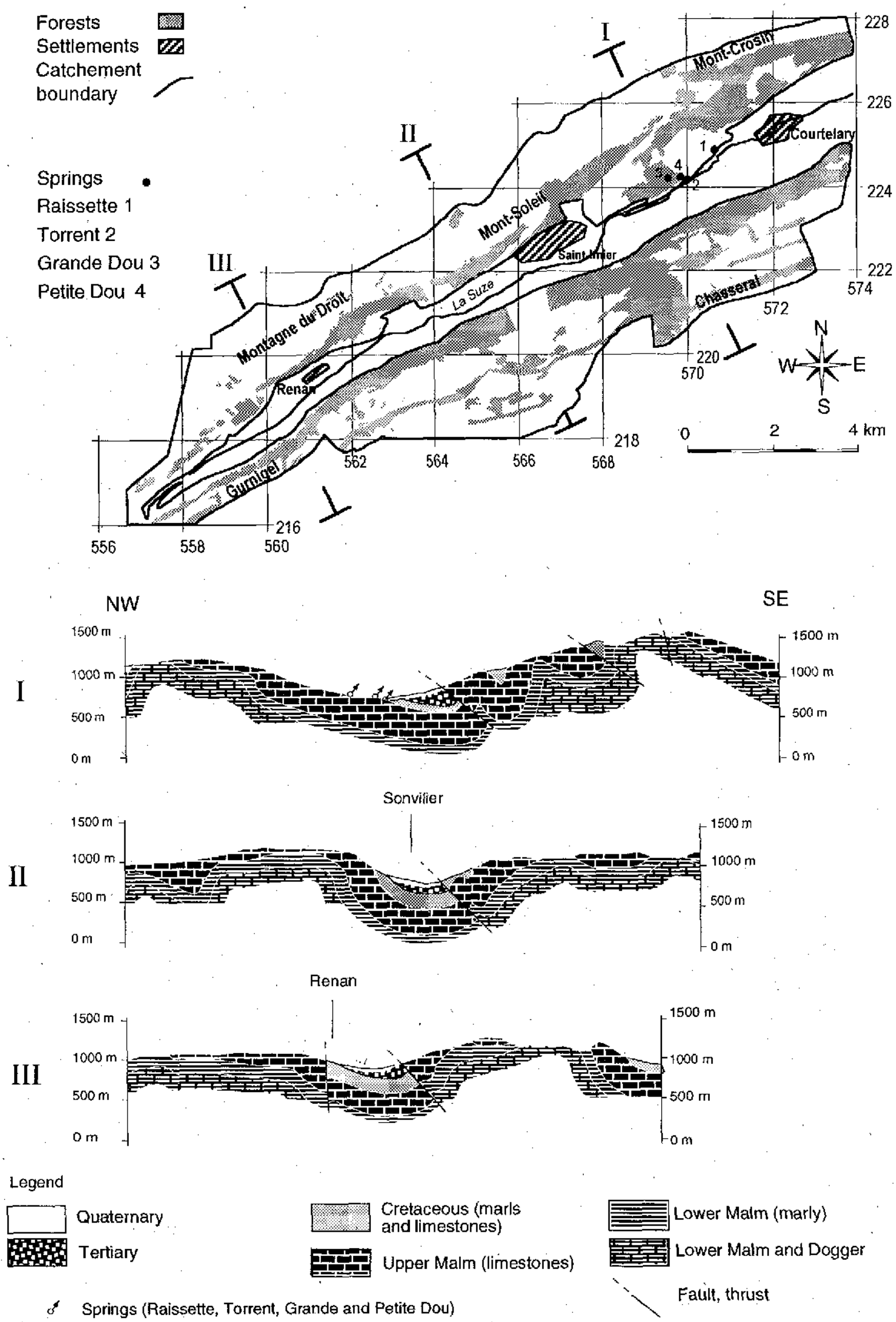


Figure 16. Location and geological cross sections across the St. Imier Springs catchment (BE).

The catchment boundaries were delineated in cooperation with Geotest AG (Zollikofen) based on relevant tracer test information, as well as existing hydrogeological reports and protection zone delineation (Jäckli AG & OEHE 1981, Schindler 1988). The bottom of the valley ***(Figure 17)*** consists mainly of Tertiary and Quaternary deposits and does not form part of the catchment.

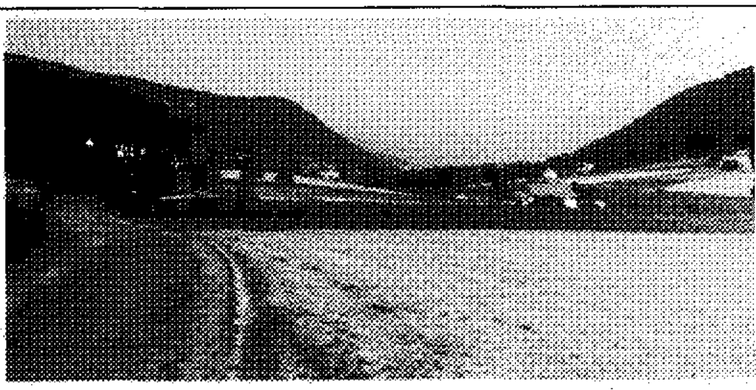


Figure 17.
North easterly view of the upstream part of the St. Imier Valley. The wooded anticlines of Montagne du Droit and Gurnigel stand out on either side of the valley.
(photo F. Pasquier)

In the case of St. Imier, it was decided at the start to classify all forest areas in the S2 zone in order to avoid the effects of permanent woodpiles and concentrated pesticide use. Thus the forested areas were not investigated during the vulnerability mapping. The areas were subsequently reclassified from S2 to S3 since the forest owners showed that they didn't have permanent woodpiles and the risk of groundwater contamination from pesticides was thus minimal.

Evaluation of the E, P, I and K Parameters

E - Epikarst *(Appendix 1)*

For the St. Imier Springs catchment, the evaluation of the presence of epikarst and its degree of development was carried out without much cost or detailed investigation, mainly by using field observations (karstic landforms and outcrop mapping), geomorphological studies and examining aerial photographs. The manually produced map was scanned and discretised to a resolution of 10 metres. The same scale was used for the discretisation of the P and I parameters.

P – Protective Cover *(Appendix 2)*

Protective cover in the study area mainly consists of soil. Only a few detrital Quaternary deposits were noted. Evaluation of the P protective cover parameter is based mainly on soil thickness determined using a manual soil corer (approximately 100 holes cored). Although the EPIK method recommends that the limit between P_2 and P_3 be set at a thickness of one metre, the limit was set at 0.5 m for this example since the method was in the process of being developed.

I - Infiltration Conditions *(Appendix 3)*

This parameter was evaluated with the help of an altitude numerical model (ANM) and topographic maps. The entire catchment basin, apart from the forests, was simulated as meadows and pasture, which largely reflected the actual situation. Consequently, a slope limit of 25% was used to characterise the I parameter.

The topographic catchment of swallow holes and their feeder streams were determined using a GIS and an ANM with a grid of 50 m. A too high precision of the resulting maps should not be expected, even though they were elaborated at a resolution of 10 m, due to practical reasons relating to handling GIS files. The results were compared to topographic maps, notably where the bases of slopes were concerned and certain anomalous points deleted. One can conclude that it is dangerous to automatically create infiltration maps using an ANM without verification in the field.

K – Karstic Network Development

Because of the lack of detailed information concerning flows and precipitation measurements, it was impossible to carry out an accurate study of the correlation between rainfall and flow for the springs under consideration. Consequently, Mangins method of karst aquifer classification could not be applied. Direct signs of a karstic network such as caves and chasms were not observed. Furthermore, neither geophysical studies nor drilling data were available. No long-term records of the physical and chemical characteristics of the water discharging from Le Torrent or La Raissette springs were available.

The K parameter was therefore evaluated globally for the entire catchment and was not mapped. Hydrographs and tracer test analyses provided evidence for the karstic character of groundwater flow.

A flow hydrograph study was carried out for La Raissette spring. It showed that its reaction to rainfall resulted in very pointed flow peaks that did not last longer than 24 hours. The recession can exceed 24 hours. This spring thus clearly has a karstic flow regime.

Insufficient ***chemical and bacteriological water quality analyses*** were available for the La Raissette spring to reach conclusions concerning the development of a karstic network (monthly samples collected independently of hydrological conditions).

In the case of Le Torrent, La Grande Dou and La Petite Dou springs, the only factors providing information on the karstic character and the degree of karstic network development are tracer tests, along with flow and water quality analyses.

Some 18 ***tracer tests*** were carried out in the catchment of the St. Imier Springs between 1967 and 1994. Besides allowing the catchment to be delineated, certain tests provided important data on the characteristics of the karstic flow regime. Given that the hydrological conditions at the time of the tests were sometimes unknown or partially known, the following remarks can be made:

The maximum tracer velocity is high; it ranges between 17 and 76 m/hour in low to medium water levels.

The sharp peak in the breakthrough curves (not always fully present in the reports) shows that the main part of the flow is probably along karstic drains. This is particularly well illustrated in the breakthrough curves for the tests carried out at Les Combes (Convers region) on 23.7.1985 (Gretillat 1986).

Tracer test result analyses of the Dou and Torrent springs and flow hydrograph analysis (from La Raissette spring) confirm the karstic nature of groundwater flow toward the St. Imier springs. ***Consequently, the entire catchment of these springs has been classified into category K_1.***

Protection Index

The protection index obtained using the method described in Paragraph 3.2 is shown on the vulnerability map in ***Figure 18***. For improved legibility, an enlarged inset is presented in ***Figure 19***. It emerges from these figures that the swallow holes are the most vulnerable with an F protection index of 9 out of a maximum of 29. The karren fields located in the forest (remembering that only forested areas crossed by a cantonal road were surveyed) also showed very high vulnerability (F = 15). The dolines have a vulnerability which is high to very high (F = 16 to 20). The dry valleys are of high to moderate vulnerability (F = 21 to 26), and were placed in the same category as zones at the bases of slopes. Dry valleys and the bases of slopes are always less vulnerable than dolines and karren fields. The high protection index values (F = 26 to 29) represent areas with moderate vulnerability (in the absence of a P_4 category, one cannot talk of low vulnerability).

Protection Zones

Based on the vulnerability maps (Figure 18 and 19), protection zones were defined using the equivalence relationship provided in Table 5. They are presented in ***Figure 21*** and ***Figure 20*** (in detail). The figures show that swallow holes and supplying water courses (with protection index values between 9 and 18), as well as dolines, karren fields and cuestas (F ranging between 13 and 19) are mostly classified as S1. Dolines with thick soil cover (P_3) outside the zone of contribution of a swallow hole or stream (I_4) occur in the S2 zone. Areas classified in E_2 and /or I_3 categories mainly correspond to the S2 protection zone. With regard to low vulnerability areas, these generally have a good protective cover, are located outside of concentrated infiltration zones or areas of marked karstic morphology, and are logically found in the S3 zone. Due to the absence of a P_4 category (more than 8m of low permeability formations) in the catchment, the S3 zone extends to the catchment boundaries.

The S1 zone represents 1% of the mapped surface of the catchment (Bernese part, 67 km^2). The S2 zone, except for the forested areas (32%, not mapped by the EPIK method, see page 34) occupies some 18% and the S3 zone, 49%.

Conclusions

Mapping the four categories has allowed the ***groundwater vulnerability map*** shown in Figure 18 to be produced. The F protection index varies between 9 and 29. Based on the equivalence relationship provided in Table 5, a new ***delineation of the S1, S2 and S3 zones*** could be established. It is shown in Figure 21. Compared to the existing protection zones, the S1 and S2 protection zones obtained using the EPIK method are clearly more numerous and distributed across the whole catchment. They are however limited to sensitive locations. They ought to allow the implementation of effective restrictions for groundwater protection, which take hydrogeological conditions into account in a manner that does not unnecessarily restrict land use.

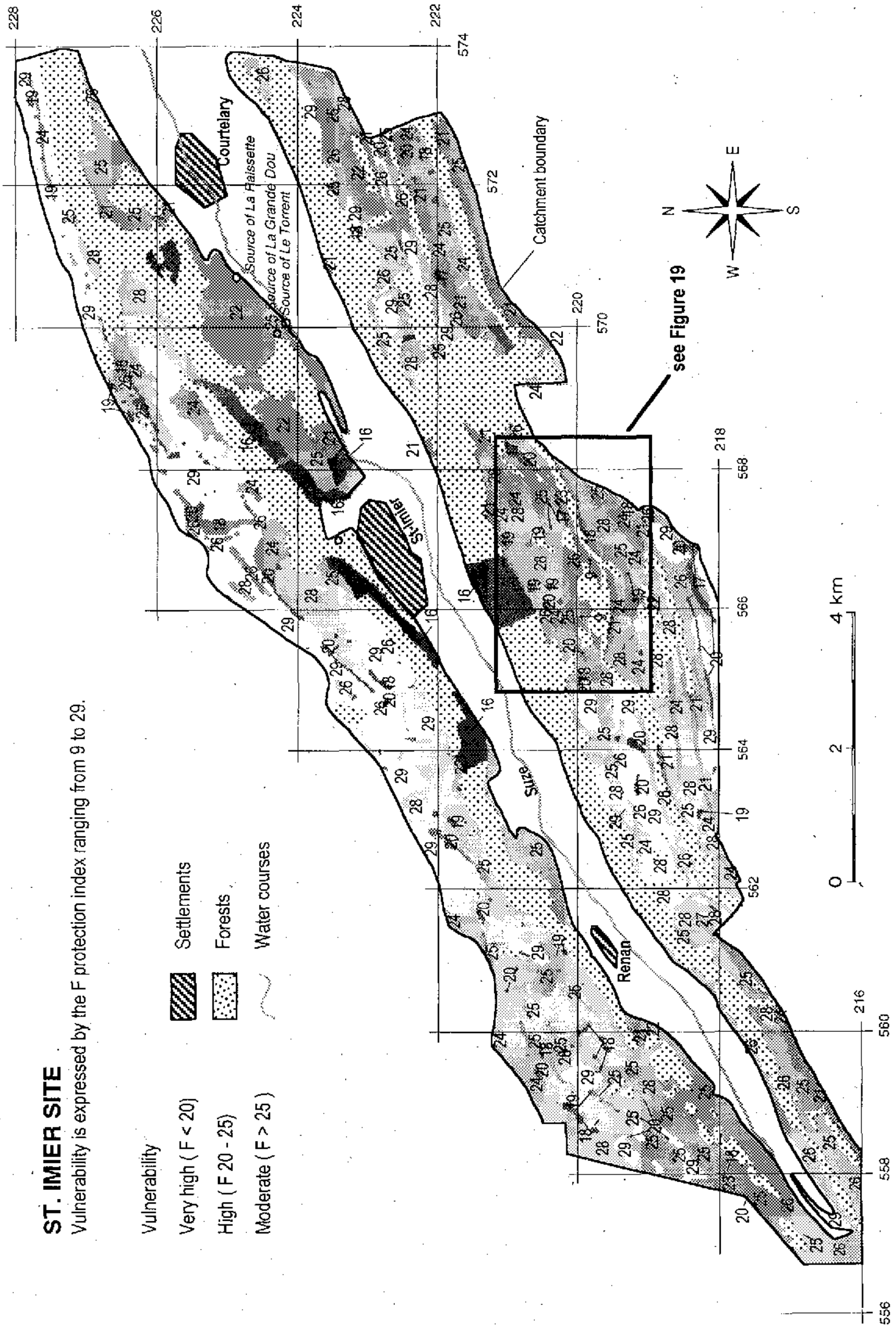


Figure 18. Vulnerability map of the St. Imier Springs catchment (BE). Part of the catchment in the canton of Berne. The shading is black to very dark grey for F<20, dark grey to medium grey for F=20-25 and light grey to white for F>25.

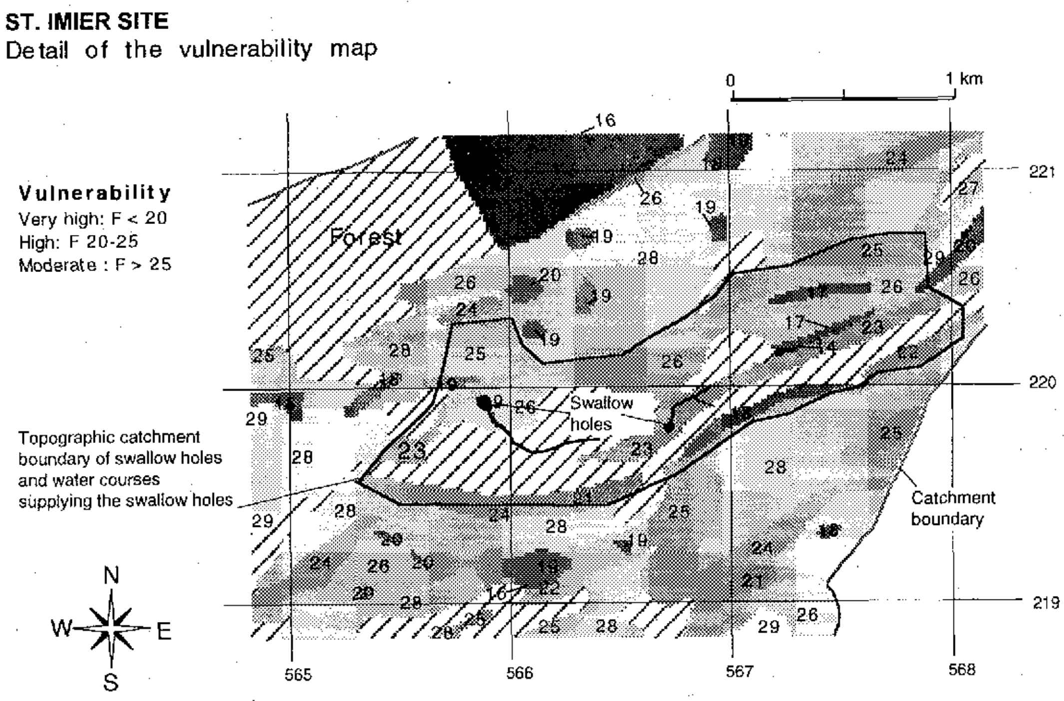


Figure 19. A more detailed map of part of the St. Imier Springs catchment (BE). The shading is black to very dark grey for F<20, dark grey to medium grey for F=20-25 and light grey to white for F>25.

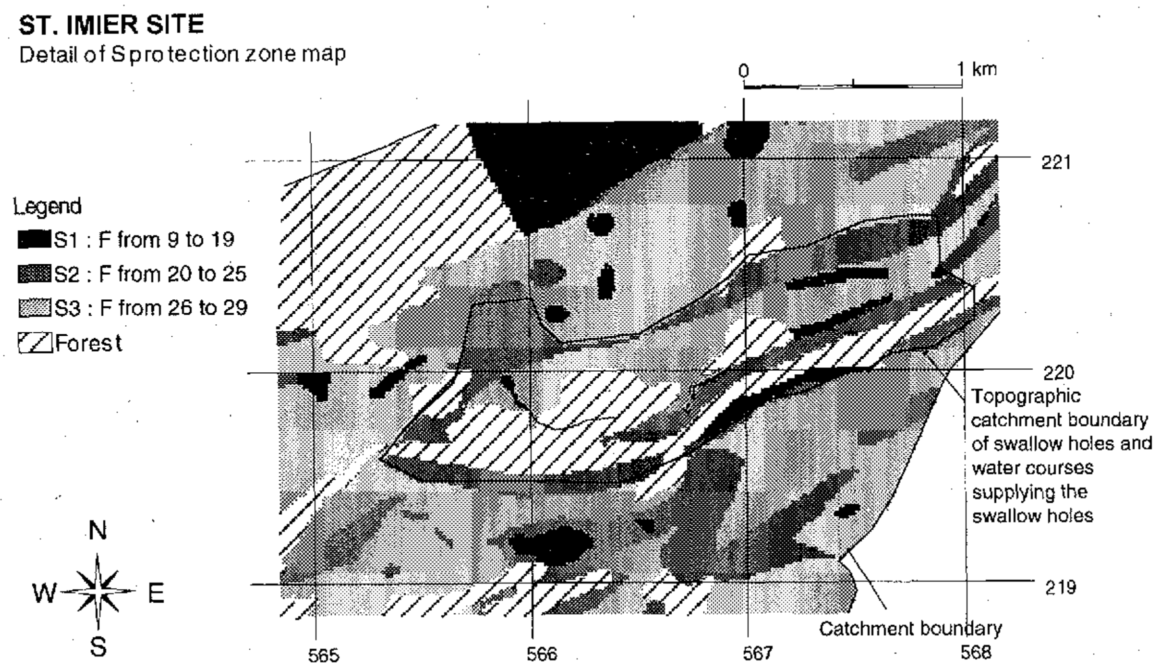


Figure 20. Detail of the St. Imier Springs catchment (BE) protection zone map.

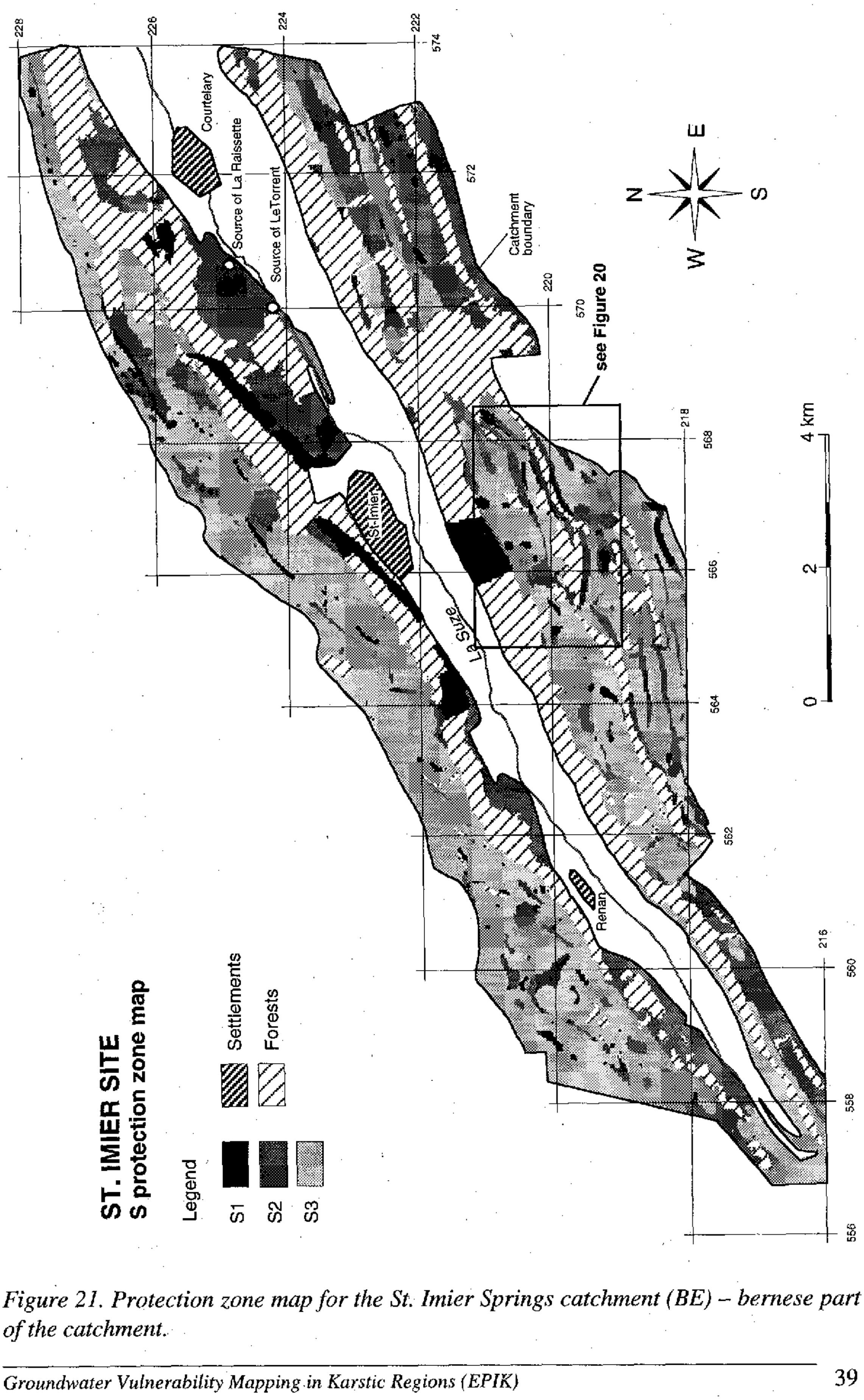


Figure 21. Protection zone map for the St. Imier Springs catchment (BE) – bernese part of the catchment.

4.2 Example of the Blatti Springs - Lenk Catchment

Introduction

The Blatti Springs (old and new, coordinates 599'935/141'240) provide water to the commune of Lenk (canton of Berne). The old source (a natural spring) was used up until 1963, when a new source 10 metres deeper was exploited to ensure sufficient flow. The catchment for both sources is situated in the Helvetic Alps at an altitude of 1200 to 3200 metres above sea level. A typical part of this basin was analysed and is presented here as an example. It is a high area situated between the northern slope of the Mittaghorn and the Niesenhorn on both sides of Lake Iffigen (***Figure 22*** and ***Figure 23***).

Geologically, the catchment contains formations from the Wildhorn Helvetic Nappe which form a series of ENE-WSW oriented folds (Wildberger 1981). The frontal part of the helvetic nappe is enclosed in ultra-helvetic secondary folds giving rise to tectonic windows such as that at Schwand. Formations extend from the Malm (Quinten Limestones) to the Paleocene (Globigerine Schists) and make up the Wildhorn Nappe in the region studied.

Karstic flow occurs mainly in the Schrattenkalk Limestones (Urgonian), along the synclinal axes. The Neocomian (Valanginian-Hauterivian) and Paleocene Limestones (Hohgant Series sandstones and nummulitic limestones) as well as marl-rich Drusberg Beds limestones are also karstified but to a lesser degree. The Globigerine Schists and Ultrahelvetic rocks (flysch) are not or only very locally karstified (Wildberger 1984).

Figure 22. Iffigbach Valley, view of Iffigläger looking southwest; the Schnidehorn can be seen at the base between the slopes of the Mittagshorn and the Hohberg. (photo A. Wildberger)

Wildbergers thesis on the karstic hydrogeology of the Rawil region as well as excavation data for the Blatti Springs protection zones delineation (Kellerhals and Haefeli AG 1988) in the Schwand tectonic window (anticline) provided very useful information for the characterisation of the different vulnerability factors.

Within the scope of the E, P, I and K parameters, the different geological formations were not differentiated. All outcropping formations in the Wildhorn Nappe (from the Hauterivian to the Hohgant Series) were considered in a global sense.

The 1:25,000 Lenk sheet of the Swiss Geological Atlas (Badoux et al. 1962) and the corresponding explanation (Badoux & Lombard 1962) as well as the hydrogeological map of the Rawil region (Wildberger 1981) served as the basic documents for this study. The field survey for the evaluation of the E, P and I parameters was carried out on a 1:10,000 base.

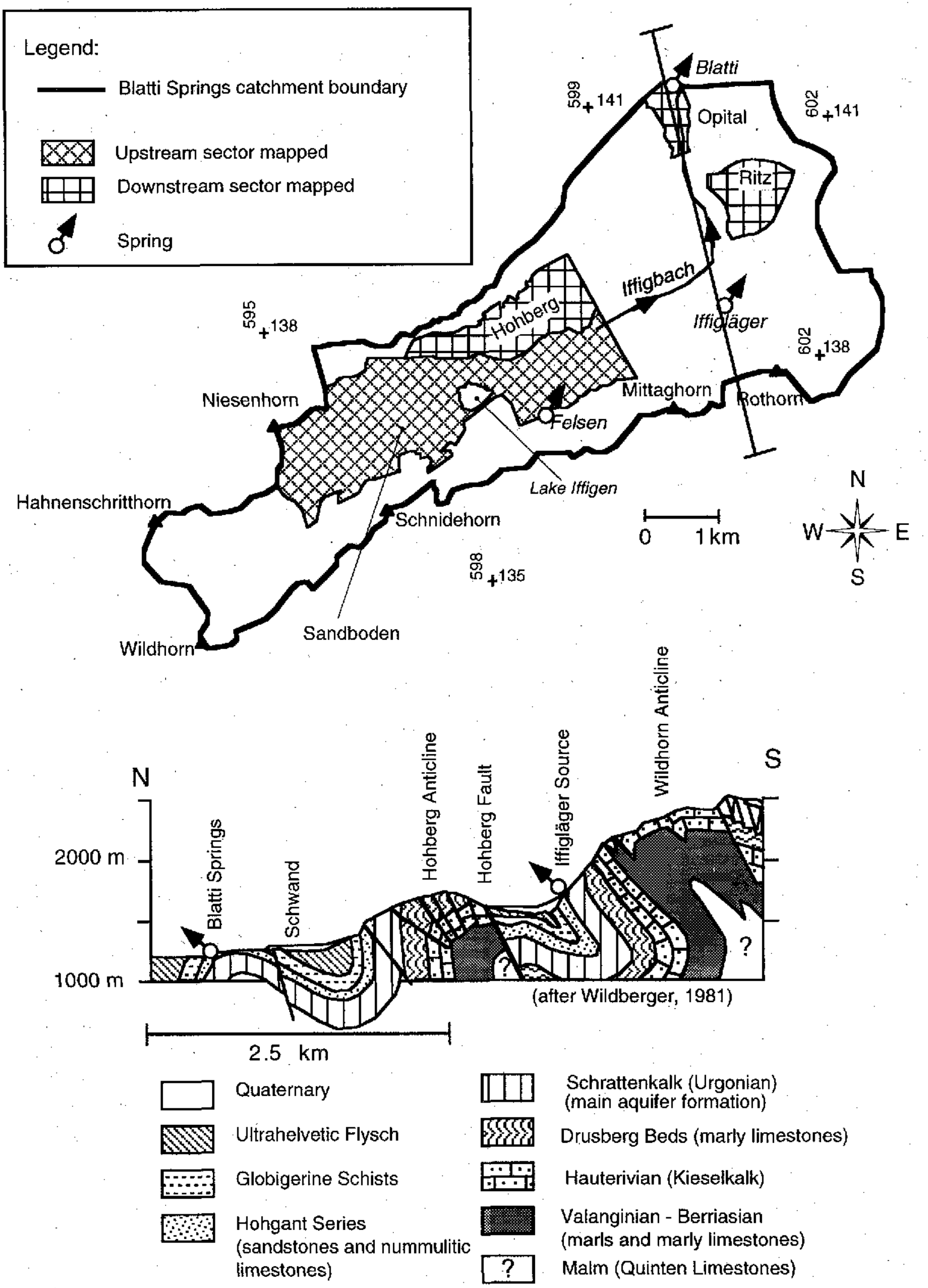


Figure 23. Location and geological cross section of the Blatti Springs catchment, Lenk (BE).

E - Epikarst *(Appendix 4)*

The Epikarst parameter was evaluated for the Blatti Springs – Lenk using aerial photographs, a topographic map of the study area at a scale of 1:10,000 and field checking.

Limestone outcrops show signs of karstification (karren and enlarged fractures) and were classified along with Lake Iffigen (***Figure 24***) as E_1. The E_2 category was assigned only to a small depression with subcropping fractured rock, east of Lake Iffigen. The rest of the study area was classified as category E_3, which represents an absence of well defined karstic morphology. The E_3 category zone covers the largest area.

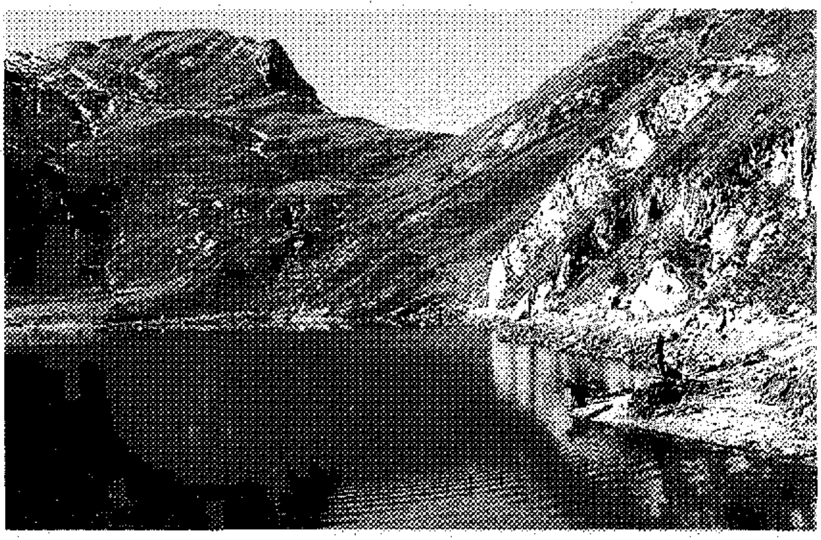


Figure 24. Lake Iffigen, looking northwest. The karstic network and epikarst are considered to be poorly developed. The protective cover is thin except to the left on the terrace (P_3) and on the lakeshore (P_2). (photo A. Wildberger)

P – Protective Cover *(Appendix 5)*

The protective cover consists of a pedological soil (with a thickness of between 0 and 30 to 40 cm) and Quaternary deposits (moraine, scree), which can reach a thickness of more than 2.5 m. This parameter was initially determined using aerial photographic observations, along with a geological map in conjunction with verification in the field and coring. However, the corer was of little use in this type of cover where the soil rarely exceeded 20 cm and heterogeneous morainic formations are difficult to penetrate.

The study region (Mittaghorn – Niesenhorn) is characterised over a large area by a thin cover (P_1 and P_2). The scree (talus) zones, which are considered here as slightly permeable were classified as category P_3 with a thickness easily exceeding one metre. The Sandboden area, consisting of Quaternary sediments several metres thick and with a low hydraulic conductivity and frequently giving rise to temporary flooding, were assigned to P_4.

I – Infiltration Conditions *(Appendix 6)*

Infiltration conditions were evaluated using a topographic map and some field checking. Areas with slopes greater than 25%, as well as the bases of slopes outside of swallow hole catchments and their feeder streams were mapped manually using a 1:10,000 scale base map. The areas covered by the bases of slopes occupied 50 metres on both sides of the slope delineation line which were greater than 10% and 25% depending on the vegetation (see Figure 11). An altitude based numerical model was not available for the region. For a moderately sized area such as this, it is entirely feasible to do this work manually and determine slopes and slope bases. Delineation of the bases of slopes using a geographical information system is admittedly quick and places results directly on the screen but also requires that the validity of results be checked in some areas.

The largest part of the study area was classified as category I_4. Three swallow holes as well as the Lake Iffigen swallow holes are classified as I_1. The areas characterised as I_2 and I_3 were those containing temporary and permanent flowing water upstream and downstream of Lake Iffigen.

K – Karstic Network Development *(Appendix 7)*

The Blatti Springs are located just downstream of the Schwand tectonic window. They upwell from the Schrattenkalk through the Hohgant Series. The old source (in a small cave set in well karstified nummulitic limestones) was used by the Lenk commune up until 1963. Following some drought periods, an improvement in discharge rate was necessary and a new source 10 metres below the natural discharge level of the old source was developed. The mean annual flow rate varies between 6,000 l/min and 9,000 l/min.

The Blatti Springs form a discharge zone at the base of a complex karstic system in the Iffigbach catchment (Wildhorn Nappe), the Felsen and Iffigläger Springs being overflow springs from the upstream system. Two main parts of the system can be distinguished; the downstream part with the Blatti Springs discharge zone, and the Hohberg anticlinal recharge zone to the north of the fault with the same name, and the upstream part comprising of the Felsen subcatchment and the Iffigläger Springs. This upstream part, consisting of the Niesenhorn and Hahnenschritthorn, lies mainly to the west and south west of Lake Iffigen.

The Blatti Springs hydrographs (Nabholz and Häberli 1972-1979) show that the two sources react in a similar manner. The new source, located at a lower level, provides a base flow with lower amplitude fluctuations. The old source emerges from a natural cave that shows the presence of a well-developed karstic network. The groundwater velocities noted in tracer tests carried out in swallow holes of Lake Iffigen reach approximately 100 metres per hour. These velocities reflect the presence of a well-developed karstic network.

The upstream part of the catchment is drained by the Felsen and Iffigen overflow springs that show characteristics typical of karstic springs draining a well-developed karstified area. However, a portion of the infiltrating water in the upstream part (in the Hauterivian and Urgonian limestones) flows directly toward the Blatti Springs (a hydraulic connection was identified using tracers tests, Wildberger 1981). In order to reach these springs, flow must preferentially occur along tectonic thrusts and across low permeability formations such as the Drusberg Beds (marl-rich limestones) and the Hauterivian siliceous limestones. These formations, having lower conductivities than those of the karstified Urgonian limestones, can be assigned the K_2 category for the upstream part of the catchment and the K_1 category for the downstream parts, including the Hohberg anticline located to the north of the fault of the same name (Doerfliger 1996b).

Protection Index

The vulnerability map (***Figure 25***) shows that the protection index varies from 11 to 32. Apart from swallow holes, the largest areas with very high vulnerability (protection index ranging from 14 to 18) are the karren fields located to the north and east of Lake Iffigen. The large high vulnerability areas (protection index of 20) represent outcrops showing karstified features, accentuated fissuring and subject to diffuse infiltration conditions (between Sandboden and Niesenhorn). The Hohberg fault sector is characterised by a protection index of between 21 and 23 and represents a high vulnerability area.

The best-protected area is Sandboden, characterised by the P_4 category and a protection index of 32. Some areas located in the south and south west of the mapped zone are also well protected (F=31).

Protection Zones

From the vulnerability map and the equivalence relationship of Table 5, the following protection zones are obtained (***Figure 26***).

The ***S1 protection zones*** are concentrated in the northeastern part of the mapped area. They consist of Lake Iffigen with its swallow holes and karren field areas, the outcrops located directly to the east and northeast of the lake as well as karren field areas on the Hohberg anticline to the north of the fault of the same name. It is notable the K_1 category is assigned to this last section as it represents, due to the position of the anticlinal limestone beds, a preferential recharge zone to the aquifer that supplies the Blatti Springs.

The ***S2 protection zone*** essentially comprises of the catchment of the stream which flows in the Hohbergtäli, a ravine flanked by scree on the southern limb of the east-west oriented Hohberg and located approximately 300 m to the north of the lake. This stream flows over Quaternary deposits, into which it infiltrates. Re-emergences occur approximately 2 km downstream, which recharge the Iffigbach at the level of the Iffigenalp (about 1 km downstream of the area mapped). The Iffigbach in turn infiltrates in the area of the Blatti Springs and contributes less than 1% to the sources discharge. Because of the heavy dilution of the Iffigbach waters with groundwater feeding the Blatti springs, and considering the good bacteriological quality of the latter, it is perhaps overstating it to wish to classify the Hohbergtäli catchment in the S2 zone as proposed here. In such a situation, the decision should be taken by a consensus between the authorities concerned and the responsible geologist.

In the area assigned as category K_2 (southern part of the upper sub-catchment) the S2 zone occupies various small regions to the west of Lake Iffigen, characterised by categories E_1, P_1 and I_1 or I_4.

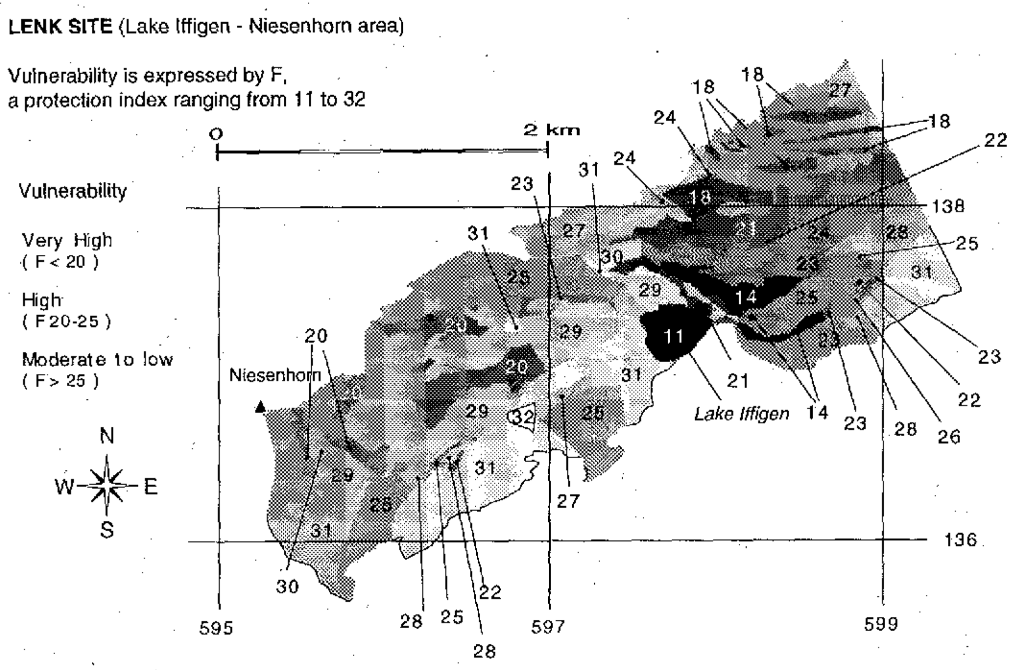


Figure 25. Vulnerability map of the upper part of the Blatti Springs catchment, Lenk (BE). The shading is black to very dark grey for F<20, dark grey to medium grey for F=20-25 and light grey to white for F>25.

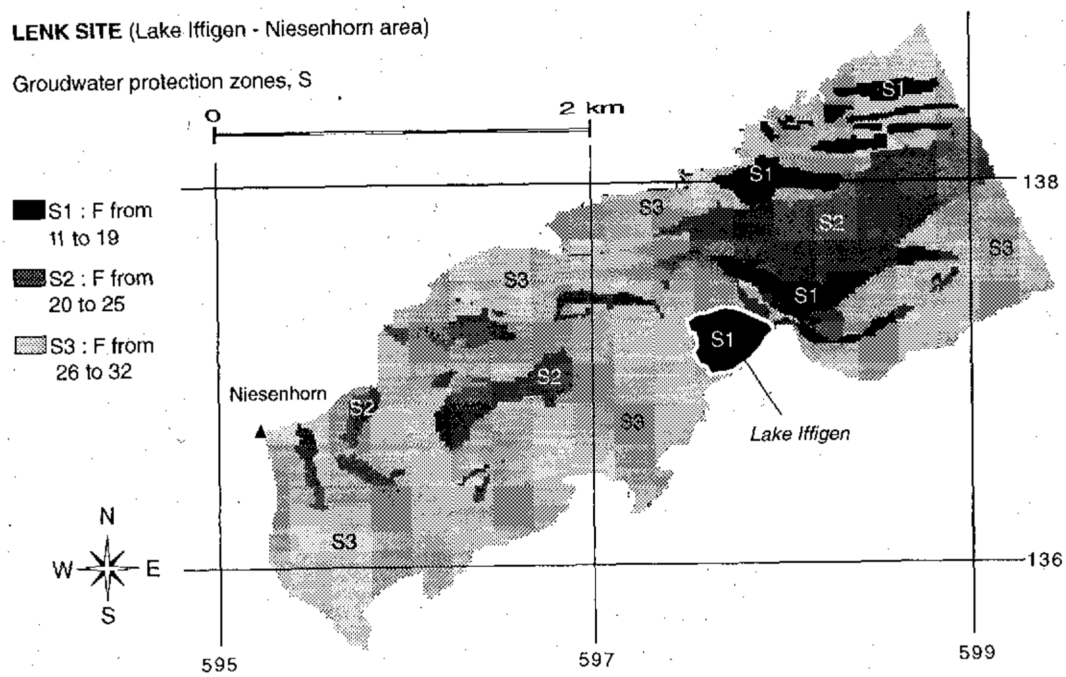


Figure 26. Protection zone map of the upper part of the Blatti Springs catchment, Lenk (BE).

The *S3 zone* extends to the limits of the catchment. Though characterised by the P_4 category and a minimal vulnerability, the Sandboden area has been included in the S3 zone due to its small extent and its situation in the centre of the catchment.

Conclusions

The Blatti Springs catchment is an alpine karstic basin (***Figure 27***). It possesses a complex structure because of its complex tectonic setting; because of this, it was appropriate to evaluate the K parameter in a different manner for the upper and lower parts of the catchment.

In this alpine setting, the Quaternary formations act as a protective cover. The soils themselves are thin and their protective role is not very important.

The surface water drainage network and the presence of porous aquifers overlying the karst are characteristic of this basin. The water in these aquifers seeps out diffusely in the Lake Iffigen area, which itself possesses sinkholes in the karstic aquifer as well as in the Iffigbach which infiltrates into the karstic aquifer close to the Blatti Springs.

The S1 protection zones are of relatively limited extent; they are related to morphological features and can be easily protected by fencing. The S2 zones occupy around 20% of the mapped area. They correspond to karren field areas, cuestas and areas of non-existent cover or are characterised by I_2 infiltration conditions (stream catchments with steep slopes).

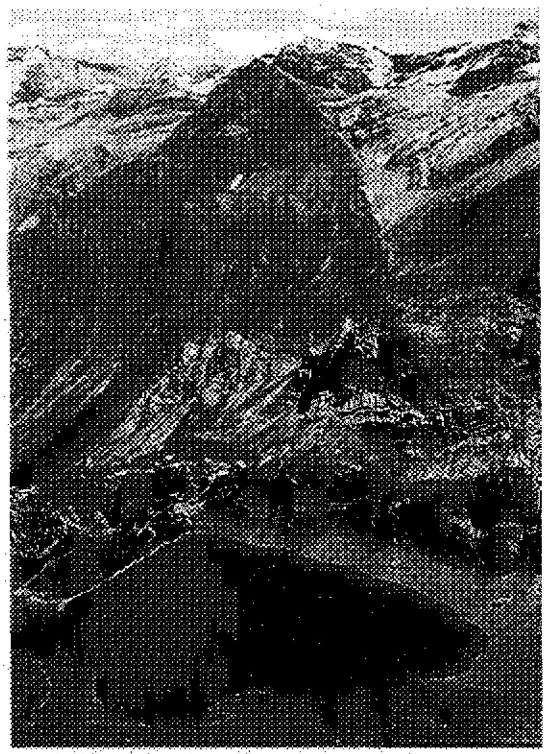


Figure 27. Lake Iffigen as seen from the buttresses of the Niesenhorn. Mittaghorn in the centre. The head of the Iffigbach valley at the base, at left. (photo A. Wildberger)

4.3 Financial Aspects

The two examples of the application of the EPIK method presented here have contributed to the development of the feasibility of the method for source protection delineation in karstified areas. They also showed that it is possible in practice to delineate in a discriminatory way, on the basis of scientifically credible factors, groundwater protection zones which are more or less sensitive to groundwater contamination.

Table 6 provides an estimate of the number of hours which were necessary to evaluate the different parameters. Regional methods (desk studies of synoptic documents) are distinguished from records of local procedures (detailed studies, particularly in the field). It is apparent that the larger the basin, the less number of hours will be required per km^2 for the study (2.1 hours for St. Imier and 5.5 hours for Lenk). The data in Table 6 do not account for time spent in digitising and data processing with the help of GIS. In the case of St. Imier (70 km^2), this work (data processing, digitisation, assignment of weighting coefficients, map production) required a further 6 days or 0.7 hours per km^2. The Lenk example (8 km^2) required a minimum of 4 days or 4.2 hours per km^2. It must be noted that regardless of the area mapped, some days will be necessary for data and graphical processing.

Table 6. Number of hours required per km^2 to evaluate the four EPIK parameters.

Parameter	E		P		I		K	
Sites	Regional methods	Local methods	Regional methods	Local methods	Regional methods	Local methods	Regional methods	Local methods
St. Imier	0.4	0.1	0.1	0.7	0.1	0.5	0.15	0.05
Total	0.5		0.8		0.6		0.2	
Lenk	0.5	3	-	1.0	0.5	-	0.4	0.1
Total	3.5		1.0		0.5		0.5	

The number of hours indicated in Table 6 for carrying out protection zone delineation in a catchment are representative if minimal geological and hydrogeological data are available. For the two examples dealt with here, protection zone delineation had already been carried out. The delineation of the catchment boundary was carried out based on existing geological and hydrogeological (tracer test) information, without which it would have been necessary to carry out additional tracer tests. In both cases hydrographs of the springs to be protected were available. On the other hand, neither soils maps nor drilling/excavation data were available for either site.

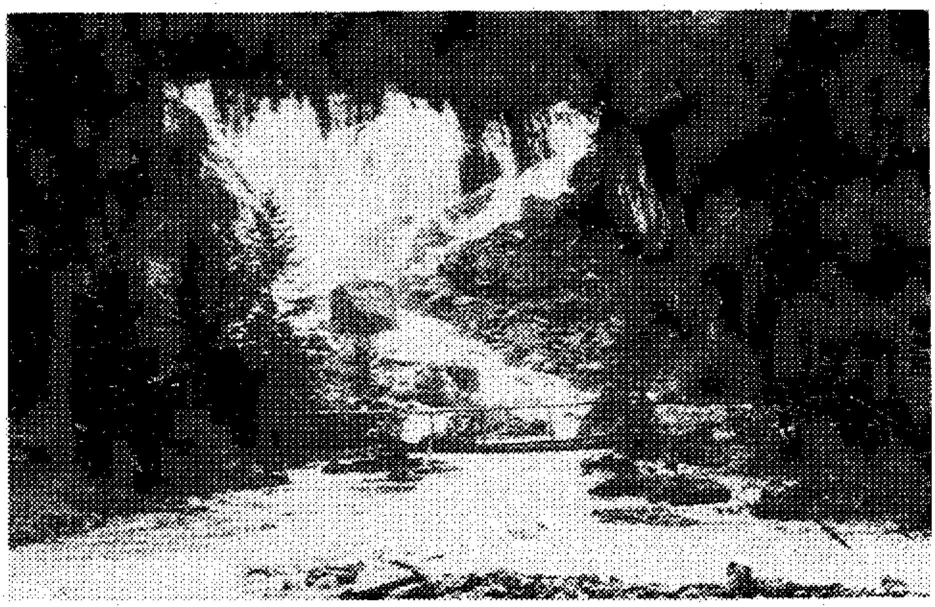
5 CONCLUSIONS AND PERSPECTIVES

The use of parameters accounting for the hydrogeological characteristics of karst, such as epikarst, protective cover, infiltration conditions and the development of a karstic network allows vulnerability maps of water sources in karstic areas to be produced.

These vulnerability maps provide a new base for developing protection zones in karstic terrain. Examples of using the method for several test areas, two of which are presented in this publication, clearly indicate the feasibility of this new approach. The test sites were chosen in various karstic environments such as the Tabular Jura Mountains, Folded Jura Mountains, the Prealps and the Alps. Results obtained to date indicate that ***the proposed method is considered suitable for Swiss conditions. For the sake of transparency, it is recommended that the data used to calculate the E, P, I and K parameters should be contained in any groundwater protection zone report. The report has to be established by a specialist (hydrogeologists).***

The use of geographical information systems (GIS) in studying different test areas, such as St. Imier, has allowed different quantitative aspects of the method to be refined, and the necessary sensitivity tests to be carried out. This tool has greatly simplified the groundwater protection index map (vulnerability map) production. Even if the use of GIS is not essential, it can nonetheless make work considerably easier, depending on the size of the basin.

Karstic aquifer contamination can be avoided. Adequately determined protection zones, with consideration given to karst hydrogeological functions, together with respective protection measures can considerably reduce pollution risks in karstic aquifers. In view of the often local nature of contamination risks in a catchment (e.g. automobile or train traffic, quarries, spreading of manure, discharges from manure pits or silos, or from garages), the EPIK method based on specific hydrogeological factors can enable in the future better protection of catchment installations in karstic areas.



Sibe Brünne Springs near Lenk, BE. (photo A. Wildberger)

6 APPENDICES

Appendix 1 Epikarst map – karstic morphology - of the St. Imier Springs catchment - part of the catchment in the canton of Berne.

Appendix 2 Protective cover map of the St. Imier Springs catchment - part of the catchment in the canton of Berne.

Appendix 3 Infiltration conditions map of the St. Imier Springs catchment - part of the catchment in the canton of Berne.

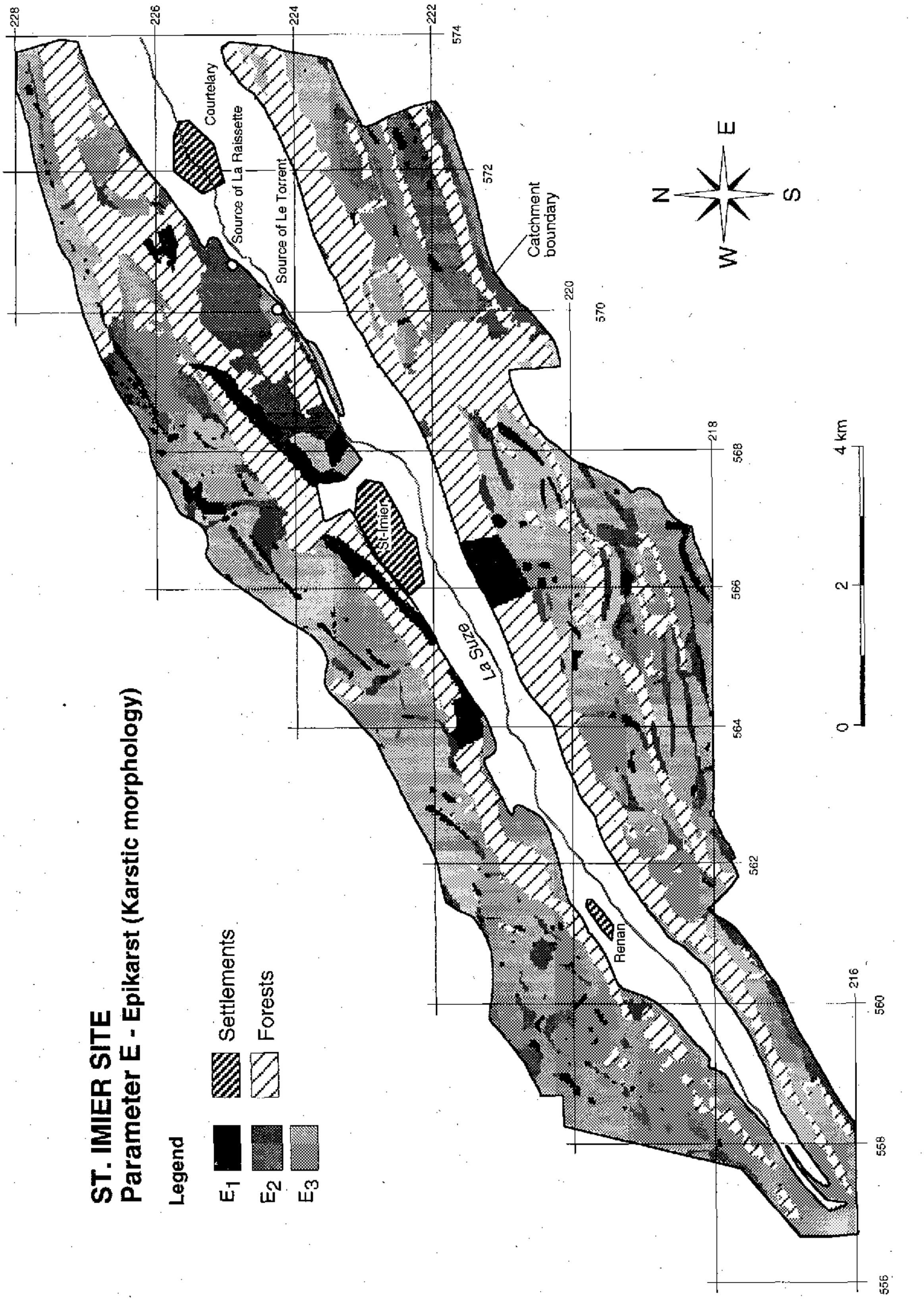
Appendix 4 Epikarst map - karstic morphology - of the upper part of the Blatti Springs catchment, Lenk, BE.

Appendix 5 Protective cover map of the upper part of the Blatti Springs catchment, Lenk, BE.

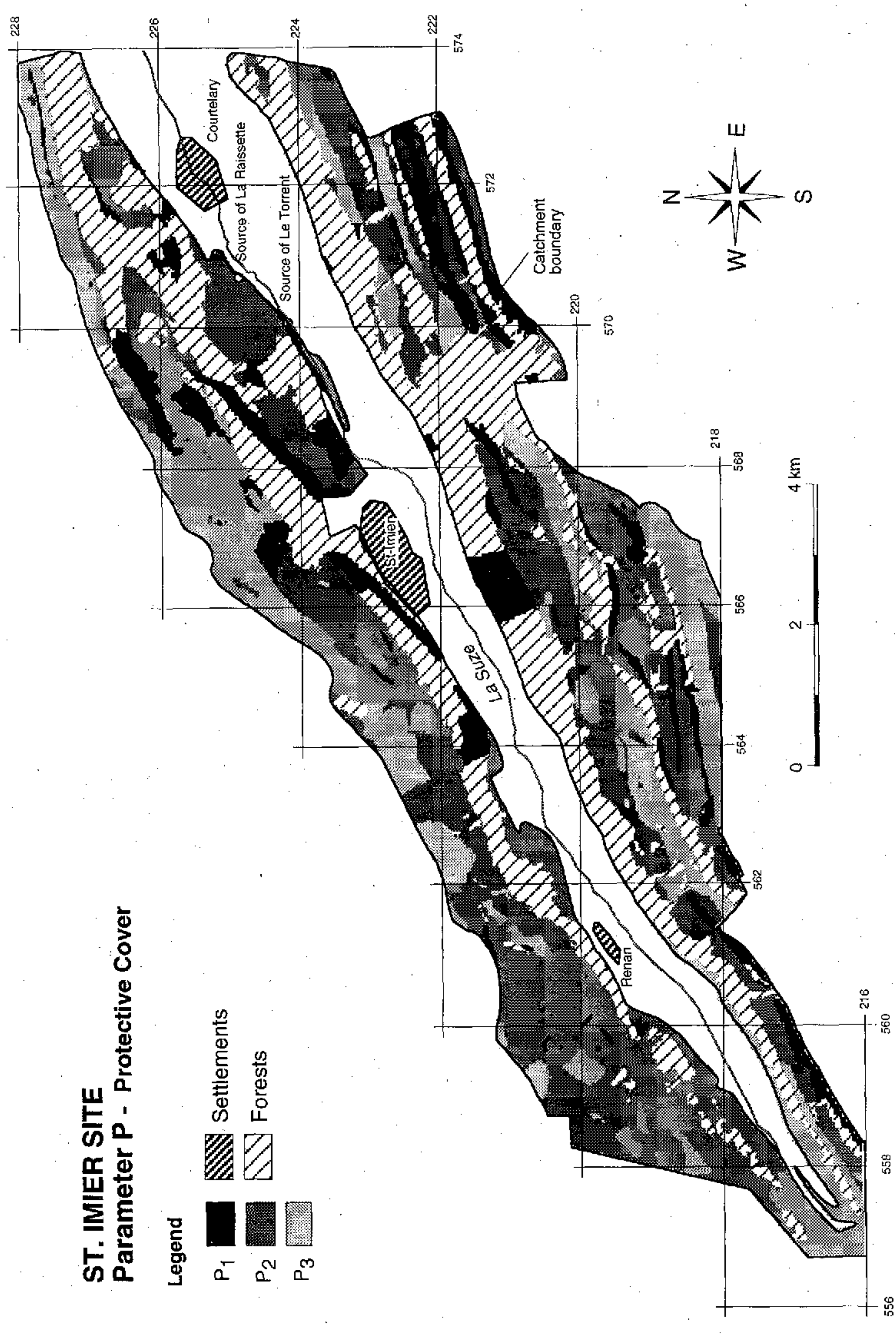
Appendix 6 Infiltration conditions map of the upper part of the Blatti Springs catchment, Lenk, BE.

Appendix 7 Karstic network development map of the upper part of the Blatti Springs catchment, Lenk, BE.

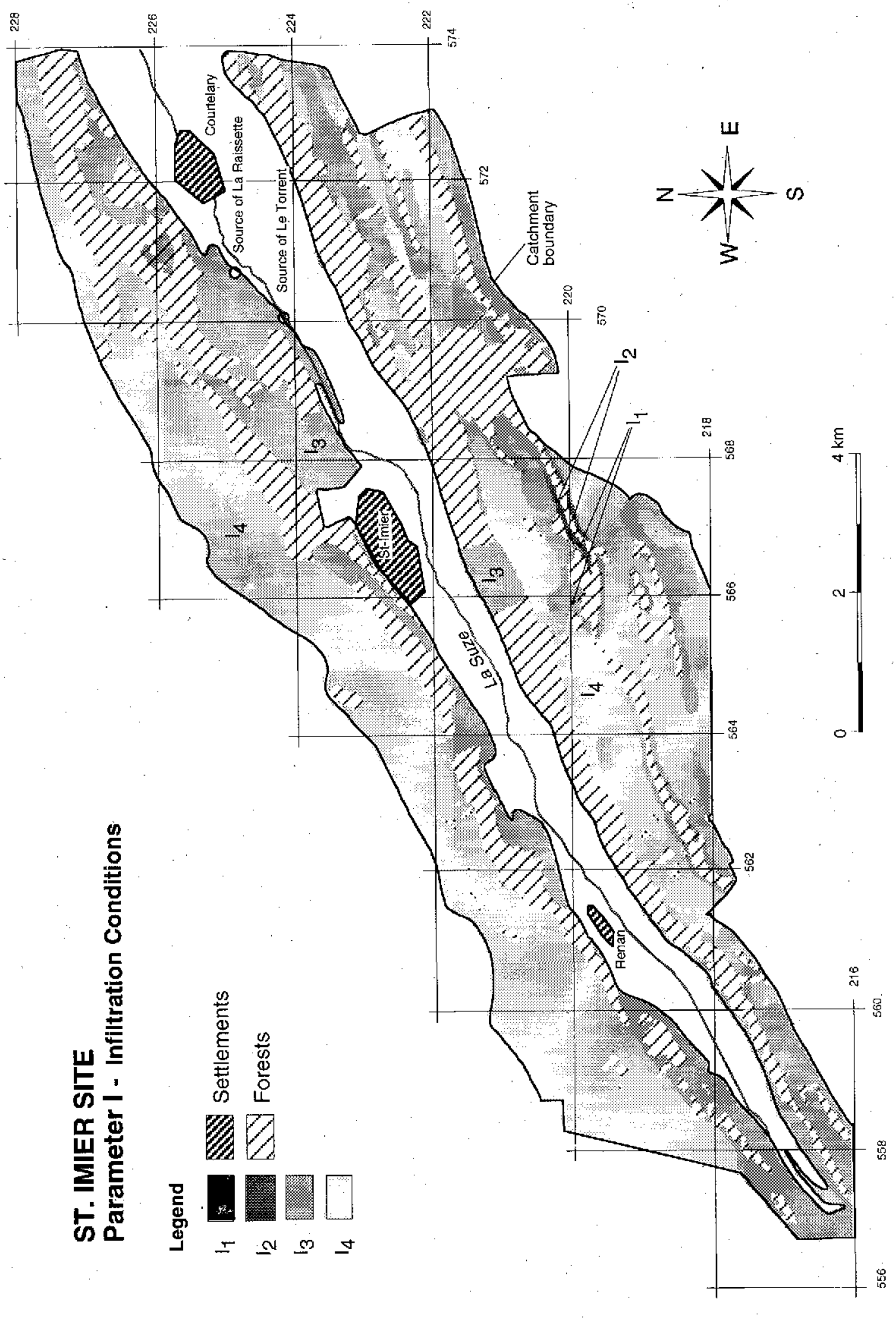
Appendix 1. Epikarst map – karstic morphology - of the St. Imier Springs catchment - part of the catchment in the canton of Berne.



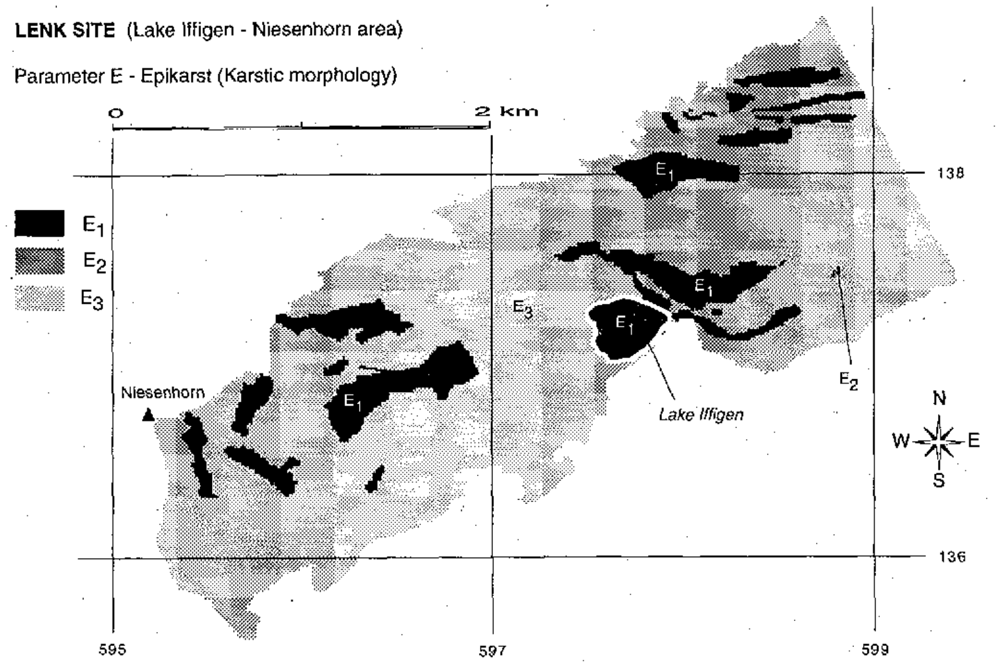
Appendix 2. Protective cover map of the St. Imier Springs catchment - part of the catchment in the canton of Berne.



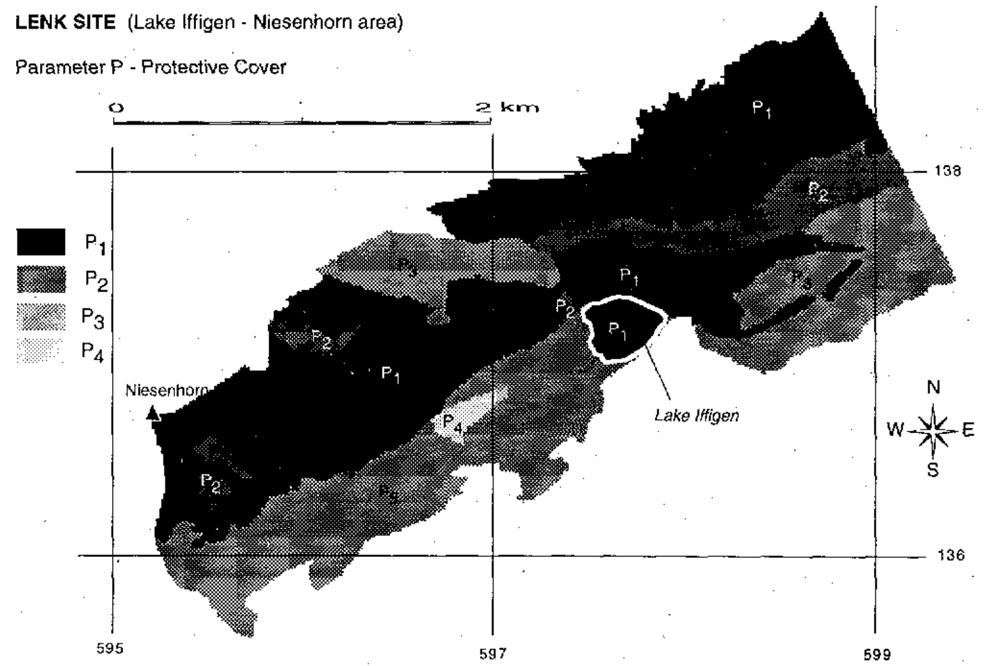
Appendix 3. Infiltration conditions map of the St. Imier Springs catchment - part of the catchment in the canton of Berne.



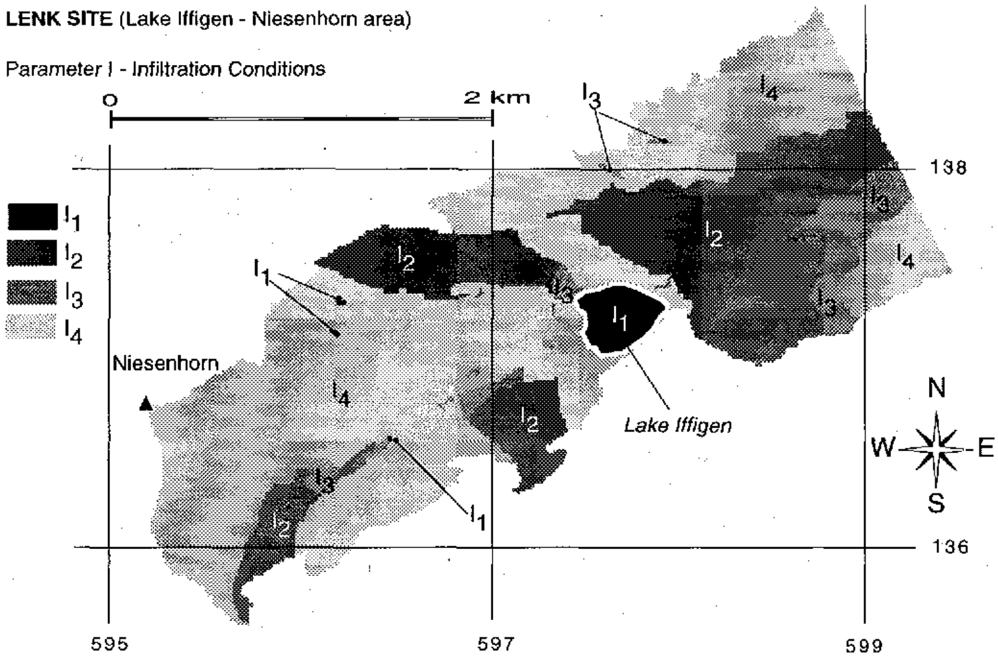
Appendix 4. Epikarst map - karstic morphology - of the upper part of the Blatti Springs catchment, Lenk, BE.



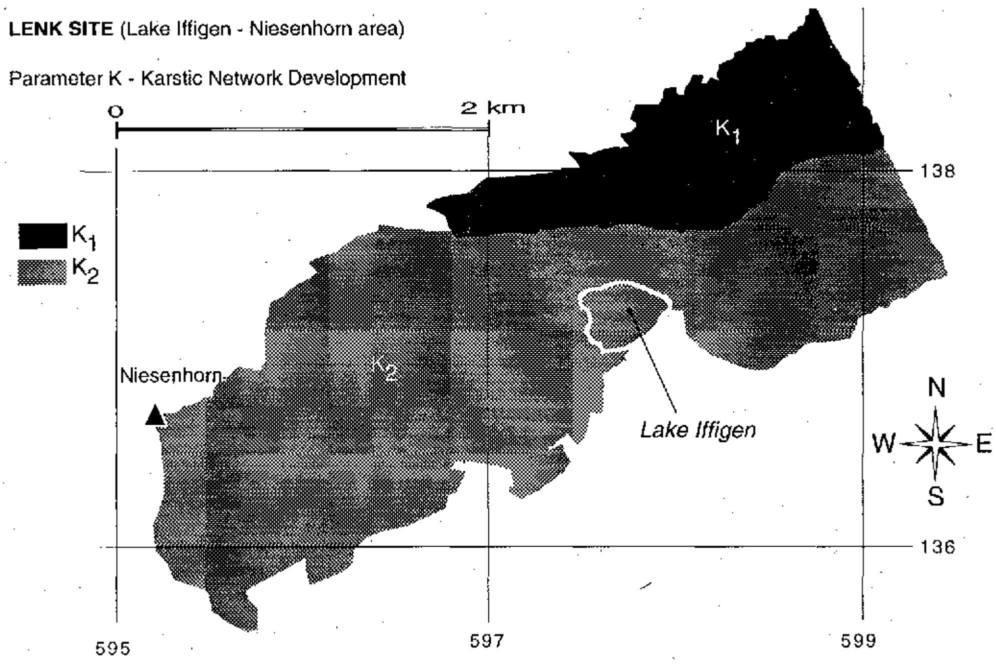
Appendix 5. Protective cover map of the upper part of the Blatti Springs catchment, Lenk, BE.



Appendix 6. Infiltration conditions map of the upper part of the Blatti Springs catchment, Lenk, BE.



Appendix 7. Karstic network development map of the upper part of the Blatti Springs catchment, Lenk, BE.



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Annex 4: Restrictions for Potentially Contaminating Activities and Facilities in Groundwater Protection Zones

Source: MARGANE & SUNNA (2002): Guideline for the Delineation of Groundwater Protection Zones in Jordan

Commercial Land Uses

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Construction or extension of facilities or plants for the production, treatment, use, processing, and storage of substances which may possibly contaminate groundwater and are non- or hardly degradable and radioactive substances, such as substances from refineries, iron, and steel mills, non-ferrous metal works, chemical plants Facilities for the storage of chemicals and nuclear facilities (excepting facilities for medical applications as well as equipment for metering, testing and control)	incompatible	incompatible	incompatible	incompatible
Handling of substances contaminating water	incompatible	incompatible	incompatible[4]	incompatible[4]
Use of materials from which contaminants may be washed or leached, such as use of rubble, residues from incinerators, slag and mining residue for the construction of road, waterway, railroad and air transportation systems and facilities or structures built for noise control	incompatible	incompatible	incompatible	incompatible
Aircraft servicing	incompatible	incompatible	incompatible	incompatible
Airports or landing grounds for aircrafts (including helicopters)	incompatible	incompatible	incompatible	incompatible
Amusement centers	incompatible	incompatible	incompatible[6]	compatible
Automotive businesses	incompatible	incompatible	incompatible	compatible
Boat servicing	incompatible	incompatible	incompatible	compatible

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Dry cleaning premises	incompatible	incompatible	incompatible	compatible
Farm supply centers	incompatible	incompatible	incompatible[6]	compatible
Garden centers	incompatible	incompatible	incompatible[6]	compatible
Laboratories (analytical, photographic)	incompatible	incompatible	incompatible	compatible
Market halls	incompatible	incompatible	incompatible[6]	compatible
Mechanical servicing	incompatible	incompatible	incompatible[6]	compatible
Pesticide operator depots	incompatible	incompatible	incompatible	compatible
Restaurants and taverns	incompatible	incompatible	incompatible[6]	compatible
Shops and shopping centers	incompatible	incompatible	incompatible[6]	compatible
Transport & municipal works depots	incompatible	incompatible	incompatible	compatible
Vehicle wrecking and machinery	incompatible	incompatible	incompatible	incompatible
Used tire storage / processing / disposal facilities	incompatible	incompatible	incompatible	incompatible
Warehouses	incompatible	incompatible	incompatible[6]	compatible

Industrial Land Uses

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Heavy Industry	incompatible	incompatible	incompatible	incompatible
Light or general Industry	incompatible	incompatible	incompatible	incompatible
Petroleum refineries	incompatible	incompatible	incompatible	incompatible
Chemical manufacture / formulation	incompatible	incompatible	incompatible	incompatible
Dye works and tanneries	incompatible	incompatible	incompatible	incompatible
Metal production /finishing	incompatible	incompatible	incompatible	incompatible
Concrete / Cement production	incompatible	incompatible	incompatible	compatible

Urban Land Uses

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Buildings	incompatible	incompatible	incompatible[6]	compatible
Development zones	incompatible	incompatible	incompatible	compatible
Development and extensions of cemeteries for earth sepulture	incompatible	incompatible	incompatible	compatible
Development and extensions of cemeteries for urn sepulture	incompatible	incompatible	compatible	compatible
Hospitals, health centers	incompatible	incompatible	incompatible	compatible
Veterinary, dental centers	incompatible	incompatible	incompatible	compatible
Prisons	incompatible	incompatible	incompatible[6]	compatible
Drinking water treatment plants	incompatible	compatible[6]	compatible[6]	compatible

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Markets, trade fairs, festivals and other similar gatherings outside appropriate facilities	incompatible	incompatible	incompatible	compatible

Energy Generation and Electricity Conveyance Systems

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Power plants	Incompatible	incompatible	incompatible	incompatible[7]
Transformers and electricity lines holding cooling or insulating fluids possibly contaminating water	incompatible	incompatible	incompatible[5]	incompatible[8]

Land Uses related to Exploration, Mining and Mineral Processing

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Extractive industries (sand, clay, peat and rock) with excavations above groundwater table	incompatible	incompatible	incompatible	compatible
Extractive industries (sand, clay, peat and rock) with excavations below groundwater table	incompatible	incompatible	incompatible	incompatible
Mineral and energy source exploration	incompatible	incompatible	incompatible	incompatible[8]
Mineral and energy source exploitation	incompatible	incompatible	incompatible	incompatible
Mineral processing	incompatible	incompatible	incompatible	incompatible
Oil or gas extraction / decontamination for transport	incompatible	incompatible	incompatible	incompatible
Quarries, if groundwater cover is reduced substantially and above all, if groundwater is uncovered permanently or high groundwater level periods or cleaning strata are uncovered and groundwater cannot be protected adequately	incompatible	incompatible	incompatible	incompatible

Agricultural Land Uses - Animals

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Animal breeding if the number of animals implies a risk to the quality of groundwater because of the limited area on which they are kept and/or the limited area available for the disposal of manure	incompatible	incompatible	incompatible	compatible
Installation and extension of liquid manure containers, solid manure sites or silos	incompatible	incompatible	incompatible	compatible
Animal sale yards and stockyard	incompatible	incompatible	incompatible	compatible
Aquaculture	incompatible	incompatible	incompatible	compatible
Dairy sheds	incompatible	incompatible	incompatible	compatible
Livestock grazing, feedlots	incompatible	incompatible	compatible	compatible
Piggeries	incompatible	incompatible	incompatible	compatible
Poultry farming (housed)	incompatible	incompatible	incompatible	compatible
Stables	incompatible	incompatible	incompatible	compatible

Agricultural Land Uses - Plants

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Application of fertilizers	incompatible	incompatible	incompatible	incompatible[2]
Application of pesticides	incompatible	incompatible	incompatible	incompatible
Application of pesticides employing air-borne distribution methods	incompatible	incompatible	incompatible	incompatible
Application of liquid or solid manure or silage seepage on waste land	incompatible	incompatible	incompatible	incompatible
Application of liquid or solid manure or silage	incompatible	incompatible	compatible	compatible
Storage of liquid or solid manure or soluble fertilizer outside permanently sealed sites and silage production outside permanent silos	incompatible	incompatible	incompatible	incompatible[3]
Deforestation, plowing of legume-grass meadows and fallow	incompatible	incompatible	incompatible	incompatible
Spray irrigation in excess of field capacity	incompatible	incompatible	incompatible	incompatible
Broad land cropping i.e. non-irrigated	incompatible	incompatible	compatible	compatible
Orchards	incompatible	incompatible	compatible	compatible

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Horticulture	incompatible	incompatible	compatible	compatible
Floriculture	incompatible	incompatible	incompatible	compatible
Nurseries (potted plants)	incompatible	incompatible	incompatible	compatible
Silviculture (tree farming)	incompatible	incompatible	incompatible	compatible
Soil amendment (clean sand, loam, clay, eat)	incompatible	incompatible	compatible	compatible
Soil amendment (industry byproducts & biosolids)	incompatible	incompatible	incompatible	compatible
Viticulture (wine & table grapes)	incompatible	incompatible	incompatible	compatible

Agricultural Land Uses – Processing Facilities

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Animal product rendering works	incompatible	incompatible	incompatible	compatible
Abattoirs	incompatible	incompatible	incompatible	compatible
Dairy product factories	incompatible	incompatible	incompatible	compatible
Manure stockpiling / processing facilities	incompatible	incompatible	incompatible	compatible
Tanneries	incompatible	incompatible	incompatible	incompatible
Wool-scourers	incompatible	incompatible	incompatible	compatible
Vegetable / food processing	incompatible	incompatible	incompatible	incompatible
Breweries	incompatible	incompatible	incompatible	incompatible
Composting / soil blending commercial	incompatible	incompatible	incompatible	compatible
Forestry product processing- pulp & paper, timber reservation, or wood fiber works	incompatible	incompatible	incompatible	compatible
Wineries	incompatible	incompatible	incompatible	incompatible

Waste Water Facilities

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Sewers (gravity)	incompatible	incompatible	incompatible[1]	incompatible[1]
Sewers (pressure mains)	incompatible	incompatible	incompatible[1]	incompatible[1]
Sewage pump stations	incompatible	incompatible	incompatible	incompatible[1]
Wastewater treatment plants	incompatible	incompatible	incompatible	incompatible[1]
Wastewater application to land	incompatible	incompatible	incompatible	incompatible
Transportation of sewage or waste water	incompatible	incompatible	compatible	compatible
Installation or extension of sewage, waste water or storm water drains	incompatible	incompatible	incompatible[1]	incompatible[1]
Discharge of waste water	incompatible	incompatible	incompatible	incompatible

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
(other than treated precipitation) into surface water, flowing into Zone II				
Discharge of waste water (other than treated precipitation) into surface water, not flowing into Zone II	incompatible	incompatible	compatible	compatible
Release of waste water to the ground inclusive of sewage distribution fields other than drainage of uncontaminated precipitation and waste water from waste water treatment plants serving individual homes	incompatible	incompatible	incompatible	incompatible
Release of storm water (other than uncontaminated water from roofs) to the ground	incompatible	incompatible	compatible	compatible

Infiltration Facilities (of Unpolluted Waters)

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Infiltration of natural waters (with chemical composition uninfluenced by human activities) and facilities thereof	incompatible	incompatible	incompatible	compatible
Infiltration of waste waters (with chemical composition influenced by human activities) and facilities thereof	incompatible	incompatible	incompatible	incompatible

Waste Disposals, Storage Facilities, Temporary Storage Facilities and Pipelines

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Injection of liquid wastes into groundwater	incompatible	incompatible	incompatible	incompatible
Plants for the treatment and disposal of solid waste (other than plants for the handling and storage of such wastes)	incompatible	incompatible	incompatible	incompatible
Plants for handling and temporary storage of solid waste	incompatible	incompatible	incompatible	compatible
Sites for the storage of	incompatible	incompatible	incompatible	incompatible

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
residue from thermal power stations and incinerators, blast-furnace slag and foundry sand				
Sites for the disposal of contaminated and uncontaminated loose and solid rocks (such as tailings) if decomposition and leaching may affect groundwater	incompatible	incompatible	incompatible	incompatible
Sites for the disposal of uncontaminated loose and solid rocks where no leaching of hazardous substances may take place	incompatible	incompatible	incompatible	compatible
Disposal of sludge from sewage treatment plants or cesspools and disposal of compost	incompatible	incompatible	incompatible	incompatible
Storage of chemical fertilizers or pesticides	incompatible	incompatible	incompatible[9]	compatible
Storage or stockpiling of mining residue	incompatible	incompatible	incompatible	incompatible
Recycling facilities	incompatible	incompatible	incompatible	compatible
Recycling depots	incompatible	incompatible	incompatible	compatible
Fuel depots	incompatible	incompatible	incompatible	incompatible
Depots of liquid gas	incompatible	incompatible	compatible	compatible
Above ground storage of toxic / hazardous substances	incompatible	incompatible	incompatible[9]	compatible
Underground storage tanks for toxic / hazardous substances	incompatible	incompatible	incompatible	incompatible
Storage of fuel oil and diesel fuel	incompatible	incompatible	incompatible[9]	compatible
Storage of liquid gas	incompatible	incompatible	compatible	compatible
Pipelines carrying fluids which may contaminate water	incompatible	incompatible	incompatible	incompatible

Facilities related to Transportation by Automobiles (e.g. Tunnels, Petrol Stations, Car Parks, etc.)

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Roads and other similar facilities for transportation (except for trails)	incompatible	incompatible	compatible	compatible
Changes of facilities for	incompatible	incompatible	compatible	compatible

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
transportation, unless made to improve the protection of groundwater				
Release of storm water from roads or other transportation systems to the ground	incompatible	incompatible	incompatible[12]	incompatible[12]
Transportation of substances possibly contaminating groundwater or radioactive substances	incompatible	incompatible	compatible	compatible
Use of pesticides for vegetation control on transportation systems, unless groundwater is protected	incompatible	incompatible	incompatible	compatible
Transportation systems	incompatible	incompatible	incompatible[10]	compatible
Gasoline stations	incompatible	incompatible	incompatible[9]	compatible
Service stations	incompatible	incompatible	incompatible[8]	compatible
Vehicle parking (commercial)	incompatible	incompatible	incompatible[6]	compatible
Roads in tunnels	incompatible	incompatible	incompatible[6]	compatible
Unpaved roads or tracks for agricultural use only	incompatible	compatible	compatible	compatible
Unpaved roads or tracks for forestry only	incompatible	compatible	compatible	compatible

Construction Sites, Constructions of Buildings and Facilities above the Land Surface and Construction Changes thereof

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Construction and extension of buildings such as for commercial and agricultural use and changes in the use of buildings and structures	incompatible	incompatible	incompatible[6]	compatible
Sites for the storage of building materials which may contaminate groundwater	incompatible	incompatible	incompatible	incompatible
Temporary construction works	incompatible	incompatible	compatible	compatible
Construction /Mining camps	incompatible	incompatible	incompatible	compatible
Penetration of strata overlying groundwater, other than laying of buried utility lines and civil	incompatible	incompatible	incompatible	compatible

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
engineering excavations				
Laying of buried utility lines and civil engineering excavations	incompatible	incompatible	incompatible[11]	compatible
Drilling operations	incompatible	incompatible	incompatible	compatible
Development and extension of artificial bodies of water	incompatible	incompatible	incompatible	compatible

Activities related to Geothermal Energy (such as Drillings, Injection Facilities, etc.)

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Production of geothermal energy	incompatible	incompatible	incompatible	incompatible
Drilling of geothermal boreholes	incompatible	incompatible	incompatible	incompatible
Groundwater use for heating or cooling purposes (with abstraction and injection facilities)	incompatible	incompatible	incompatible	incompatible

Underground Constructions

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Development of underground facilities for storage of substances contaminating water	incompatible	incompatible	incompatible	incompatible

Recreational and Sports Facilities, Tourism Facilities

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Equestrian centers	incompatible	incompatible	incompatible	compatible
Golf courses	incompatible	incompatible	incompatible	incompatible
Permanent motor racing facilities	incompatible	incompatible	incompatible	incompatible
Motor racing	incompatible	incompatible	incompatible	compatible
Swimming pools	incompatible	incompatible	compatible	compatible
Recreational parks - irrigated	incompatible	incompatible	compatible	compatible
Rifle ranges	incompatible	incompatible	incompatible	incompatible
Caravan parks	incompatible	incompatible	compatible	compatible
Motels, hotels, lodging houses, hostels, resorts	incompatible	incompatible	incompatible	compatible
Clubs-sporting or recreation	incompatible	incompatible	compatible	compatible

Educational and Research Land Uses

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Community education centers	incompatible	incompatible	incompatible[6]	compatible
Primary / Secondary schools	incompatible	incompatible	incompatible[6]	compatible
Scientific research institutes	incompatible	incompatible	incompatible[6]	compatible
Tertiary Education Facilities	incompatible	incompatible	incompatible[6]	compatible

Military Sites and Shooting Ranges

Land use/Activity	Zone I	Zone II	Zone IIIA	Zone IIIB
Military training camps and casernes	incompatible	incompatible	incompatible	incompatible[6]
Military airfields	incompatible	incompatible	incompatible	incompatible
Military storage facilities of substances hazardous to groundwater	incompatible	incompatible	incompatible	incompatible
Military shooting ranges	incompatible	incompatible	incompatible	incompatible

Notes:

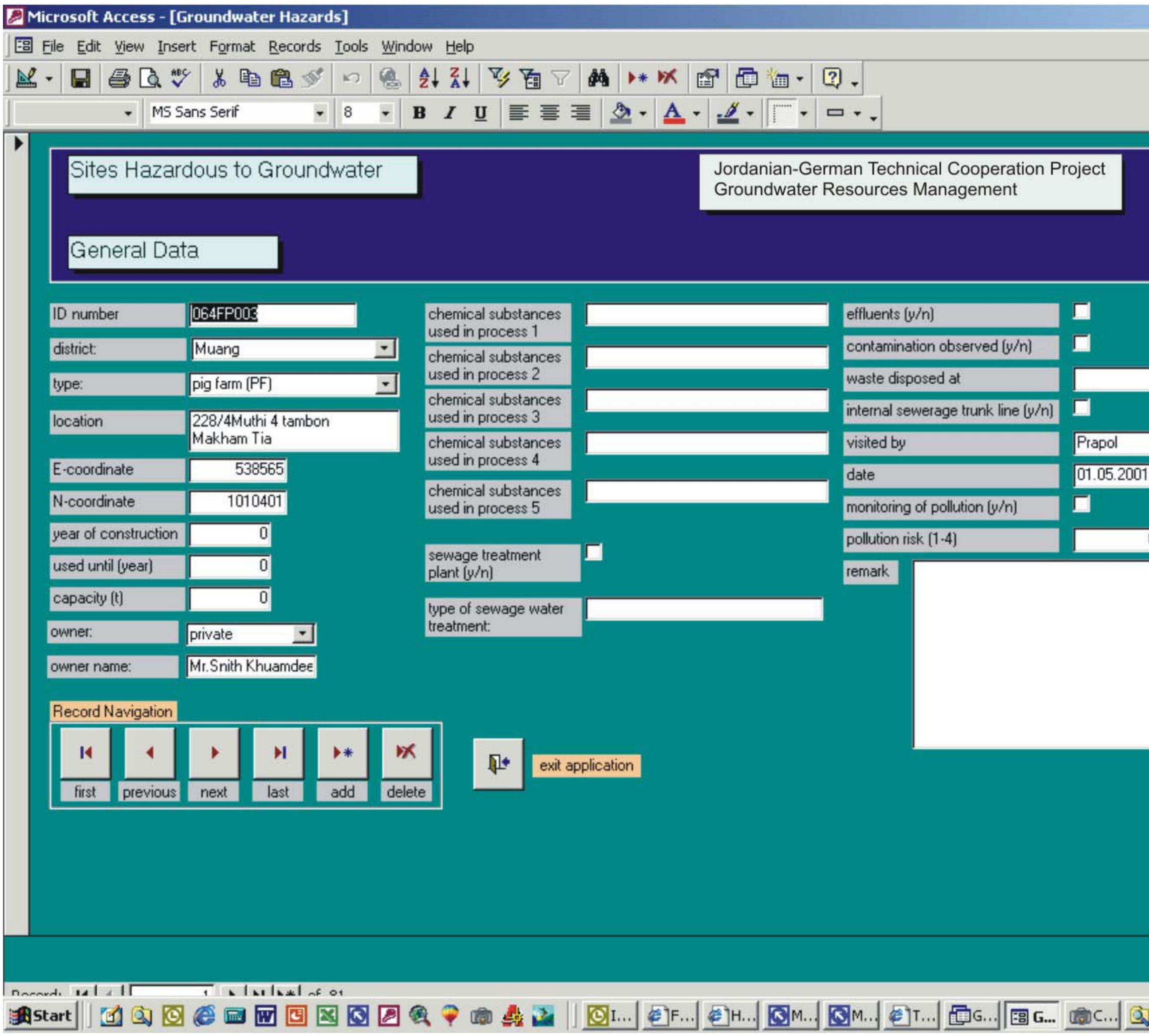
[1] unless checked for defects at regular intervals
[2] unless in keeping with good agricultural practices as regards timing and quantities
[3] excepting silage-making under plastic sheeting on tight base plates surrounded by retention basins
[4] except for minor quantities for residential use, storage of fuel oil for residential use and storage of diesel fuel for farming operations
[5] except for above ground lines or installations
[6] unless sewage and waste water other than uncontaminated precipitation are completely and safely piped outside
[7] unless gas-fired
[8] unless substances used are not hazardous to groundwater or technical loss of substances cannot occur
[9] unless technical loss of substances is proven not to occur (checks on regular basis)
[10] unless sewage and waste water other than uncontaminated precipitation are completely and safely piped outside
[11] unless no substances hazardous to groundwater are used and precautions are being taken against the infiltration of such substances into the ground
[12] except for embankment drainage and large distribution systems in ground with vegetation

Annex 5: Inventory Sheet of Potentially Contaminating Sites – Mapping of Hazards to Groundwater

The sheet is to be filled for each hazard to groundwater in the groundwater protection zone

Groundwater Protection Zone:	
TYPE & NO.	
NAME	
LOCATION	
COORDINATES	Palestine Grid-EAST : Palestine Grid-NORTH :
YEAR OF CONSTRUCTION	
USED UNTIL	
CAPACITY	
CHEMICAL SUBSTANCES USED IN PROCESS	
EFFLUENTS (yes/no)	
CONTAMINATION (yes/no)	
WASTE DISPOSED AT	
INTERNAL SEWERAGE SYSTEM (yes/no)	
CONNECTED TO MAIN SEWERAGE TRUNK LINE (yes/no)	
VISITED BY	
DATE	
MONITORING OF POLLUTION (yes/no)	
POLLUTION RISK, range of 1 - 4, 4 - pollution detected 3 - pollution highly probable 2 - mediocre pollution risk 1 - no risk of pollution	
REMARKS	

Annex 6: Input Form of ACCESS Database Hazards to Groundwater



Annex 7: Index of Potential Sources of Drinking Water Contamination

(Potential Source and Possibly Associated Contaminant)

POTENTIAL SOURCE	CONTAMINANT
Commercial / Industrial	
Above-ground storage tanks	Arsenic, Barium, Benzene, Cadmium, 1,4-Dichlorobenzene or P-Dichlorobenzene, cis 1,2-Dichloroethylene, tra Dichloroethylene, Dichloromethane or Methylene Chloride, Lead, Trichloroethylene (TCE), Tetrachloroethylene (Perc)
Automobile, Body Shops/Repair Shops	Arsenic, Barium, Benzene, Cadmium, Chlorobenzene, Copper, cis 1,2-Dichloroethylene, trans 1,2-Dichloroethy Dichlorobenzene or P-Dichlorobenzene, Lead, Fluoride, 1,1,1-Trichloroethane or Methyl Chloroform, Dichlorom Chloride, Tetrachloroethylene or Perchlorethylene (Perc), Trichloroethylene (TCE), Xylene (Mixed Isomers)
Boat Repair/Refinishing/Marinas	Benzene, Cadmium, cis 1,2-Dichloroethylene, Coliform, Cryptosporidium, Dichloromethane or Methylene Chlori Lead, Mercury, Nitrate, Nitrite, trans 1,2-Dichloroethylene, Tetrachloroethylene or Perchlorethylene (Perc), Tric Vinyl Chloride, Viruses
Cement/Concrete Plants	Barium, Benzene, Dichloromethane or Methylene Chloride, Ethylbenzene, Lead, Styrene, Tetrachloroethylene (Perc), Toluene, Xylene (Mixed Isomers)
Chemical/Petroleum Processing	Acrylamide, Arsenic, Atrazine, Alachlor, Aluminum (Fume or Dust), Barium, Benzene, Cadmium, Carbofuran, C Chlorobenzene, Copper, Cyanide, 2,4-D, 1,2-Dibromoethane or Ethylene Dibromide (EDB), 1,2-Dichlorobenzer Dichlorobenzene, 1,4-Dichlorobenzene or P-Dichlorobenzene, 1,1-Dichloroethylene or Vinylidene Chloride, cis Dichloromethane or Methylene Chloride, Di(2-ethylhexyl) adipate, Di(2-ethylhexyl) phthlate, 1,2-Dichloroethane Dioxin, Endrin, Epichlorohydrin, Ethylbenzene, Hexachlorobenzene, Hexachlorocyclopentadiene, Lead, Mercur Methoxychlor,Polychlorinated Biphenyls, Selenium, Styrene, Sulfate, Tetrachloroethylene or Perchlorethylene (Trichlorobenzene, 1,1,1-Trichloroethane or Methyl Chloroform, Trichloroethylene (TCE), Vinyl Chloride, Xylene (Fume or Dust)
Construction/Demolition	Arsenic, Asbestos, Benzene, Cadmium, Chloride, Copper,Cyanide, cis 1,2-Dichloroethylene, trans 1,2-Dichloro Dichloromethane or Methylene Chloride, Fluorides, Lead, Selenium, Tetrachloroethylene or Perchlorethylene (F Trichloroethane or Methyl Chloroform, Trichloroethylene (TCE), Turbidity, Xylene (Mixed Isomers), Zinc (Fume
Dry Cleaners/Dry Cleaning	Tetrachloroethylene or Perchlorethylene (Perc), 1,1,1-Trichloroethane or Methyl Chloroform, 1,1,2-Trichloroetha
Dry Goods Manufacturing	Barium, Benzene, Cadmium, Copper, Dichloromethane or Methylene Chloride, Di(2-ethylhexyl) phthlate, Lead, or Methyl Chloroform, Polychlorinated Biphenyls, Tetrachloroethylene or Perchlorethylene (Perc), Toluene, Tric Xylene (Mixed Isomers)
Electrical/Electronic Manufacturing	Aluminum (Fume or Dust), Antimony, Arsenic, Barium, Benzene, Cadmium, Chlorobenzene, Copper, Cyanide, 1,2-Dichlorobenzene or O-Dichlorobenzene, 1,2-Dichloroethane or Ethylene Dichloride, cis 1,2-Dichloroethylen Dichloroethylene, Dichloromethane or Methylene Chloride, Di(2-ethylhexyl) phthlate, Ethylbenzene, Lead, Merc Biphenyls, Selenium, Styrene, Sulfate, Tetrachloroethylene or Perchlorethylene (Perc), 1,1,1-Trichloroethane o 1,1,2-Trichloroethane, Trichloroethylene (TCE), Thallium, Toluene, Vinyl Chloride, Xylene (Mixed Isomers), Zin
Fleet/Trucking/ Bus Terminals	Arsenic, Acrylamide, Barium, Benzene, Benzo(a)pyrene, Cadmium, Chlorobenzene, Cyanide, Carbon Tetrachl Dichlorobenzene or O-Dichlorobenzene, 1,4-Dichlorobenzene or P-Dichlorobenzene, 1,2-Dichloroethane or Eth 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Dichloromethane or Methylene Chloride, Di(2-ethylhexyl) phth Heptachlor (and Epoxide), Lead, Mercury, Methoxychlor, Pentachlorophenol, Propylene Dichloride or 1,2-Dichlo Styrene, Toxaphene, Tetrachloroethylene or Perchlorethylene (Perc), Toluene, 1,1,1-Trichloroethane or Methyl Trichloroethylene (TCE), Vinyl Chloride, Xylene (Mixed Isomers)

POTENTIAL SOURCE	CONTAMINANT
Food Processing	Arsenic, Benzene, Cadmium, Copper, Carbon Tetrachloride, Dichloromethane or Methylene Chloride, Lead, Me Tetrachloroethylene or Perchlorethylene (Perc), Toluene, 1,1,1-Trichloroethane or Methyl Chloroform, Trichloro (Mixed Isomers)
Funeral Services/Taxidermy	Glyphosate, Dichloromethane or Methylene Chloride, Nitrate, Nitrite, Total Coliforms, Viruses
Furniture Repair/Manufacturing	Barium, 1,2-Dichloroethane or Ethylene Dichloride, Dichloromethane or Methylene Chloride, Ethylbenzene, Lea Trichloroethylene (TCE)
Gas Stations (see also above ground/underground storage tanks, motor-vehicle drainage wells)	cis 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Dichloromethane or Methylene Chloride, Tetrachloroethyle (Perc), Trichloroethylene (TCE)
Graveyards/Cemetaries	Dalapon, Lindane, Nitrate, Nitrite, Total Coliforms, Viruses.
Hardware/Lumber/Parts Stores	Aluminum (Fume or Dust), Barium, Benzene, Cadmium, Chlorobenzene, Copper, Dichloromethane or Methyler ethylhexyl)adipate, Di(2-ethylhexyl) phthlate, 1,4-Dichlorobenzene or P-Dichlorobenzene, Ethylbenzene, Lead, Tetrachloroethylene or Perchlorethylene (Perc), 1,1,1-Trichloroethane or Methyl Chloroform, Trichloroethylene (Mixed Isomers)
Historic Waste Dumps/Landfills	Atrazine, Alachlor, Carbofuran, cis 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Diquat, Dalapon, Glyphosa Methylene Chloride, Nitrate, Nitrite, Oxamyl (Vydate), Sulfate, Simazine, Tetrachloroethylene or Perchlorethyler Trichloroethylene(TCE)
Home Manufacturing	Arsenic, Barium, Benzene, Cadmium, Chlorobenzene, Copper, Carbon Tetrachloride, 1,2-Dichlorobenzene or C 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Dichloromethane or Methylene Chloride, Di(2-ethylhexyl) phth Lead, Mercury, Selenium, Styrene, Tetrachloroethylene or Perchlorethylene (Perc), 1,1,1-Trichloroethane or Me Trichloroethylene (TCE), Toluene, Turbidity, Xylene (Mixed Isomers)
Industrial Waste Disposal Wells (see UIC for more information on concerns, and locations)	Acrylamide, Arsenic, Atrazine, Alachlor, Aluminum (Fume or Dust), Ammonia, Barium, Benzene, Cadmium, Car Tetrachloride, Chlorobenzene, Copper, Cyanide, 2,4-D, 1,2-Dibromoethane or Ethylene Dibromide (EDB), 1,2-D Dichlorobenzene, 1,4-Dichlorobenzene or p-Dichlorobenzene, 1,1-Dichloroethylene or Vinylidene Chloride, cis Dichloromethane or Methylene Chloride, Di(2-ethylhexyl) adipate, Di(2-ethylhexyl) phthlate, 1,2-Dichloroethane Dioxin, Endrin, Epichlorohydrin, Hexachlorobenzene, Hexachlorocyclopentadiene, Lead, Mercury, Methoxychlo Polychlorinated Biphenyls, Selenium, Styrene, Sulfate, Tetrachloroethylene or Perchlorethylene (Perc), Toluene Trichlorobenzene, 1,1,1-Trichloroethane or Methyl Chloroform, Trichloroethylene (TCE), Vinyl Chloride, Xylene (Fume or Dust)
Junk/Scrap/Salvage Yards	Barium, Benzene, Copper, Dalapon, cis 1,2-Dichloroethylene, Diquat, Glyphosate, Lead, Polychlorinated Biphe Trichloroethylene (TCE), Tetrachloroethylene or Perchlorethylene (Perc)
Machine Shops	Arsenic, Aluminum (Fume or Dust), Barium, Benzene, Boric Acid, Cadmium, Chlorobenzene, Copper, Cyanide, 2,4-D, 1,4-Dichlorobenzene or P-Dichlorobenzene, 1,2-Dichloroethane or Ethylene Dichloride, 1,1-Dichloroethy Chloride, cis 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Dichloromethane or Methylene Chloride, Di(2-eth Ethylbenzene, Fluoride, Hexachlorobenzene, Lead, Mercury, Polychlorinated Biphenyls, Pentachlorophenol, Se Tetrachloroethylene or Perchlorethylene (Perc), Toluene, 1,1,1-Trichloroethane or Methyl Chloroform, 1,1,2-Tric Trichloroethylene (TCE), Xylene (Mixed Isomers), Zinc (Fume or Dust)
Medical/Vet Offices	Arsenic, Acrylamide, Barium, Benzene, Cadmium, Copper, Cyanide, Carbon Tetrachloride, Dichloromethane or 1,2-Dichloroethane or Ethylene Dichloride, Lead, Mercury, Methoxychlor, 1,1,1-Trichloroethane or Methyl Chlor Selenium, Silver, Tetrachloroethylene or Perchlorethylene (Perc), 2,4,5-TP (Silvex), Thallium, Xylene (Mixed Iso
Metal Plating/Finishing/Fabricating	Antimony, Aluminum (Fume or Dust), Arsenic, Barium, Benzene, Cadmium, Carbon Tetrachloride, Chlorobenze Copper, Cyanide, 1,4-Dichlorobenzene or P-Dichlorobenzene, cis 1,2-Dichloroethylene, trans 1,2-Dichloroethyl or Methylene Chloride, Di(2-ethylhexyl) adipate, Ethylbenzene,Lead, Mercury, Polychlorinated Biphenyls, Penta Selenium, Styrene, Sulfate, Tetrachloroethylene or Perchlorethylene (Perc), , Thallium, Toluene, 1,1,1-Trichloro Chloroform, 1,1,2-Trichloroethane, Trichloroethylene(TCE), Vinyl Chloride, Xylene (Mixed Isomers), Zinc (Fume

POTENTIAL SOURCE	**CONTAMINANT**
Military Installations	Arsenic, Barium, Benzene, Cadmium, Chlorobenzene, 1,2-Dichlorobenzene or O-Dichlorobenzene, 1,2-Dichlor Dichloride, cis 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Dichloromethane or Methylene Chloride, Hexa Mercury, Methoxychlor, 1,1,1-Trichloroethane or Methyl Chloroform, Radionuclides, Selenium, Tetrachloroethyl Perchlorethylene (Perc), , Toluene, Trichloroethylene (TCE)
Mines/Gravel Pits	Lead, Selenium, Sulfate, Tetrachloroethylene or Perchlorethylene (Perc), 1,1,1-Trichloroethane or Methyl Chlor
Motor Pools	cis 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Dichloromethane or Methylene Chloride,
Motor Vehicle Waste Disposal Wells (gas stations, repair shops) See UIC for more on concerns for these sources http://www.epa.gov/safewater/uic/cv-fs.html	Arsenic, Barium, Benzene, Cadmium, Chlorobenzene, Copper, cis 1,2-Dichloroethylene, trans 1,2-Dichloroethy Dichlorobenzene or P-Dichlorobenzene, Lead, Fluoride, 1,1,1-Trichloroethane or Methyl Chloroform, Dichlorom Chloride, Tetrachloroethylene or Perchlorethylene (Perc), Trichloroethylene (TCE), Xylene (Mixed Isomers)
Office Building/Complex	Barium, Benzene, Cadmium, Copper, 2,4-D, Diazinon, 1,2-Dichlorobenzene or O-Dichlorobenzene, Dichlorome Chloride, Diquat, 1,2-Dichloroethane or Ethylene Dichloride, Ethylbenzene, Glyphosate, Lead, Mercury, Seleni Tetrachloroethylene or Perchlorethylene (Perc), 1,1,1-Trichloroethane or Methyl Chloroform, Trichloroethylene Xylene (Mixed Isomers**)**
Photo Processing/Printing	Acrylamide, Aluminum (Fume or Dust), Arsenic, Barium, Benzene, Cadmium, Carbon Tetrachloride, Chloroben 1,1-Dichloroethylene or Vinylidene Chloride, cis 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Dichlorometh Chloride, Di(2-ethylhexyl) phthlate, 1,2-Dichlorobenzene or O-Dichlorobenzene, 1,4-Dichlorobenzene or P-Dich Dichloroethane or Ethylene Dichloride, 1,2-Dibromoethane or Ethylene Dibromide (EDB), Heptachlor epoxide, Lead, Lindane, Mercury, Methoxychlor, Propylene Dichloride or 1,2-Dichloropropane, Selenium, Styrene, Tetra Perchlorethylene (Perc), 1,1,1-Trichloroethane or Methyl Chloroform, Toluene, 1,1,2-Trichloroethane, Trichloro Chloride, Xylene (Mixed Isomers), Zinc (Fume or Dust)
Synthetic / Plastics Production	Antimony, Arsenic, Barium, Benzene, Cadmium, Carbon Tetrachloride, Chlorobenzene, Copper, Cyanide, 1,2-D Dichlorobenzene, 1,4-Dichlorobenzene or P-Dichlorobenzene, 1,2-Dichloroethane or Ethylene Dichloride, cis 1, trans 1,2-Dichloroethylene, Dichloromethane or Methylene Chloride, Di(2-ethylhexyl) adipate, Di(2-ethylhexyl) p Hexachlorobenzene, Lead, Mercury, Methyl Chloroform or 1,1,1-Trichloroethane, Pentachlorophenol, Selenium Tetrachloroethylene or Perchlorethylene (Perk), Toluene,, Trichloroethylene (TCE), Vinyl Chloride, Xylene (Mix (Fume or Dust)
RV/Mini Storage	Arsenic, Barium, Cyanide, 2,4-D, Endrin, Lead, Methoxychlor
Railroad Yards/Maintenance/Fueling Areas	Atrazine, Barium, Benzene, Cadmium, Dalapon, 1,4-Dichlorobenzene or P-Dichlorobenzene, cis 1,2-Dichloroet Dichloroethylene, Dichloromethane or Methylene Chloride, Lead, Mercury, Tetrachloroethylene or Perchlorethy Trichloroethylene (TCE).
Research Laboratories	Arsenic, Barium, Benzene, Beryllium Powder, Cadmium, Carbon Tetrachloride, Chlorobenzene, Cyanide, 1,2-D Ethylene Dichloride, 1,1-Dichloroethylene or Vinylidene Chloride, cis 1,2-Dichloroethylene, trans 1,2-Dichloroet Dichloromethane or Methylene Chloride, Endrin, Lead, Mercury, Polychlorinated Biphenyls, Selenium, Tetrachl Perchlorethylene (Perc), Thallium, Thiosulfates, Toluene, 1,1,1-Trichloroethane or Methyl Chloroform, Trichloro Chloride, Xylene (Mixed Isomers)
Retail Operations	Arsenic, Barium, Benzene, Cadmium, 2,4-D, 1,2-Dichloroethane or Ethylene Dichloride, Lead, Mercury, Styren or Perchlorethylene (Perc), Toluene, 1,1,1-Trichloroethane, Vinyl Chloride
Underground Storage Tanks	Arsenic, Barium, Benzene, Cadmium, 1,4-Dichlorobenzene or P-Dichlorobenzene, cis 1,2-Dichloroethylene, tra Dichloroethylene, Dichloromethane or Methylene Chloride, Lead, Tetrachloroethylene or Perchlorethylene (Per (TCE).
Wood Preserving/Treating	cis 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Lead, Sulfate

POTENTIAL SOURCE	CONTAMINANT
Wood/Pulp/Paper Processing	Arsenic, Barium, Benzene, Cadmium, Carbon Tetrachloride, Copper, Dichloromethane or Methylene Chloride, Dichloroethane or Ethylene Dichloride, Ethylbenzene, Lead, Mercury, Polychlorinated Biphenyls, Selenium, Sty Tetrachloroethylene or Perchlorethylene (Perc), Trichloroethylene (TCE), Toluene, 1,1,1-Trichloroethane or Me (Mixed Isomers)
Residential / Municipal	
Airports (Maintenance/Fueling Areas)	Arsenic, Barium, Benzene, Cadmium, Carbon Tetrachloride, cis 1,2- Dichloroethylene, Dichloromethane or Met Ethylbenzene, Lead, Mercury, Selenium, Tetrachloroethylene or Perchlorethylene (Perc), 1,1,1-Trichloroethane Trichloroethylene (TCE), Xylene (Mixed Isomers)
Apartments and Condominiums	Atrazine, Alachlor, Coliform, Cryptosporidium, Dalapon, Diquat, *Giardia Lambia*, Glyphosate, Nitrate, Nitrite, Picloram,Sulfate,Simazine, Vinyl Chloride, Viruses
Camp Grounds/RV Parks	Benomyl, Coliform, Cryptosporidium, Diquat, Dalapon, *Giardia Lambia*, Glyphosate, Isopropanol, Nitrate, Nitrite Picloram,Sulfate,Simazine, Turbidity, Vinyl Chloride, Viruses
Cesspools - Large Capacity (see UIC for more information)	Atrazine, Alachlor, Carbofuran, Coliform, Cryptosporidium, Diquat, Dalapon, *Giardia Lambia*, Glyphosate, Nitrat (Vydate), Picloram,Sulfate,Simazine, Vinyl Chloride, Viruses
Drinking Water Treatment Facilities	Atrazine, Benzene, Cadmium, Cyanide, Fluoride, Lead, Polychlorinated Biphenyls, Toluene, Total Trihalometha Trichloroethane or Methyl Chloroform
Gas Pipelines	cis 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Dichloromethane or Methylene Chloride, Tetrachloroethyle (Perc), Trichloroethylene or TCE
Golf Courses and Urban Parks	Arsenic, Atrazine, Benzene, Chlorobenzene, Carbofuran, 2,4-D, Diquat, Dalapon, Glyphosate, Lead, Methoxycl Picloram, Simazine, Turbidity
Housing developments	Atrazine, Alachlor, Coliform, Cryptosporidium, Carbofuran, Diquat, Dalapon, *Giardia Lambia*, Glyphosate, Dichl Methylene Chloride, Nitrate, Nitrite, Picloram, Simazine, Trichloroethylene (TCE), Turbidity, Vinyl Chloride, Viru
Landfills/Dumps	Arsenic, Atrazine, Alachlor, Barium, Benzene, Cadmium, Carbofuran, cis 1,2 Dichloroethylene, Diquat, Glyphos Mercury, 1,1,1-Trichloroethane or Methyl Chloroform, Dichloromethane or Methylene Chloride, Nitrate, Nitrite, F Simazine, Trichloroethylene (TCE)
Public Buildings (e.g., schools, town halls, fire stations, police stations) and Civic Organizations	Arsenic, Acrylamide, Barium, Benzene, Beryllium Powder, Cadmium, Carbon Tetrachloride, Chlorobenzene, Cy Dichlorobenzene or O-Dichlorobenzene, 1,4-Dichlorobenzene or P-Dichlorobenzene, Dichloromethane or Meth ethylhexyl) phthlate, 1,2-Dichloroethane or Ethylene Dichloride, Endothall, Endrin, 1,2-Dibromoethane or Ethyle Lead, Lindane, Mercury, Methoxychlor, Selenium, Toluene, 1,1,1-Trichloroethane or Methyl Chloroform, Trichlo Chloride, Xylene (Mixed Isomers)
Septic Systems	Atrazine, Alachlor, Carbofuran, Coliform, Cryptosporidium, Diquat, Dalapon, *Giardia Lambia*, Glyphosate, Nitrat (Vydate), Picloram, Sulfate, Simazine, Vinyl Chloride, Viruses
Sewer Lines	Coliform, Cryptosporidium, Diquat, Dalapon, *Giardia Lambia*, Glyphosate, Nitrate, Nitrite, Oxamyl (Vydate), Picl Vinyl Chloride, Viruses
Stormwater infiltration basins/injection into wells (UIC Class V), runoff zones	Atrazine, Alachlor, Coliform, Cryptosporidium, Carbofuran, Chlorine, Diquat, Dalapon, *Giardia Lambia*, Glyphos or Methylene Chloride, Nitrate, Nitrite, Nitrosamine, Oxamyl (Vydate), Phosphates, Picloram, Simazine, Trichlor Turbidity, Vinyl Chloride, Viruses
Transportation Corridors (e.g., Roads, railroads)	Dalapon, Picloram, Simazine, Sodium, Sodium Chloride, Turbidity
Utility Stations	Arsenic, Barium, Benzene, Cadmium, Chlorobenzene, Cyanide, 2,4-D, 1,4-Dichlorobenzene or P-Dichlorobenz Dichloroethane or Ethylene Dichloride, cis 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Dichloromethane o Lead, Mercury, Picloram, Toluene, 1,1,2,2- Tetrachloroethane, Tetrachloroethylene or Perchlorethylene (Perc), (TCE), Xylene (Mixed Isomers)
Waste Transfer /Recycling	Coliform, Cryptosporidium, *Giardia Lambia*, Nitrate, Nitrite, Vinyl Chloride, Viruses

POTENTIAL SOURCE	CONTAMINANT
Wastewater Treatment Facilities/Discharge locations (incl. land disposal and underground injection of sludge)	Cadmium, Coliform, Cryptosporidium, cis 1,2-Dichloroethylene, trans 1,2-Dichloroethylene, Dichloromethane or Fluoride, *Giardia Lambia*, Lead, Mercury, Nitrate, Nitrite, Tetrachloroethylene or Perchlorethylene (Perc) Seleni sulfate,Trichloroethylene (TCE), Vinyl Chloride, Viruses
Agricultural / Rural	
Auction Lots/Boarding Stables	Coliform, Cryptosporidium, *Giardia Lambia*, Nitrate, Nitrite,Sulfate,Viruses
Animal Feeding Operations/ Confined Animal Feeding Operations	Coliform, Cryptosporidium, *Giardia Lambia*, Nitrate, Nitrite, Sulfate, Turbidity, Viruses
Bird Rookeries/Wildlife feeding /migration zones	Coliform, Cryptosporidium, *Giardia Lambia*, Nitrate , Nitrite , Sulfate, Turbidity, Viruses
Crops - Irrigated + Non-irrigated	Benzene, 2,4-D, Dalapon, Dinoseb, Diquat, Glyphosate, Lindane, Lead, Nitrate, Nitrite , Picloram, Simazine, Tu
Dairy operations	Coliform, Cryptosporidium, *Giardia Lambia*, Nitrate , Nitrite,Sulfate,Turbidity, Viruses
Drainage Wells, Lagoons and Liquid Waste Disposal - Agricultural	Atrazine, Alachlor, Coliform, Cryptosporidium, Carbofuran, Diquat, Dalapon, *Giardia Lambia*, Glyphosate, Nitrat (Vydate), Picloram,Sulfate,Simazine, Vinyl Chloride, Viruses
Managed Forests/Grass Lands	Atrazine, Diquat, Glyphosate, Picloram, Simazine, Turbidity
Pesticide/Fertilizer Storage Facilities	Atrazine, Alachlor, Carbofuran, Chlordane, 2,4-D, Diquat, Dalapon, 1,2-Dibromo-3-Chloropropane or DBCP, Gl Nitrite, Oxamyl (Vydate), Picloram, Simazine, 2,4,5-TP (Silvex)
Rangeland/Grazing lands	Coliform, Cryptosporidium, *Giardia Lambia*, Nitrate, Nitrite, Sulfate, Turbidity, Viruses
Residential Wastewater lagoons	Atrazine, Alachlor, Carbofuran, Coliform, Cryptosporidium, Diquat, Dalapon, *Giardia Lambia*, Glyphosate, Nitrat (Vydate), Picloram,Sulfate,Simazine, Vinyl Chloride, Viruses
Rural Homesteads	Atrazine, Alachlor, Carbofuran, Coliform, Cryptosporidium, cis 1,2-Dichloroethylene, trans 1,2-Dichloroethylene *Giardia Lambia*, Glyphosate, Nitrate, Nitrite,Oxamyl (Vydate), Picloram, Sulfate, Simazine, Vinyl Chloride, Virus
MISCELLANEOUS SOURCES	
Abandoned drinking water wells (conduits for contamination)	Atrazine, Alachlor, Coliform, Cryptosporidium, Carbofuran, Diquat, Dalapon, *Giardia Lambia*, Glyphosate, Dichl Methylene Chloride, Nitrate, Nitrite, Oxamyl (Vydate), Picloram, Simazine, Trichloroethylene (TCE), Turbidity, V
Naturally Occurring	Arsenic, Asbestos, Barium, Cadmium, Chromium, Coliform, Copper, Cryptosporidium, Fluoride, *Giardia Lambi* Manganese, Mercury, Nitrate, Nitrite, Radionuclides, Selenium, Silver, Sulfate, Viruses, Zinc (Fume or Dust)
Underground Injection Control (UIC) Wells CLASS I - deep injection of hazardous and non-hazardous wastes into aquifers separated from underground sources of drinking water	see UIC (link: http://www.epa.gov/safewater/types)
UIC Wells CLASS II deep injection wells of fluids associated with oil/gas production (for more detailed list of sites click here)	see UIC
UIC Wells CLASS III re-injection of water/steam into mineral formations for mineral extraction	see UIC
UIC Wells CLASS IV - officially banned. Inject hazardous or radioactive waste into or above underground sources of drinking	see UIC

POTENTIAL SOURCE	CONTAMINANT
water	
UIC Wells Class V (SHALLOW INJECTION WELLS). Click here for more information on sources of UIC Class V wells	see UIC

Source: US Environmental Protection Agency (http://www.epa.gov/safewater/swp/sources1.html)

Annex 8: Potential Drinking Water Contaminant Index

(Contaminants, Maximum Allowable Contents and Potential Sources)

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	Potential Source(s)	
PRIMARY DRINKING WATER CONTAMINANTS*				
Inorganic Contaminants				
Antimony	0.006	0.006	**Commercial / Industrial**	Electrical / Electronic Manufacturing, Fire Retardents, Metal Petroleum Processing, Synthetics / Plastics Production
Arsenic	0.05	None	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Chemical / Petroleu Demolition, Electrical / Electronic Manufacturing, Fleet / Truc Processing, Home Manufacturing, Machine Shops, Medical Finishing / Fabricating, Military Installations, Photo Processi Retail Operations, Wood / Pulp / Paper Processing
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Golf Courses and P Buildings and Civic Organizations, Schools, Utility Stations
			Agricultural/Rural	Orchards, Hebicides, Erosion of Natural Deposits
Asbestos	7 million fibers per Liter	7 million fibers per Liter	**Commercial / Industrial**	Construction / Demolition, Erosion of natural deposits
Barium	2	2	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Cement / Concrete Processing, Dry Goods Manufacturing, Electrical / Electroni Bus Terminals, Furniture Repair / Manufacturing, Hardware Manufacturing, Junk / Scrap / Salvage Yards, Machine Sho Medical / Vet Offices, Metal Plating / Finishing / Fabricating, Processing / Printing, Railroad Yards / Maintenance / Fuelin Retail Operations, Synthetics / Plastics Production, Undergr Paper Processing
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Landfills / Dumps, P Organizations, RV / Mini Storage, Utility Stations, Erosion of
Beryllium Powder	0.004	0.004	**Commercial / Industrial**	Research Laboratories, Metal Plating/Finishing/Fabricating, Electrical/Electronic Manufacturing, Aerospace and Defense

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	**Potential Source(s)**	
			Residential / Municipal	Public Buildings and Civic Organizations, Schools
Cadmium	0.005	0.005	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Boat Repair / Refin Processing, Construction / Demolition, Drinking Water Treat Electrical / Electronic Manufacturing, Fleet / Trucking / Bus T Hardware / Lumber / Parts Stores, Home Manufacturing, Ma Finishing / Fabricating, Military Installations, Office Building / Printing, Medical / Vet Offices, Railroad Yards / Maintenance Laboratories, Retail Operations, Synthetics / Plastics Produc Wood / Pulp / Paper Processing
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Landfills / Dumps, P Organizations, Schools, Utility Stations, Wastewater
Chromium	0.1	0.1	**Commercial / Industrial**	Metal Plating / Finishing / Fabricating, Erosion of natural dep
Copper	TT[3]	1.3	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Chemical / Petroleu Demolition, Dry Goods Manufacturing, Electrical / Electronic Hardware / Lumber / Parts Stores, Home Manufacturing, Jun Shops, Medical / Vet Offices, Metal Plating / Finishing / Fabr Photo Processing / Printing, Synthetics / Plastics Producers, Pulp / Paper Processing , Erosion of natural deposits
Cyanide	0.2	0.2	**Commercial / Industrial**	Chemical / Petroleum Processing, Construction / Demolition Manufacturing, Fertilizer Factories, Fleet / Trucking / Bus Te Vet Offices, Metal Plating / Finishing / Fabricating, Photo Pro Laboratories, Synthetics / Plastics Producers
			Residential / Municipal	Waste Water Treatment, Public Buildings and Civic Organiz Utility Stations
Fluoride	4	4	**Commercial / Industrial**	Construction / Demolition, Fertilizer Factories, Aluminum Fa
			Residential/Municipal	Drinking Water Treatment additive, Erosion natural deposits
Lead	TT	0.015	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Boat Repair / Refin Chemical / Petroleum Processing, Construction / Demolition Electrical / Electronic Manufacturing, Fleet / Trucking / Bus T Furniture Repair / Manufacturing, Hardware / Lumber / Parts Scrap / Salvage Yards, Machine Shops, Medical / Vet Office Fabricating, Military Installations, Mines / Gravel Pits, Office Processing / Printing, Railroad Yards / Maintenance / Fuelin Retail Operations, Synthetics / Plastics Producers, Undergro Distribution Activities, Wood Preserving / Treating, Wood / P

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	**Potential Source(s)**	
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Drinking Water Pipe Landfills / Dumps, Public Buildings and Civic Organizations, Wastewater, Erosion of natural deposits
Inorganic Mercury	0.002	0.002	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Boat Repair / Refin Processing, Electrical / Electronic Manufacturing, Fleet / Tru Processing, Furniture Repair / Manufacturing, Hardware / Lu Manufacturing, Machine Shops, Office Building / Complex, F Vet Offices, Metal Plating / Finishing / Fabricating, Military In Maintenance / Fueling Areas, Research Laboratories, Retail Producers, Wood / Pulp / Paper Processing
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Landfills / Dumps, P Organizations, RV / Mini Storage, Schools, Utility Stations, W
			Agricultural / Rural	Crops - Irrigated + Non irrigated, Erosion of Natural Deposits
Nitrate	10	10	**Commercial / Industrial**	Boat Repair / Refinishing, Historic Waste Dumps / Landfills
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks, Landfills / Dumps, Septic Systems Waste Transfer / Recyclin
			Agricultural / Rural	Auction Lots / Boarding Stables, Confined Animal Feeding C irrigated, Lagoons and Liquid Waste, Pesticide / Fertilizer / P Homesteads , Erosion of Natural Deposits
Nitrite	1	1	**Commercial / Industrial**	Boat Repair / Refinishing, Historic Waste Dumps / Landfills
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks, Landfills / Dumps, Septic Systems, Waste Transfer / Recycli
			Agricultural / Rural	Auction Lots / Boarding Stables, Confined Animal Feeding C Waste, Pesticide / Fertilizer / Petroleum Storage Sites, Rura Non irrigated, Erosion of Natural Deposits
Selenium			**Commercial / Industrial**	Chemical / Petroleum Processing, Construction / Demolition Manufacturing, Fleet / Trucking / Bus Terminals, Furniture R Manufacturing, Machine Shops, Medical / Vet Offices, Metal Military Installations, Mines / Gravel Pits, Office Building / Co Research Laboratories, Synthetics / Plastics Producers, Wo Erosion of Natural Deposits
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Landfills / Dumps, P Organizations, Schools, Wastewater
Thallium	0.002	0.0005	**Commercial / Industrial**	Electrical / Electronic Manufacturing, Medical / Vet Offices, M Research Laboratories
Organic Contaminants				

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	**Potential Source(s)**	
Acrylamide	TT	zero	**Residential/Municipal**	Drinking Water and Waste Water Treatment
Alachlor	0.002	zero	**Commercial / Industrial**	Chemical / Petroleum Processing, Historic Waste Dumps / L
			Residential / Municipal	Apartments and Condominiums, Housing, Injection Wells, La Wells
			Agricultural / Rural	Injection Wells, Lagoons and Liquid Waste, Pesticide / Fertil Homesteads
Atrazine	0.003	0.003	**Commercial / Industrial**	Chemical / Petroleum Processing, Funeral Services / Grave Landfills, Injection Wells, Office Building / Complex, Railroad
			Residential / Municipal	Apartments and Condominiums, Some Surface Water Drink and Parks, Housing, Injection Wells, Landfills / Dumps, Scho Wells
			Agricultural / Rural	Injection Wells, Lagoons and Liquid Waste, Managed Fores Storage Sites, Rural Homesteads
Benzene	0.005	zero	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Boat Repair / Refin Chemical / Petroleum Processing, Construction / Demolition Electrical / Electronic Manufacturing, Fleet / Trucking / Bus T Hardware / Lumber / Parts Stores, Home Manufacturing, Jur Shops, Medical / Vet Offices, Metal Plating / Finishing / Fabr Building / Complex, Photo Processing / Printing, Railroad Ya Research Laboratories, Retail Operations, Synthetic / Plastic Producers, Underground Storage Tanks, Wholesale Distribu Processing
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Drinking Water Trea Landfills / Dumps, Public Buildings and Civic Organizations,
			Agricultural / Rural	Crops - Irrigated + Non irrigated
Benzo(a)pyrene	0.0002	zero	**Commercial / Industrial**	Fleet / Trucking / Bus Terminals
Carbofuran	0.04	0.04	**Commercial / Industrial**	Chemical / Petroleum Processing, Historic Waste Dumps / L
			Residential / Municipal	Golf Courses and Parks, Housing, Injection Wells, Landfills /
			Agricultural / Rural	Injection Wells, Lagoons and Liquid Waste, Pesticide / Fertil Homesteads, Rice and Alfalfa Fields
Carbon Tetrachloride	0.005	zero	**Commercial / Industrial**	Chemical / Petroleum Processing, Electrical / Electronic Mar Terminals, Food Processing, Home Manufacturing, Machine Plating / Finishing / Fabricating, Photo Processing / Printing, Plastics Producers, Wood / Pulp / Paper Processing
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Public Buildings and
Chlordane	0.002	zero	**Agricultural / Rural**	Pesticide / Fertilizer / Petroleum Storage Sites

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	**Potential Source(s)**	
Chlorobenzene	0.1	0.1	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Chemical / Petroleu Manufacturing, Fleet / Trucking / Bus Terminals, Hardware / Manufacturing, Machine Shops, Metal Plating / Finishing / F Photo Processing / Printing, Research Laboratories, Synthe
			Residential / Municipal	Golf Courses and Parks, Public Buildings and Civic Organiz
2,4-D	0.07	0.07	**Commercial / Industrial**	Chemical / Petroleum Processing, Fleet / Trucking / Bus Ter Operations, Office Building / Complex
			Agricultural / Rural	Crops - Irrigated + Non irrigated, Pesticide / Fertilizer / Petro
			Residential / Municipal	Golf Courses and Parks, Public Buildings and Civic Organiz Utility Stations
Dalapon	0.2	0.2	**Commercial / Industrial**	Historic Waste Dumps / Landfills, Injection Wells, Junk / Scr
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks Systems, Transportation Corridors, Utility Stations, Wells, G
			Agricultural / Rural	Crops - Irrigated + Non irrigated, Injection Wells, Lagoons a / Petroleum Storage Sites, Rural Homesteads
Di(2-ethylhexyl) adipate	0.4	0.4	**Commercial / Industrial**	Chemical / Petroleum Processing, Hardware / Lumber / Part Fabricating, Synthetics / Plastics Producers
Di(2-ethylhexyl) phthalate	0.006	zero	**Commercial / Industrial**	Chemical / Petroleum Processing, Dry Goods Manufacturin Manufacturing, Fleet / Trucking / Bus Terminals, Hardware / Manufacturing, Machine Shops, Photo Processing / Printing
			Residential / Municipal	Public Buildings and Civic Organizations
Dibromochloropropane	0.0002	zero	**Agricultural / Rural**	Pesticide / Fertilizer / Petroleum Storage Sites; Soybeans, C
1,2-Dibromoethane or Ethylene Dibromide (EDB)	0.00005	zero	**Commercial / Industrial**	Chemical / Petroleum Processing, Photo Processing / Printi
			Residential / Municipal	Public Buildings and Civic Organizations
1,4-Dichlorobenzene or P-Dichlorobenzene	0.075	0.075	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Chemical / Petrole Terminals, Hardware / Lumber / Parts Stores, Machine Sho Fabricating, Photo Processing / Printing, Railroad Yards / M Synthetics / Plastics Producers, Underground Storage Tank

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	Potential Source(s)	
			Residential / Municipal	Public Buildings and Civic Organizations, Schools Utility Sta
1,2-Dichlorobenzene or O-Dichlorobenzene	0.6	0.6	**Commercial / Industrial**	Chemical / Petroleum Processing, Electrical / Electronic Mar Terminals, Home Manufacturing, Military Installations, Photo Plastics Production, Office Building / Complex
1,2-Dichloroethane or Ethylene Dichloride	0.005	zero	**Commercial / Industrial**	Chemical / Petroleum Processing, Electrical / Electronic Mar Terminals, Furniture Repair / Manufacturing, Machine Shops Installations, Office Building / Complex, Photo Processing / P Production, Research Laboratories, Retail Operations
			Residential / Municipal	Public Buildings and Civic Organizations, Schools, Wood / F Stations
			Residential / Municipal	Public Buildings and Civic Organizations, Schools
1,1-Dichloroethylene or Vinylidene Chloride	0.007	0.007	**Commercial / Industrial**	Chemical / Petroleum Processing, Machine Shops, Photo Processing / Printing, Research Laboratories
cis 1,2 - Dichloroethylene	0.07	0.07	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Chemical / Petroleu Demolition, Electrical / Electronic Manufacturing, Fleet / Truc Historic Waste Dumps / Landfills, Home Manufacturing, Injec Yards, Machine Shops, Metal Plating / Finishing / Fabricatin Photo Processing / Printing, Synthetic / Plastics Production, Laboratories, Wood Preserving / Treating
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Injection Wells, Lanc Wastewater
			Agricultural / Rural	Injection Wells, Rural Homesteads
trans 1,2 - Dichloroethylene			**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Chemical / Petroleu Demolition, Electrical / Electronic Manufacturing, Fleet / Truc Historic Waste Dumps / Landfills, Home Manufacturing, Injec Yards, Machine Shops, Metal Plating / Finishing / Fabricatin Photo Processing / Printing, Synthetic / Plastics Production, Laboratories, Wood Preserving / Treating
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Injection Wells, Lanc Wastewater
			Agricultural / Rural	Injection Wells

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	**Potential Source(s)**	
Dichloromethane or Methylene Chloride	0.005	zero	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Cement / Concrete Processing, Construction / Demolition, Dry Goods Manufact Manufacturing, Funeral Services / Graveyards, Fleet / Truck Processing, Gas Stations, Hardware / Lumber / Parts Stores Shops, Medical / Vet Offices, Metal Plating / Finishing / Fabr Pools, Office Building / Complex, Photo Processing / Printin Fueling Areas, Research Laboratories, Synthetics / Plastics Processing
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Public Buildings and
Dinoseb	0.007	0.007	**Agricultural / Rural**	Crops - Irrigated + Non irrigated, Soybeans and vegetables
Dioxin	3E-08	zero	**Commercial / Industrial**	Chemical / Petroleum Processing, Wood / Pulp / Paper Proc
Diquat	0.02	0.02	**Commercial / Industrial**	Funeral Services / Graveyards, Historic Waste Dumps / Lan Injection Wells, Office Building / Complex
			Residential / Municipal	Apartments and Condominiums, Housing, Injection Wells, La Systems, Wells, Camp Grounds / RV Parks, Golf Courses a
			Agricultural / Rural	Crops - Irrigated + Non irrigated, Injection Wells, Lagoons ar Pesticide / Fertilizer / Petroleum Storage Sites, Rural Homes
Endothall	0.1	0.1	**Residential / Municipal**	Injection Wells, Public Buildings and Civic Organizations, Sc
Endrin	0.002	0.002	**Commercial / Industrial**	Chemical / Petroleum Processing, Research Laboratories
			Residential / Municipal	Public Buildings and Civic Organizations, RV / Mini Storage,
Ethylbenzene	0.7	0.7	**Commercial / Industrial**	Cement / Concrete Plants, Chemical / Petroleum Processing Manufacturing, Furniture Repair / Manufacturing, Hardware Manufacturing, Machine Shops, Metal Plating / Finishing / Fa Synthetics / Plastics Producers, Wood / Pulp / Paper Proces
			Residential / Municipal	Airports (Maintenance / Fueling Areas)
Glyphosate	0.7	0.7	**Commercial / Industrial**	Funeral Services / Graveyards, Historic Waste Dumps / Lan Salvage Yards, Office Building / Complex
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks, Injection Wells, Landfills / Dumps, Schools, Septic Systems,
			Agricultural / Rural	Crops - Irrigated + Non irrigated, Injection Wells, Lagoons ar Pesticide / Fertilizer / Petroleum Storage Sites, Rural Homes
Heptachlor (and Epoxide)	0.0004	zero	**Commercial / Industrial**	Fleet / Trucking / Bus Terminals, Photo Processing / Printin

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	Potential Source(s)	
	-0.0002			
			Residential / Municipal	Wells
Hexachlorobenzene	0.001	zero	**Commercial / Industrial**	Chemical / Petroleum Processing, Machine Shops, Military I Printing, Synthetics / Plastics Producers
Hexachlorocyclopentadiene	0.05	0.05	**Commercial / Industrial**	Chemical / Petroleum Processing
Lindane	0.0002	0.0002	**Commercial / Industrial**	Construction / Demolition, Fleet / Trucking / Bus Terminals,
			Residential / Municipal	Landfills / Dumps, Public Buildings and Civic Organizations
			Agricultural / Rural	Crops - Irrigated + Non irrigated
Methoxychlor	0.04	0.04	**Commercial / Industrial**	Chemical / Petroleum Processing, Fleet / Trucking / Bus Ter Installations, Photo Processing / Printing
			Residential / Municipal	Golf Courses and Parks, Public Buildings and Civic Organiz
Oxamyl (Vydate)	0.2	0.2	**Commercial / Industrial**	Chemical / Petroleum Processing, Historic Waste Dumps / L
			Residential / Municipal	Apartments and Condominiums, Housing, Injection Wells, La Wells
			Agricultural / Rural	Injection Wells, Lagoons and Liquid Waste, Pesticide / Fertil Homesteads , apple, potato, and tomato farming
Pentachlorophenol	0.001	zero	**Commercial / Industrial**	Fleet / Trucking / Bus Terminals, Food Processing, Machine Fabricating, Synthetics / Plastics Producers
Picloram	0.5	0.5	**Commercial / Industrial**	Historic Waste Dumps / Landfills, Injection Wells
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks, Injection Wells, Landfills / Dumps, Septic Systems, Transpo Wells
			Agricultural / Rural	Crops - Irrigated + Non irrigated, Injection Wells, Lagoons a Pesticide / Fertilizer / Petroleum Storage Sites, Rural Home
Polychlorinated Biphenyls	0.0005	zero	**Commercial / Industrial**	Chemical / Petroleum Processing, Dry Goods Manufacturin Manufacturing, Junk / Scrap / Salvage Yards, Machine Sho Fabricating, Research Laboratories, Wood / Pulp / Paper Pr
			Residential / Municipal	Drinking Water Treatment
Propylene Dichloride or 1,2-Dichloropropane	0.005	zero	**Commercial / Industrial**	Fleet / Trucking / Bus Terminals, Photo Processing / Printin

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	**Potential Source(s)**	
Simazine	0.004	0.004	**Commercial / Industrial**	Historic Waste Dumps / Landfills, Injection Wells, Junk / Scr Complex
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks, Injection Wells, Landfills / Dumps, Septic Systems, Transpo Wells
			Agricultural / Rural	Crops - Irrigated + Non irrigated, Lagoons and Liquid Waste Fertilizer / Petroleum Storage Sites, Rural Homesteads
Styrene	0.1	0.1	**Commercial / Industrial**	Cement / Concrete Plants, Chemical / Petroleum Processin Manufacturing, Fleet / Trucking / Bus Terminals, Home Man Plating / Finishing / Fabricating, Photo Processing / Printing, Plastics Producers, Wholesale Distribution Activities, Wood
Tetrachloroethylene or Perchlorethylene (Perc)	0.005	zero	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Cement / Concrete Processing, Construction / Demolition, Drinking Water Treat Dry Goods Manufacturing, Electrical / Electronic Manufactur Food Processing, Gas Stations, Hardware / Lumber / Parts S Landfills, Home Manufacturing, Injection Wells, Junk / Scrap Medical / Vet Offices, Metal Plating / Finishing / Fabricating, Pits, Motor Pools, Office Building / Complex, Photo Processi Maintenance / Fueling Areas, Research Laboratories, Retail Producers, Wood / Pulp / Paper Processing
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Injection Wells, Pub Schools, Utility Stations, Wastewater
Toluene	1	1	**Commercial / Industrial**	Cement / Concrete Plants, Chemical / Petroleum Processin Goods Manufacturing, Electrical / Electronic Manufacturing, Food Processing, Hardware / Lumber / Parts Stores, Home Medical / Vet Offices, Metal Plating / Finishing / Fabricating, Laboratories, Synthetics / Plastics Producers, Retail Operati Photo Processing / Printing, Wood / Pulp / Paper Processin
			Residential / Municipal	Public Buildings and Civic Organizations, Schools, Utility St
Total Trihalomethanes	0.1	None	**Residential / Municipal**	Drinking Water Treatment
Toxaphene	0.003	zero	**Commercial / Industrial**	Fleet / Trucking / Bus Terminals
2,4,5-TP (Silvex)	0.05	0.05	**Commercial / Industrial**	Medical / Vet Offices
			Agricultural / Rural	Pesticide / Fertilizer / Petroleum Storage Sites

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	**Potential Source(s)**	
1,2,4-Trichlorobenzene	0.07	0.07	**Commercial / Industrial**	Chemical / Petroleum Processing
1,1,2-Trichloroethane	0.005	0.003	**Commercial / Industrial**	Dry Cleaners / Dry Cleaning, Electrical / Electronic Manufact / Finishing / Fabricating, Photo Processing / Printing
1,1,1-Trichloroethane or Methyl Chloroform	0.2	0.2	**Commercial / Industrial**	Body Shops/Repair Shops, Chemical / Petroleum Processin Goods Manufacturing, Electrical / Electronic Manufacturing, Food Processing, Hardware / Lumber / Parts Stores, Home Medical / Vet Offices, Metal Plating / Finishing / Fabricating, Pits, Office Building / Complex, Photo Processing / Printing, Operations, Wholesale Distribution Activities, Wood / Pulp /
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Construction / Demo Treatment, Landfills / Dumps, Naturally Occurring, Public Bu Schools
Trichloroethylene or TCE	0.005	zero	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Chemical / Petroleu Manufacturing, Electrical / Electronic Manufacturing, Fleet / Processing, Furniture Repair / Manufacturing, Hardware / Lu Dumps / Landfills, Home Manufacturing, Injection Wells, Jun Shops, Metal Plating / Finishing / Fabricating, Military Install Complex, Photo Processing / Printing, Railroad Yards / Mai Laboratories, Synthetics / Plastics Producers, Underground Processing
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Injection Wells, Pub Schools, Utility Stations
Vinyl Chloride	0.002	zero	**Commercial / Industrial**	Boat Repair / Refinishing, Chemical / Petroleum Processing Manufacturing, Metal Plating / Finishing / Fabricating, Office Processing / Printing, Fleet / Trucking / Bus Terminals, Rese Operations, Synthetic / Plastics Production
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks Organizations, Septic Systems, Waste Transfer / Recycling
			Agricultural / Rural	Confined Animal Feeding Operations Lagoons and Liquid W
Xylene (Mixed Isomers)	10	10	**Commercial / Industrial**	Automobile Body Shops / Repair Shops, Cement / Concrete Processing,

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	**Potential Source(s)**	
				Construction / Demolition, Dry Goods Manufacturing, Electri Trucking / Bus Terminals, Food Processing, Hardware / Lum Manufacturing, Machine Shops, Medical / Vet Offices, Metal Office Building / Complex, Photo Processing / Printing, Rese Plastics Production, Wood / Pulp / Paper Processing
			Residential / Municipal	Airports (Maintenance / Fueling Areas), Public Buildings and Stations,
Micro-Organisms				
Coliform	5.0%[4]	Zero	**Commercial / Industrial**	Boat Repair / Refinishing
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks, Transfer / Recycling, Wastewater
			Agricultural / Rural	Auction Lots / Boarding Stables, Confined Animal Feeding C Waste, Rural Homesteads
Cryptosporidium			**Commercial / Industrial**	Boat Repair / Refinishing
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks, Transfer / Recycling, Wastewater
			Agricultural / Rural	Auction Lots / Boarding Stables, Confined Animal Feeding C Liquid Waste Dsiposal Sites, Rural Homesteads, Wildlife fee
Giardia Lambia			**Commercial / Industrial**	Boat Repair / Refinishing
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks, Transfer / Recycling, Wastewater
			Agricultural / Rural	Auction Lots / Boarding Stables, Confined Animal Feeding C Waste, Rural Homesteads,
Legionella	zero	TT	**All**	Surface Water
Viruses	TT	N/A	**Commercial / Industrial**	Waste Water
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks, Transfer / Recycling, Wastewater
			Agricultural / Rural	Auction Lots / Boarding Stables, Confined Animal Feeding C Lagoons and Liquid Waste, Rural Homesteads, Wildlife mig
Turbidity	TT	N/A	**Commercial / Industrial**	Construction / Demolition, Home Manufacturing, Mines / Gra
			Residential / Municipal	Camp Grounds / RV Parks, Golf Courses and Parks, Housin Stormwater discharge sites, Transportation Corridors
			Agricultural / Rural	Crops - Irrigated + Non irrigated, Managed Forests, Animal g feedlots, Dairies

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	**Potential Source(s)**	
Radionuclides				
Beta particles and photon emitters*	Beta: 4 millirems per year;	none	**Commercial / Industrial**	Medical / Vet Offices, Military Installations, Naturally Occurri
Gross Alpha particle activity	15 pCi/L per year;	none	same as above	same as above
Radium 226 & Radium 228 (combined)	5 pCi/L per year	none	same as above	same as above
SECONDARY DRINKING WATER CONTAMINANTS				
Contaminant Name	**MCL (mg/L)**	**MCLG[2] (if applicable) (mg/L)**	**Potential Source(s)**	
Aluminum (Fume or Dust)		0.05 to 0.2	**Commercial / Industrial**	Chemical / Petroleum Processing, Electrical / Electronic Ma Parts Stores, Machine Shops, Metal Plating / Finishing / Fab
Chloride		250	**Commercial / Industrial**	Construction / Demolition
Iron		0.3	**Commercial / Industrial**	Historic Waste Dumps / Landfills, Junk / Scrap / Salvage Ya
			Residential / Municipal	Naturally Occurring
			Agricultural / Rural	Naturally Occurring
Manganese		0.05	**Commercial / Industrial**	Historic Waste Dumps / Landfills, Junk / Scrap / Salvage Ya
			Residential / Municipal	Naturally Occurring
Silver		0.1	**Commercial / Industrial**	Medical / Vet Offices, Naturally Occurring
			Residential / Municipal	Naturally Occurring
			Agricultural / Rural	Naturally Occurring
Sulfate		250	**Commercial / Industrial**	Chemical / Petroleum Processing, Electrical / Electronic Ma Landfills, Metal Plating / Finishing / Fabricating, Mines / Gra Injection Wells, Junk / Scrap / Salvage Yards
			Residential / Municipal	Apartments and Condominiums, Camp Grounds / RV Parks Wastewater, Wells, Naturally Occuring
			Agricultural / Rural	Auction Lots / Boarding Stables, Confined Animal Feeding C and Liquid Waste, Rural Homesteads, Naturally Occuring

Contaminant Name	MCL 1 (mg/L)	MCLG2 (if applicable) (mg/L)	**Potential Source(s)**	
Total Dissolved Solids		500		
Zinc (Fume or Dust)		5	**Commercial / Industrial**	Chemical / Petroleum Processing, Construction / Demolition Manufacturing, Machine Shops, Metal Plating / Finishing / F Printing, Synthetic / Plastics Production

Notes:

[1]MCL - Maximum Contaminant Level; the maximum permissable level of a contaminant in water which is delivered to any user of a public water system standards. Listed in Milligrams per Liter (Mg/L) unless otherwise noted.

[2]MCLG – Maximum Contaminant Level Goal; the maximum level of a contaminant in drinking water at which no known or anticipated adverse effect on and which allows for an adequate margin of safety. MCLGs are non-enforceable public health goals. Listed in Milligrams per Liter (Mg/L) unless other

[3]TT- Treatment Technique

[4] No more than 5.0% of samples should detect total coliforms in one month. Every system that detects total coliform must be analyzed for fecal coliform

Source: US Environmental Protection Agency (http://www.epa.gov/safewater/swp/sources1.html)

Annex 9: Example for an Application of the GLA-Method in Jordan: The Groundwater Vulnerability Map of the Irbid Area, Northern Jordan

The Groundwater Vulnerability Map of the Irbid Area was established by the Jordanian-German Technical Cooperation Project Ádvisory Services to the Water Authority of Jordan – Groundwater Resources of Northern Jordan' (MARGANE et al., 1997, MARGANE et al., 1999, MARGANE et al., 2002).

The map covers an area of approximately 1,500 km^2. The Irbid area is characterized by sequences of limestone units interbedded with marl units. Rainfall is high in the mountainous area, reaching up to 500 mm/a and more, whereas it is low in the eastern part that becomes increasingly arid (hardly exceeding 150 mm/a). Therefore, groundwater recharge highly varies throughout the area.

As can be seen on *Figure 9-1*, groundwater vulnerability is high or very high in much of the outcrop area of the limestone units (B4 aquifer and A7/B2 aquifer). The high vulnerability in these areas is confirmed by the high level of bacteriological contamination (especially in the B4 aquifer) and the high nitrate contents. The present water supply strongly depends on the Wadi al Arab well field, which is located around 15 km west of Irbid, near the Jordan Valley. This well field is at risk to become polluted by sewage water from the city of Irbid and surrounding communities. The establishment of a groundwater protection zone for this well field and the implementation of land use restrictions is of highest priority. The intention of the new Technical Cooperation Project 'Groundwater Resources Management' is to establish this groundwater protection zone (MARGANE & SUNNA, 2002) and help implementing the required actions in order to preserve this important groundwater resource.

For the establishment of recommendations, the compilation of a map of hazards to groundwater (*Figure 9-2*), using the legend proposed by VRBA & ZAPOROZEC (1994) and the availability of piezometric maps of all relevant aquifers proved to be highly valuable.

Figure 9-1: Groundwater Vulnerability Map of the Irbid Area, Northern Jordan

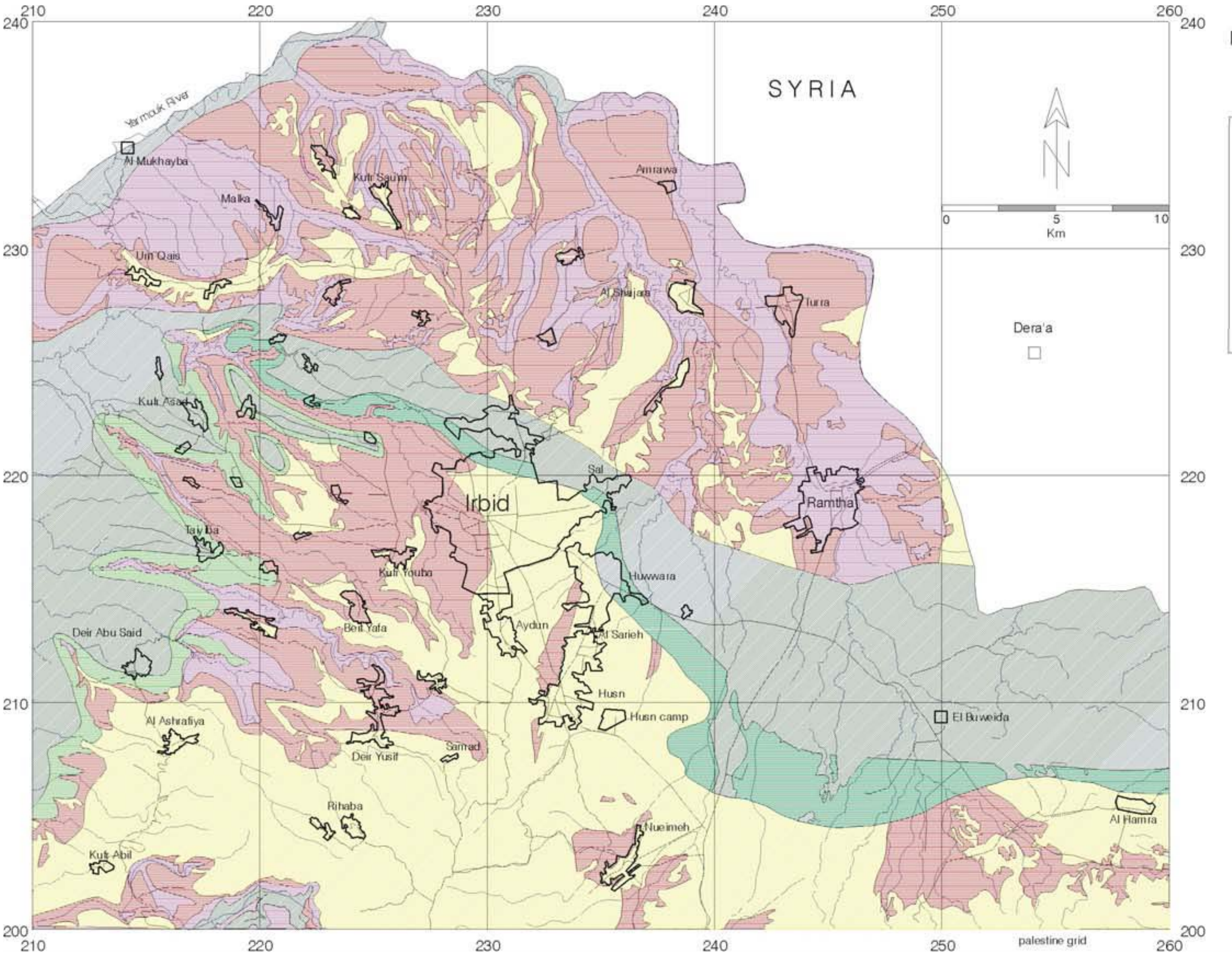
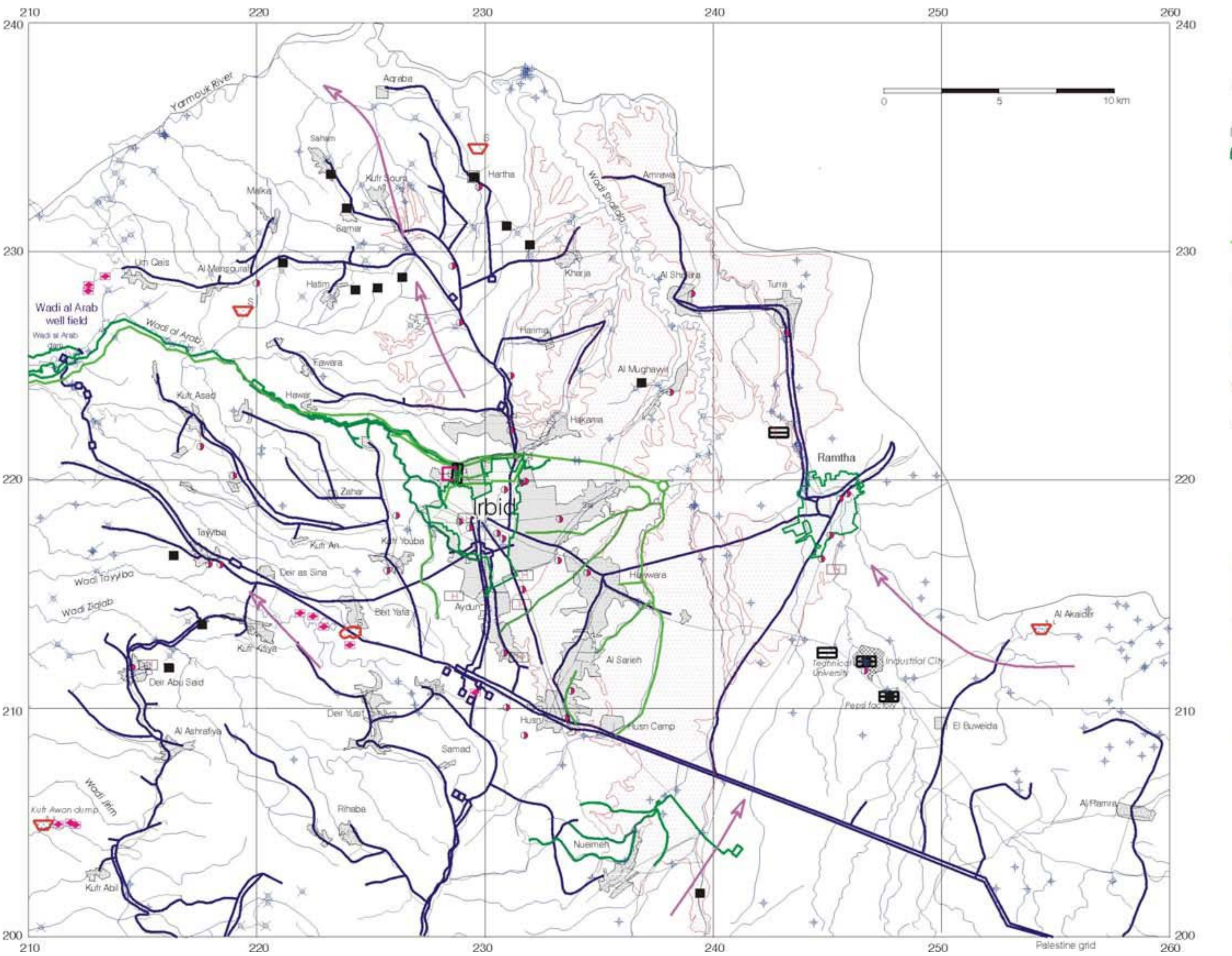


Figure 9-2: Map of Hazards to Groundwater of the Irbid Area, Northern Jordan



Annex 10: Example for an Application of the GLA-Method in Syria: The Groundwater Vulnerability Map of the Ghouta Plain, Central Syria

The groundwater vulnerability map of the Ghouta Plain was compiled by the Technical Cooperation Project 'Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region' (HOBLER & RAJAB, 2002).

Groundwater withdrawal in Damascus and the Ghouta plain contributes essentially to the water supply of the city and the surrounding areas. However, rapidly increasing water demand, deteriorating groundwater recharge conditions and a succession of dry years led to severe over-pumping of the aquifers in recent years. Springs and shallow wells dried up in many areas and the productivity of water wells decreased. Lack of water now seriously affects agricultural production, especially in the southern and eastern parts of the area. Furthermore, most of the surface water is heavily polluted. Human activities like the disposal of untreated industrial effluents into rivers and channels, the use of polluted or insufficiently treated water for irrigation, uncontrolled garbage disposal and intensive use of fertilizers and pesticides endanger the quality of the groundwater.

Nowadays most of the domestic wastewater of Damascus is pumped to a treatment plant in Adra, about 15 - 20 km northeast of the city. From there, the treated wastewater is pumped back to the northern and central part of the Ghouta and used for irrigation. The problem remains, however, that groundwater withdrawal far exceeds the average annual recharge in large parts of the Ghouta and a sustainable use of the groundwater resources seems impossible without substantial changes in the management and protection of the resources.

Due to the high protective effectiveness of the soils in the Ghouta Plain, contamination of the groundwater by heavy metals and organic compounds still appears to be rather low in most parts of the study area. But pollution problems are increasing and there is a very real risk that some of the scarce water resources are being lost for domestic and even agricultural water supply due to pollution problems. Nitrate contents in the groundwater already by far exceed the permissible values for drinking water of 40 mg/l in many locations.

Based on the results of vulnerability mapping (*Figure 10-1*), recommendations for reducing the risks of groundwater contamination have been listed. Implementation of these recommendations would improve the prospects for a more sustainable use of the water resources. In general it can be stated that waste disposal sites and uncontrolled handling of contaminating substances should be avoided by any means in areas of high groundwater vulnerability. Areas less sensitive to pollution can be taken into consideration as 'search areas' for the identification of suitable locations for hazardous activities.

Limestones and conglomerates in the adjacent mountain ranges north of the city form productive aquifers and their outcrop areas should be seen as high-risk areas. The use of abandoned limestone quarries for garbage disposal poses a very serious threat to the groundwater and should therefore be stopped immediately (e.g. El Tal waste disposal site).

In the ACSAD – BGR Cooperation Project the evaluation of the groundwater vulnerability has been combined with studies of the vulnerability of the soils and the present status of soil contamination (for details see Vol. 3 of the project reports). In general, the vulnerability of the Ghouta soils can be classified as relatively low. Areas of comparatively higher soil vulnerability have been delineated in the central part of the pilot area. In large parts, these areas coincide with areas, where the protective effectiveness of the unsaturated zone above the aquifer is low too. In some of these areas, e.g. the tannery area at the eastern outskirts of the city, the hazards of groundwater pollution have to be considered as high.

Concerns about water pollution and environmental problems are increasing in the relevant governmental institutions and the population. Efforts however, to actively protect the groundwater resources are still insufficient.

Figure 10-1: Groundwater Vulnerability Map of the Ghouta Plain, Central Syria

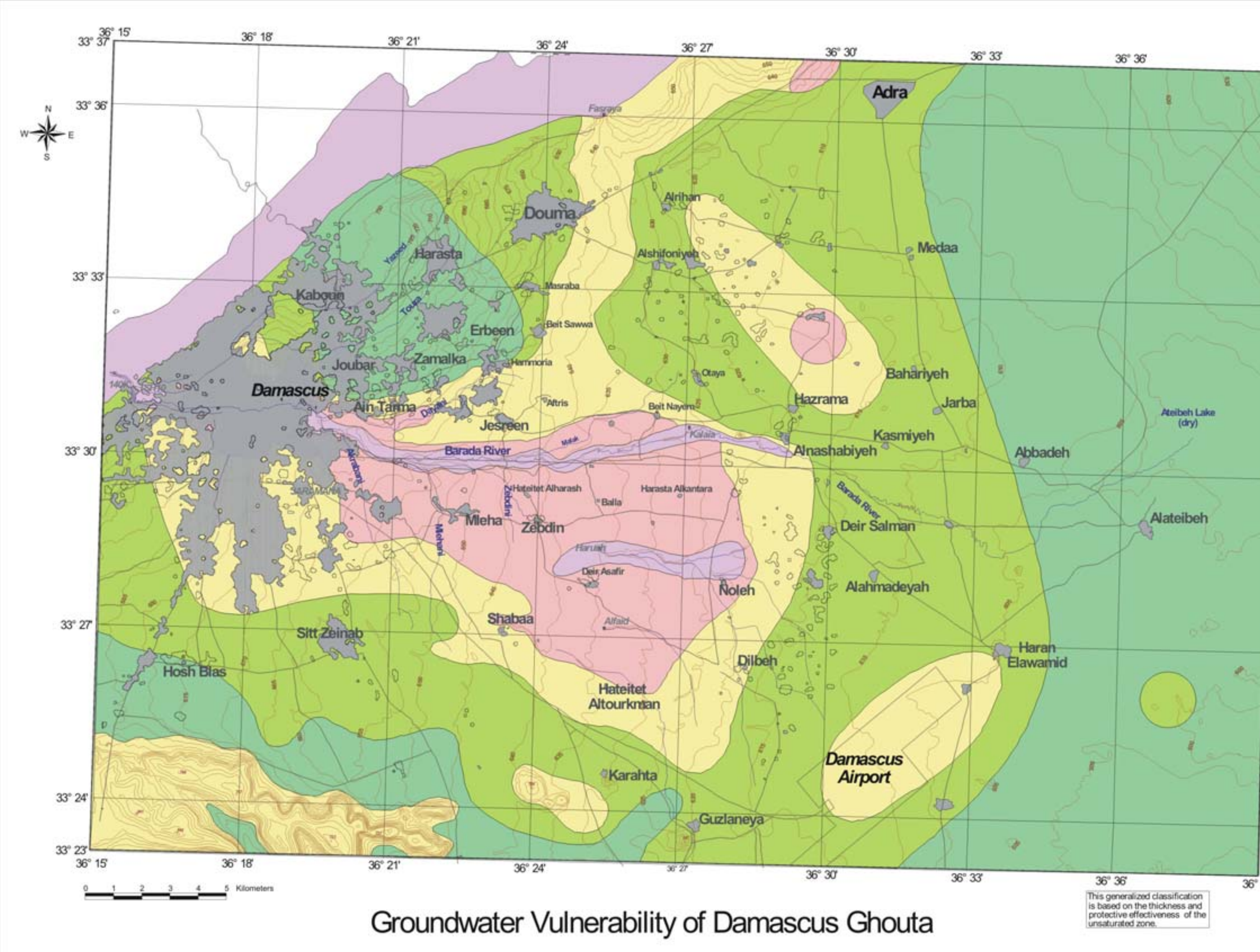
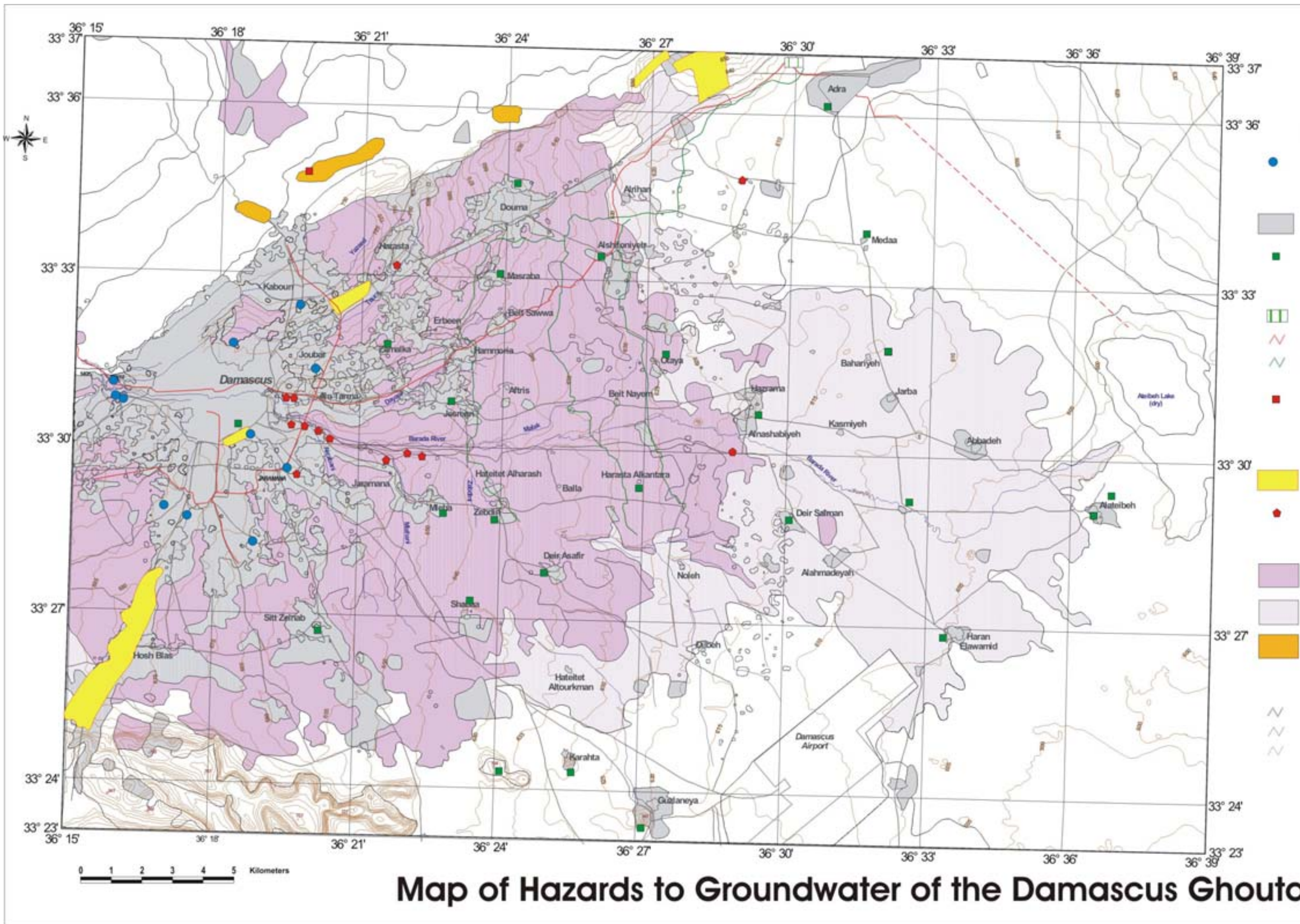


Figure 10-2: Map of Hazards to Groundwater of the Ghouta Plain, Central Syria



Annex 11: Example for an Application of the DRASTIC-Method in Egypt: The Groundwater Vulnerability Map of the Western Nile Delta, Northern Egypt

A groundwater vulnerability of the western Nile Delta area was prepared by the Research Institute for Groundwater (RIGW), Egypt, using DRASTIC (KHATER, pers. comm.). The DRASTIC method was modified to achieve a result that reflects the observed groundwater quality impact.

The hydrogeological conditions are such that some of the DRASTIC parameters do not really have an influence on the groundwater vulnerability, such as the topography (which is generally flat) and the recharge (which, concerning natural recharge, is distributed evenly throughout the area). Important for the evaluation of groundwater vulnerability are only the parameters: depth to groundwater, aquifer media, soil media, clay thickness (representing the impact of the vadose zone) and hydraulic conductivity.

In order to obtain a vulnerability map that better reflects the observed groundwater quality impact, recorded groundwater pollution events (samples, where one or more parameters exceed the drinking water standards) were also taken into consideration. Both maps, the one using the 'classic' and the one using the 'modified' approach, are shown in *Figures 11-1 and 11-2.*

Figure 11-1: Groundwater Vulnerability Map of the Western Nile Delta, Northern Egypt using the Classical DRASTIC Approach

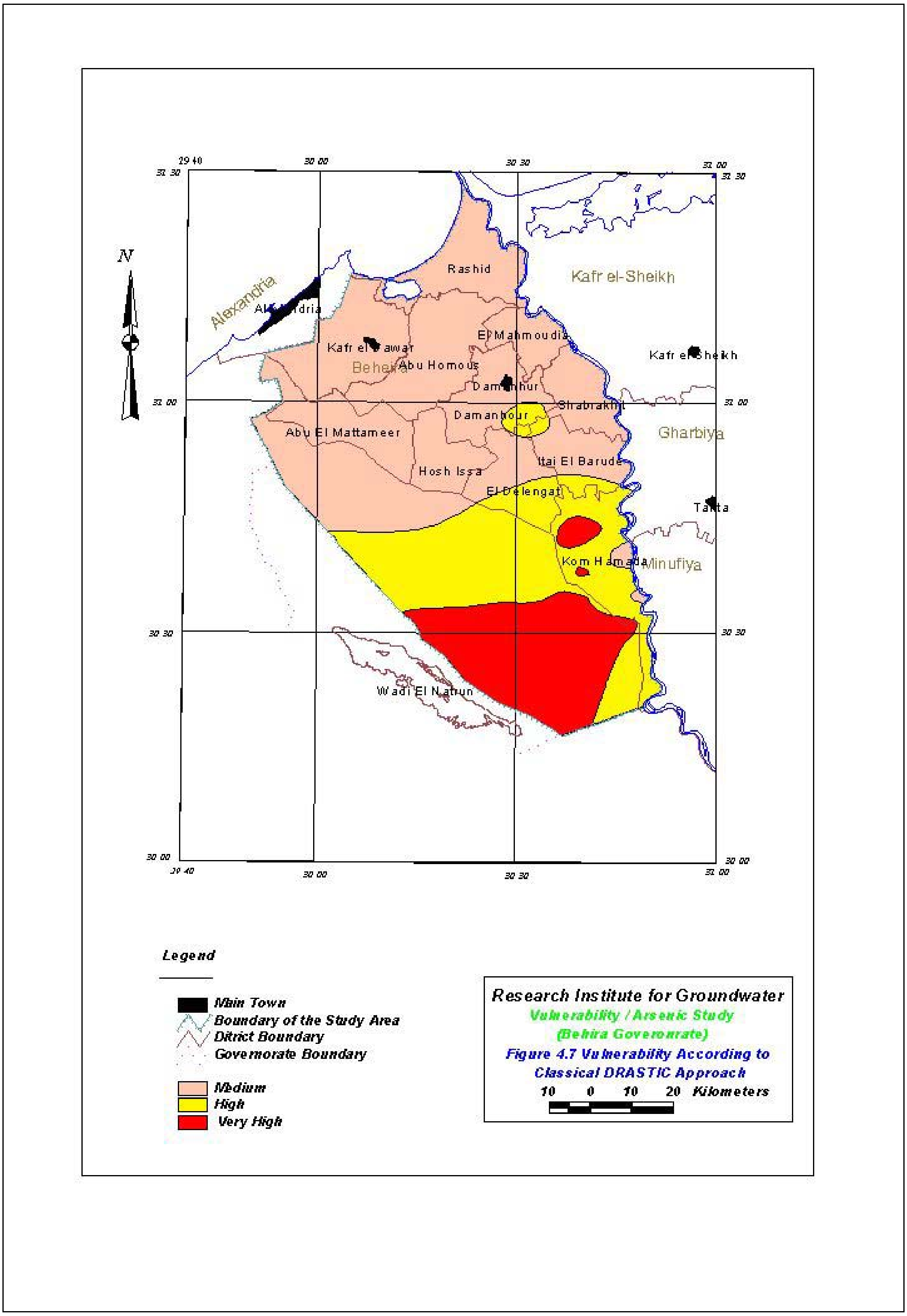


Figure 11-2: Groundwater Vulnerability Map of the Western Nile Delta, Northern Egypt using a Modified DRASTIC Approach