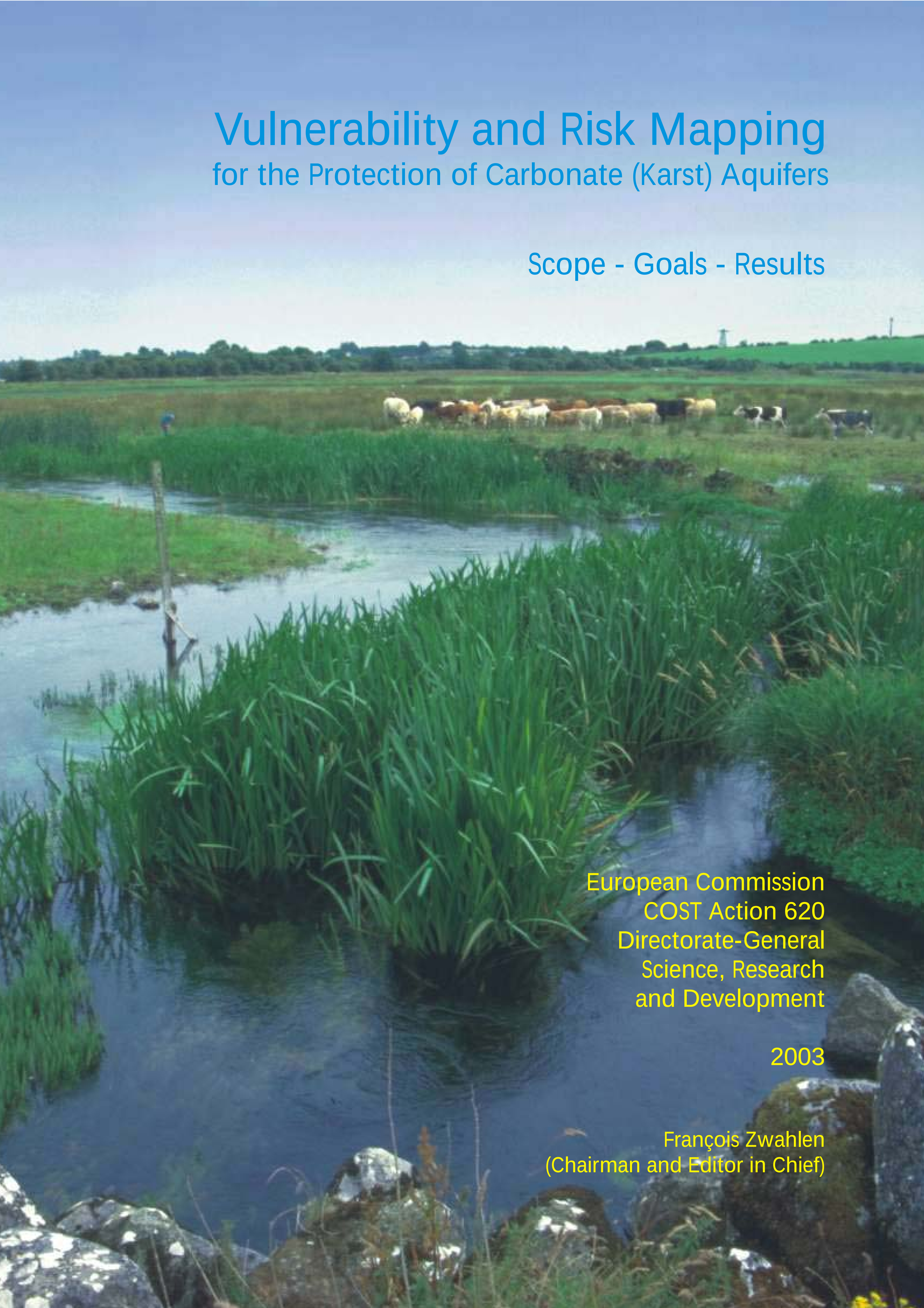

Vulnerability and Risk Mapping

for the Protection of Carbonate (Karst) Aquifers

Scope - Goals - Results

European Commission
COST Action 620
Directorate-General
Science, Research
and Development

2003

François Zwahlen
(Chairman and Editor in Chief)

Karst pond, Bodensee, Nassfeld, Carinthia, Austria
photo: M. von Hoyer

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Preface

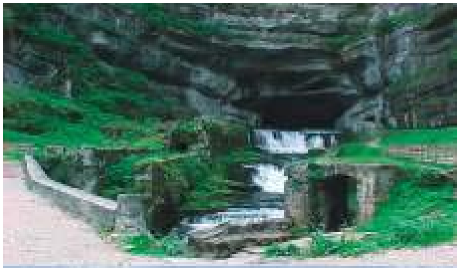
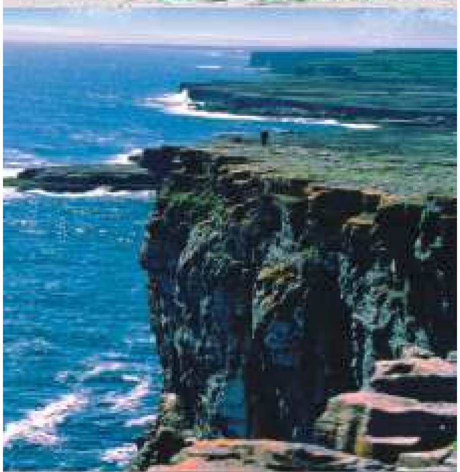
The biggest issue facing European hydrogeologists over the last decade has been the need to protect the quality and quantity of groundwater resources. The European Water Framework Directive published on 23rd October 2000 reinforces the efforts that have been made, requiring member states to develop and implement plans to maintain and improve the aquatic environment. This directive puts into context the work of the COST Action 620, which began in 1997 and continued until 2003.

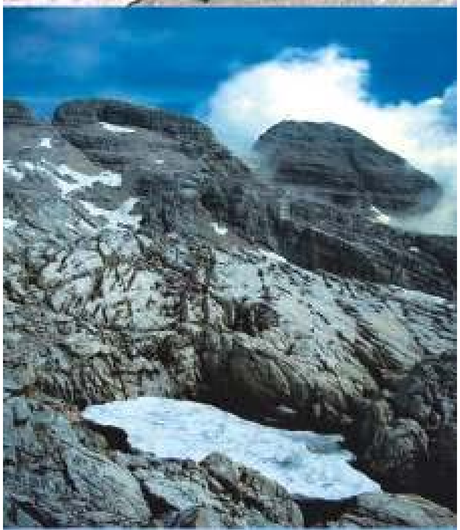
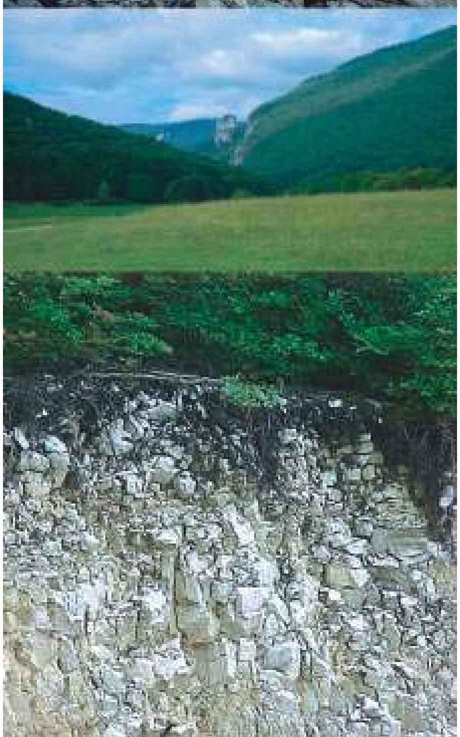
Our Action 620, entitled “Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers” was tasked with the development of an improved and consistent European approach for the protection of karst groundwater. The Action saw the production of new tools to assist in the management of karst areas and their water resources. One of the main criteria for these tools was to ensure that their transparency and ease of use, whilst primarily for experts, still reflected the needs of practical hydrogeologists. As a result, the participants of the Action worked hard to establish common approaches for delineating vulnerability in the field. The identification of the most vulnerable recharge areas where protection measures must be at their greatest is critical, whilst greater flexibility in land use planning can be considered in less vulnerable areas.

Action 620 brought together experts from several disciplines including: hydrogeology, karst geomorphology, environmental chemistry and microbiology, all having specialised knowledge of varying aspects of karst aquifers. These specialists combined their expertise to holistically consider the specific behaviour of these aquifers and their particular sensitivity to anthropogenic impacts. Karst groundwater is extensively used for drinking water supply in many European countries. The importance of these vulnerable karst groundwater resources for potable supply emphasises the importance of the work undertaken by the Action 620, so as to protect their quality for future generations.

The work undertaken by the Action 620 was both interesting and difficult, not least due to the different regulations and practises carried out in the 15 participating countries and the varying points of view of the numerous experts. By proposing new transparent procedures based on detailed knowledge of karst groundwater behaviour we believe we have made a significant contribution to the groundwater protection 'tool box', opening new perspectives for future development on this important topic. The separate “Final Report” issued by the Directorate-General for Science, Research and Development of the European Commission presents the results of the COST Action 620.

Neuchâtel, August 2003
François Zwahlen
Chairman COST Action 620

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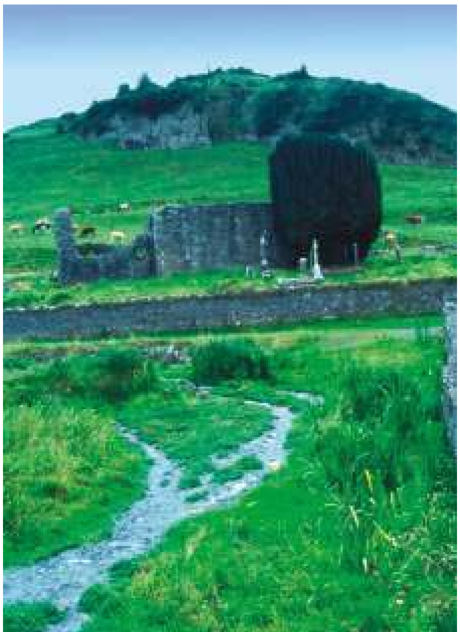
Karst landscapes in Europe

The result of different climatological and geological conditions

Predjama Caves, big enough to house the Predjama Castle, Slovenia

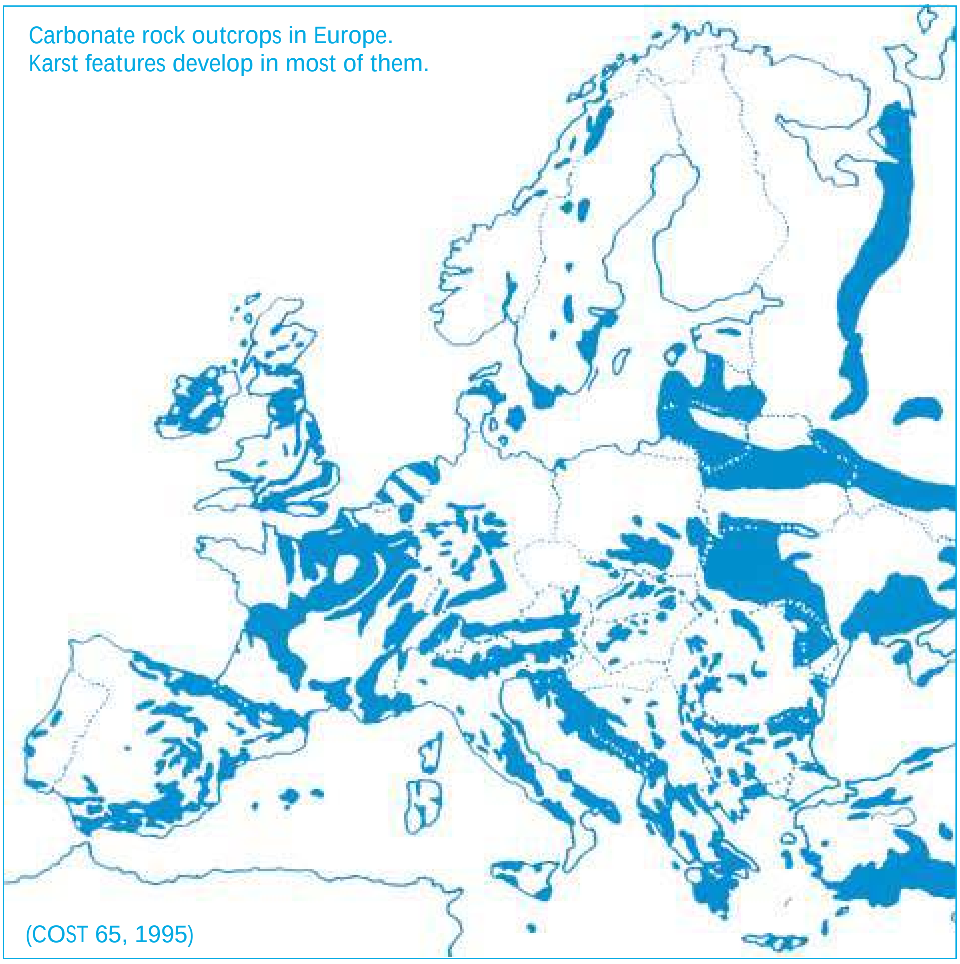
Bare karst exhibiting a network of solution enlarged fissures and bedding planes and several solution cavities, Sierra de Líbar, Spain; photo: P. Jiménez



Karst spring flowing from a limestone area, lowlands of County Westmeath, Ireland; photo: D. Drew

Loussoi polje in the North-Central Peleponnesus, Greece. The soil covered floor of the polje supports agriculture; photo: R. Koutsi

Carbonate rock in Europe




Karst plateau, Burren, County Clare, Ireland.
Photo: D. Drew


The Dolomites at Pala, Italy;
photo: N. Goldscheider

How important is karst groundwater in Europe?




Karst is primarily a terrain with specific landforms developed over limestone and dolomite by dissolution of carbonate rock. Karst areas are widespread in Western, Southern and Eastern Europe. Some of the most scenic landscapes are found in karst terrain. The biggest springs in Europe are karst springs like the Aachquelle in Germany, the Fontaine de Vaucluse in France or the Rjecina in Croatia. These as well as the many cave systems developed in the karstic rock attract thousands of tourists.

For drinking water supply groundwater in karst aquifers is of high importance. In countries with a large proportion of karst areas, like Austria or Slovenia, as much as 50% of the total water supply may come from karst groundwater. The figures in Table 1 showing the percentage of karst groundwater in the total water supply in different European countries do not fully reflect local situations, as in many rural areas karst groundwater is the only source of water supply.

Karst springs are the source of many rivers in Europe. Wetlands and aquatic ecosystems in karst areas depend on the flow of water from karst aquifers.

Karst areas in Europe and proportion of karst groundwater in total water supply (COST 65, 1995)

Country	Total area of country km²	Carbonate area %	Percent of ground-water in total water supply	Percent of karst groundwater in total water supply
Austria	83 856	23,7	98	50
Belgium	30 513	14	90	31
Croatia	56 538	40	90	36
Estonia	45 100	67	80	16
France	547 026	33	45	25
Germany	356 910	6,5	70	6,3
Hungary	93 030	1,45	10	2,8
Ireland	70 282	45	25	5
Italy	301 230	14,2	?	23
Poland	312 680	9,8	14,3	4
Portugal	92 082	2,3	60	10
Romania	237 499	1,8	13	2
Slovakia	48 900	6,3	85	27
Slovenia	20 251	43	90	50
Spain	504 750	22,3	25	12,5
Switzerland	41 290	20	80	15
Turkey	780 776	33	6	1,5
United Kingdom	244 820	22	30	20

Karst groundwater needs protection...

As a most valuable resource karst groundwater needs careful management and protection against pollution. We are awed by the subterranean world of karst cave systems and admire the translucent purity of the groundwater in caves. We enjoy the crystal clear water flowing from a karst spring and the rich plant and animal life in wetlands fed by karst groundwater. Clean groundwater is a natural asset, which must be guarded closely and used wisely.

One of the most important objectives is to prevent pollution. Because once contaminated it takes a long time and much effort and cost to clean up a karst groundwater resource. The protection against contamination requires certain preventive measures regarding the handling of groundwater hazardous substances in karst areas. Frequently there are competing interests between the need for the protection of groundwater on the one hand and unrestricted use and disposal of contaminants on the other hand. Land use planning must integrate socio-economic and groundwater protective requirements and guide land use decisions in such a way that best use is made of land resources while protecting groundwater resources.

For the planning process information about the sensitivity or vulnerability of the different areas overlying a karst aquifer against the introduction of contaminants is needed, as this has a direct influence on the acceptability of potentially polluting activities in the different areas and thus on the restrictions on land use. The assessment and mapping of the vulnerability together with a hazard and risk assessment can readily provide the required data.

COST Action 620 scope and goals

Continuing the work from COST Action 65, the Action 620, starting in 1997 and completing its work in 2003, set out to:

- develop a European approach to assess the vulnerability of karst groundwater, based on sound scientific principles;
- define and assess the risks posed by human activity and establish the significance of intrinsic and specific vulnerability in karst hydrogeological environment;
- apply methods developed from the European approach at national test sites in various karst settings across Europe.

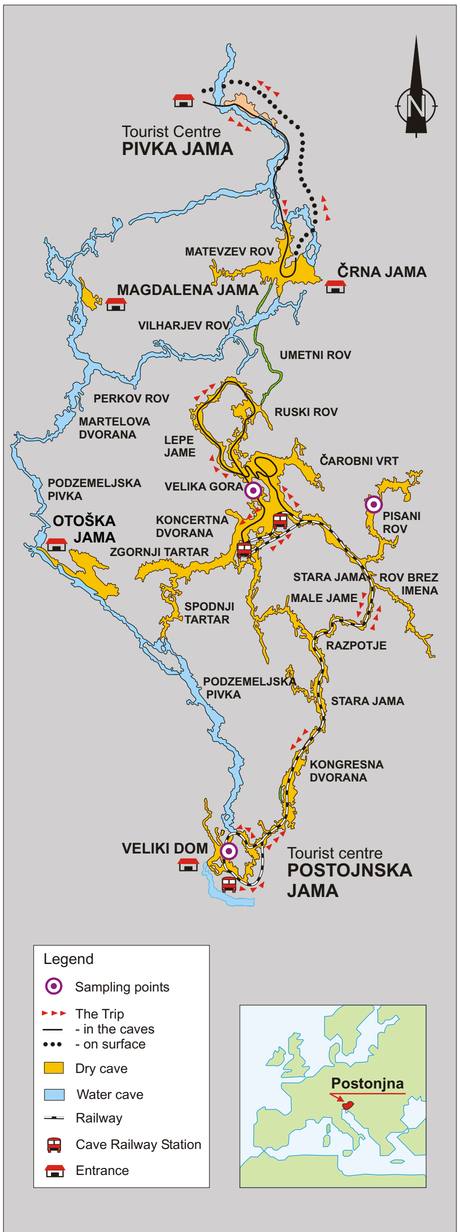
A key objective was to ensure that the developed methods could be used to effectively produce maps for relatively large areas. The project provided a unique opportunity to bring together experts from across Europe to jointly work on the development of a method for the protection of karst groundwater resources.

Karst spring Vagenakia, North-Central Peloponnesus, Greece; photo: R. Koutsi

Karst aquifers have unique characteristics

In hard rock groundwater circulates in open fissures. The flow in carbonate rock initially also occurs along fissures, but later the fissures are gradually enlarged due to the dissolution of the carbonate. Shafts, cavities, pipes and eventually cave systems develop. This process is called karstification. With progressing karstification, groundwater flow in the karst aquifer develops from a flow in an interconnected fissure network to a flow concentrated in several large diameter pipes, interconnected cavities and eventually in a proper cave system. With increasing flow concentration the flow velocity in the system increases. A karst flow system may dewater a large catchment area and may even tap onto water from a neighbouring surface catchment. In alpine areas the disruption of carbonate aquifers by tectonic structures and deeply incised valleys may give rise to complex karst flow systems.

Typical for a karst area is the lack of streams, ponds and lakes. This is due to the fast percolation of run-off into solution-enlarged fissures. Streams may sink into swallow holes, dolines or to the floor of dry valleys. The dissolution and removal of carbonate rock is particularly active near the land surface where a dense network of solution features may develop, the so-called epikarst. Advanced removal of carbonate rock material may lead to subsurface instability and local collapse over cavities, making karst particularly hazardous for civil engineering works. In Mediterranean karst large areas are devoid of soil, limiting agriculture and forestry to karst depressions where some remaining soil has accumulated.

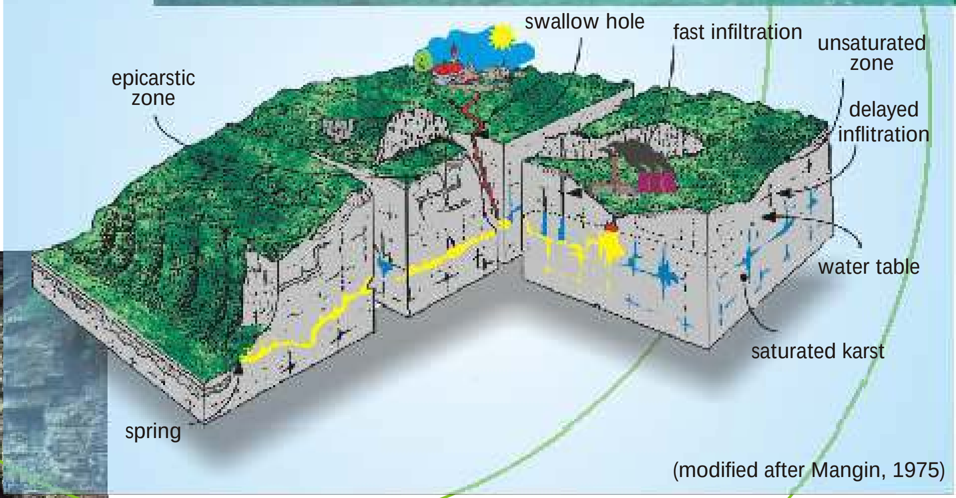


Postojna cave system, Slovenia: cave development controlled by a fracture network (modified from Krajnc, A. 1998)

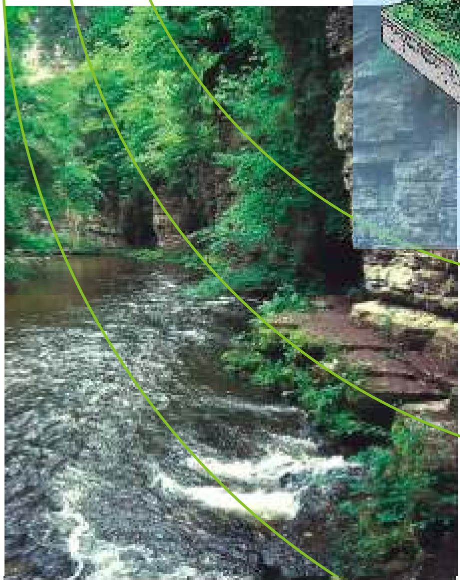
Karst surface pitted with dolines,Cièarija, Istria, Slovenia; photo: A. Kranjc

Groundwater flow in karst

Plateau karst: Truskmore mountain, County Sligo, Ireland; photo: D. Drew



(modified after Mangin, 1975)



Resurgence of the River Wutach from limestone after two kilometres of subterranean flow, SW-Germany; photo: N. Goldscheider

The schematic block-diagram shows the stages of karst development from a network of dissolution enlarged fissures (right) to concentrated conduit flow towards the karst spring (left). Polluting effluents from a village and an industrial plant enter the flow system initially with high concentration of pollutants (red). Dilution reduces the contaminant concentration (yellow). Clean groundwater (blue) circulates in the uncontaminated compartments of the system.

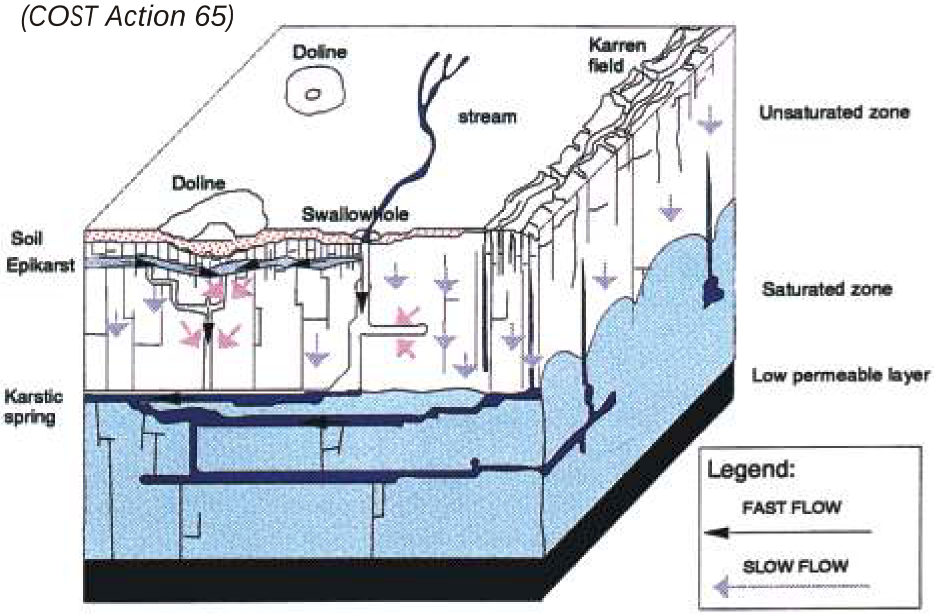
Karst aquifers
are highly vulnerable to pollution

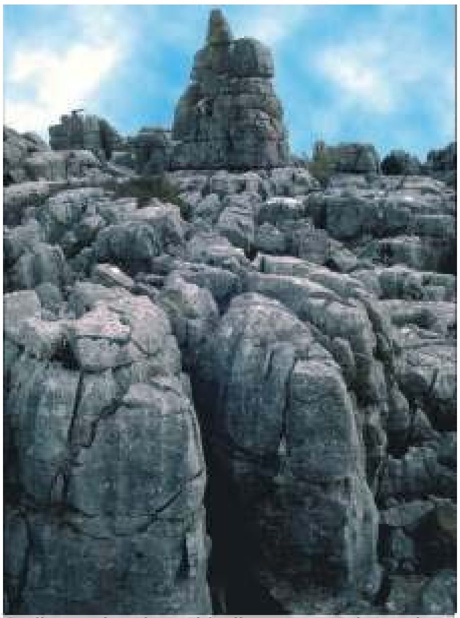
Contaminants released on fissured karst rock or carried by surface water into a swallow hole percolate fast in solution channels through the unsaturated zone. Once in the groundwater they travel rapidly (from ten to several hundred meters per hour) through the aquifer towards a spring or well. Where a thick cover of soil and low permeable sediments overly the karst rock, contaminants are attenuated to a different degree depending on the nature of the contaminant. A well-developed epikarstic zone may act as a temporal reservoir for the percolating water introducing a delay in the downward movement of a contaminant. Rapid flow rates in the karst network quickly spread pollution far from its point of entry. Self-purification is largely reduced.

In fact, dilution may be the main form of attenuation in many karst aquifers. In parts of a karst system less karstic with fine fissures water moves slowly and here the residence time may be prolonged. On the other hand, the rapid flow through the network generates a speedy replacement of water in storage and thus a removal of the contaminant. Pollutants retained in a zone of the flow system less well connected to the main flow conduits may be washed out days or weeks later without any dilution during a flood. The short residence time of karst groundwater in the underground is of special concern in respect of bacteriological pollution, since the duration of underground passage is often shorter than the lifetime of bacteria. Therefore germs can easily and quickly be transported from a contamination source to an abstraction point for drinking water supply even over longer distances.

The concentration of surface run-off towards a swallow hole, doline or dry valley sinks is a special feature in karst terrain and is of great relevance in connection with the propagation of pollution. Any surface contamination occurring within the catchment of such a feature is carried by the surface water via the sink directly into the karst groundwater, in this way bypassing any protective function of low permeable cover layers.

Conceptual model of a karst system
(COST Action 65)




Epikarst developed in limestone, Sierra de Líbar, Spain; photo: N. Goldscheider

The "European Approach"

Planning karst groundwater protection

The scientists working together in COST Action 620 had set as their goal the development of a method which would help to integrate karst groundwater protection into land and water resources management. The method had to be practical in its use and applicable to the karst aquifers of the various climatic zones encountered in Europe from the cool humid climate in the North to the warm dry climate of the Mediterranean. It had to be applicable to the various morphological settings from the undulating hills of Ireland, England and Belgium, to the high plateaus of southern Germany, France, Spain, Slovenia, Croatia, Slovakia and Hungary, to the mountainous regions of the Pyrénées, the Alps, the Dinarides, the Appenin and the Pelepones. The method to be developed had to take into account the highly variable availability of hydrological and geological data in the different European countries. Soon it was apparent, that due to the great variability of local conditions, it would not be possible to design one method which would be suitable for any area. Rather a conceptual framework setting out the key factors for an assessment of aquifer vulnerability, contamination hazard and risk was needed; a common European approach had to be worked out.

A direct link exists to the European Water Framework Directive (2000) which demands sustainable water use based on a long-term protection of water resources. In Annex II, Section 2.1, the Directive requires a characterisation of all groundwater bodies to assess their uses and the degree to which they are at risk.

COST Action 620 defined the central terms of the European Approach as follows:

- The **intrinsic vulnerability** of groundwater to contaminants takes into account the geological, hydrological and hydrogeological characteristics of an area, but is independent of the nature of the contaminants and the contamination scenario.

Alpine karst plateau in the Dachstein Massiv, Austria; photo: L. Plan

- The **specific vulnerability** takes into account the properties of a particular contaminant or group of contaminants and its (their) relationship(s) to the various aspects of the intrinsic vulnerability of the area.

The concept of groundwater vulnerability is based on an **origin-pathway-target model** for environmental management.

  - The **origin** (source of contamination) is the assumed place of release of a contaminant.
  - The **target** is the groundwater, which has to be protected. For **resource protection** the target is the groundwater surface in the aquifer. For **source protection** it is the water in a well or spring.
  - The **pathway** includes everything between the origin and the target. For resource protection, the pathway consists of the mostly vertical passage within the protective cover. For source protection it also includes horizontal flow in the aquifer.

- A **hazard** is a potential source of contamination resulting from human activities taking place mainly at the land surface. The main impacts are considered to emanate from the handling of harmful substances, through their production, transport, storage and disposal as well as their use and application in a wide range of activities. A **hazard assessment** considers the potential degree of harmfulness for each type of hazards and is determined by both the toxicity and the quantity of harmful substances which may be released.
- Combined with vulnerability assessment, which considers the inherent hydrogeological and geological characteristics of a rock sequence through which the contaminants travel, **groundwater risk assessment** is used to establish the consequences of a potential contamination event. The possible spatial extent of a contamination event, based on groundwater flow direction and velocity, as well as the economic value of the groundwater are among the factors which are taken up in risk assessment.

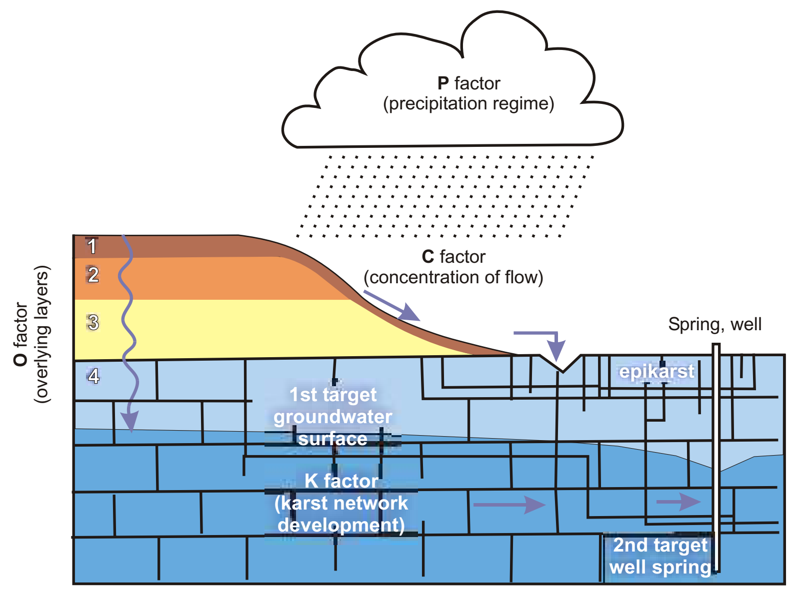
Mapping intrinsic vulnerability

Plitvice River cascading over karst limestone, Plitvice Lakes National Park, Croatia. Photo: M. Kuhta

When assessing intrinsic vulnerability one basically evaluates the protective capacity of cover layers to the introduction and transport of contaminants into the groundwater. Three aspects are important: (1) the transit time between the contamination source and the groundwater table and the well or karst spring, (2) the process of physical attenuation of the contaminant along the flow path by dispersion, dilution, fixation and dual porosity effects, (3) the quantity of contaminants in relation to the volume of water entering the karst system as well as the type of underground transport flow, i.e. flash flood or consistent flow.

Concept of the „European Approach" for intrinsic vulnerability mapping: (a) Regional resource vulnerability, 1st target groundwater; vulnerability assessment of the overlying layers down to the groundwater surface. (b) Source vulnerability; 2nd target well or spring; including the assessment of the karst network.

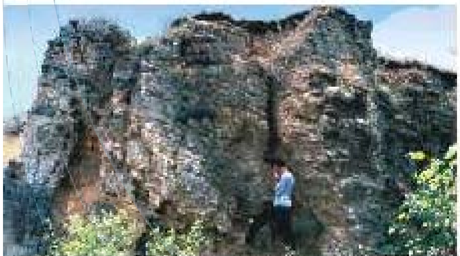
The precipitation (P) generates the flow rates and drives the whole flow system. The overlying layers (O) may consist of up to four layers: (1) topsoil, (2) subsoil, (3) non-karstic bedrock, (4) unsaturated karstic bedrock, epikarst if present. The degree of karstification and flow system development (K) from initially fissured rock to dissolution enlarged fractures and cavities and finally to the formation of conduits and caves is the controlling factor for the flow velocity. In some karst areas surface run-off is concentrated and channeled into swallow holes (C) whereby the protective function of cover layers is bypassed.

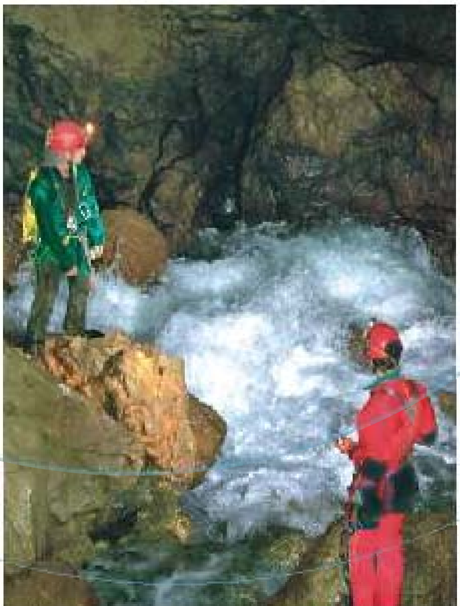


The many faces of karst…


Polje Mljet, Croatia, *exposed karst groundwater table*; photo: N. Goldscheider


Dry bed of the sinking stream Trstenik, Muranska Planina Plateau, Slovakia; photo: P. Malik


Epikarst developed in limestone, Veszprém-Kádárta Plateau, Hungary; photo: G. Halupka


Underground river in the Rokina Bezdana Cave near Jezerane, Croatia; photo: M. Kuhta


Shaft doline, 60 m depth, Hochschwab, Styria, Austria; photo:L. Plan


Karren, solutional channels in limestone, Muotatal, Switzerland; photo: N.Goldscheider

From field data to a resource intrinsic vulnerability map

An example from the Sierra de Líbar in Spain

The Líbar karst system, located in the western part of the Málaga Province in Spain, is formed by Jurassic dolomites and limestones over 400 m thick. The relief is characterised by a central rugged plateau with steep slopes along the escarpment. Karst features are abundant and include dolines, swallow holes, karren fields, cavities and several poljes. Soil is only encountered in the poljes. Bare rock is outcropping over the remaining area. Rainfall is high with 1500 mm per year. The climate is Mediterranean with a hot dry season and high evapotranspiration. The karst system drains into several springs located along the southern fringe of the karst area. Streams dry up during the hot dry season.

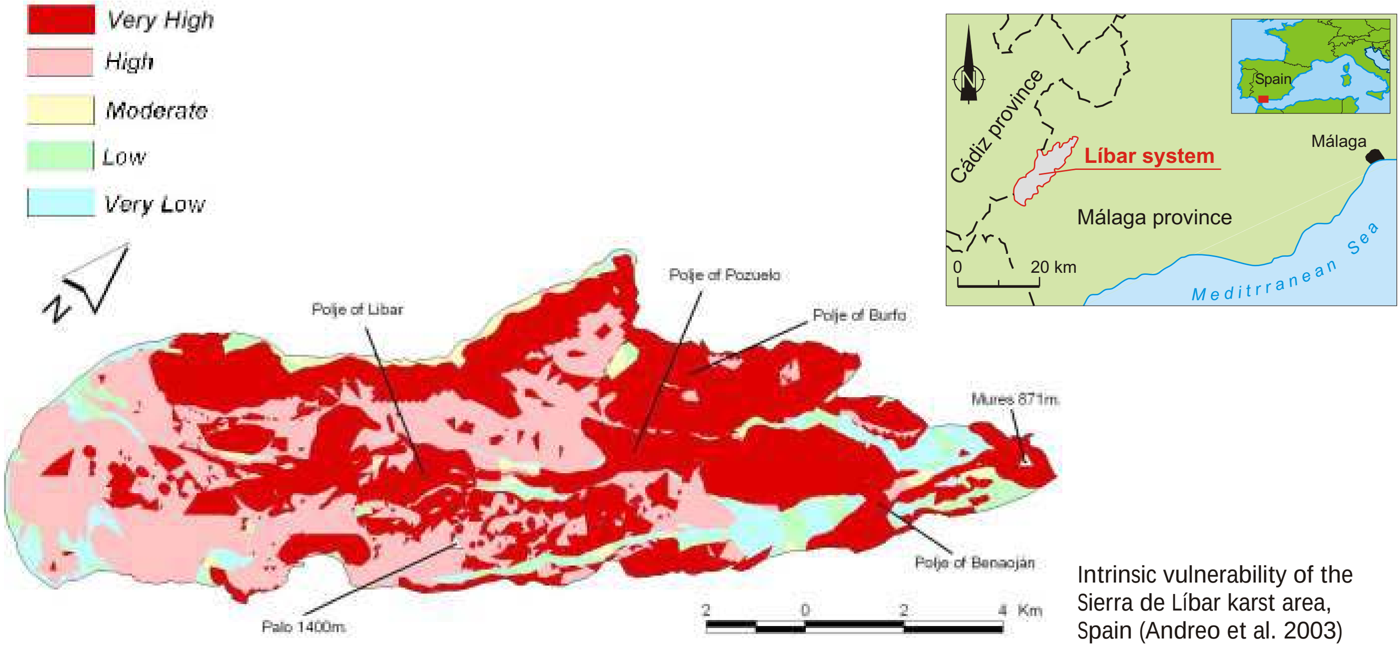

Typical Mediterranean karst in the Sierra de Líbar, Spain; photo: P. Jiménez

Applying the "European Approach" the resource intrinsic vulnerability of the Líbar karst system has been assessed and mapped. The factors O – overlying layers, C – concentration of flow and P – precipitation have been considered. On the resulting map the large areas of very high and high vulnerability reflect the high degree of karstification of the area, the almost complete absence of a soil cover and the large areas on the plateau with gentle slopes covered with vegetation favouring fast infiltration. The poljes, despite their soil-covered floor, stand out as features of very high vulnerability because of the presence of swallow holes, which provide a direct access for run-off water to the karst groundwater.


Polje of Benaojan, Sierra de Líbar, Spain; photo: P. Jiménez

Interpreting the information on the map in the light of land use, development planning and groundwater protection, the Líbar karst area requires great care regarding the handling and storage of contaminating substances, the application of fertilizers and herbicides, the handling and disposal of solid waste and sewage. Strict protection measures need to be implemented and enforced.

Intrinsic vulnerability of the Sierra de Líbar karst area, Spain



Intrinsic vulnerability of the Sierra de Líbar karst area, Spain (Andreo et al. 2003)

A rain swollen stream disappearing into a swallow hole, Sierra de Libar, Spain; photo: N. Goldscheider

Gato karst spring in flood, Sierra de Líbar, Spain; photo: P. Jiménez

Contaminant specific vulnerability mapping

Sierra de Libar, Spain

Intrinsic vulnerability assesses the passage of water through the different layers of an aquifer. Contaminants (biological and chemical) behave differently from water, because they interact in various ways with the surrounding rock. Where the aquifer vulnerability to a particular contaminant needs to be known, an assessment of the behaviour of the specific contaminant substance along its flow path through the layers of the aquifer is required. COST 620 has developed a method that allows an integrated intrinsic-specific assessment. The resulting S-factor represents both layer and contaminant attenuation capacities.

To arrive at the S-factor two contributing factors are evaluated: the "layer factor" and the "contaminant factor". The layer factor describes the physical and chemical properties of the layers, e.g. the composition and thickness of the topsoil, subsoil, non-karstic rock, unsaturated and saturated karst. The contaminant factor determines if the substance is liable to be affected by a specific attenuation process.

In the Sierra de Líbar, following the determination of the intrinsic vulnerability characteristics, the vulnerability of the karst system to microbial contaminants (Faecal coliforms) and to the hydrocarbon contaminants BTEX (Benzene, Toluene, Ethylbenzene, Xylene) was assessed. In this rural area microbial contaminants may mainly derive from sewage water and animal excrement. BTEX-substances may come from spills at petrol stations and fuel tanks for agricultural use. These two contaminants behave differently in their passage through the layers.

Faecal coliforms suffer retardation and degradation by sorption and filtering and die off. However, where bypass occurs by preferential (fast) flow in cracks, fissures and conduits, none of the retardation and degradation processes are effective. Over about 90% of the aquifer area soils and non-karstic rock are absent and preferential fast flow prevails. Small areas of moderate and low vulnerability to microbial contaminants coincide with soil covered marly limestone and flysch. The specific vulnerability map does not differ greatly from the intrinsic vulnerability map.


Soil on karst rock, Sierra de Líbar; photo: N. Goldscheider

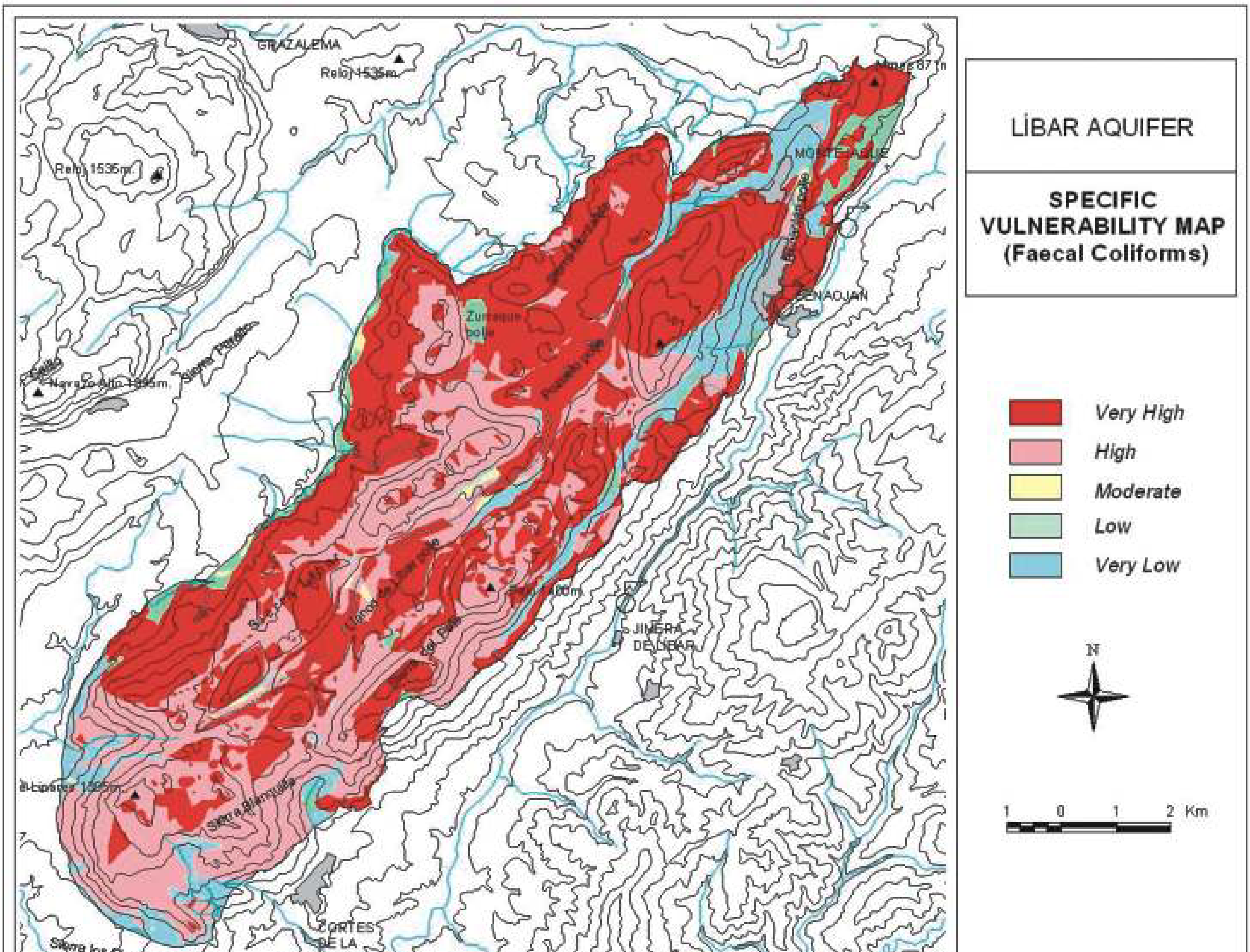
BTEX compounds are affected mainly by biodegradation and volatilisation. Biodegradation requires organic matter for microbial life. Since the rocks and soils in the catchment have very low organic matter content, biodegradation is regarded as insignificant. Volatilisation takes place in the fast turbulent flow in fissures and conduits in the limestone and dolomite and is considered of significant importance for attenuation. Intrinsic and BTEX vulnerability differ greatly as can be seen from the maps. Very high specific vulnerability is retained for the poljes, where the karst water table is close to the surface.


Dolomite and limestone karst in the Sierra de Líbar; photo: N. Goldscheider

Specific vulnerability map

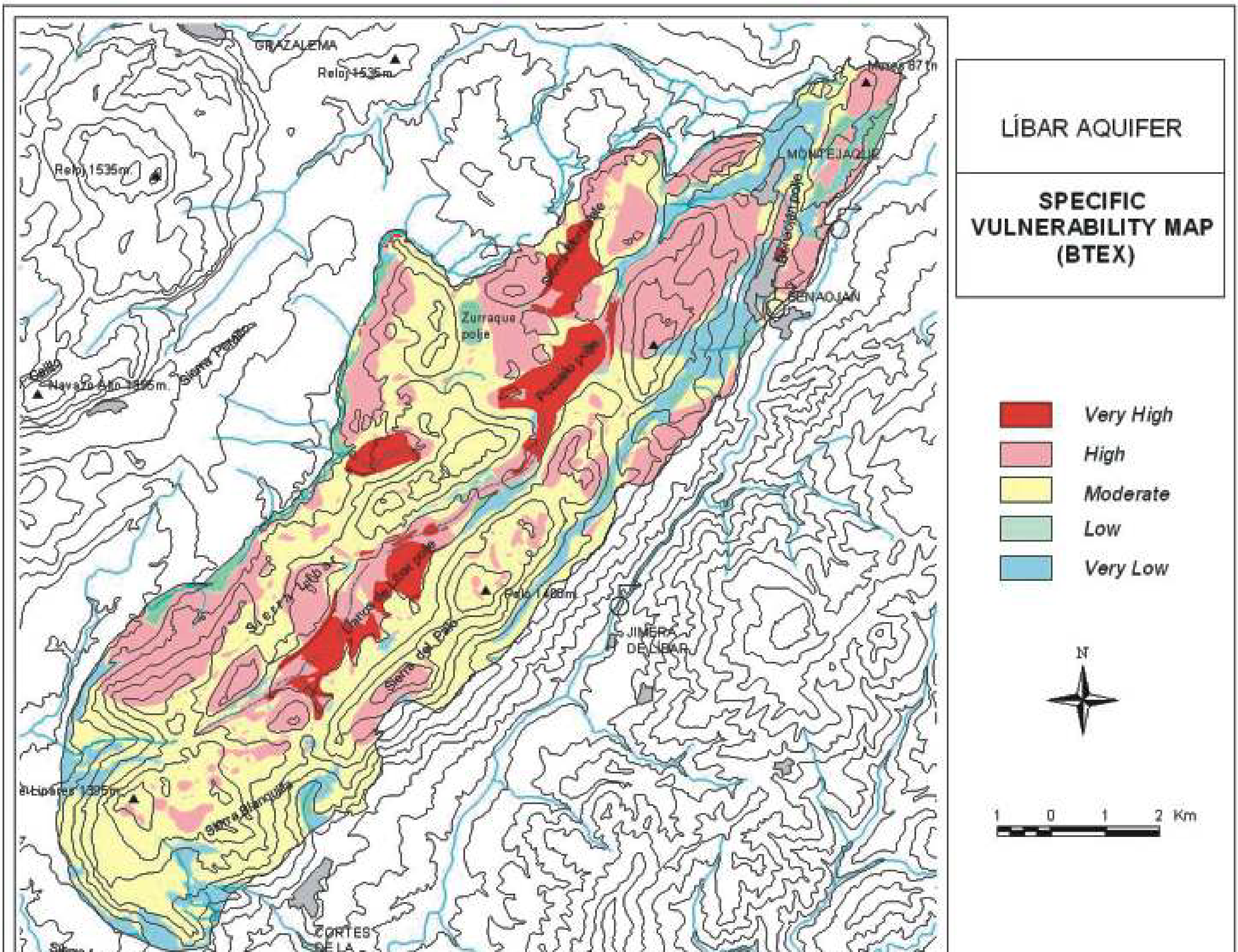
Faecal Coliforms

Sierra de Líbar, Spain



(Andreo, B. et al. 2003)

Specific vulnerability map
Hydrocarbons (BTEX)
Sierra de Líbar, Spain



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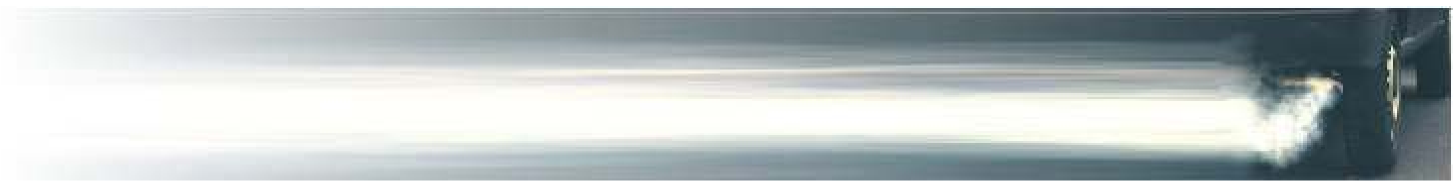


Assessing the intrinsic vulnerability in a groundwater protection area

An example from the Swabian Alb in Germany

Groundwater from the Swabian Alb karst in Southwest Germany provides drinking water to many communities in the region. Groundwater protection areas have been delineated in which specific regulations govern the handling and disposal of contaminating substances. In the catchment area of karst springs supplying the town of Engen and neighbouring villages with water, the vulnerability of the karst aquifer has been assessed. The topography of the area is that of a flat gently sloping plateau rising from 470 to 690 m, into which two rivers are deeply incised. The main karst aquifer is made up of Jurassic limestone in bedded and massive facies and intercalated marl beds. The limestone forms steep slopes along the valleys. On the plateau the karstic limestone is covered by soil and by glacial gravel, sand and loam. These sediments form minor local aquifers, which perch above the main karst aquifer. Groundwater from the perched aquifers collects in streams and sinks into the underlying karst via swallow holes. In the southern part of the area the karst aquifer dips below a complete cover of low permeable sediments which generate a pressure confinement for the groundwater in the karst. Due to the complete soil cover exokarst features are rare and often not noticeable. However, in outcrops and quarries a locally well-developed epikarst is exposed. The fertile soils on the plateau are used for agriculture. Woods grow in the steep valleys and ravines. The annual rainfall varies between 740 and 895 mm. The climate is temperate and cool with a snow cover during the winter months. Streams and rivers have water flowing all year round.

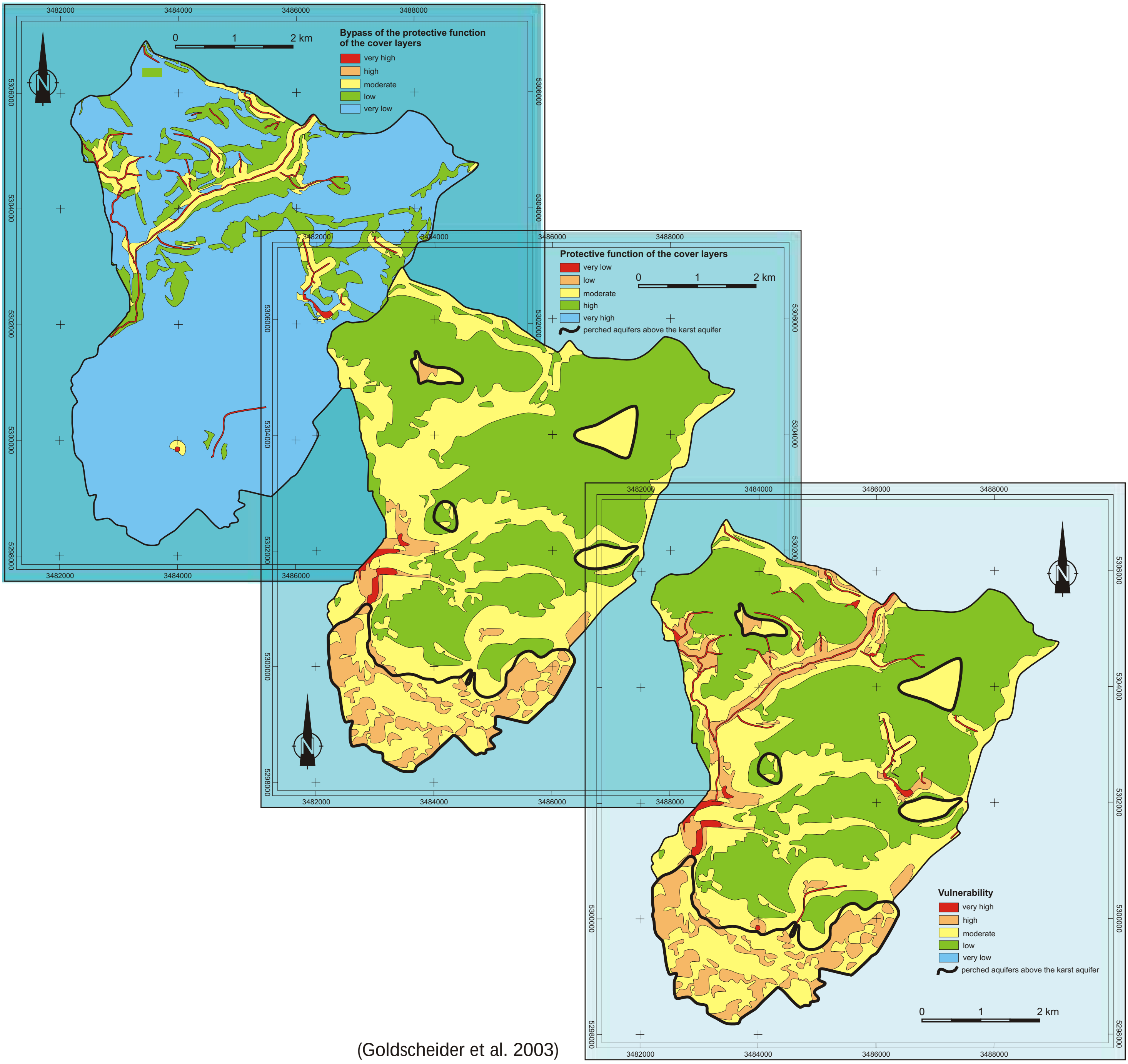

The “Aachquelle” in the Swabian Alb, Germany: one of Europe's biggest karst springs; photo: N. Goldscheider


Epikarst with a loam filled karst shaft, Swabian Alb, Germany; photo: M. von Hoyer

Applying the concept of the “European Approach” the factors O overlying layers, C concentration of flow and P precipitation have been considered. The widespread covering layers provide a good protection for the karst groundwater and therefore these areas have a low vulnerability. The black lines in the map outline the position of the perched aquifers and in the southern part the area of confined karst groundwater. Sinking streams plus their catchments are areas of high and very high vulnerability. In terms of groundwater protection measures, the vulnerability map is the tool for a differentiated application of land use restrictions; in the sense that the regulations for the handling and storage of groundwater contaminating substances can be more relaxed in areas of low vulnerability, while in high vulnerability areas contaminants are not permitted.

Intrinsic vulnerability in a groundwater protection area

An example from the Swabian Alb in Germany



(Goldscheider et al. 2003)

Hazard assessment

Determining the potential thread to groundwater

An example from the Swabian Alb in Germany

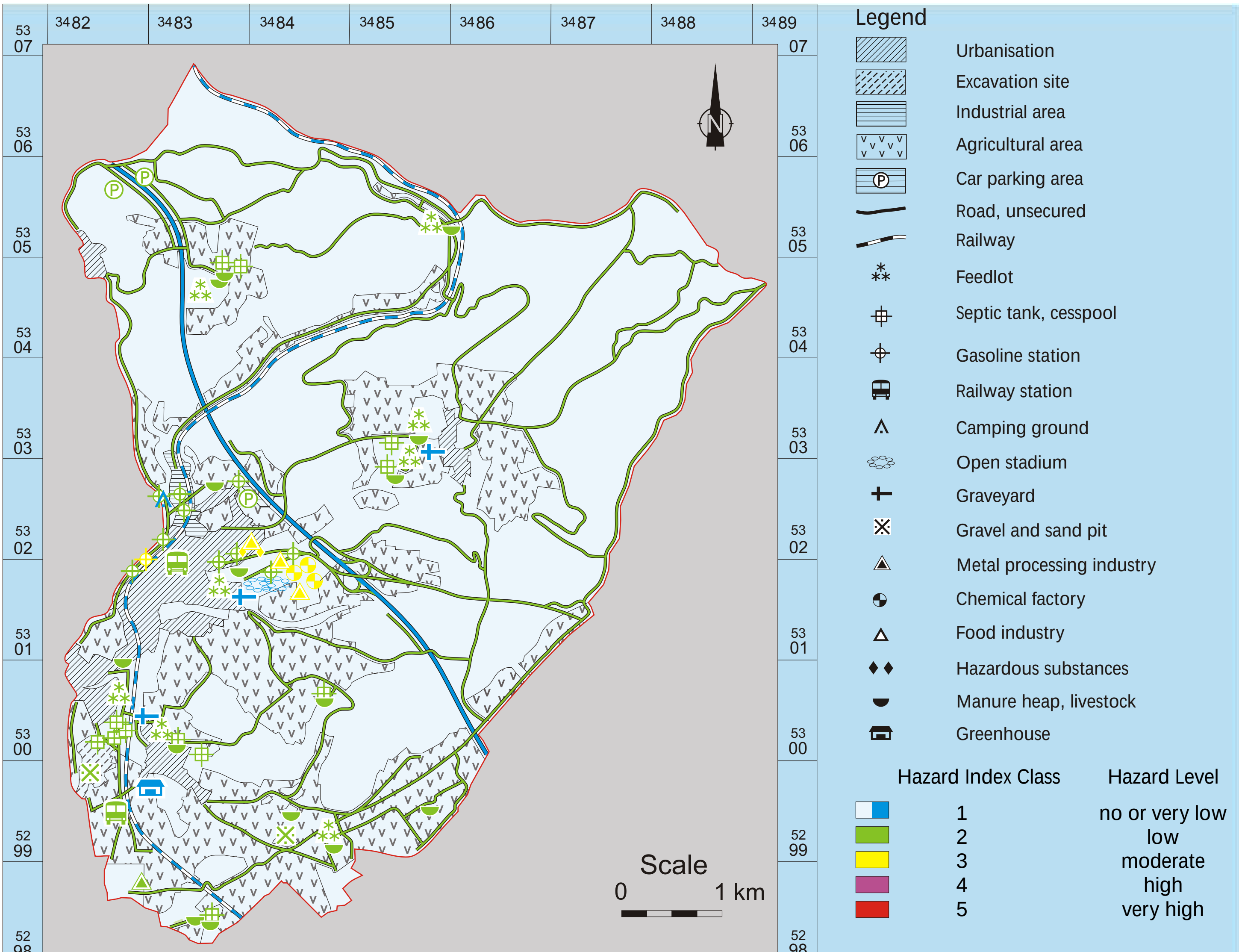
Catchment of the "Engen springs" Swabian Alb, Germany: Engen town, agricultural land, villages, farm homesteads, country roads; photo: M. von Hoyer

A **hazard** to groundwater is posed by any potentially polluting activity at the land surface above a karst aquifer. In the catchment of the karst springs supplying the town of Engen hazards include urban areas with leaking sewers, industrial parks, gravel pits, areas under intensive agriculture, railway lines, main and country roads, farm homesteads with cess pools, petrol stations. In the assessment process (NEUKUM 2003) all hazards are given a *weighting factor*, which describes the harmfulness of the hazard to the groundwater (e.g. toxic substances have a higher harmfulness than manure). A *ranking factor* was introduced to consider the range of technical specifications of each hazard type, e.g. urban areas with sewers ranked according to the number of inhabitants, petrol stations according to the number of pumps, roads according to traffic density, agricultural areas ranked according to the crop rotation and number of livestock. In addition a *reduction factor* is applied to consider the technical status and level of maintenance of industrial plants, waste storage and treatment plants etc.

The resulting map provides an inventory of the occurring hazards, their location in the spring catchment area and the degree of harmfulness. It reflects the situation in the year 2001. Any subsequent changes of land use may introduce additional hazards or reduce their number and change their hazardous nature.

Groundwater contamination hazards

Karst area Engen, Germany



Classified groundwater contamination hazards in 2001(after Goldscheider et al. 2003)

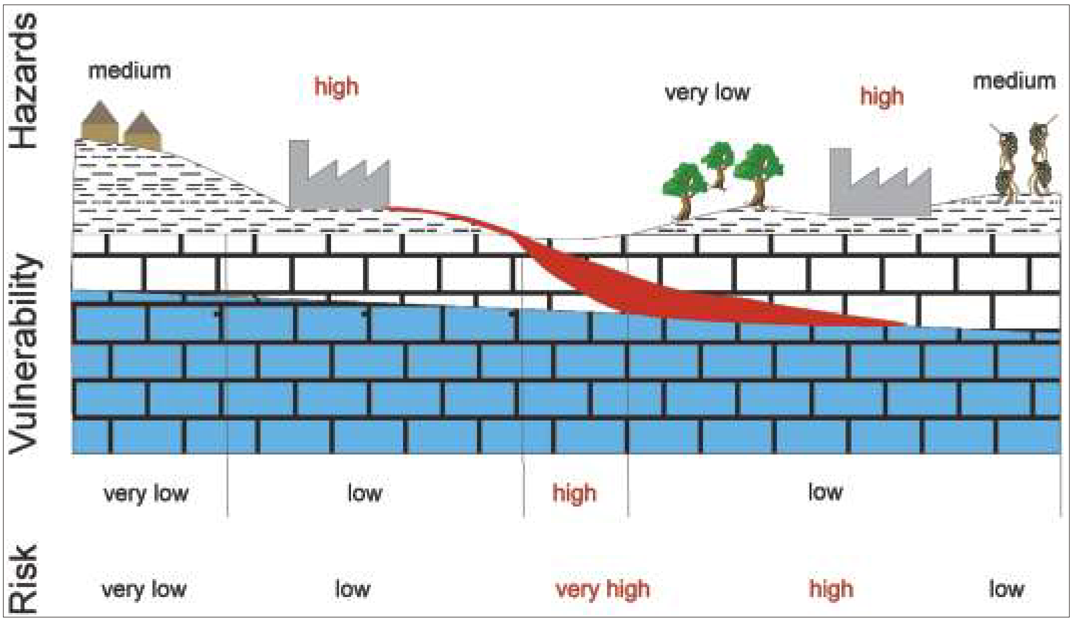
Risk assessment

A proactive tool for groundwater protection

An example from a mixed urban and rural area in the Swabian Alb in Germany

To prevent aquifer pollution to occur is certainly easier than to remediate a contaminated groundwater resource. The removal of contaminants from a groundwater system entails costly long-term operations and the temporary loss of a supply source. Practical groundwater protection can be preventive, if potential sources of contamination are identified through hazard mapping and are specially controlled. The planning of protection measures in a groundwater catchment area is further focused by risk assessment. In combining the information of a hazard map with that of a vulnerability map, the consequences of a potential contamination event can be predicted. Clearly any polluting activity taking place in an area of low aquifer vulnerability is less likely to cause pollution of the groundwater, than the same activity carried out in an area of high or extreme vulnerability. Depending on the protective capacity of the different covering layers in a karst catchment area and the varied nature of polluting activities, areas of different contamination risk can be defined. Strategic land development planning can support groundwater protection by directing groundwater hazardous activities to areas of low vulnerability, requiring less stringent protective measures.

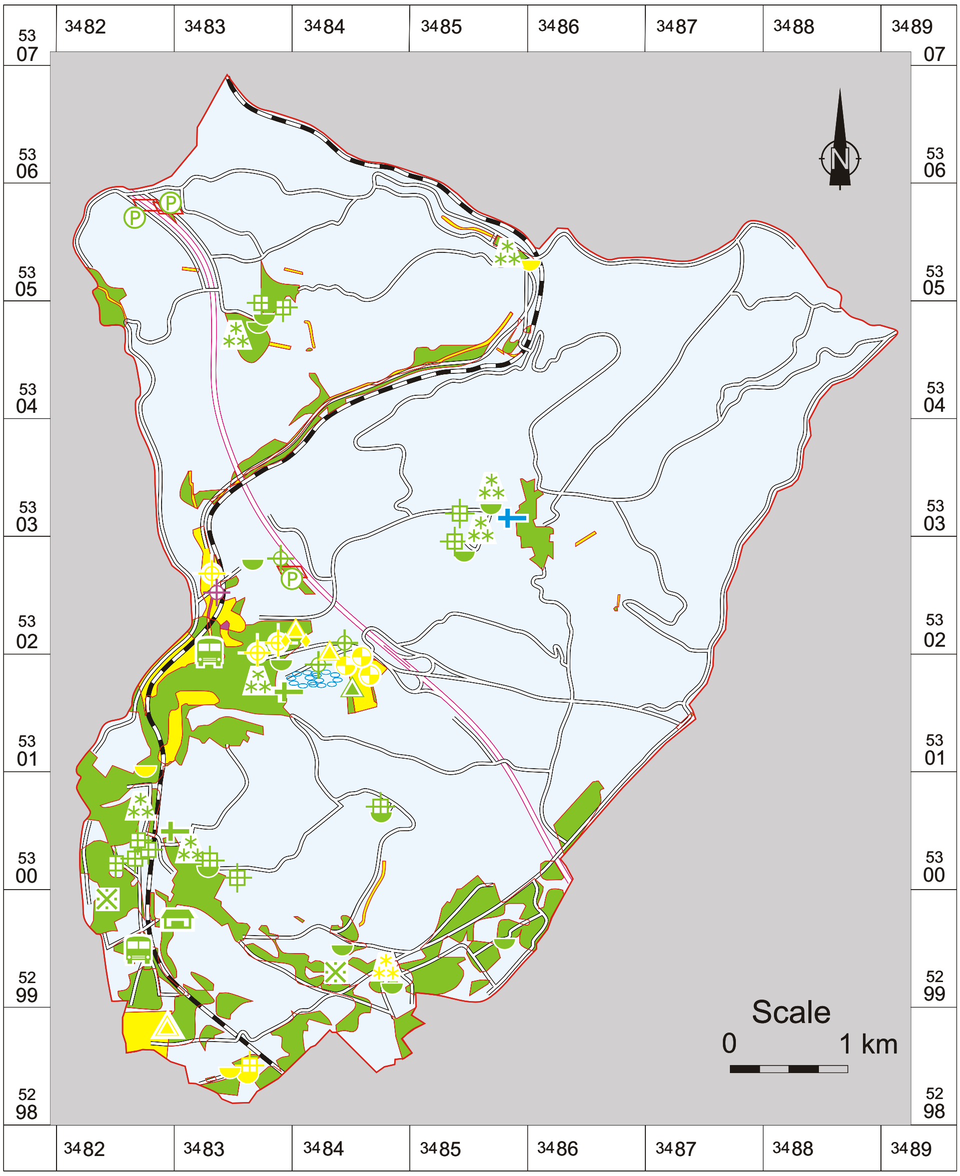
The risk assessment for the Engen spring catchment area (Goldscheider et al. 2003) gives the following results: 86% of the area (northern and central part) represent "no or very low" risk to groundwater. This is due to the absence of hazards but also due to low vulnerability. Hazards concentrate in the urban areas in the south and west, where they combine with "high" and "extreme" vulnerability to areas of "moderate" and "high" risk. A road section crossing the catchment in the northwest runs along a valley in which karst limestone outcrops and vulnerability is "extreme", resulting in a strip of "moderate" and "low" risk. Viewing the result of the risk assessment under the aspect of groundwater protection and land development, the following is observed: Only few hazards exist in the major part of the spring catchment (status 2001). This is largely the result of the introduction of groundwater protection zones several years back and their restrictive impact on land use. So far there have been no reports of groundwater pollution in the area. The low vulnerability areas offer a certain degree of flexibility for future land use planning. Special attention must be given to the localities exhibiting "high" risk. The existing hazards must be closely monitored and where possible removed from the "high" vulnerability areas.



Risk assessment of groundwater considering the superimposed effects of hazards and vulnerability (Hötzl et al. 2003)

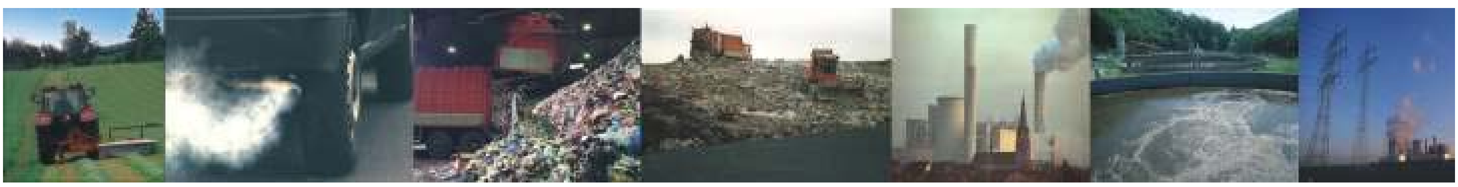
Potential contamination risk

Karst springs catchment area Engen, Swabian Alb, Germany



Risk Class	Risk Level
1	no or very low
2	low
3	moderate
4	high
5	very high

Potential groundwater contamination risk in respect of the hazards present in 2001 (after Goldscheider et al. 2003)



Mapping intrinsic vulnerability in a highly complex Alpine flow system

An example from the Winterstaude area in Austria

Two springs at the foot of the Winterstaude mountain chain serve as drinking water sources for the town of Bezau. A hydrogeological research programme was carried out with the aim to design a groundwater protection scheme. The catchment area of the springs rises from 650 m in the Bezau valley to the mountain chain topped by the Winterstaude with 1877 m altitude. The annual rainfall ranges between 1800 and 2000 mm. The climate is cool and humid with snow in winter.

Doline in the Winterstaude area; photo: N. Goldscheider

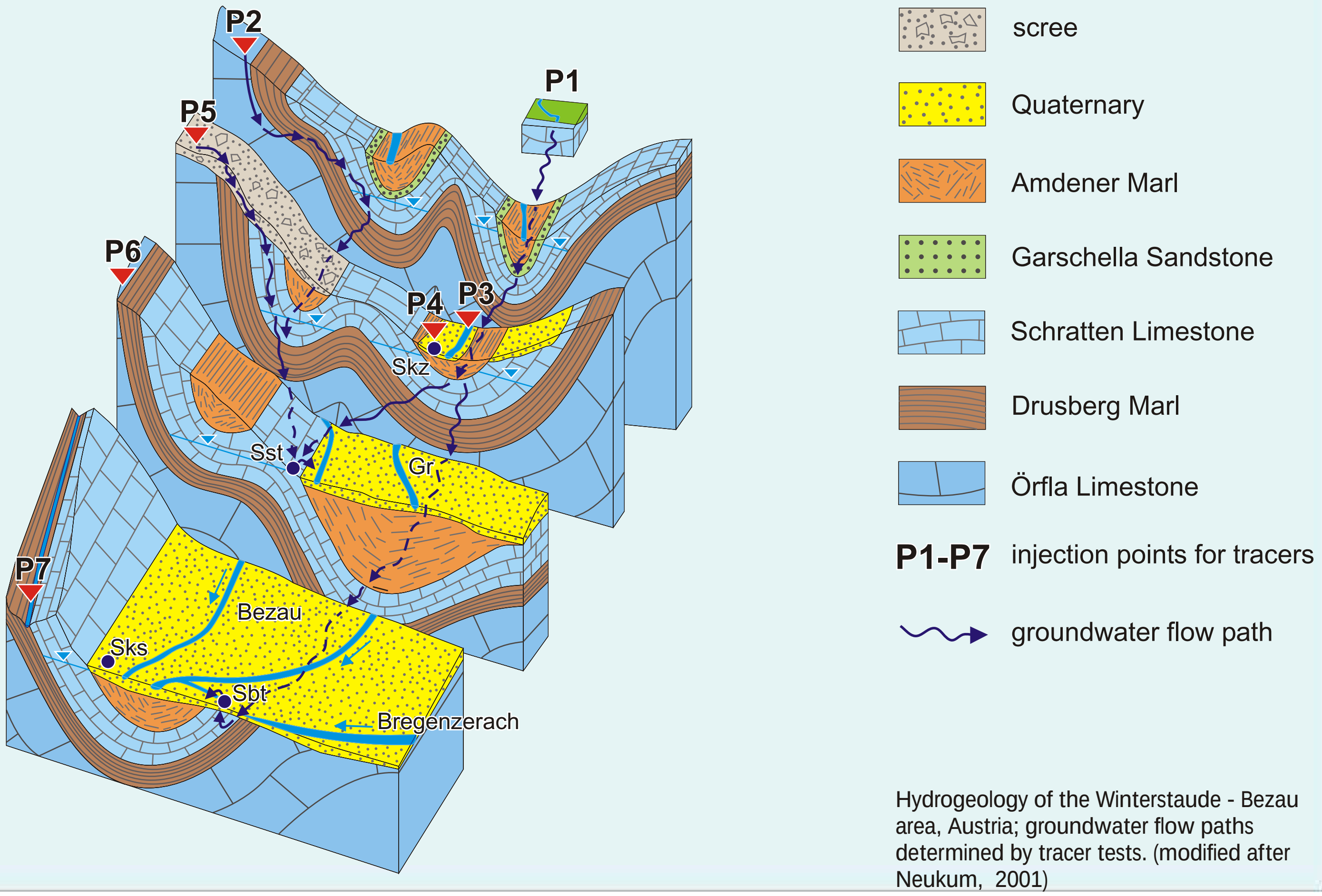
Two limestone complexes, the 160 m thick Örfla limestone and the 100 m thick Schrattenkalk limestone are karst aquifers. The limestone complexes are separated by a 60 m marl bed and are under- and overlain by marls. The whole sequence of marls and limestones is folded up into a number of parallel synclines which are disrupted by faults, together creating a highly complex hydrogeological setting. The Örfla limestone forming the crest of the mountain chain is little karstified. The Schrattenkalk which forms the lower slopes of the valley is a well-developed karst aquifer with high flow velocities and fast reaction to rainfall events. The limestone is covered with shallow soil and overgrown with pine forest in many places. Surface karst features like karren and stream sinks are frequent. Dolines are aligned along the synclinal axes and fault traces. Surface and underground drainage intensely interact. A number of tracer tests were carried out which showed that lithological stratification, fold and fault tectonics control the underground drainage pattern. It is evident, that groundwater from the higher Örfla karst system enters into the lower lying Schrattenkalk aquifer via faults that cut through the interlaying marls. Flow velocities in the karst system ranges from 12 to 90 m per hour.

Tracer test with uranine, Schwarzwasserhöhle, Austria; photo: N. Goldscheider

The mapping of the intrinsic vulnerability of the catchment area together with the results from tracer tests established the base for the delineation of drinking water protection zones for the springs in the Bezau valley.

Mapping intrinsic vulnerability

Geology and tracer tests

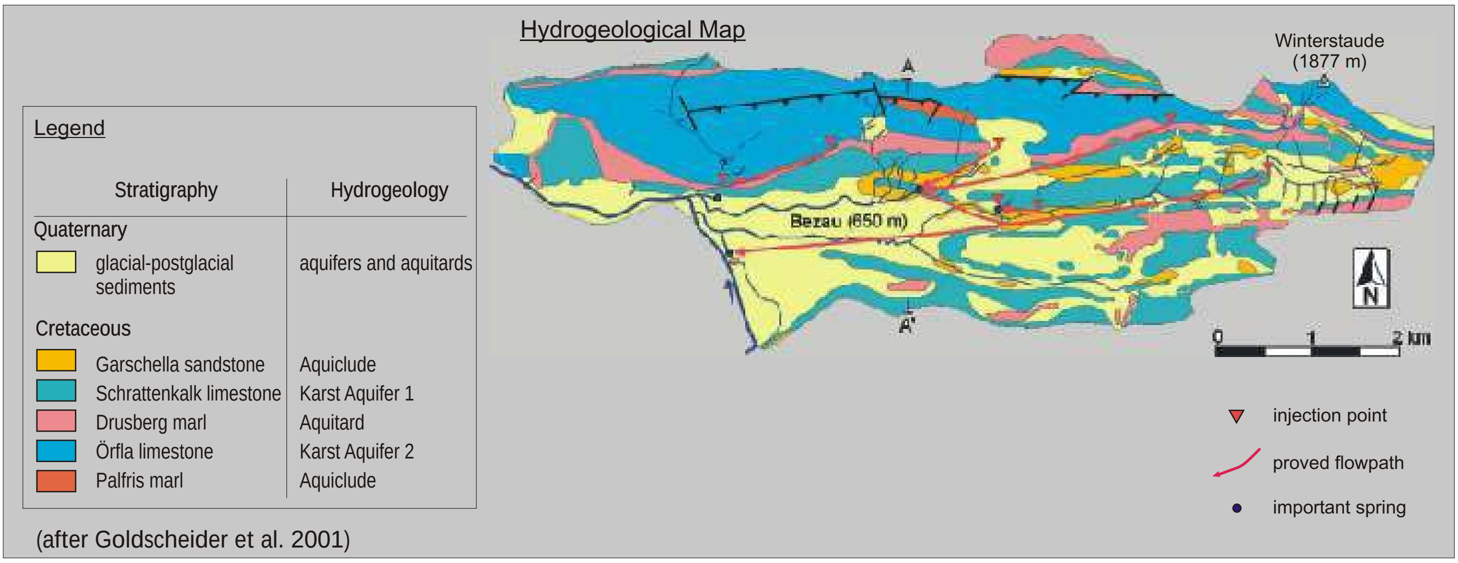


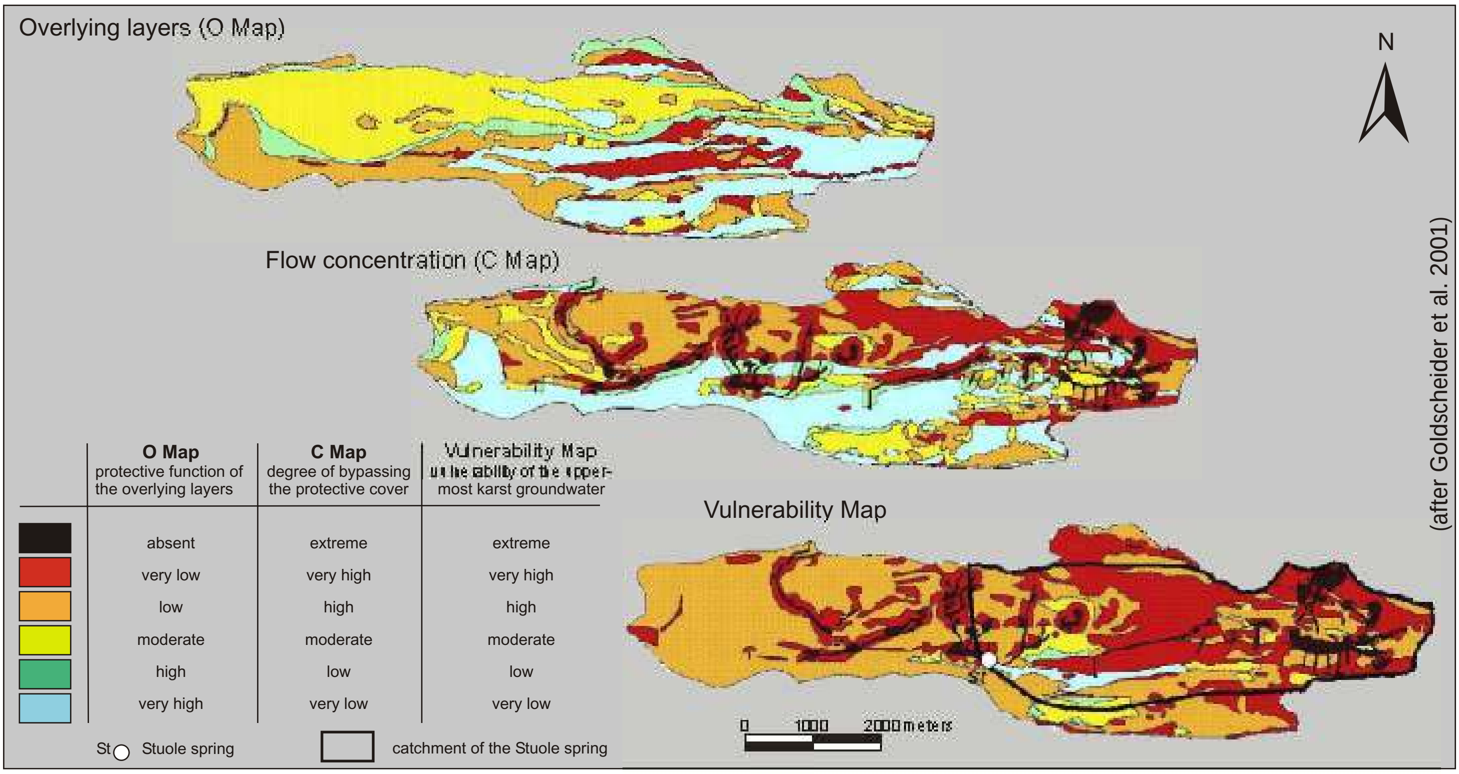
Hydrogeology of the Winterstaude - Bezau area, Austria; groundwater flow paths determined by tracer tests. (modified after Neukum, 2001)

View of the Winterstaude area; photo: N. Goldscheider

Intrinsic vulnerability map

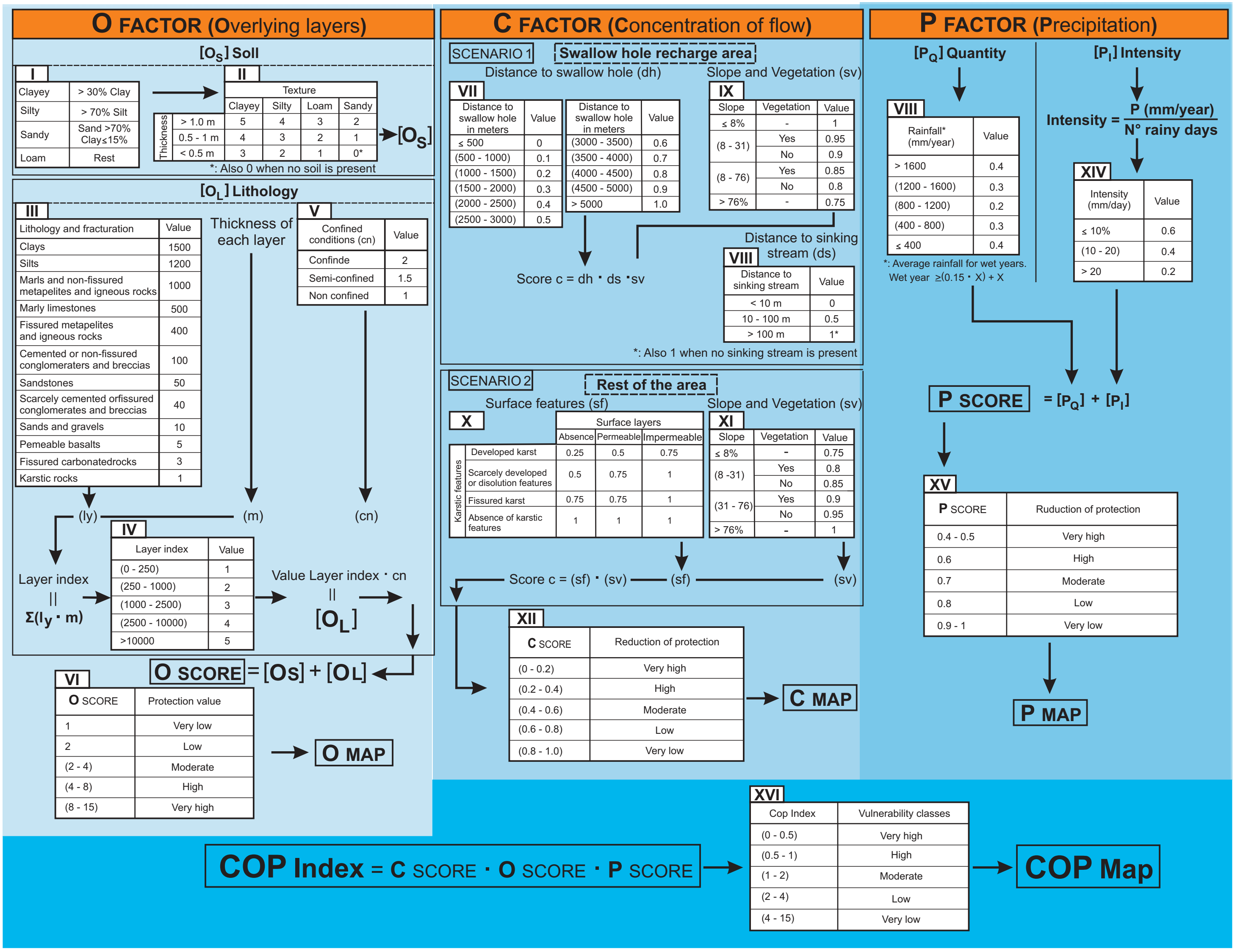
Winterstaude, Austria





Intrinsic vulnerability

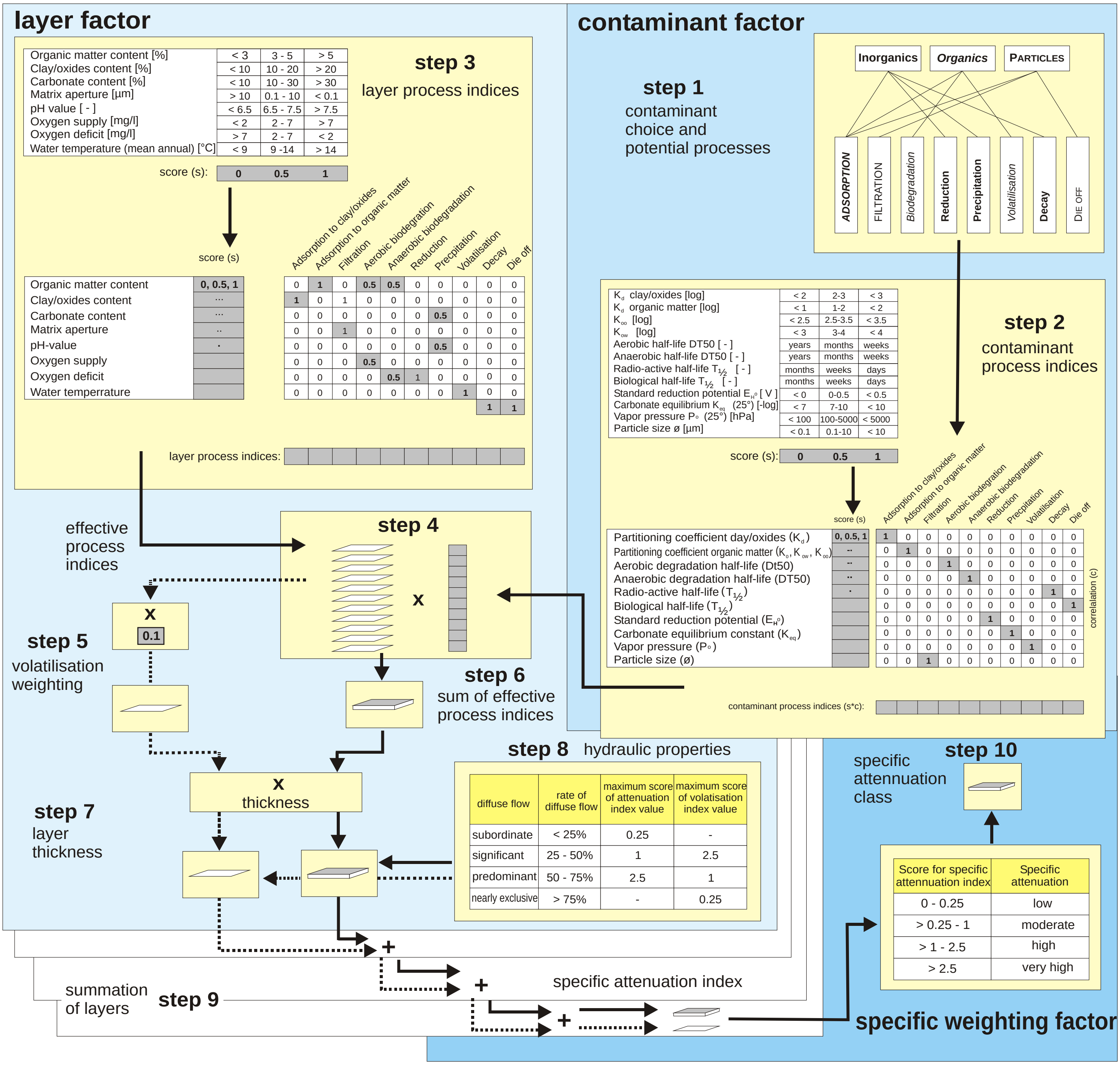
Flow chart to determine factor C, O and P



Assessment scheme to determine intrinsic vulnerability. Deails of the method are described in the COST 620 Final Report (Zwahlen 2003).

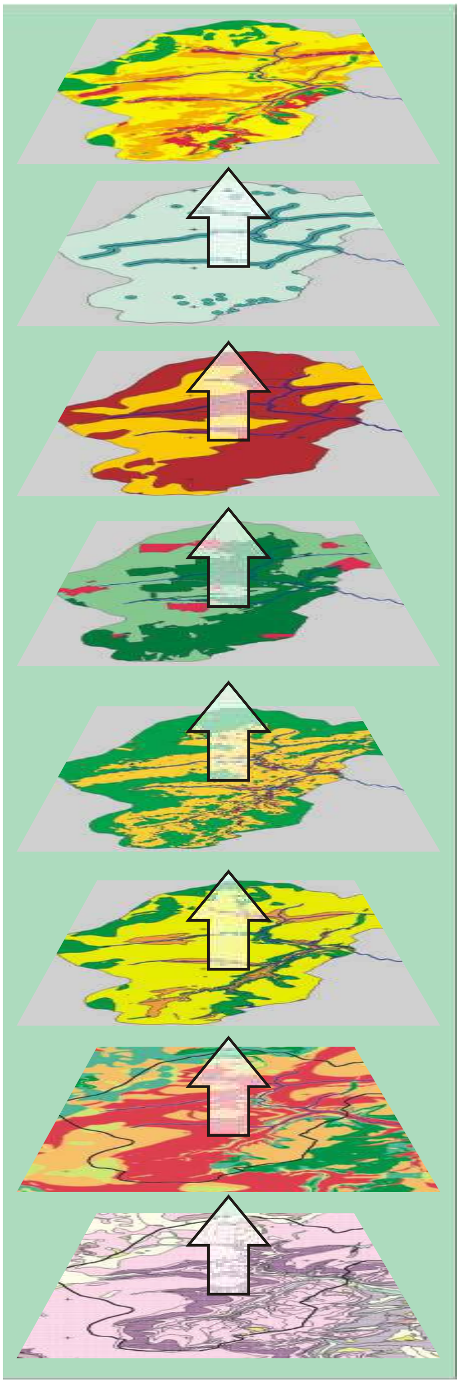
Specific vulnerability

Flow chart to determine specific attenuation



Assessment scheme to determine specific vulnerability. Deails of the method are described in the COST 620 Final Report (Zwahlen 2003).

Data needed for vulnerability, hazard and risk mapping



Mapping of **intrinsic vulnerability** entails the assessment of the entire flow system of a karst aquifer in respect of all factors that govern the percolation of recharge water. In order to study the system in the light of its protective capacity one needs to evaluate all available data from rainfall to soil properties, vegetation, morphology, drainage, lithology of covering layers to the degree and development of the karst network. The flow chart for the COP-method on the previous page provides an overview of the data evaluation steps leading towards the intrinsic vulnerability.

The behaviour with which different inorganic and organic contaminants react physically and chemically with the surrounding formation is in principal established scientific knowledge. In **specific vulnerability** mapping the reactive processes taking place between the contaminant and the different lithological layers are qualitatively assessed by applying the layer specific attenuation characteristics previously established while determining the intrinsic vulnerability. The ten-step assessment approach and the required data are illustrated on the previous page.

Hazard mapping is an inventory of anthropogenic activities hazardous to groundwater for a particular area and at a specific point in time. All human activities are scrutinized for their impact on the karst aquifer and the groundwater quality. This task requires access to all existing data of human enterprise in the area under study, in particular to data on the nature of commercial, industrial and agricultural activities. Of particular importance is information regarding the production, storage and handling of substances harmful to groundwater.

With **risk assessment** the protective properties of the overlying layers are related to existing contamination hazards and the level of risk for a pollutant break-through is established. Consideration of the loss of value to a water supply source due to contamination may amplify the risk assessment into an economical dimension.

In the process of vulnerability, hazard and risk assessment point specific data are collected and evaluated for several hundreds of location points. These large volumes of data need to be put into a coherent and logical structure. Geographical Information Systems (GIS) provide the ability to store, manage and analyse geo-referenced and interrelated data.

Bearing in mind the fact of greatly differing data availability across the European countries, the methods developed by COST 620 for vulnerability, hazard and risk assessment are adaptable to different data density. Low data density obviously only permits a low level of precision for the conclusions. Reliable data quality is however an absolute requirement.

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Online access to the Final Report: http://capella.unine.ch.chyn/

The "lost river" Ogulinska Dobra, Croatia, at its entrance to the 16 km long Medvedica cave system. Photo: M. Kuhta.

above: river dry

below: river in flood.

Glossary

Attenuation: The breakdown or lessening of the concentration of a contaminant in groundwater due to a wide range of processes.

Conduits: Solutionally enlarged passageways in karst systems in which most of the karst groundwater may flow. Conduits allow the rapid flow of water and are a major reason why karst groundwater is often highly vulnerable to contamination.

Contamination: Deterioration in the quality of groundwater due to human activities. Note that in general usage the terms contamination and pollution are often used with a range of meanings, which can easily lead to confusion. Because of the number of authors contributing to this publication the single broad term contamination only is used to describe a worsening in water quality resulting from human activities.

Contaminant: Any substance causing contamination.

Diffuse recharge: Infiltration of water through many small entry points so that recharge to an aquifer takes place spatially in a relatively uniform manner.

Doline: Small to medium sized surface depression formed by solution and typical of karst areas. Dolines range in size from a few metres to a few hundreds of metres in diameter. Synonym in USA is sinkhole.

Dry valley: A valley in which the waters of the stream/river that originally cut the valley now flow below the present land surface by means of an underground drainage network.

Epikarst: An upper weathered zone in a karst system with relatively high permeability. It can range in thickness from less than two to tens of metres. Not present everywhere in karst areas.

Groundwater resource: All the groundwater in an area that can be used.

Groundwater source: A point at which a water supply is abstracted from an aquifer.

Hazard: An event, process or activity, which has the potential to degrade the quality of the environment, in this case the quality of the groundwater.
Intrinsic vulnerability: The Intrinsic vulnerability of groundwater takes into account the geological and hydrogeological characteristics of an area, but is independent of the nature of the contaminants and the contaminant scenario.

Karst: An area of limestone or other soluble rocks, in which the landforms are mainly the result of dissolution by water and where most drainage is underground in enlarged fractures and conduits. Used as a noun and frequently as an adjective.

Karstic: Pertaining to karst. Less commonly used adjectival form of the word karst.

Karstification: The development of karst landscapes and karst drainage mainly through the process of dissolution by water.

Karst system: An interconnected area of karst rock, which forms a hydrogeological unit.

Non-karst rock: Rock the composition of which is such that chemical solution (dissolution) is not a significant process during weathering.

Origin: Assumed place of release of a contaminant in the context of the origin-pathway target concept of contamination. Synonym: source (in sense of cause of contamination).

Pathway: Everything between origin and target.

Phreatic zone: See saturated zone.

Point recharge: Infiltration of water to an aquifer through a limited number of entry sites so that the recharge is locally concentrated. Is typical of karst areas due to the presence of such features as swallow holes.

Polje: A steep-sided, flat-bottomed, closed depression found in many karst districts and ranging in extent from 1 km2 to hundreds of km2. Poljes are usually partly covered by sediments and are liable to seasonal flooding.

Protection zone: Delineated area in which groundwater is protected by restrictions on human activities. Logically the most severe restrictions are applied in those zones close to groundwater sources and in areas of very high vulnerability.

Risk: Probability of occurrence of adverse events multiplied by the consequential damage.
Saturated zone: The zone below the water table in which all spaces are water filled. Synonym: phreatic zone.

Specific vulnerability: The Specific Vulnerability of groundwater takes into account the properties of a particular contaminant or group of contaminants in addition to the intrinsic vulnerability of an area.

Subsoil: The unlithified granular material between the topsoil and the bedrock. Synonyms: overburden, superficial deposits.

Swallow hole: point where a sinking stream goes underground.

Target: The water that has to be protected. Synonym receptor. For groundwater resource protection the target is the surface of the groundwater in the aquifer; for groundwater source protection the target is the water in the well or spring.

Travel time: The time taken by a contaminant to move from its point of entry to the ground until that contaminant reaches the target.

Topsoil: The biologically active zone of weathering of the uppermost layer of the earth's crust.

Unsaturated zone: The zone between the land surface and the water table. Synonyms: zone of aeration.

Vulnerability: The sensitivity of a groundwater system to contamination.

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Legend

The last column describes the function of the respective person in COST Action 620

MC: Management Committee Member
Editor: Member of the Editors Team
WG1: Member of Working Group 1
Leader: Leader of the Respective WG (two Leaders per WG)
Chairman and Vice Chairman of COST Action 620
<A5>: Coordinator of Chapter 5 in Part A
C: Contributor to the Final Report (Author of at least one section)
note: all Editors and Chapter Coordinators are also Contributors

COST 620 Commitee

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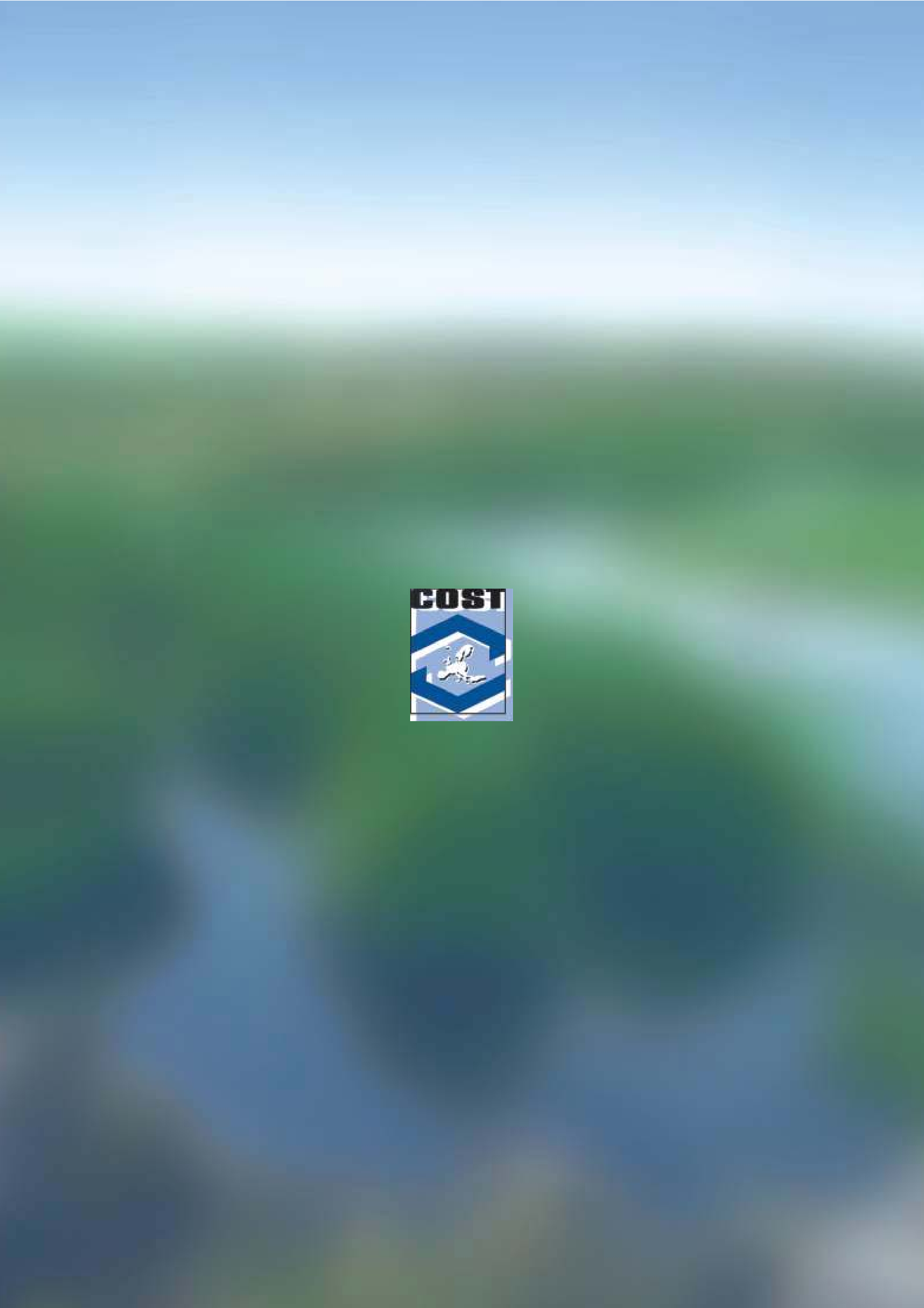
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