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SPECIAL ISSUE

Karst morphology and groundwater vulnerability of high alpine karst plateaus

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Abstract High alpine karst plateaus are recharge areas for major drinking water resources in the Alps and many other regions. Well-established methods for the vulnerability mapping of groundwater to contamination have not been applied to such areas yet. The paper characterises this karst type and shows that two common vulnerability assessment methods (COP and PI) classify most of the areas with high vulnerability classes. In the test site on the Hochschwab plateau (Northern Calcareous Alps, Austria), overlying layers are mostly absent, not protective or even enhance point recharge, where they have aquiclude character. The COP method classifies 82% of the area as highly or extremely vulnerable. The resulting maps are reasonable, but do not differentiate vulnerabilities to the extent that the results can be used for protective measures. An extension for the upper end of the vulnerability scale is presented that allows identifying *ultra vulnerable* areas. The proposed enhancement of the conventional approach points out that infiltration conditions are of key importance for vulnerability. The method accounts for karst genetical and hydrologic processes using qualitative and quantitative properties of karst depressions and sinking streams including parameters calculated from digital elevations models. The method is tested on the Hochschwab plateau where 1.7% of the area is delineated as ultra vulnerable. This differentiation could not be reached by the COP and PI methods. The resulting vulnerability map highlights spots of maximum vulnerability and the combination with a hazard map enables protective measures for a manageable area and number of sites.

Keywords Groundwater vulnerability · Alpine karst · Karst morphology · Karst plateau

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Introduction

Water from karstic catchment areas is very important for drinking water supply (e.g. European Commission 1995; Ford and Williams 2007 and references cited therein). This is particularly true for several large cities of Austria including Vienna, Salzburg, and Innsbruck. In total, about 4.1 million inhabitants, i.e. about 50% of the national population, are supplied from areas with karstic carbonate rocks (Kralik 2001). Karst aquifers generally suffer from the problem that transit times from the surface to the water body or the spring are relatively short and therefore the vulnerability to pollutants is generally very high, although the spatial distribution of vulnerability to contamination is inhomogeneous. High vulnerability and the importance of the resource call for high protective efforts. Beside techniques to assess groundwater vulnerability in general, many countries have developed methods that are especially designed for carbonate catchments. In Europe two major EU programmes dealing with the topic and a conceptual framework as well as several individual methods have been developed, applied, and validated (European Commission 1995; Zwahlen 2004).

Vienna is the classical example of a big city (1.7 million inhabitants) that is almost entirely (i.e. 96 %; Rumpold

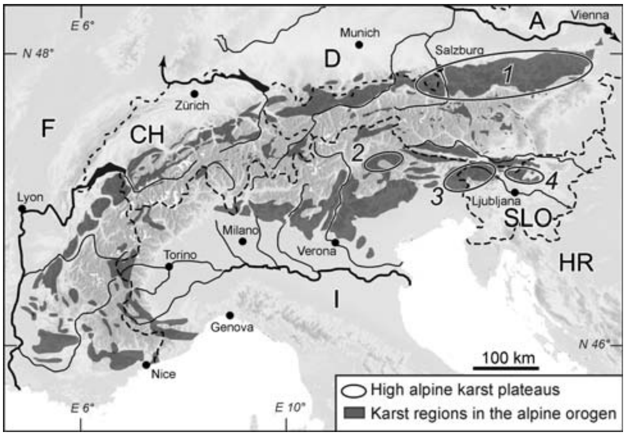

Fig. 1 Simplified map of Alpine karst regions (modified after Audra et al. 2006) with occurrences of high alpine plateau karst: *1* Northern Calcareous Alps, *2* Dolomites, *3* Julian Alps, and *4* Kamnik Alps

2007) supplied with water from karstic catchment areas. The developed springs are located at the foot of four karst massifs in the eastern part of the Northern Calcareous Alps (NCA, Fig. 1). Sixty percentage of the water derives from the Hochschwab Massif (Fig. 2). Together with several other studies, research on karst morphology has been carried out within the framework of the EU projects KATER I and II, which were initiated by the Vienna Waterworks in order to assure quality and reliance of long-term water supply (Kuschnig 2007). However, one of the standard methods like the *COP* or *PI* method (e.g. Zwahlen 2004) to assess vulnerability has not been applied yet.

In this paper, the term *vulnerability* is used for *vulnerability of groundwater to contamination* (Margat 1968). We only address *intrinsic vulnerability*, which reflects the natural property of an area regardless of the type of contamination. It has to be stated that in most concepts vulnerability is a relative, non-measurable, and dimensionless property and the higher the vulnerability the lower is the natural protection against contamination (Vrba and Zaporozec 1994). Ideally, vulnerability assessment should provide the end user with three parameters on the contaminant that decreases water quality at the target: transit time, concentration, and duration of the contamination (e.g. Bouyère 2004; Ravbar 2007). As this would require vulnerability maps for different hydrological as well as contamination scenarios, most concepts consider only transit time as main parameter and are hence designed for average high-water conditions (e.g. the *PI* method considers *average storm conditions*). An existing computer program that calculates contaminant transport at selected points is the *VULK* method (Jeannin et al. 2001), but parameters on concentrated infiltration have not been implemented into this complex model yet.

The first part of the current paper introduces high alpine karst plateaus and their special properties. This karst drainage type is found in several parts of the Alps and other mountainous regions where the partly extensive catchment areas represent major drinking water resources and are of key importance for water supply. Therefore, it is surprising that none of the existing methods for vulnerability assessment was tested in such a karst terrain yet. We demonstrate that applications of two previously proposed methods classify most of these areas as highly vulnerable. The results are reasonable, but the overall high vulnerability is not practicable under the aspect of catchment area protection, especially in high alpine karst plateaus. Although these areas are generally uninhabited and protected by law, land-use conflicts arise from pasture, tourism, forestry, and hunting. A complete protection of all extremely vulnerable areas is not possible and only a small and manageable number of extremely vulnerable sites can be subjected to rigid protective measures.

The second part of the paper therefore addresses the delineation of the most vulnerable spots in the catchment in order to select these sites for special protective measures such as fencing or regular inspections. Such *ultra vulnerable* sites are delimited using a new method extending existing methods by a further vulnerability class. The approach accounts for quantitative and qualitative data on karst features.

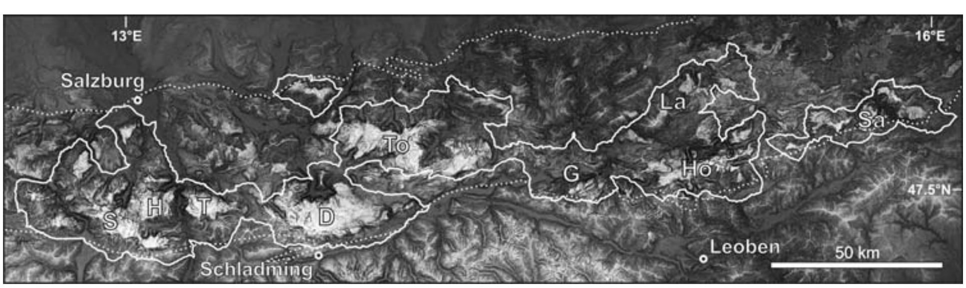

Fig. 2 The plateau-like karst massifs (white polygon) within the Northern Calcareous Alps (NCA). Greyscale of the background map depicts elevation and slope gradient highlighting elevated karst plateaus in *white* (data base: SRTM); the *dotted lines* delimit the NCA; Karst plateaus: *S* Steinernes Meer, *H* Hagengebirge, *T* Tennengebirge, *D* Dachstein, *To* Totes Gebirge, *G* Gesäuseberge, *Ho* Hochschwab, *La* Lassingalpen, *Sa* Schneeberger Alpen

Geohydrological properties of plateau-like high alpine karst

Definitions

Hötzl (1992) and Goldscheider and Hötzl (1999) differentiate two main karst drainage types in the Alps according to their geological and tectonical structures: (1) the *plateau-like karst massifs* and (2) the *folded alpine karst*. These two types differ significantly with respect to their underground drainage pattern as the plateau-like massifs mainly represent deep karsts whereas the folded units often develop shallow karsts. As the latter has been already studied with respect to vulnerability in several detailed works (e.g. Goldscheider 2002) this study will focus on plateau-like karst in high alpine settings.

The plateau-like alpine karst massifs are dominated by a thick carbonate sequence and karstified strata that partly reach well below the base level. The extensive plateau systems are often surrounded by steep slopes and major springs drain large catchments. Drainage is primarily controlled by base-level conditions, faults and, if present, the dip of the underlying aquiclude, while folding is of minor importance. Vegetation and topsoils are scarce or absent due to climate and karstification and karst morphology is very pronounced. In the Alps (Fig. 1), high alpine karst plateaus are found in the Northern Calcareous Alps (Austria and Germany), the Dolomites (Italy and Austria), the Julian Alps (Slovenia and Italy), and the Kamnik- or Steiner Alps (Slovenia and Austria). Prominent non-alpine examples are the Picos de Europa (Spain), the Velebit (Croatia) and the Arabica Massif (Georgia). Further information on the characteristics and the involved processes of alpine karst and karst genesis, respectively, are given by Frisch et al. (2002); Trimmel and Waltham (2004), and Audra et al. (2006).

Examples from the Northern Calcareous Alps

High alpine karst plateaus dominate the central and eastern parts of the NCA. Examples from west to east are Steinernes Meer, Hagengebirge, Tennengebirge, Dachstein, Totes Gebirge, Hochschwab, and Schneeberger Alpen. In the NCA, plateau-like high alpine karst massifs sum up to roughly 5000 km^2 (Fig. 2), which is 25% of the karst regions of Austria. These karstic catchment areas provide more than 2.5 million people with fresh water. Most of the resources are still unused.

The massifs are dominated by a sequence of limestones and dolostones of Middle and/or Late Triassic age with thicknesses in the order of 2,000 m (Mandl 2000) and only in some areas, minor Jurassic and Cretaceous rocks are present. At least on one side of the plateaus major aquiclude units are found well below the base level. As part of the alpine fold and thrust belt, the strata are affected by polyphase deformation and the tectonics is very complex. Partly vast plateau systems of assumed Eocene origin (Frisch et al. 2002) are preserved in areas not affected by glacial erosion, which were Pleistocene nunataks sticking out of the alpine ice stream network. Surface and subsurface karst features are generally well developed. The vadose zone has thicknesses in the range of 1000 to more than 1500 m.

The Hochschwab Massif test site

Geographical and geological outline

The Hochschwab range covers an area of about 560 km^2 including about 85 km^2 of an elevated karst plateau. The elevation ranges from about 1400 to the summit at 2277 m whereas valley floors lie at about 600 m. In the summit area, mean annual temperature is around freezing point and precipitation is in the order of 2,000 mm/a. The lowermost parts (<1600 m) are covered with scattered forests dominated by spruce, larch, and beech trees, whereas mugo pines occur up to about 1,900 m. Grassy vegetation on thin soil covers persists partly up to the summits.

Hochschwab is part of the non-metamorphic cover nappes of the NCA. The lithostratigraphic succession (Fig. 3b) comprises more than 1500 m thick, mainly Triassic sediments (Mandl et al. 2002). It consists of Lower Triassic sandstone and shale (Werfen Formation), up to 900 m of mostly shallow-marine Middle Triassic limestone and dolostone (Steinalm-, Wetterstein Fm.). A thin layer of Upper Triassic siliciclastic aquicludes (Raibl Fm.), and platform carbonates (Hauptdolomit-, Dachsteinkalk Fm.) are only of local importance. Clastic sediments of the Cretaceous to Paleocene Gosau Group overly the sequence locally. The carbonates combine to a huge aquifer, which is for the most part devoid of significant internal aquicludes and extends from the plateau down below the base level. The Werfen Fm. is the only significant aquiclude. The Hochschwab is characterised by a complex polyphase tectonic evolution including thin-skin fold and thrust deformation, strike-slip faulting along WNW-trending dextral strike-slip faults, and sinistral wrenching along major E- to ENE-trending faults (Decker et al. 2006).

Investigation methods and observations

The Hochschwab Plateau has been field mapped in detail (1:5,000) by Plan and Decker (2006). Data and results are summarised in a karst morphological GIS which covers 59 km^2. Entities are linked to an extensive database comprising information on 12,700 karst features including karst

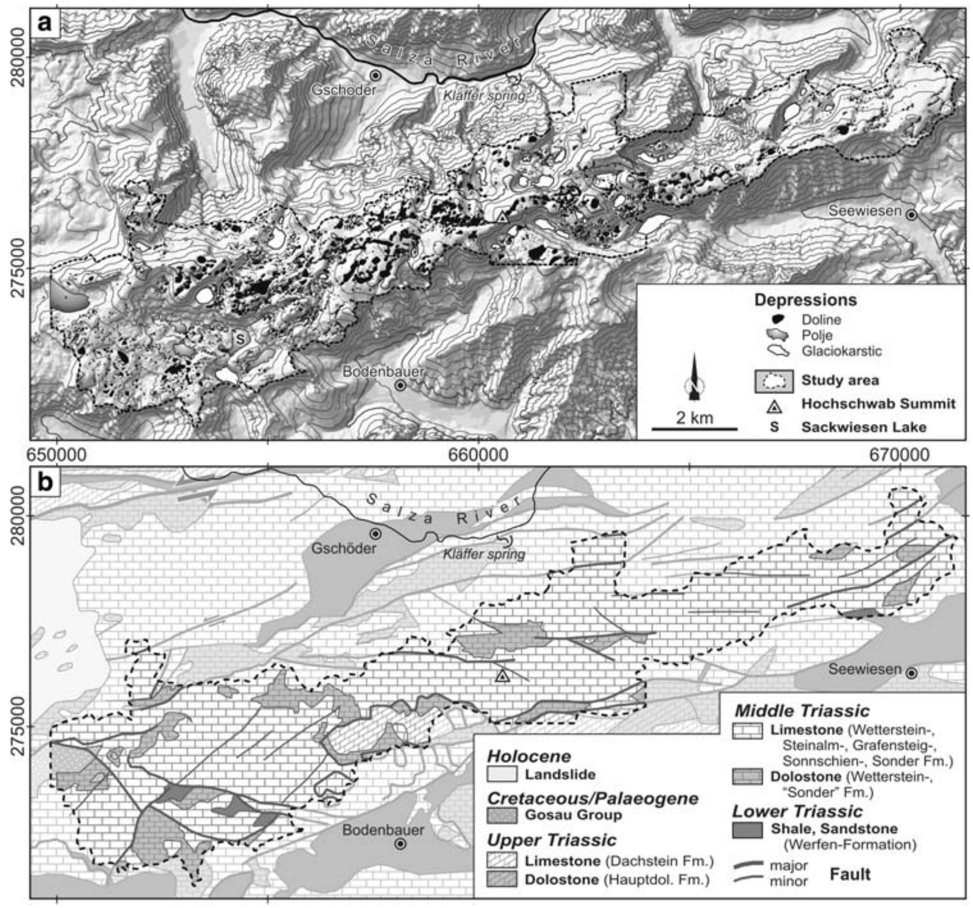

Fig. 3 **a** Simplified karst morphological map of the Hochschwab plateau (modified from Plan and Decker 2006). Note that most dolines are not visible because of their small size. **b** Simplified geological map of the Hochschwab Massif modified from Mandl et al. (2002); grid: metric Austrian Bundesmeldenetz (BMN)

landforms (dolines, poljes, polygenetic glaciokarstic-depressions, dry valleys, caves, and karren), hydrological items (springs, surfaces streams, ponors, and ponds), geologic items relevant as protective covers (Cenozoic clay covers and glacial deposits), and anthropogenic features as possible sources of pollution (mountain huts, hiking trails, gravel roads, meadows used for pasture, and gravel pits).

With respect to vulnerability, the following karst morphological observations are relevant. Dolines are very frequent with 7,151 features exceeding 2 m in diameter. Average doline density is 122 features per km^2 but the distribution is inhomogeneous mainly due to glacial erosion. Very high densities of small dolines are found in formerly glaciated areas and few, but big features (up to 500 m diameter) occur on palaeo surfaces (Plan and Decker 2006). Doline morphology is mostly funnel, bowl, or pit shaped and most features are observed to be of solutional origin. Several structural poljes developed on the aquiclude Werfen Fm., which is uplifted with respect to the surrounding Triassic carbonates at major tectonic faults. Poljes show a surface drainage system infiltrating into ponors. Polygenetic glaciokarstic depressions are found in areas with massive glacial erosion and reach diameters of more than 500 m and depths of 60 m. All closed depressions make up 11.4% of the area of investigation (Fig. 3a).

The area is also rich in caves. More than 1,000 entrances have been mapped. Deep vadose canyon shafts up to 700 m depth show that the karst water table is partly more than 1,000 m below the plateau (Plan 2004). Springs, streams, and ponors are rare throughout the karst plateau except for the poljes. Seepages that feed short minor streams are mostly found on dolostones. Temporary streams are only active after heavy rainfall or during snowmelt and mainly form on steep slopes in combination with dolostone bedrock. In spring during snowmelt, when the soil and small epikarst voids are still frozen, surface flow is widespread. Up to some metres thick clays that are interpreted as palaeosoils (Frisch et al. 2002) cover 2.4% of the plateau. These clays create flat floors with mostly sharp steps, dolines, or ponors at the edges to the surrounding carbonates that indicated the aquiclude character and the concentration of flow. More detailed descriptions concerning karst morphology, lithology, and structural geology including detailed karstmorphological maps are presented in Plan and Decker (2006). Apart from airborne pollution, potential hazards to the karst aquifer mainly originate from pasture, tourism, forestry, and an unnaturally high game population (mainly chamois and deer).

The influence of karst morphology on vulnerability assessment

Existing approaches

The first method for groundwater vulnerability assessment especially designed for karst terrains was the *EPIK* method (Doerfliger et al. 1999). Beside the factors ***P****rotective cover* and ***K****arst network development* it considers ***E****pikarst development* and ***I****nfiltration conditions* with high priority. Epikarst development is evaluated from the existence of shafts, ponors, dolines, and karren fields.

Within the COST Action 620 (Zwahlen 2004), several separately developed methods for intrinsic vulnerability assessment have been proposed. The so-called *European Approach* (Daly et al. 2002, Zwahlen 2004) is a general conceptual framework of the individual methods. Up to four main factors are considered within the model (Goldscheider and Popescu 2004, Fig. 4a): The internal characteristics of a karst system are based on the factors *O* (*Overlying layers*), *C* (*Concentration of flow*), and *K* (*Karst network development*). The external characteristics are described by the *P* factor (precipitation regime) which is mainly relevant if catchments in different climatic regimes are compared, as variations are minor within a single drainage basin.

The *PI* method is one of the most frequently applied ways to implement the *European Approach* (Goldscheider et al. 2000, Goldscheider 2005) considering the factors *Protective cover* (*P*) and *Infiltration conditions* (*I*). The *P* factor specifies the protective function of the layers between the surface and the groundwater table. It represents the O factor (overlying layers) of the *European Approach*. The *I* factor describes the infiltration conditions, in particular the degree to which the protective cover is bypassed in the catchment of a ponor or sinking stream and is thus equivalent to the *C* factor (concentration of flow). In detail, karst features are incorporated as follows: every swallow hole (ponor), the contributory stream, and a 10-m buffer zone are indexed in a way that vulnerability is classified as *extremely high.* Other areas within the catchment of active ponors are classified according to distance from the sinking stream, dominant flow process, land use, and slope gradient. Large dolines can be classified like any other area and thus vulnerability is mainly dependent on sediment and soil cover. Dolines that are too small for this assessment are classified according to their sediment fill. Active or dry dolines without sediments are classified as *extreme,* and dolines with partial sediment fill with *high* vulnerability.

The *COP* method (Vías et al. 2006) is straightforward related to the European approach. The influence of karst morphology is considered within the *C* factor (adapted from the European Approach). In the *Localized European Approach* (*LEA*; Dunn 2004) karst morphology has top-ranking as all areas with karst features including a buffer zone are regarded as *extremely vulnerable*.

SINTACS (Civita and De Maio 2000) uses eight parameters whereas a revised version of the weighting and rating system (Cucchi et al. 2004) uses a special treatment

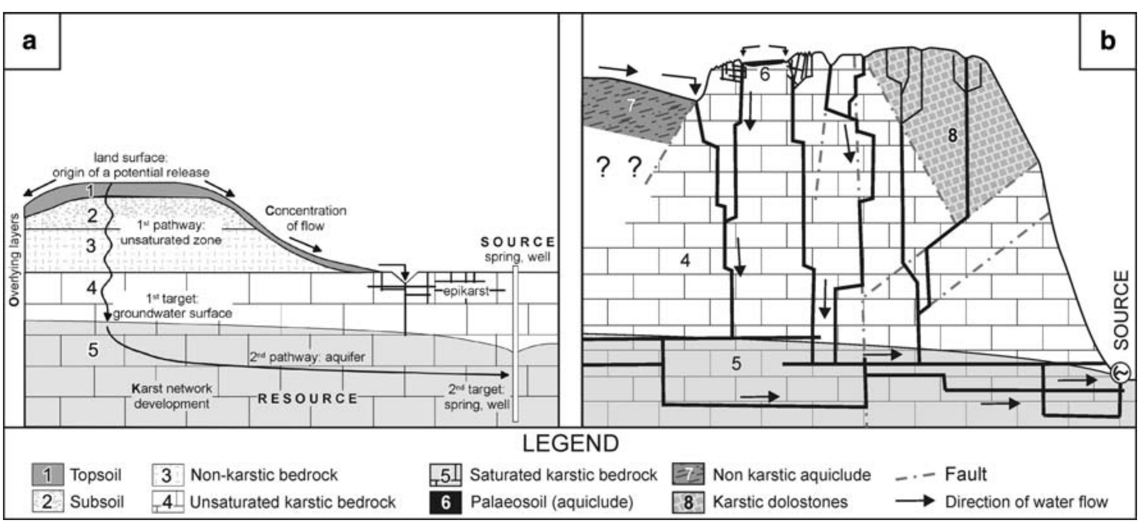

Fig. 4 **a** Origin-pathway-target conceptual model of the European Approach to groundwater vulnerability mapping after Goldscheider and Popescu (2004). **b** Conceptual model illustrating infiltration and flow in a high alpine karst plateau. Most of the plateau is devoid of protective layers. Both aquicludes (6 and 7) lead to a concentration of flow. The concentrated infiltration of surface water into karst conduits depends mainly on the properties of the sinking stream and the karst depressions

for doline and polje slopes as well as karren fields that is considered within the factor *hydrologic role of the topographic slope*.

The newly developed *Duality Method* (also *Simplified Method*; Nguyet and Goldscheider 2006) which was designed for developing countries where the data basis is insufficient was tested in a tropical karst area in Vietnam. The method accounts for the fact that tracer experiments and field observations (e.g. Perrin et al. 2004) have shown that infiltration and flow velocities in the vadose zone can be high even if surface karst features are absent. Therefore, only *dolines that actually act as swallow holes* are assigned with extreme vulnerability and *the rest of the karst area that is covered with less than 30 cm of soil is classified as highly vulnerable*.

Vulnerability assessment in alpine settings

Several methods described in Zwahlen (2004) and others like *EPIK* have been applied in various test sites including pre-alpine (Kralik and Kaimel 2003, Laimer 2006) and high alpine settings (e.g. Goldscheider 2002, Cichocki et al. 2004), but none of them was applied in high alpine plateau settings yet.

VURAAS (Cichocki et al. 2004) is especially designed for high alpine settings and is based on the *PI* method, but includes data on the hydrodynamics derived from hydrochemistry and isotope-hydrology. It was tested on the Nassfeld in Carnian Alps but the site has no pronounced karst morphology. Laimer (2006) employed this method in a pre-alpine karst setting in the NCA including minor low lying ($\sim$1400 m) plateaus. Independent of the complex geology all parts that show the character of a plateau including well-developed karst features were classified as *very high* throughout.

Though the *Time-Input* method (Kralik and Kaimel 2003) was developed and tested in a pre-alpine dolomite karst in the NCA with inconspicuous karst morphology, no proper treatment for dolines or karst features at all was implemented into the assessment scheme.

The Sierra de Líbar (Southern Spain; Andreo et al. 2006) is somehow similar to alpine plateau settings as it is characterised by a variety of karst features and especially bare karren fields and poljes. Using the *PI* method most of the area was classified as *extremely vulnerable* and with the *COP* method significant parts of these areas were rated as *high* whereas the other parts were also rated *very high*.

The COP method applied to the Hochschwab plateau

Vulnerability of the Hochschwab plateau was assessed with the COP method whereas the following factors were used:

(1) **The *O* factor:** Soils [O_S] are often absent. Thin (mostly 0–0.5 m) loamy soils mainly occur in vegetated areas. Palaeosoils were classified as *clayey*. In most areas, the lithology [O_L] consists of a massive layer of karstic rock of 350–1400 m thickness from the surface down to an assumed karst water table. A higher protection level is provided by sandstones of the Gosau Group as well as shales and sandstones of the Werfen Fm. The *O*-Map is shown in Fig. 5a. As the vadose zone has thickness of more than 250 m throughout, there are no areas with *very low* protection value.

(2) **The *C* factor:** *Scenario I*, where water infiltrates into a swallow hole, is found within the polygenetic alpine poljes, on some dolomitic slopes, and on several occurrences of palaeo soils, where marginal dolines and small ponors indicate swallow hole recharge. As distances to the ponors are less than 500 m throughout, slope and vegetation do not modify the very high concentration of flow. *Scenario II* (rest of the area) is mainly characterised by developed or scarcely developed karst. Closed karst depressions make up more than 11% of the area and more than 2,000 entrances of caves, shafts, and small epikarst shafts have been mapped. Karren fields are frequent and the development of an epikarst layer is expected in most areas. Further indicators for a well-developed karstification are the presence of deep (>700 m) vertical shafts (Plan 2004), the correlation of tectonic structures with karst structures (Decker et al. 2006), and hydrographs of the main springs that shows a responds to hydrological events after 7 h (Stadler et al. 2001). The karstified areas are partly covered by debris, till, or impermeable layers of palaeosoils. Slope gradient and vegetation additionally modify these factors. The *C*-Map is shown in Fig. 5b.

(3) **The *P* factor:** Precipitation is above 1,600 mm/a and according to approx. 200 rainy days per year the factor for temporal distribution [P_I] is below 10. Therefore, the *P* factor is negligible for the COP map.

The resulting COP map is shown in Fig. 5c. Thirty-five percentage of the area is classified with *very high* vulnerability, 47% with *high*, 17% with *moderate*, 1% with low and no area with *very low* vulnerability.

The PI method applied to the Hochschwab plateau

Vulnerability estimates of the Hochschwab area using the PI method consider the following factors:

(1) **The *P* factor**: *Topsoils* are absent or generally thin and discontinuous. Only below mugo pines (*Pinus mugo*) significant soils have developed. *Subsoils*,

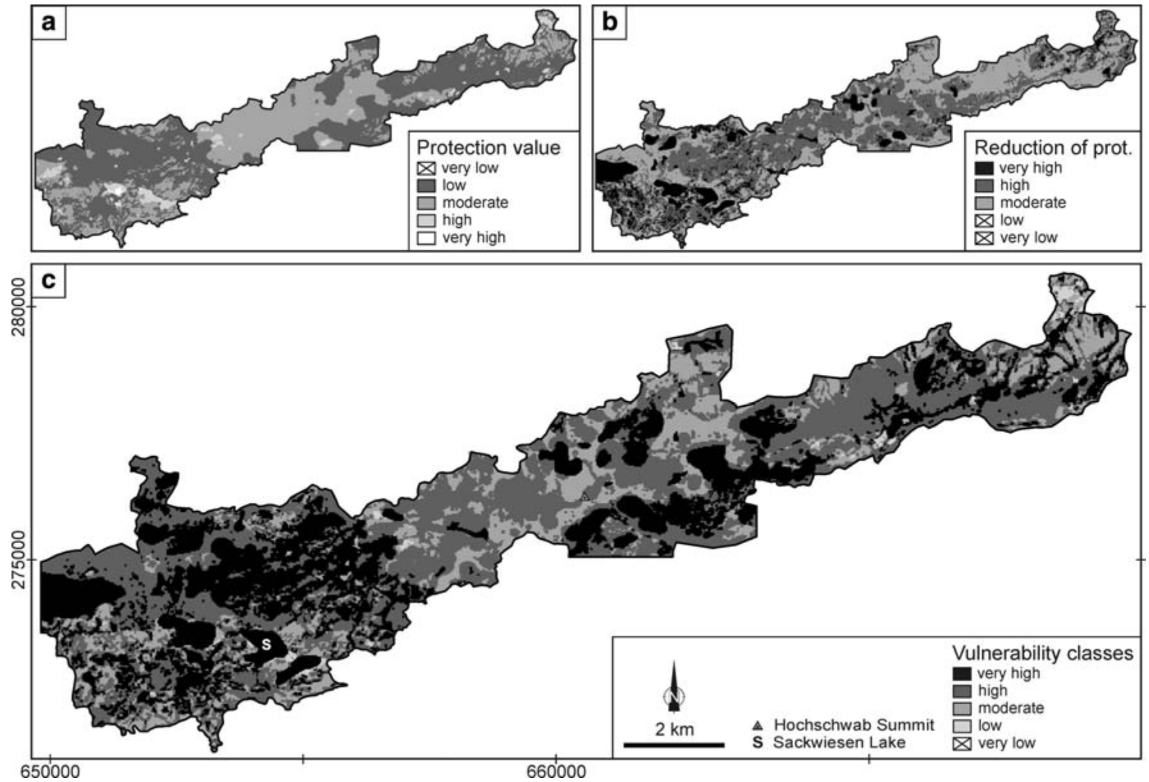

Fig. 5 Application of the COP method on the Hochschwab test site; **a** O map with protection values of overlying layers; **b** The C map displays the reduction of protection by the concentration of flow; **c** COP map of the Hochschwab plateau resulting from the combination of (**a**) and (**b**)

represented by the clay covers, reach thicknesses of sometimes several metres and cover 2.4% of the area. Till and periglacial material only slightly enhance the protective properties. For most parts, *Lithology* consists of several hundred metres of karstified carbonates where *Fracturing* is very high (low *P* value). *Precipitation* is in the order of 1,600–2,200 mm/a and therefore diminishes the function of protective covers.

(2) **The *I* factor:** As for the carbonate areas without subsoils, the *P* factor indicates that strata overlying the karst water body are not protective and thus for any value of the *I* factor vulnerability will remain high. Aquiclude shales and sandstones lead to surface streams that drain into ponors, and in most of these areas, polygenetic alpine poljes have formed. Therefore, both aquiclude geological units and subsoils lead to surface runoff that infiltrates into well-developed karst conduits. Within the plateau area of Hochschwab, 100% of the runoff infiltrates into the karst body and no surface runoff exists that reaches the base level. As dolines lacking soil- and sediment-fill or secondary dolines at the margin of clay infillings indicate direct infiltration, these features are attributed as extremely vulnerable throughout.

According to these considerations, resource vulnerability assessment with the PI method also classifies most of the plateau area as *extremely vulnerable* and subordinately *highly vulnerable*. This estimate is in accordance with other areas where both, the PI and the COP method were applied (e.g. Andreo et al. 2006; Ravbar 2007). There, the PI method assigned even higher vulnerability classes than the COP method.

Proposed method

Adaptation of the European Approach for high alpine plateau settings

In areas with few karst features and a karst aquifer that is significantly protected by overlying layers, there are some highly vulnerable areas and it is a feasible task to protect all of them. However, in the previous chapter we have seen vulnerability assessments from a high alpine plateau setting and similar areas obtained by different methods that assign the two highest vulnerability classes to most of the area. Even though this result seems reasonable, it is not satisfactory for water suppliers or land use administrations to see that most of the area is extremely vulnerable without further differentiation. The results do not provide a useful tool for setting punctual protective measures. This shortcoming demands an adaptation of the conceptual model of the *European Approach*. In many carbonate areas, the *O* factor is the most important one, as it describes the permeability of geologic layers that overlie the karst aquifer and concentrated infiltration is rather considered as the exception (Fig. 4a).

In high alpine plateau karst, the overlying rocks do not significantly purify the water and the model has to be adopted as shown in Fig. 4b. Most localities are devoid of different overlying layers. The several-hundred-metres-thick sequence of well-karstified carbonates is not interrupted by less karstifiable rocks and does not protect the karst water body very much. Transit times from the infiltration to the saturated zone are short. Aquiclude units at the surface lead to surface streams that directly infiltrate via ponors into the conduit system. Occasionally occurring palaeosoils are the only significant subsoils but they do not diminish vulnerability, as they favour a concentration of flow. A crucial point is the occurrence of epikarst, which was formerly considered as a factor increasing vulnerability (for instance in the EPIK-Method; Doerfliger et al. 1999). However, recent studies (e.g. Perrin et al. 2004) reveal that water storage within the epikarst is important and therefore it has a significant protective function, especially if other protective covers like soils are missing. Within the saturated zone, a well-developed conduit system leads the water to the source, which is a major karst spring.

According to this modification, the concentration of flow (*C* factor of the *European Approach*) is the most important factor for vulnerability assessment on high alpine karst plateaus and therefore, the determination of karst geomorphology and (near) surface hydrology is of key importance. Within the European approach data on the *C* factor, karst morphology is incorporated in a qualitative way, which leads to an undifferentiated extreme vulnerability for most of the area of high alpine plateaus. The PI method assigns extreme vulnerability to a carbonate area with thin soil cover, where epikarst is expected from nearby karren fields. The same vulnerability class is assigned to a shallow doline as well as to a permanently active swallow hole (ponor) and its contributory stream. However, it seems straightforward to regard the area directly drained by a permanently active ponor more vulnerable than a shallow doline exclusively drained by subsurface flow. Conventional methods for vulnerability assessment in karst suffer from shortcomings concerning the upper end of the vulnerability scale, which prevent discrimination between the two scenarios. In the following, we recommend introducing qualitative and quantitative data on karst morphological features such as dolines and ponors for a further differentiation of highly vulnerable areas.

Delineation of ultra vulnerable areas

The presented method is an extension of existing vulnerability methods. The weighting and rating schemes to determine vulnerability classes as well as the terminology should not be changed in order to underline that most of the area is indeed highly vulnerable. For example, the PI method uses five classes, namely very low, low, moderate, high, and extreme. In the following we extend the upper end of the scale with an additional class which here is referred to as *ultra vulnerable*.

Lowest points within closed karst depressions like dolines and poljes have the function of a ponor and are points of direct infiltration, at least under flood conditions or for subsurface flow within the epikarst. The expression *sink* will be used as a general term for these points.

Hydrological and karst genetical models as well as morphological considerations suggest that (1) flow type towards a sink, (2) infiltration conditions, (3) karst depressions type, and (4) slope gradient within the sink's catchment are major factors that influence vulnerability. The proposed method accounts for these facts. It is based on the considerations of the *duality method* (Nguyet and Goldscheider 2006) in which only active dolines and sinking streams are regarded as extremely vulnerable. To enable the user to define an amount of ultra vulnerable areas, that is useful for the area to be assessed and the specific protective measures, the following threshold values are suggestions which were adopted from the COP and the PI methods. However, thresholds can be refined by the user.

Flow type

Surface or near-surface flow towards a sink is easily classified into three types. These are (1) permanent surface streams (Fig. 6), (2) intermittent surface streams (Fig. 7), and (3) entire subsurface flow. Permanent surface flow is regarded as most vulnerable as there is always an agent to carry the pollutant to the resource or source. Subsurface flow within the epikarst is only highly critical on steep doline slopes close to the sink.

Infiltration

For the infiltration of surface streams, we distinguish (1) point recharge and (2) diffuse infiltration. The second type is common on glacial or periglacial debris where mainly diffuse recharge is observed. According to field tests by Perrin et al. (2004) these materials show some retention and self cleaning potential and are therefore regarded as less vulnerable.

All permanent sinking streams including a small buffer zone (e.g. 10 m) with a maximum distance upstream from

Fig. 6 A shaft ponor (*arrow* right of waterfall) permanently draining an alpine polje (cattle for scale) classified as *ultra vulnerable*

Fig. 7 Intermittent ponor (*arrow*) within a major depression in dolomitic bedrock classified as *ultra vulnerable*. The alluvial fan is about ~50 m wide

the ponor (e.g. 500 m) are mapped as ultra vulnerable. Intermittent surface streams are only considered (using the same distance limits), if they show point recharge into a ponor or a restricted area.

Depression type

Closed depressions in karst areas and especially in high alpine settings, result from a variety of genetical mechanisms including glacial processes, which cause distinct hydrological properties. Alpine poljes often show a permanently active surface drainage network and concentrated infiltration at one or few ponors. Therefore, poljes host the most vulnerable areas. Solution dolines are by far of the most common depression type that is generally well connected with a sub vertical drainage system. Collapse dolines are rare and do not necessarily have a connection to the hydrologically active conduit system. Some of the features that look similar to dolines are pits that have been truncated by glacial erosion and were reshaped by surface weathering, which are well connected to the conduit system. Glaciokarstic depressions are not necessarily well linked to a conduit system at their deepest point and are therefore regarded as the least vulnerable depression type. Therefore, subsurface flow within this type is not regarded to result in ultra vulnerable conditions even in cases where slopes are steep.

Slope gradient close to the sink

Steep slopes favour surface flow velocities but also high velocities of subsurface flow. According to well-established models on the subsurface flow within the epikarst (e.g. Williams 1983; Sauro 2005) the following conclusions can be drawn: (1) subsurface topography of the subcutaneous water table follows surface topography and (2) slope gradient is proportional to subsurface flow velocity towards a vertical conduit. Slope gradients of karst depressions therefore are a major factor determining the transit time of water infiltrating via subsurface flow. This approach is a simplification of the considerations used for the evaluation of the *I* factor in the *PI method* (Goldscheider et al. 2000). Steep slopes (e.g. >78%) and the area directed towards a sink are a further criterion for the delineation of ultra vulnerable areas. Furthermore, only slopes with a certain distance (e.g. 50 m) from the sink point are considered.

Assessment of the parameters

The data acquisition includes GIS-based computations and field assessment (Fig. 8). The area-wide detailed field mapping at least considers: type, depth, and diameter or outline of karst depressions, permanent and intermittent surface streams and their infiltration conditions. Field mapping has to check the data calculated from the DEM.

Morphometric data on larger depressions are computed on a high resolution (at least 20 m) digital elevation model (DEM), which is also used for delineating closed depressions and sink points. For the calculations, we use WinGeol-TerraMath GIS (Faber 2007). As morphometric data calculated from the DEM is limited by its resolution karst depression with a diameter smaller than five-times the DEM grid resolution are characterised by field data. For these smaller features, the slope gradient is calculated from depth and the average diameter measured in the field.

Areas within large dolines or poljes are assigned with ultra vulnerability when having both, steep slopes (e.g. >78%) and small distances from the sink (e.g. <50 m;

Fig. 8 Workflow for the assessment of ultra vulnerable areas. The thresholds used for the assessment on the Hochschwab test site (marked with *asterisk*) can be modified by the user

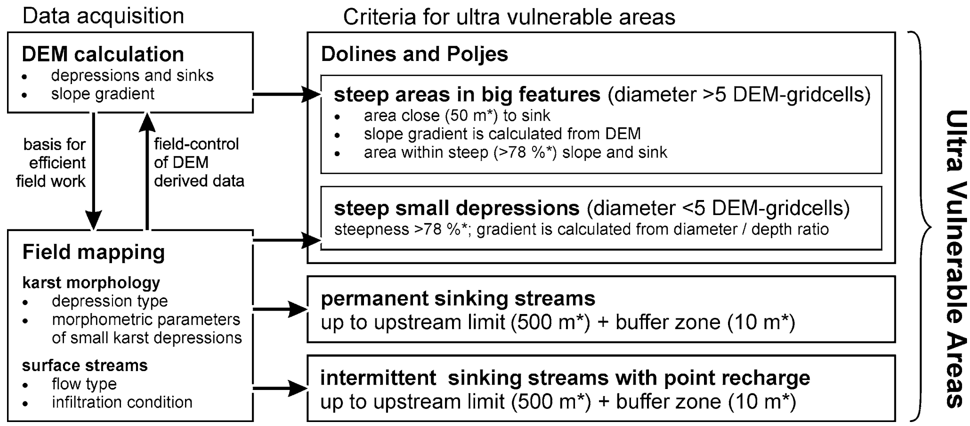

Fig. 9). These parameters can be calculated from the DEM by the combination of the following layers:

- Distance to sink (local minima—i.e. grid cells that are surrounded by cells with higher cell values—are computed and the buffer zone is calculated around these points).
- Slope gradient.
- Area between steep slopes and sink point, which can be calculated with a flow accumulation algorithm (e.g., the D8 flow direction algorithm; O'Callaghan and Mark 1984) where the flow path is traced downward from steep-slope-cells only. As flow-paths within the doline are in most cases straight towards the sink point, it is also possible to consider all cells in between steep cells and the sink point instead.

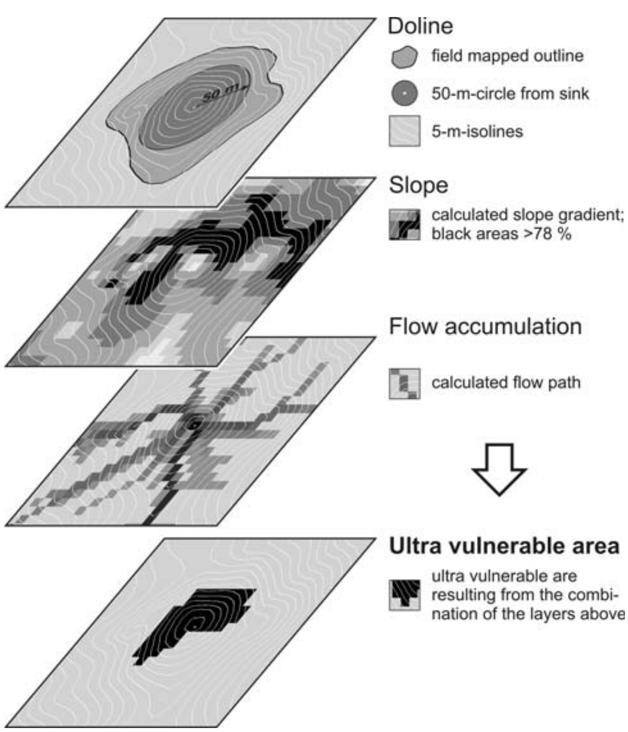

Fig. 9 Example of a *doline* with 150 m diameter and 40 m depth analysed using a 10-m-DEM. The linkage of the layers 50-m-distance from sink, slope gradient, and flow accumulation results in the delineation of an ultra vulnerable area

These data are plotted on a preliminary map and validated in the field in order to exclude slopes from glaciokarstic depressions and to detect errors of the DEM. The map of ultra vulnerable areas is created using the following grid layers, which are linked with a logical OR:

- sinking streams including a buffer with the upstream distance limit (intermittent streams are only considered if they exhibit point recharge), OR
- areas within karst depressions with steep slopes derived from the field mapping (for depression diameter <five-times DEM-grind-size), OR
- areas with steep slopes that are within a certain radius of sink (for depression diameter >five-times DEM-grid-size).

Application to the Hochschwab test site

For the Hochschwab plateau, data were provided by the karst morphological field mapping and morphometric data for bigger depressions were calculated from a DEM with 20 m resolution. The calculation used the threshold values suggested in the previous chapter. The resulting map of ultra vulnerable areas is shown in Fig. 10. Within the test site, 1.7% (1.0 km^2) of the area is delineated as ultra vulnerable. Most of these areas are intermittent sinking streams (0.55 km^2) whereas permanent sinking streams sum up to only 0.12 km^2. A small lake (Sackwiesensee) that directly drains into a ponor accounts for 0.04 km^2. Steep doline and polje slopes of small features (<100 m diameter) derived from the field mapping make up 0.18 km^2 and for big features, which were derived from the DEM, steep slopes and the connection to the sink sum up to 0.13 km^2.

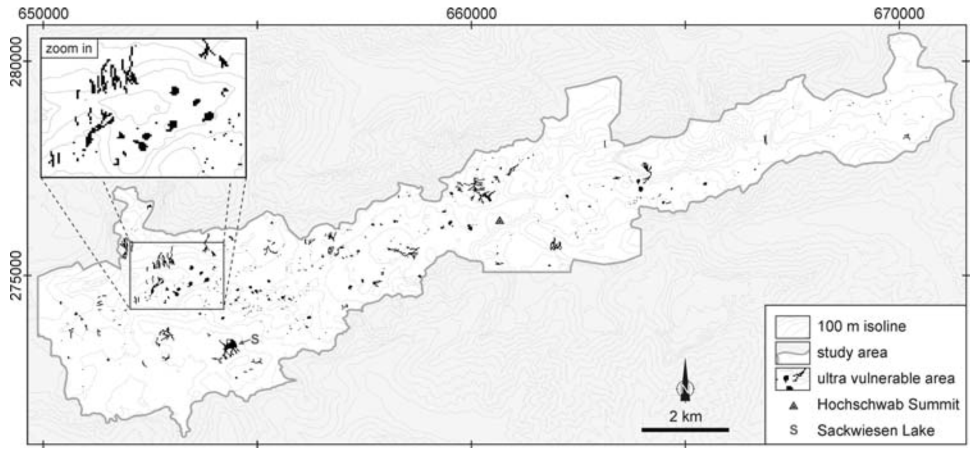

Fig. 10 Ultra vulnerable areas at the Hochschwab test site. The sites are delineated on the basis of karst morphological and hydrological criteria. (Grid: metric Austrian Bundesmeldenetz, BMN). The *zoom box* in the *upper left* shows more detail of the map

Discussion

The determination of surface streams as ultra vulnerable sites, as suggested in the proposed method, is based on the arguments presented within Nguyet and Goldscheider (2006) to introduce the *duality method*. As there, highlighting permanent sinking streams has the advantage that it accounts for the fact that water is always present to carry the pollutant into the karst system. This is not the case for any other site.

The determination of the thresholds for the quantitative parameters, like slope gradient and buffer to the sinking stream, are based on other methods but are nevertheless empirical. However, vulnerability is a non-measurable relative property and it is important that the results are practical. Therefore, these values can be adjusted to result in a reasonable portion of ultra vulnerable areas for which protective measures are possible and feasible.

The usage of a DEM implies always a simplification of nature and the results have to be handled with care. Generally, DEMs with resolutions of less than 20 m are not regarded as sufficiently accurate for automatic karst morphological mapping. Probably within the next years, also DEMs obtained by laser scanning (LIDAR) that have cell sizes of 1 m or less will be available and GIS based detailed morphometric analysis of karst features will be facilitated.

Especially flat areas with very low gradient and valleys with valley floors narrower than a single DEM-cell frequently show lowest points, which are data artefacts (or false sinks). On significantly dipping slopes these errors are rare. As most of these artefacts only affect a single cell, these errors are negligible. Theoretically, within highly asymmetric depressions, the sink point is closer than 50 m to the outline of the topographic catchment and therefore parts of other catchments could be considered that are not close to a sink. However, we checked this possibility by employing a flow accumulation algorithm and couldn't find any case where the slope of the adjacent catchment is steeper than 78% which would have given wrong results.

A shortcoming of the presented method is that it has not been validated yet by means of dye tracer experiments as has been done for some other methods and test sites (e.g. Perrin et al. 2004). However, many elements of the assessments are based on existing methods that have already been successfully validated. A comprehensive tracer experiment is planned for the upcoming years, whose results will help to validate or improve the proposed method. At present, the proposed method uses only travel time of the contaminant to assess intrinsic vulnerability, as it is used by most methods. Within further studies, it will be challenging to introduce more complex contamination parameters and hydrological scenarios into the approach.

The assessed ultra vulnerable areas (Fig. 9) are in good agreement with the COP map (Fig. 5c) as most of them lie within areas of very high vulnerability. Exceptions are only found on steep doline slopes in carbonate areas with a vadose zone of more than 1,000 m thickness which assigns a moderate protection value to the elevated parts of the plateau. However, according to field observation in deep shafts on the Hochschwab, where water falls down more or less freely for several hundred metres, the protective value for *karstified rocks* seems to be overestimated. If this 1,000-m-threshold is neglected, 49% of the area is assigned with very high vulnerability and all ultra vulnerable sites fall within the highest vulnerability class throughout. This modification is in accordance with the *Slovene Approach* (Ravbar 2007) that is an enhancement of the COP method, where a new *ly* value of 0.2 for *extremely karstified areas* (instead of using 1 for karstified rocks throughout) was introduced to account for similar considerations.

The presented method can also be used independently, i.e. without a common vulnerability mapping method applied in advance, if only points of extreme vulnerability should be delineated or if for all areas in the investigation area no arguments can be found, that the vulnerability is moderate or low. The introduction of *ultra vulnerability* as an additional vulnerability class may cause confusion and the user of the map must be aware that also areas of high vulnerability have to be protected.

Conclusion

High alpine karst plateaus play an important role as catchment areas for drinking water supply. They are characterised by a very thick sequence of well-karstified carbonates, widespread point infiltration into numerous dolines, and direct infiltration of surface streams into ponors that occurs on aquiclude or aquitard geological units and on clay covers. If standard methods for vulnerability assessment such as the COP or the PI method are applied on these sites, most of the area is classified with the two highest vulnerability classes, which is not a satisfactory result. The nearly total absence of protective layers or a protective cover overlying the karst aquifer, which is regarded the most important parameter in many methods, requires a modified methodology for intrinsic vulnerability assessments. The proposed modified methodology considers parameters on karst morphology and near surface hydrology in the epikarst as essential for vulnerability assessment and allows a further differentiation of highly vulnerable areas.

We present an improved method as an extension of existing methods, which defines an additional class for the upper end of the vulnerability scale. The so-called ultra vulnerable sites are delineated by data on flow type towards a recharge point, infiltration conditions, karst depressions type, and slope gradient within depression. The method was applied to the Hochschwab plateau where 1.7% of the area was classified as *ultra vulnerable*. Thus, the resulting map in combination with a hazard map enables protective measures for a small and manageable number of sites and areas.

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